



# **Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats**

## **(STO-TR-HFM-270)**

### **Executive Summary**

The increasingly complex and technologically sophisticated threat environment to NATO member nations continues to increase the threats, especially those posed by explosive devices and weapons. These weapons of choice with NATO adversaries continue to dominate modern warfare, and the injuries they cause can be complex and catastrophic. Developing an end-to-end representation of potential threats and their possible mitigation and/or medical treatment through an integrated computational modeling framework will provide improved warfighting capability to the NATO members and is the scope of this RTG.

In the last 25 years, computational modeling has made a significant impact on blast threat prediction and performance of protective equipment and systems. These simulation results have suggested that a comprehensive, whole human blast effects modeling capability could provide the ability of NATO nations to counter rapidly emerging blast threats, as well as create safer environments for training and combat scenarios. To address these aspects of modeling and simulation, the NATO Human Factors and Medicine (HFM) Panel established the NATO HFM-270 Research Task Group (RTG), "Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats". The HFM-270 RTG comprised 22 appointed members from 10 nations: Canada, France, Germany, Israel, Netherlands, South Africa, Sweden, Turkey, United Kingdom, and the U.S. This team represented medical, operational and materiel development communities, and diverse disciplines, including engineering, biological sciences, and medicine.

The overarching objective of the RTG was to leverage previous, ongoing, and planned blast injury biomedical research and computational modeling efforts among the participating nations to develop a conceptualized framework of computational models capable of providing threat-to-outcome modeling and simulation of blast effects on humans to support rapid development, testing, and fielding of effective protection equipment to Service members.

This RTG conducted an in-depth review of modelling and simulation as the first task. The key characteristics addressed by the researchers were documented, and the limitations in developing a simulation-based approach were identified. The three major deficiencies noted were: a) Lack of end-to-end connection and continuity in the simulation model to address combat injuries utilizing the techniques; b) Insufficient and incomplete material models essential for such simulations; and c) Limited validation of the models based on the necessary experimental data. In this report, these findings are used to create an end-to-end – threat to clinical diagnosis – modeling and simulation framework and explain how such a framework can be implemented in practice by NATO members with examples. This framework can be applied in pieces or as a whole by NATO member nations in identifying research needs and executing projects to enhance scientific and technical capabilities for NATO advantage over its adversaries. The framework can also be implemented to assess new threats, new science and technology tools, and new protective systems to determine their effectiveness. Lastly, the framework can also support the science and technology needs for a programmatic development of future blast-related research in NATO member nations.

# **Cadre de modélisation et de simulation de la létalité, des blessures et des déficiences humaines dues aux menaces associées aux explosions**

## **(STO-TR-HFM-270)**

### **Synthèse**

De plus en plus complexe et technologiquement sophistiqué, l'environnement dans lequel évoluent les nations membres de l'OTAN se caractérise par une aggravation des menaces, notamment celles posées par les engins explosifs et les armes. Or ces armes de choix pour les adversaires de l'OTAN, qui continuent à dominer la guerre moderne, provoquent parfois des blessures complexes et catastrophiques. De ce point de vue, l'élaboration d'une représentation intégrale des menaces potentielles et de leurs possibles atténuation et/ou traitement médical au moyen d'un cadre de modélisation informatique intégré offrira des capacités de combat accrues aux membres de l'OTAN : c'est elle qui constitue l'objet du présent RTG.

Ces 25 dernières années, la modélisation informatique a eu un impact considérable sur la prédiction des menaces liées aux explosions et des performances des équipements et systèmes de protection. Les résultats de ces simulations suggèrent que l'existence de capacités de modélisation intégrale des effets de souffle sur l'ensemble du corps humain aurait de quoi procurer la capacité aux nations de l'OTAN de contrer les menaces d'explosions en émergence rapide, mais également d'instaurer un environnement plus sûr pour les scénarios de formation et de combat. Soucieuse de prendre en compte ces aspects de modélisation et de simulation, la Commission sur les facteurs humains et la médecine (FHM) de l'OTAN a créé le Groupe de recherche (RTG) HFM-270 de l'OTAN, baptisé « Cadre de modélisation et de simulation de la létalité, des blessures et des déficiences humaines dues aux menaces associées aux explosions ». Le RTG HFM-270 comprend 22 membres désignés au sein de 10 nations (Afrique du Sud, Allemagne, Canada, États-Unis, France, Israël, Pays-Bas, Suède, Turquie, et Royaume-Uni). L'équipe ainsi formée représente les communautés médicale, opérationnelle et du développement de matériels, ainsi que différentes disciplines, dont l'ingénierie, les sciences biologiques et la médecine.

L'objectif ultime du RTG consiste à mettre à profit les efforts passés, présents et prévus menés par les nations participantes dans le domaine de la recherche biomédicale et de la modélisation informatique des blessures par souffle pour élaborer un cadre conceptualisé de modèles informatiques capables de modéliser et de simuler, depuis la menace jusqu'au résultat, des effets de souffle sur les humains dans l'optique d'un développement, d'essais et d'une mise en service rapides d'équipements de protection efficaces pour les militaires en service.

Ce RTG a conduit un examen approfondi de la modélisation et de la simulation pour première tâche. Les principales caractéristiques abordées par les chercheurs ont été documentées, et les limites du développement d'une approche fondée sur la simulation identifiées. Les trois grandes déficiences ainsi relevées sont : a) le déficit général de liaison et de continuité dans le modèle de simulation pour remédier aux blessures au combat en utilisant les techniques ; b) l'insuffisance et l'incomplétude des modèles de matériaux indispensables à ces simulations ; et c) les limites de la validation des modèles à partir des données expérimentales nécessaires. Dans le présent rapport, ces conclusions permettent de créer un cadre de modélisation et de simulation intégral (depuis la menace jusqu'au diagnostic clinique), et d'expliquer comment un tel cadre peut être mis en pratique par les membres de l'OTAN à l'aide d'exemples. Ce cadre peut alors être appliqué en partie ou en totalité par les nations membres de l'OTAN afin d'identifier

les besoins de recherche et d'exécuter des projets visant à renforcer les capacités scientifiques et techniques dotant l'OTAN d'un avantage par rapport à ses adversaires. Il peut également être mis en œuvre dans le but d'évaluer de nouvelles menaces, de nouveaux outils scientifiques et technologiques, et de nouveaux systèmes de protection permettant d'en déterminer l'efficacité. Enfin, le cadre peut également contribuer à remplir les besoins scientifiques et techniques associés au développement programmatique de futures recherches sur les explosions dans les nations membres de l'OTAN.





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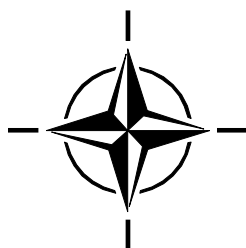
STO TECHNICAL REPORT

TR-HFM-270

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Final Report of Task Group HFM-270.



Published January 2023

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# The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the powerhouse of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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# **Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats**

## **(STO-TR-HFM-270)**

### **Executive Summary**

The increasingly complex and technologically sophisticated threat environment to NATO member nations continues to increase the threats, especially those posed by explosive devices and weapons. These weapons of choice with NATO adversaries continue to dominate modern warfare, and the injuries they cause can be complex and catastrophic. Developing an end-to-end representation of potential threats and their possible mitigation and/or medical treatment through an integrated computational modeling framework will provide improved warfighting capability to the NATO members and is the scope of this RTG.

In the last 25 years, computational modeling has made a significant impact on blast threat prediction and performance of protective equipment and systems. These simulation results have suggested that a comprehensive, whole human blast effects modeling capability could provide the ability of NATO nations to counter rapidly emerging blast threats, as well as create safer environments for training and combat scenarios. To address these aspects of modeling and simulation, the NATO Human Factors and Medicine (HFM) Panel established the NATO HFM-270 Research Task Group (RTG), “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats”. The HFM-270 RTG comprised 22 appointed members from 10 nations: Canada, France, Germany, Israel, Netherlands, South Africa, Sweden, Turkey, United Kingdom, and the U.S. This team represented medical, operational and materiel development communities, and diverse disciplines, including engineering, biological sciences, and medicine.

The overarching objective of the RTG was to leverage previous, ongoing, and planned blast injury biomedical research and computational modeling efforts among the participating nations to develop a conceptualized framework of computational models capable of providing threat-to-outcome modeling and simulation of blast effects on humans to support rapid development, testing, and fielding of effective protection equipment to Service members.

This RTG conducted an in-depth review of modelling and simulation as the first task. The key characteristics addressed by the researchers were documented, and the limitations in developing a simulation-based approach were identified. The three major deficiencies noted were: a) Lack of end-to-end connection and continuity in the simulation model to address combat injuries utilizing the techniques; b) Insufficient and incomplete material models essential for such simulations; and c) Limited validation of the models based on the necessary experimental data. In this report, these findings are used to create an end-to-end – threat to clinical diagnosis – modeling and simulation framework and explain how such a framework can be implemented in practice by NATO members with examples. This framework can be applied in pieces or as a whole by NATO member nations in identifying research needs and executing projects to enhance scientific and technical capabilities for NATO advantage over its adversaries. The framework can also be implemented to assess new threats, new science and technology tools, and new protective systems to determine their effectiveness. Lastly, the framework can also support the science and technology needs for a programmatic development of future blast-related research in NATO member nations.

# **Cadre de modélisation et de simulation de la létalité, des blessures et des déficiences humaines dues aux menaces associées aux explosions**

## **(STO-TR-HFM-270)**

### **Synthèse**

De plus en plus complexe et technologiquement sophistiqué, l'environnement dans lequel évoluent les nations membres de l'OTAN se caractérise par une aggravation des menaces, notamment celles posées par les engins explosifs et les armes. Or ces armes de choix pour les adversaires de l'OTAN, qui continuent à dominer la guerre moderne, provoquent parfois des blessures complexes et catastrophiques. De ce point de vue, l'élaboration d'une représentation intégrale des menaces potentielles et de leurs possibles atténuation et/ou traitement médical au moyen d'un cadre de modélisation informatique intégré offrira des capacités de combat accrues aux membres de l'OTAN : c'est elle qui constitue l'objet du présent RTG.

Ces 25 dernières années, la modélisation informatique a eu un impact considérable sur la prédiction des menaces liées aux explosions et des performances des équipements et systèmes de protection. Les résultats de ces simulations suggèrent que l'existence de capacités de modélisation intégrale des effets de souffle sur l'ensemble du corps humain aurait de quoi procurer la capacité aux nations de l'OTAN de contrer les menaces d'explosions en émergence rapide, mais également d'instaurer un environnement plus sûr pour les scénarios de formation et de combat. Soucieuse de prendre en compte ces aspects de modélisation et de simulation, la Commission sur les facteurs humains et la médecine (FHM) de l'OTAN a créé le Groupe de recherche (RTG) HFM-270 de l'OTAN, baptisé « Cadre de modélisation et de simulation de la létalité, des blessures et des déficiences humaines dues aux menaces associées aux explosions ». Le RTG HFM-270 comprend 22 membres désignés au sein de 10 nations (Afrique du Sud, Allemagne, Canada, États-Unis, France, Israël, Pays-Bas, Suède, Turquie, et Royaume-Uni). L'équipe ainsi formée représente les communautés médicale, opérationnelle et du développement de matériels, ainsi que différentes disciplines, dont l'ingénierie, les sciences biologiques et la médecine.

L'objectif ultime du RTG consiste à mettre à profit les efforts passés, présents et prévus menés par les nations participantes dans le domaine de la recherche biomédicale et de la modélisation informatique des blessures par souffle pour élaborer un cadre conceptualisé de modèles informatiques capables de modéliser et de simuler, depuis la menace jusqu'au résultat, des effets de souffle sur les humains dans l'optique d'un développement, d'essais et d'une mise en service rapides d'équipements de protection efficaces pour les militaires en service.

Ce RTG a conduit un examen approfondi de la modélisation et de la simulation pour première tâche. Les principales caractéristiques abordées par les chercheurs ont été documentées, et les limites du développement d'une approche fondée sur la simulation identifiées. Les trois grandes déficiences ainsi relevées sont : a) le déficit général de liaison et de continuité dans le modèle de simulation pour remédier aux blessures au combat en utilisant les techniques ; b) l'insuffisance et l'incomplétude des modèles de matériaux indispensables à ces simulations ; et c) les limites de la validation des modèles à partir des données expérimentales nécessaires. Dans le présent rapport, ces conclusions permettent de créer un cadre de modélisation et de simulation intégral (depuis la menace jusqu'au diagnostic clinique), et d'expliquer comment un tel cadre peut être mis en pratique par les membres de l'OTAN à l'aide d'exemples. Ce cadre peut alors être appliqué en partie ou en totalité par les nations membres de l'OTAN afin d'identifier

les besoins de recherche et d'exécuter des projets visant à renforcer les capacités scientifiques et techniques dotant l'OTAN d'un avantage par rapport à ses adversaires. Il peut également être mis en œuvre dans le but d'évaluer de nouvelles menaces, de nouveaux outils scientifiques et technologiques, et de nouveaux systèmes de protection permettant d'en déterminer l'efficacité. Enfin, le cadre peut également contribuer à remplir les besoins scientifiques et techniques associés au développement programmatique de futures recherches sur les explosions dans les nations membres de l'OTAN.



## Chapter 1 – INTRODUCTION

### 1.1 BACKGROUND

The military threat environment is rapidly evolving and becoming more complex as NATO's adversaries develop and employ increasingly sophisticated weapons and tactics. However, this increasingly complex and technologically sophisticated threat environment has not diminished the long-standing and enduring threat posed by explosive devices and weapons which span the sophistication spectrum, from low- to high-tech, and therefore are a likely weapon of choice for adversaries. Explosive devices and weapons continue to dominate modern warfare, and the injuries they cause can be complex and catastrophic.

The complexity and severity of injuries caused by explosive devices present significant injury prevention, treatment, and rehabilitation challenges. The types of injuries, impairment, and pathological findings encompassed under the umbrella headings of "blast-related injury" or "blast injury" are diverse and wide-ranging, from hemorrhage caused by penetrating fragments and traumatic amputation to internal organ injuries from blast overpressure to blunt impact injuries and burns. Furthermore, evidence suggests a possible association between blast exposure and other pathological findings, such as mild traumatic brain injury, which requires further study. Overcoming these challenges requires the coordinated efforts of diverse medical and non-medical communities, and equally diverse scientific, medical, engineering, and operational disciplines.

Countering the rapidly evolving blast threat environment requires an agile and streamlined approach to designing, testing, and fielding blast protection equipment for NATO Service members in both mounted and dismounted operations. Computational modeling tools can support this agile and streamlined approach by providing the capability to predict the human response to emerging blast threats, and to rapidly devise and test novel protection concepts in a virtual environment thereby increasing the number of promising concepts and reducing the number of prototypes that require expensive and time-consuming development and live-fire testing. Ultimately, these computational modeling tools offer the potential to dramatically accelerate the delivery of effective blast protection equipment to Service members.

Recognizing the value of computational modeling and the potential impact that a comprehensive, whole human blast effects modeling capability could have on the ability of NATO nations to counter rapidly emerging blast threats, the NATO Human Factors and Medicine (HFM) Panel established the NATO HFM-270 Research Task Group (RTG) titled, "Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats". The HFM-270 RTG comprised 22 appointed members from 10 nations: Canada, France, Germany, Netherlands, Israel, South Africa, Sweden, Turkey, United Kingdom, and the U.S. These RTG members represented diverse medical, operational, and materiel development communities, and diverse disciplines, including engineering, biological sciences, and medicine.

The overarching objective of the RTG was to leverage previous, ongoing, and planned blast injury biomedical research and computational modeling efforts among the participating nations to develop a conceptualized framework of component computational models capable of providing threat-to-outcome modeling and simulation of the effects of blast on the human to support the rapid development, testing and fielding of effective blast protection equipment to Service members.

This report describes the activities of the RTG during its three-year term and documents the RTG's methods, findings, and recommendations.

## **1.2 PREVIOUS NATO ACTIVITY**

This RTG's efforts are a logical follow-on to the 2011 HFM-207 Symposium titled, "A Survey of Blast Injury Across the Full Landscape of Military Science", and the 2013 – 2016 HFM-234 RTG titled, "Environmental Toxicology of Blast Exposures: Injury Metrics, Modeling, Methods, and Standards". These previous activities recognized the importance of a multidisciplinary approach to blast injury problem solving and highlighted the potential value of biomedically-valid computational models of blast injury that incorporate both biomechanical and physiological responses in solving blast injury, prevention, and treatment challenges.

One of the key recommendations from the HFM-207 symposium was to explore the relevancy and value of computational models of blast, human physiology, biomechanics, and toxicology to address blast injury problems using the classical toxicology problem-solving approach where the etiology of the injury requires an understanding of the dose, mechanism of delivery of the dose, and dose-response endpoints. In other words, leverage computational models to describe the blast threat, the interaction of the threat with the protection system, the interaction of the protection system with the human, the ultimate blast loading on the human, or blast dose, and the spectrum of human responses to the dose received, ranging from impairment, to injury, to lethality.

Similarly, the HFM-234 RTG recognized the potential power of computational modeling, and devoted an entire chapter in the final technical report on using computational models to address challenges in understanding blast injury mechanisms. This RTG highlighted an urgent need to develop blast injury mitigation strategies, and suggested that computational modeling could provide a framework to understand injury mechanisms, guide experimental testing, interpret data, and facilitate the development of effective protection equipment and treatments.

## **1.3 CONCEPT AND SCOPE**

### **1.3.1 Defining "Computational Modeling Framework"**

The RTG's first task was to establish a common understanding among the members of the term, "computational modeling framework" which can be somewhat vague and confusing. To better conceptualize this term the team agreed that the commonly understood concept of a "black box" would be an appropriate analogy for the framework. Using the black box analogy, the computational modeling framework converts input data describing the threat scenario in both mounted and dismounted operational environments into meaningful output predictions of lethality, injury, and impairment. These predictions may be of significant value to many communities for a variety of purposes. For example, the medical community may use these predictions to perform health hazard assessments of weapon systems for the purpose of identifying and mitigating or eliminating potential health risks to the Service members who use the weapon systems. The materiel development community may use these predictions to guide the design and testing of new blast protection equipment, including personal protection equipment and combat platform occupant protection systems. And, the test and evaluation community may use these predictions to assess occupant survivability during virtual survivability testing of combat platforms, such as vehicles, ships, and aircraft. This "black box" analogy for the framework is illustrated in Figure 1-1.

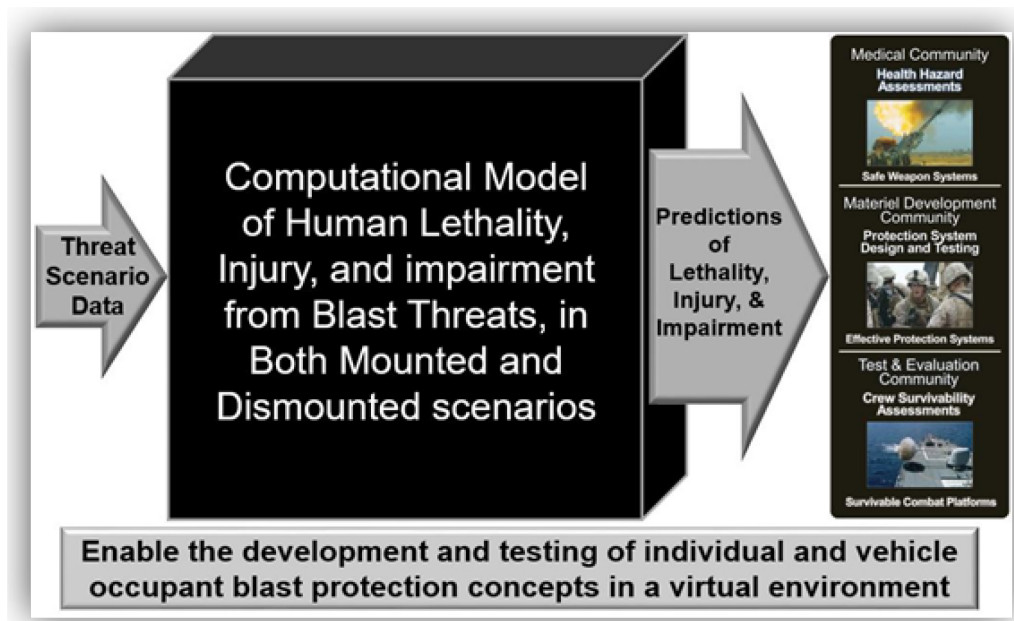


Figure 1-1: 'Black Box' Analogy for the Framework.

Continuing with the black box concept, the RTG members recognized that no single computational model can possibly perform all the functions necessary to achieve the capabilities attributed to the black box. It's more likely that the framework will contain many types of interacting models, where the output from one model serves as the input for another. Returning to the black box analogy, the individual models and model interactions can be visualized by removing the cover of the black box, as shown in Figure 1-2.

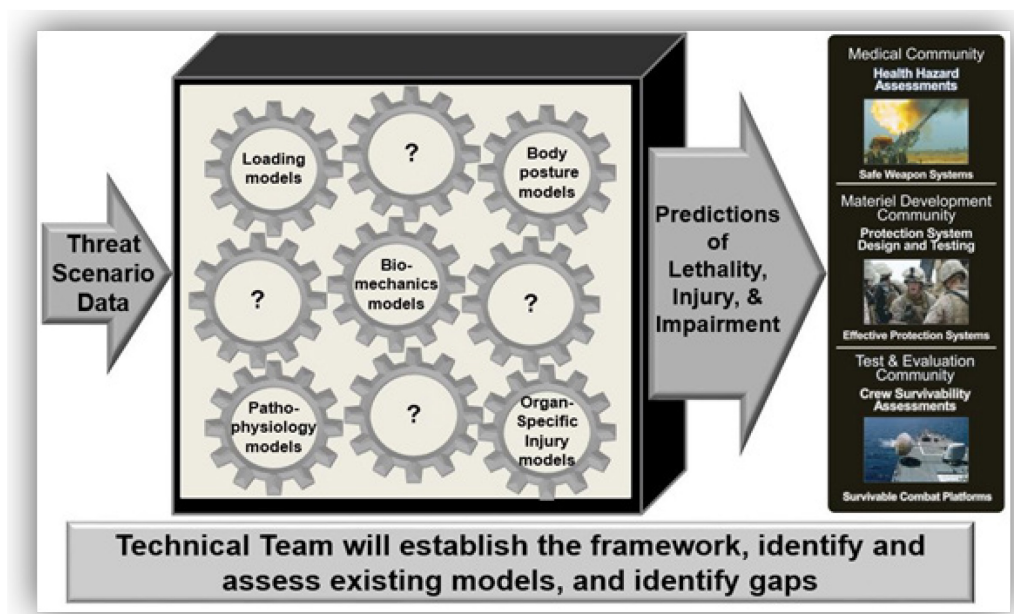


Figure 1-2: 'Black Box' with Cover Removed.

## INTRODUCTION

Figure 1-2 illustrates two important concepts. First, it highlights the diversity of models that are needed to provide the framework's comprehensive modeling capability. The types of models needed include those describing biomechanics, pathophysiology, specific organ injuries, loading on the body, and body posture, to name just a few. The second and equally important concept is the certainty that some key models don't exist. This concept is illustrated in the figure as gears containing question marks. The RTG members agreed that it is just as important to identify existing models for incorporation into the framework as it is to identify that gaps that must be filled if the framework's ultimate capability is to be realized. The RTG chair reviewed this black box analogy at the start of each RTG meeting to help sustain a common understanding and focus among the RTG members.

### 1.3.2 Establishing the Scope of the Framework's Capabilities

After reaching a common understanding of the computational modeling framework and its desired capabilities, the RTG members' next task was to establish a common understanding of the scope of blast injuries that the framework will address. The members agreed to use the definition of "blast injuries" in the U.S. Department of Defense (DoD) Directive 6025.21E, 5 July 2006, subject: Medical Research for Prevention, Mitigation, and Treatment of Blast Injuries, which is the governing directive that assigns medical research coordination responsibilities to the DoD Executive Agent for blast injury research. This definition, as shown in Figure 1-3, includes a wide spectrum of injuries that may result from exposure to threat explosive weapons as well as blast-producing weapon systems used by NATO Service members, and are grouped into five categories: primary, secondary, tertiary, quaternary, and quinary. Chapter 2 describes the physical phenomena created by a blast that can cause injuries. The RTG members agreed that the framework must be capable of addressing the entire spectrum of blast mechanisms and injuries depicted in Figure 1-3. In keeping with the overarching objective of the RTG, the members also agreed that the framework must be capable of predicting the entire spectrum of human responses to blast threats, including lethality, injury, and impairment, in all types of blast threat scenarios.

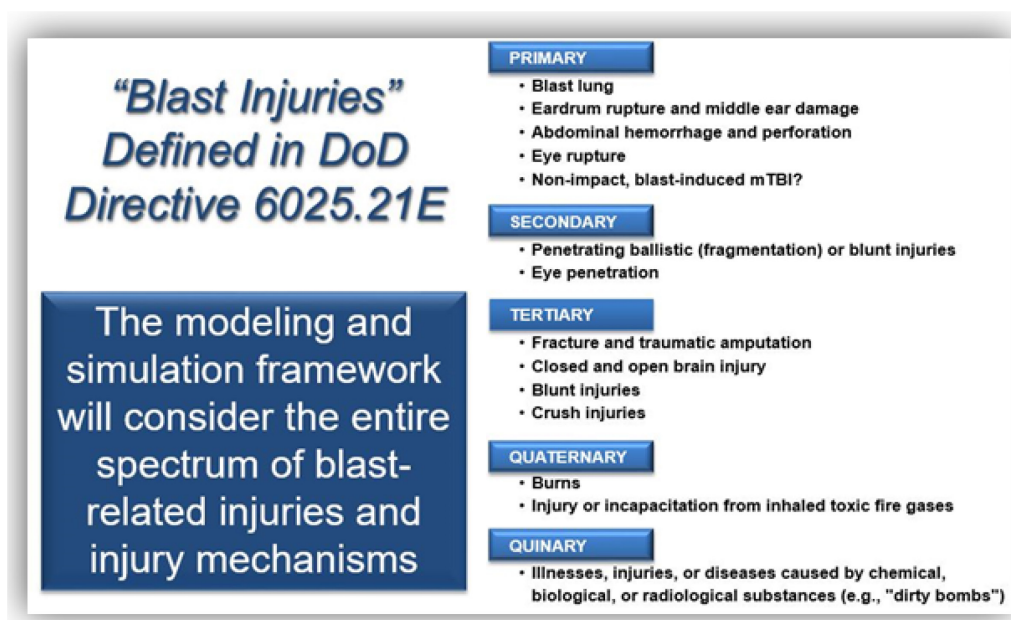


Figure 1-3: Taxonomy of Injuries from Explosive Devices Adapted from DoD Directive (DoDD) 6025.21E.

## **1.4 RTG OBJECTIVES, PROGRAM OF WORK, AND DELIVERABLES**

### **1.4.1 Objectives**

The RTG members met for the first time on 5 – 6 October 2016 in a kick-off meeting held at the NATO Science and Technology Organization (STO) Collaboration Support Office (CSO) in Neuilly-sur-Seine, Paris, France. The purpose of the kick-off meeting was to review the Technical Activity Description (TAD), and to establish a Program of Work (PoW) that would guide the RTG's efforts throughout its three-year term.

The TAD states that the objective of the RTG is to leverage previous, ongoing, and planned blast injury biomedical research and computational modeling efforts among the participating nations to develop a framework for translating scientific information into the capability to model the mechanisms of human lethality, injury, and impairment across the spectrum of blast-related threats. The TAD further states that the proposed RTG will also develop the framework for creating and evaluating effective systems that protect against these blast-related threats.

Over the course of the RTG's three-year term, the general objectives stated in the TAD became more refined and focused. The members' restated objective is to develop a conceptualized framework with component computational models that is capable of providing threat-to-outcome Modeling and Simulation (M&S) of human lethality, injury, and impairment in all blast threat environments. The M&S capability that will be enabled by the framework may make it possible to respond to anticipated and emerging blast threats by rapidly developing and testing novel blast protection concepts in a virtual environment. This capability could dramatically reduce the time and cost required to develop, build, and live-fire test prototype blast injury protection equipment, and accelerate the delivery of effective blast protection equipment to NATO Service members. Additionally, it could be used in wargaming to assess blast threats by predicting casualty numbers and types and thus requirements for deploying medical assets. The RTG members also recognized and highlighted the uniqueness of the envisioned framework because it reflects the knowledge, perspectives, and needs of the diverse communities and disciplines represented by the RTG members.

### **1.4.2 Program of Work**

After achieving a common understanding of the RTG's objectives, the RTG members developed a Program of Work (PoW) with 5 specific objectives:

- 1) Identify elements of the computational modeling Framework.
- 2) Identify existing, ongoing, and planned models, databases, and injury criteria for each element.
- 3) Develop assessment criteria for inclusion of models in the Framework.
- 4) Identify gaps where no suitable models exist.
- 5) Develop the Framework (integration of models).

### **1.4.3 Deliverables**

After establishing the RTG's objectives, the members formulated seven specific deliverables that focused the efforts of the team throughout its three-term. These deliverables are:

- 1) Framework for a computational modeling capability that can predict human lethality, Injury, and impairment from all blast threats in all operational scenarios.

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- 2) Dynamic repository of existing models and modeling capabilities among the participating nations that are relevant to the framework.
- 3) Gaps in modeling capabilities necessary to achieve the full capability of the framework.
- 4) Comprehensive dictionary of Modeling and Simulation terms which builds upon the comprehensive dictionary of blast injury research terms created in HFM-234 RTG.
- 5) TAP for new HFM RTG which would build upon HFM-270 to develop standardization and validation criteria and approaches for implementing the framework.
- 6) Publications on the work of the HFM-270 RTG in peer-reviewed literature.
- 7) Final NATO technical report describing the framework, dynamic repository of existing models and modeling capabilities, gaps in modeling capabilities, recommendations, and the comprehensive dictionary and TAP as addenda.

## 1.5 METHODOLOGY

### 1.5.1 Meeting Schedule

Acknowledging the ambitious objectives of this RTG, the RTG members recognized the need for three in-person meetings every twelve months to facilitate the completion of the PoW and development of the deliverables. Several members volunteered to host meetings with the understanding that they needed to coordinate with their respective organizations to confirm their commitment to host a meeting. The members agreed that meetings will generally be three days in duration. Given the multidisciplinary makeup of the RTG, the members agreed that each meeting should include presentations by Subject Matter Experts (SMEs) to enable the RTG members to establish a common understanding of critical concepts in computational modeling, biomedical research, and medicine that are relevant to the overall effort of this team. The RTG members agreed that SMEs would be invited to give their presentations, but would not be privy to follow-on discussions among the RTG members. The RTG members also agreed that the nation hosting the meeting would be responsible for the SME travel costs. The NATO STO CSO offered to provide funding to support SME travel if the host nation requested it; however, this option was not exercised by any of the member nations. In addition to the in-person meetings, the members agreed to hold a virtual meeting via WebEx or telecon midway between each in-person meeting. Unfortunately, time zone differences and the availability of members made it very difficult to consistently hold these virtual mid-point meetings. The members also agreed to maximize the use of the Science Connect website for information sharing and document development. The meeting schedule agreed to during the kick-off meeting is shown in Table 1-1.

**Table 1-1: Program of Work, Schedule, and Milestones.**

| Activity/<br>Workshop   | Month/Year      | Purpose                                                                             | Host/Location | Point of Contact    |
|-------------------------|-----------------|-------------------------------------------------------------------------------------|---------------|---------------------|
| 1 <sup>st</sup> Meeting | 5 – 6 Oct. 2016 | HFM-270 (RTG) Kick-off                                                              | STO CSO/Paris | LtCol (Dr.) Wessels |
| 1 <sup>st</sup> WebEx   | Mid Nov. 2016   | Finalize Agenda and<br>Invited Speakers for Next<br>Meeting, and Finalize<br>Survey | WebEx         | Mr. Leggieri        |

| Activity/<br>Workshop   | Month/Year                                    | Purpose                                                                                  | Host/Location                                             | Point of Contact      |
|-------------------------|-----------------------------------------------|------------------------------------------------------------------------------------------|-----------------------------------------------------------|-----------------------|
| 2 <sup>nd</sup> Meeting | 10 – 12 Jan.<br>2017                          | Identify Elements of The Framework                                                       | USA/Frederick,<br>MD                                      | Mr. Leggieri          |
| 2 <sup>nd</sup> WebEx   | Mid Apr. 2017                                 | Finalize Agenda and Invited Speakers for Next Meeting                                    | WebEx                                                     | Mr. Leggieri          |
| 3 <sup>rd</sup> Meeting | 11 – 13 Jul. 2017                             | Scope Breadth of Existing Models                                                         | GBR/Porton Down                                           | Drs. Kirkman/Watts    |
| 3 <sup>rd</sup> WebEx   | Mid Sept. 2017                                | Finalize Agenda and Invited Speakers for Next Meeting                                    | WebEx                                                     | Mr. Leggieri          |
| 4 <sup>th</sup> Meeting | 7 – 9 Nov. 2017                               | Overview of Existing Computational Models                                                | NLD/Rijswijk                                              | Mr. Philippens        |
| 4 <sup>th</sup> WebEx   | Mid Jan. 2018                                 | Finalize Agenda and Invited Speakers for Next Meeting                                    | WebEx                                                     | Mr. Leggieri          |
| 5 <sup>th</sup> Meeting | 6 – 8 Mar. 2018                               | Overview of Existing Computational Models                                                | DEU/Koblenz                                               | Drs. Franke/Bieler    |
| 5 <sup>th</sup> WebEx   | Mid May 2018                                  | Finalize Agenda and a List of Assessment Criteria to Use at Next Meeting                 | WebEx                                                     | Mr. Leggieri          |
| 6 <sup>th</sup> Meeting | 10 – 12 Jul. 2018                             | Apply Assessment Criteria                                                                | Suffield Research Center, Alberta, CAN                    | Drs. Bouamoul/Sawyers |
| 6 <sup>th</sup> WebEx   | Early Oct. 2018                               | Finalize Agenda                                                                          | WebEx                                                     | Mr. Leggieri          |
| 7 <sup>th</sup> Meeting | <del>4 – 6 Dec. 2018</del><br>3 – 7 Dec. 2018 | Finalize the Framework and Develop Blast Scenarios                                       | <del>TUR/Ankara</del><br>CSIR, Stellenbosch, South Africa | Mr. Reinecke          |
| 7 <sup>th</sup> WebEx   | Mid Feb. 2019                                 | Finalize Agenda                                                                          | WebEx                                                     | Mr. Leggieri          |
| 8 <sup>th</sup> Meeting | 3 – 5 Apr. 2019                               | Review Demonstration Results, Identify Gaps and Finalize Dictionary, TAP and Manuscripts | SWE/Stockholm                                             | Dr. Risling           |
| 8 <sup>th</sup> WebEx   | Late Jun. 2019                                | Review Draft Final Report Revisions                                                      | WebEx                                                     | Mr. Leggieri          |
| 9 <sup>th</sup> Meeting | 3 – 6 Sept. 2019                              | Finalize All Deliverables                                                                | STO CSO/Paris                                             | LTC Erik Laenen       |

### **1.5.2 Meeting Format**

The RTG Chair began each meeting by reviewing the RTG's objectives and deliverables. He reviewed the U.S. DoD definition of blast injuries as defined in DoD Directive 6025.21E, noting that the framework should consider the entire spectrum of blast-related injuries and injury mechanisms. He reviewed the black box analogy for a framework of computational models capable of predicting human lethality, injury, and impairment from all blast threats, in both mounted and dismounted scenarios, and in all threat environments. He emphasized the primary objectives of the RTG to develop the framework, to identify and evaluate existing computational models for inclusion in the framework, and to identify gaps where necessary models do not exist.

Following the Chair's introduction, the RTG members reviewed the status of the action items from the previous meeting, and then proceeded to work on specific tasks described in the meeting schedule in the PoW. Meetings also included relevant SME presentations arranged by the host nation. Also, each meeting typically included a tour of the host nation's blast injury research facilities to help the RTG members achieve a common understanding of each nation's research interests and capabilities. Finally, each meeting concluded with a review of assigned tasks and the plans and objectives for the next meeting.

### **1.5.3 Work Groups**

The RTG members established three Work Groups (WGs) that focused on specific deliverables described in the PoW: a Dictionary WG tasked to develop the comprehensive dictionary of commonly used computational modeling and simulation terms that builds upon the comprehensive dictionary of blast injury research terms developed by the HFM-234 RTG; a Publications WG tasked to identify and guide the publication of the RTG's work in appropriate peer-reviewed journals; and a TAP WG tasked to draft a TAP for a HFM-270 follow-on RTG which will develop standardization and validation criteria and approaches for the framework.

### **1.5.4 Methodical Approach to Accomplishing the Objectives**

The following paragraphs provide a synopsis of the RTG's logical and methodical approach to accomplishing the five objectives stated in the PoW. The following chapters describe the approach in detail.

#### **1.5.4.1 Identify Elements of the Computational Modeling Framework**

The RTG members recognized that the first task in developing the computational modeling framework was to identify the framework's basic elements. To this end, the members defined a chain of events that defines the boundaries of the framework's overarching capability to provide threat-to-outcome Modeling and Simulation (M&S) of human lethality, injury, and impairment in all blast threat environments. The chain of events begins with the blast threat scenario and concludes with an outcome parameter which describes the human response. The members used this chain of events and the Toxicology Framework for Blast Injury developed by the HFM-234 RTG to develop a matrix comprising the computational modeling framework elements, and then applied a simple blast scenario example to test the logic and completeness of the elements.

Further discussions lead to the grouping of the individual elements into interacting modules, where the output from one module serves as the input for another, and where changes made to one module can modulate or change the output of another module.

Chapter 5 provides a detailed discussion of the framework's elements and modules.

#### **1.5.4.2 Identify Existing, Ongoing and Planned Models, Databases, and Injury Criteria for Each Element**

The RTG's next task was to survey the participating nations to identify existing models and modeling capabilities that are relevant to the framework. To accomplish this task, the RTG developed a comprehensive survey tool that each member used to canvass their nation's models and modeling capabilities. Chapter 4 provides a detailed discussion of the RTG's efforts to identify existing models and modeling capabilities.

#### **1.5.4.3 Develop Assessment Criteria for Inclusion of Models in the Framework**

After identifying the existing models and modeling capabilities, the RTG developed criteria needed to assess the relevance of the models and capabilities to the framework. The RTG members painstakingly reviewed and summarized relevant published papers describing the identified models and modeling capabilities, and then used the assessment criteria to determine where the model fit into the matrix. These summaries will serve as the basis for the dynamic repository of models and modeling capabilities.

#### **1.5.4.4 Identify Gaps Where No Suitable Models Exist**

Based on an in-depth review of modeling and simulation, three major deficiencies were noted. The first limitation was a lack of end-to-end connection and continuity in the simulation model to utilize such models and simulation techniques for injury prediction and suggest course of clinical treatment. The second was the insufficiency and incompleteness in material models essential for such simulations. Third, all the models only provided limited validations with experimental data, thus suggesting additional work needs to be done to utilize them models for a linked, end-to-end prediction of injury and clinical treatment from a new threat.

### **1.6 CONCLUSIONS**

A comprehensive, threat to human health effects and consequences outcome computational modeling capability can support an agile and streamlined approach to designing, testing, and fielding blast protection equipment for NATO Service members; however, such a capability does not currently exist. This RTG's three-year effort produced a computational modeling framework that lays the groundwork for developing such a capability. The framework provides a comprehensive and logical structure within which individual models can interact to produce the desired threat-to-outcome modeling capability. The framework is unique because it reflects the knowledge, perspectives, and needs of the diverse communities and disciplines represented by the RTG members and provide an end-to-end linking threat models to human body and protective equipment models, injury models and clinical diagnoses and treatment models and knowledge base.

### **1.7 RECOMMENDATIONS**

Each nation should consider the gaps identified by this RTG when planning future investments in computational modeling efforts. A nation and organization should be designated to maintain and update the dynamic repository of existing models and modeling capabilities among the participating nations that are relevant to the framework.

The RTG recommends that each NATO nation should consider the gaps identified by this RTG when planning future investments in computational modeling efforts. Also, each nation as well as an organization, like the NATO, could designate resources to maintain and update a dynamic repository of existing models and simulation capabilities relevant to the framework. The framework as well as the repository can become

## INTRODUCTION

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a resource for advanced research, software- and hardware-based product development, advancing the state of science in related fields, and better mitigate blast injuries for Warfighters in participating nations. Validation of such models using data from adequately documented experimental results should be a key expectation in future research so that the models can be incorporated in the framework presented here.

## **Chapter 2 – BLAST PHYSICS, LOADING, INJURY AND COMPUTATIONAL MODELING**

### **2.1 SCOPE OF THE CHAPTER**

This chapter places module1 into context by detailing the different types of explosives, war wounding, the devastating effects of explosive devices, and the blast-wave types generated in the environment. The chapter then focuses on describing the different classifications of blast injury.

### **2.2 EXPLOSIVES CATEGORIES**

Explosives are categorized as either High-order Explosives (HE) or Low-order Explosives (LE). The difference between the two classifications is in the type of explosive wave produced. In HE explosions a supersonic, shock wave is generated and sustained as the detonation wave travels through the medium. LE explosives produce a subsonic explosion and do not produce an over-pressurization wave [1]. For LE explosives the energy in the charge is released much slower as compared to HE and the explosive is burned through a process known as deflagration. In HE explosives the charge combusts near instantaneously (typical detonation velocity is approximately 6900 m/s for Trinitrotoluene (TNT) explosive [2]), releasing the energy almost instantaneously. HE explosives are generally more stable than LE explosives. Examples of LE explosives are black powder, gunpowder, and rocket propellants. Examples of HE explosives include nitroglycerine, ammonium nitrate, trinitrotoluene, Composition C-4 (C4), Research Department eXplosive (RDX) and Ammonium Nitrate Fuel Oil (ANFO) [3]. Conventional explosives contain compounds of hydrogen, oxygen, nitrogen, and carbon. The explosive material may be in the form of a liquid, gas or solid and are classified as either primary or secondary explosives.

### **2.3 EXPLOSIVE IGNITION**

Explosives inflict injury through the formation of an explosion – the phenomenon of a rapid increase in volume and pressure that result from a sudden release of energy [4]. They are substances which have within themselves energy stored in the form of molecular bonds. When these bonds are broken, as initiated by a detonator, an immense quantity of energy is released. The detonator is in itself a smaller explosive with highly sensitive initiator material activated by mechanical, electrical or magnetic switch. When triggered, the detonator releases a supersonic exothermic blast to the surrounding less sensitive but high energy main charge. This travels through and compresses this surrounding material, resulting in a chemical reaction in which the solid or liquid explosive is subsequently transformed into a gas with the liberation of a large amount of energy, at a near exponential rate [5]. Figure 2-1 shows the fireball, shockwave, and ground reflection of blast.

This rapid chemical reaction occurs with chemical decomposition at speeds greater than the speed of sound – a process known as propagation. This reaction and release of energy is almost instantaneous. The result is a region of highly compressed and heated gas which expands to occupy a volume far greater than the original explosive: pressure at the point of the detonation is 20 – 30 GPa (200,000 – 300,000 atmospheric pressure) with temperatures reaching 7,000°C [4]. The rapid expansion of gas compresses the surrounding air which propagates supersonically away from the point of detonation. This is known as a blast wave. The blast wave consists of two parts: a shock wave of high pressure (the peak/static overpressure) and compressed gas, which travels at supersonic speed, followed closely by a blast wind – an increase in pressure (the dynamic overpressure) and a mass movement of air, travelling at subsonic speeds as shown in Figure 2-1.

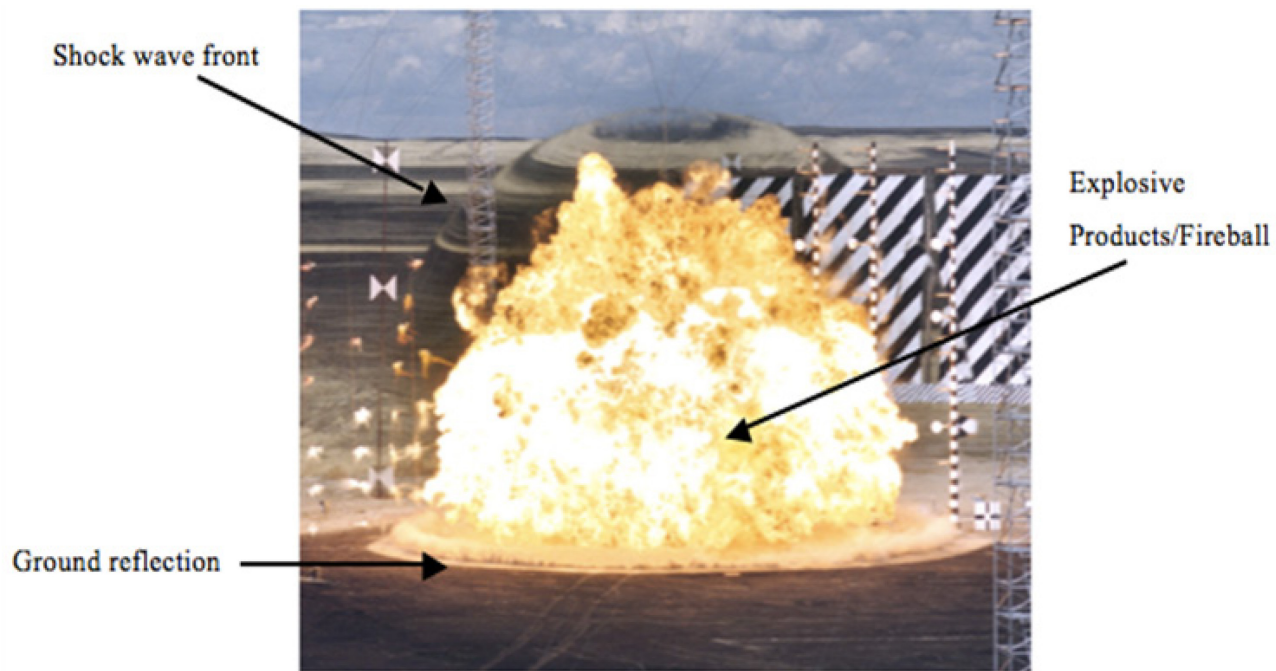


Figure 2-1: Photograph of Above Ground Detonation.

## 2.4 BLAST PRESSURE

Blast exposure is defined in multiple ways: pressure histories, peak pressure and positive phase duration or maximum positive phase impulse. These values in fact refer only to the static overpressure condition which is referenced since it is the most easily measured gas-dynamic condition and published injury criteria relate these values. However, static pressure alone does not fully define the blast exposure; two pressure measurements that report the same static pressure history may produce vastly different loading conditions and injury due to dynamic pressure effects.

### 2.4.1 Total Pressure

The total, or stagnation, pressure can be measured through the use of a Pitot pressure gauge; under certain simplifying conditions of incompressible isentropic flow relevant to the Bernoulli equation the total pressure is simply the sum of the static and dynamic pressure. In the case of a spherically expanding blast in the free field, the dynamic pressure can often be estimated using empirical relationships; however, these estimates are not easily applied inside blast tubes and definitely not near the open shock tube end.

### 2.4.2 Static Pressure

In shock and blast tubes, static pressure gauges are generally mounted in the tube sidewall while in free-field testing gauges are mounted on sharp-edged plates placed normal to the flow direction. The static pressure (often just called “pressure”) is related to the thermodynamic state of the fluid and does not indicate the degree of the kinetic energy of the flow.

### **2.4.3 Dynamic Pressure**

While it is commonplace to only measure and report the static pressure, the dynamic component of the blast should not be neglected as it contributes substantially to the damage potential of the blast. The dynamic pressure represents the magnitude of the kinetic energy of the blast flow. The dynamic pressure is associated with the blast wind and therefore the drag exerted on exposed objects. The dynamic pressure is a more challenging value to measure than the static pressure since it depends on both the density and velocity of the flow and usually requires a sensor to face into the flow, greatly increasing its vulnerability to particulate impact and damage.

### **2.4.4 Reflected Pressure**

As the blast wave encounters an object or the test specimen, the particle velocity is arrested, and the pressure temperature and density are increased at the object surface. This is named the reflected region. Reflected pressures at this region also grow proportionally with the blast wind, furthering the need to properly measure the dynamic pressure.

### **2.4.5 Impulse**

The impulse of a blast wave refers to the integration of the pressure over time. Often only the positive phase portion of the static pressure is used to determine the impulse from a blast load.

## **2.5 THE RISE OF IMPROVISED EXPLOSIVE DEVICES**

The most recent military conflicts have seen blast injury as the leading mechanism of wounding and death, with the Improvised Explosive Device (IED) rising as the signature weapon of choice [6]. This has changed the nature of injuries from penetrating gunshot wounds in prior conflicts, to the extensive, heavily contaminated tissue loss associated with blast injury [7]. Injuries sustained from explosives are dependent upon a number of factors, including the nature of the explosive device, the environment in which the explosion occurred, the distance of the casualty from the device and any Personal Protective Equipment (PPE) worn by the casualty.

The improvised explosive device represents the most common threat to soldiers worldwide. They have become the weapon of choice where enemy forces do not have access to traditional weapons and so create devices from accessible materials. It is thought that their use will continue to rise, given the relative ease and low cost to manufacture and activate [8].

While IED explosions results multiple types of injuries in every body region, open blast fractures of the pelvis are considered to be the most severe [9]. In a UBB event, a seated occupant will have load paths into the feet and up the legs through the floor and into the pelvis and up the spine through the seat. The seat response is critical in mitigating pelvis and lumbar spine injuries.

## **2.6 EXPLOSIVE EFFECTS WITH ENVIRONMENT**

It has been well recognized throughout the literature that there are two types of blast waves depending on the environment. The open space environment results in a well-known form of blast wave called the Friedlander and the confined environment results in complex blast wave [10].

## 2.6.1 Ideal Blast Wave

In order to study the injury caused by explosions in air it is necessary to simplify and understand the blast loading wave. To understand the fundamentals of blast waves it is necessary to consider an idealistic blast wave in free-field conditions (i.e., no interactions with the ground, bodies, or other objects). The approach is to examine an idealistic blast wave in air before it has contacted other surfaces or objects.

The blast wave is defined by its pressure and direction of travel. Within an ideal free-field space, where the blast wave does not come into contact with any interference, this would propagate perpendicular to the surface of the explosive as a sphere. The pressure changes and wave characteristics of an explosion within a free-field blast are classically described by Friedlander [11].

A simple free-field explosion as described above rarely occurs in conflict. The blast wave comes under the influence of sand, water and solid objects resulting in complex wave forms with further reflection and refraction, and varying modalities of energy transfer. Semi-confined (and enclosed) spaces generate an environment where, due to repeated reflection and refraction, large pressures are created for extended periods of time.

An idealized blast wave is characterized by an instantaneous rise in pressure followed by an exponential decay in pressure to ambient conditions (Figure 2-2). The pressure then drops below ambient and returns to ambient. The time from the instantaneous rise in pressure until the decay reaches ambient is called the positive phase duration and the time the pressure is below ambient until it returns to ambient is referred to as the negative phase duration.

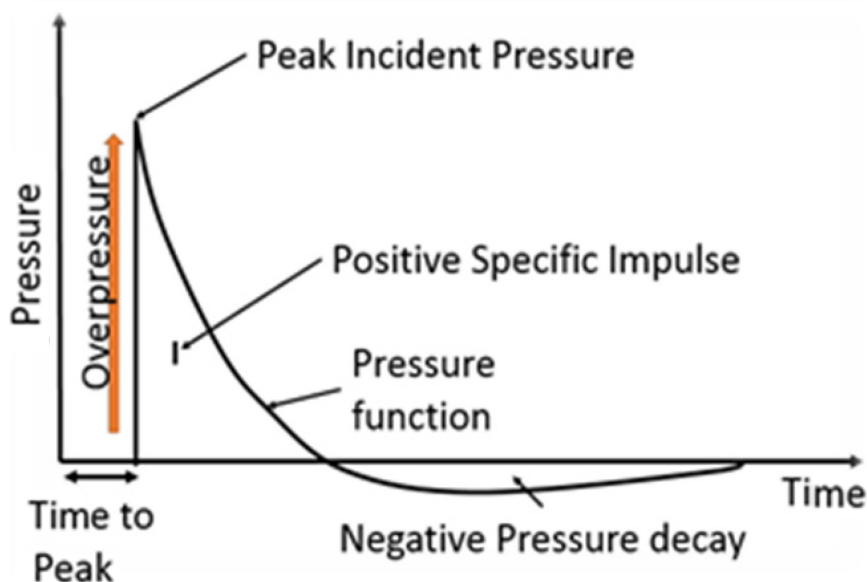


Figure 2-2: Idealized Friedlander Waveform.

### **2.6.2 Complex Blast Wave**

When charges are initiated the blast wave moves radially outwards into the undisturbed air. In areas where there are other objects close to the blast source the blast wave will eventually interact with objects, creating a complex wave field including reflections and attenuations. To further complicate injury prediction the blast wave will behave differently in enclosed spaces than in an open free-field area. Estimating injury in the free field has been studied and correlations have been made which relate injury to charge size and distance. Injury estimate curves have been produced and are a result from early animal testing and from accounts of troops on the battlefield. These empirical correlations are however not valid for explosions in enclosed spaces or in any situation where a complex blast wave is generated. In many situations a complex blast wave is produced, such as in urban warfare situations where there is fighting in close quarters [12]. The geometry of these situations leads itself to producing complex blast waves when an explosive source is detonated.

Blast waves can be reflected off a variety of surfaces, including walls, floors, and ceilings. As the blast wave impacts the surface the reflected waves strength is related to the angle of contact with the surface; low angles produced lower strength reflection pressures whereas perpendicular angles produce very high reflected pressures. The strongest reflected wave results when the high-pressure wave impacts perpendicular to the surface. At this point the blast wave is further compressed on impact and a reflecting wave begins to travel towards the incident wave. The region where this occurs is known as the reflected region. It contains a very high pressurized zone as compared to a region where no reflection has occurred. The shock wave in this single reflected region can end up being 2 to 20 times greater than the incident shock [13]. Stronger and more complicated shocks are produced in enclosed spaces or when the shock makes contact with multiple reflecting surfaces. In enclosed spaces the blast wave may undergo repeated reflections from the interior walls and any objects in the space. Complex blast waves in an enclosure have three characteristics:

- 1) The incident blast wave.
- 2) A number of reflected waves.
- 3) The static pressurization of the enclosure.

A complex blast wave in an enclosure will lead to a longer pressure-time history as compared to a blast in the free field. The longer pressure-time histories enable the gases to heat and expand, filling the enclosure and then eventually venting through any openings [5]. One of the simplest scenarios that produce a complex blast wave is the detonation of an explosive in an enclosed room. Even with the simple geometry and a charge placed in the center of the room the resulting blast waves are complex and require Computational Fluid Dynamics simulations to predict the blast flow field [14]. For enclosed spaces the risk increases, as a result of the amplification in pressure from the reflecting waves Figure 2-3.

When the blast wave comes in contact with a solid or denser object the wave is reflected and depending on the material properties of the object and the angle of impact the resultant reflective wave will vary. As the blast impacts an idealized fully reflective surface the particle velocity is stopped and the pressure, density and temperature all increase above the values of the incident wave. When the reflective wave catches with the incident wave, a Mach stem is formed as shown in Figure 2-4. The path where the incident wave, reflected wave, and the Mach stem meets is referred to as the triple point. For strong shocks the reflected wave at the wall can be much higher than the acoustic approximation of twice as much as the incident wave; the reflected pressure from a blast wave can be greater than eight times the incident wave [15].

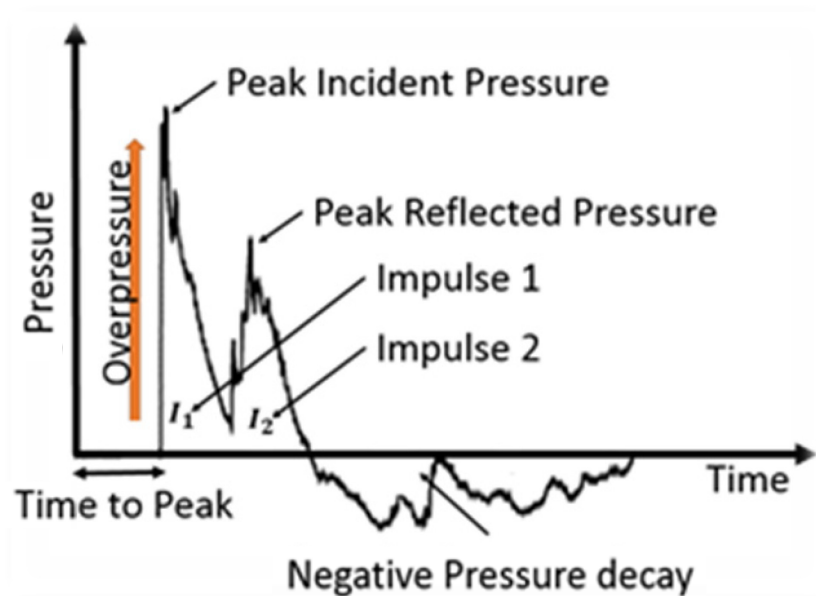


Figure 2-3: Complex Pressure Waveform Example.

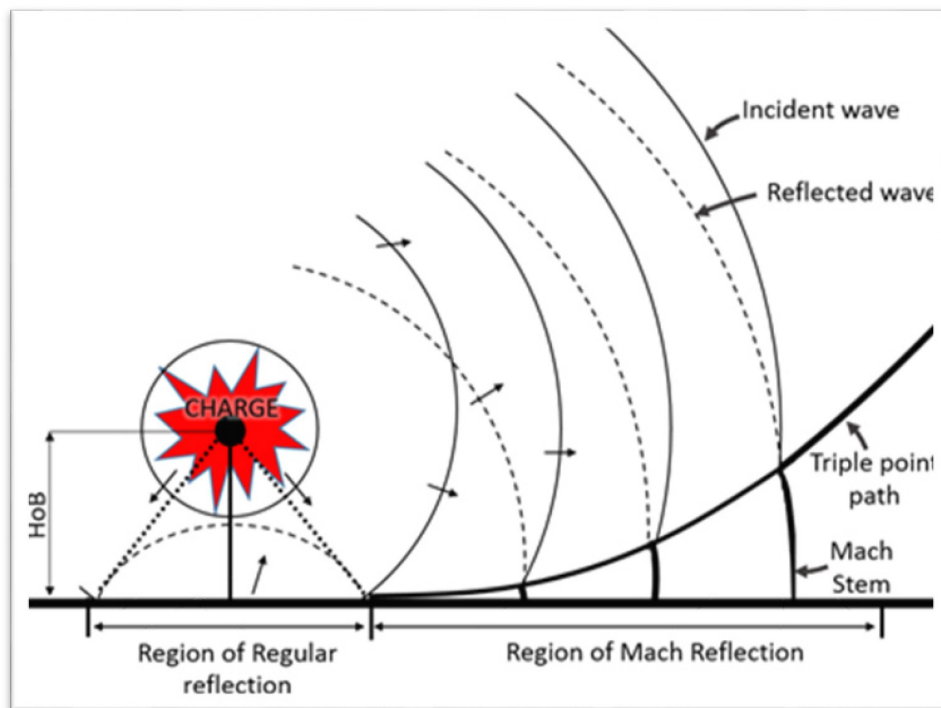


Figure 2-4: Schematic of the Mach Stem Formation and the Triple Point Path from Complex Blast [15].

## 2.7 BLAST INJURY CATEGORIES

Blast Injuries are often simplified and classified into five categories: primary, secondary, tertiary, quaternary, and quinary blast injury. The different loading from the blast can have altering injury patterns depending upon the region of the body affected. provides an overview of the blast categories (Figure 2-5 and Table 2-1).

When referring to blast, the resultant body loading is not only caused by the overpressure; the overpressure is just one potential loading mechanism caused by the explosion. Other mechanisms that are injurious are fragmentation loads, heat loads. The injuries observed in each of the categories are somewhat specific to the loading mechanism

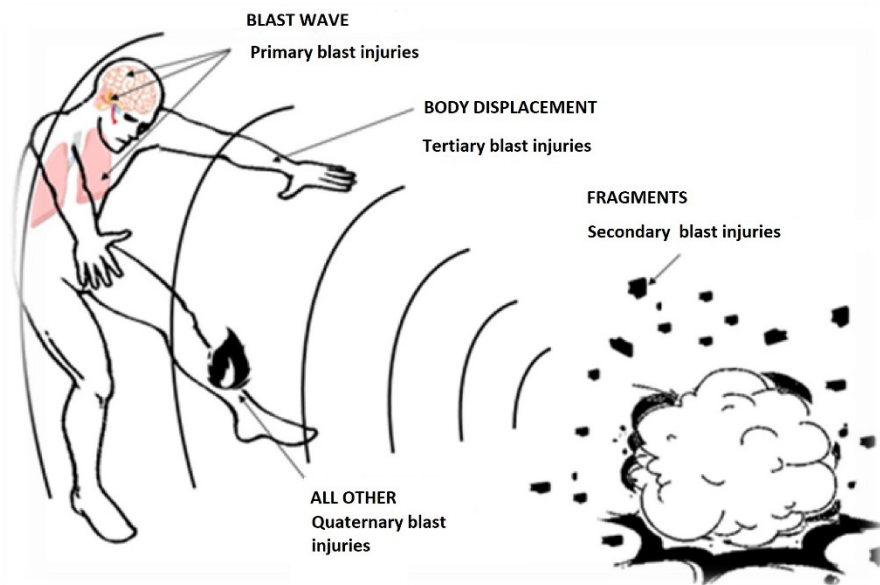


**Figure 2-5: Graphically Representation of Blast Injury Categories [10].**

**Table 2-1: Blast Injury Types and Mechanisms.**

| Blast Injury Type | Mechanism                                                                                                             |
|-------------------|-----------------------------------------------------------------------------------------------------------------------|
| Primary           | Direct interaction of the blast wave with the body.                                                                   |
| Secondary         | Wounds caused by fragments and projectiles energized by the explosion.                                                |
| Tertiary          | Injury due to displacement of the body with subsequent impact or crush, including “solid blast” or “underbody blast”. |
| Quaternary        | Miscellaneous injuries including burns, inhalation of smoke or toxic substances, and psychological sequelae.          |
| Quinary           | Injury caused by exposure to deliberately added chemical, microbial or radiation elements of a device.                |

## 2.7.1 Primary Blast Injury

Primary blast injuries are caused directly from the shock wave overpressure. The high-pressure wave delivers injury by impacting the body and transferring its energy into the body and organs. Injury can result from direct transmission of the wave through susceptible tissues, as well as compression and acceleration. Changes in stress propagation between materials of different densities and impedance results in differential acceleration with spallation (throwing off materials), implosion (compression of less dense compartments) and shearing forces (inertial effects due to relative movement of tissues to one another) [5]. This is most pronounced in the tissue/air interfaces of the lung, gastrointestinal tract, and auditory system. The shock wave overpressure also affects solid abdominal organs, the musculoskeletal system and the brain; the exact extent and mechanism of injury for each has been described but is still not fully understood [16], [17], [18]. Most survivors of blast injury have sustained secondary or tertiary injuries, with few survivors with significant primary blast injuries. This is due to casualties with the necessary blast loading being killed immediately from a combination of all effects or dying subsequently from respiratory failure secondary to Traumatic Blast Lung Injury (TBLI) [19].

## 2.7.2 Secondary Blast Injury

Secondary blast injuries are due to penetrating injury caused by energized fragments accelerated by the blast wind such as casing, shrapnel, or the surrounding environment (sand, soil, or stones) and the resultant collision of fragments with the body. [20] The addition of fragments in explosive charges increases the risk of human injury, as there is the possibility of these fragments penetrating the body. Fragments, balls, bolts nails, encasing are the leading cause of injury in terrorist bombings [3]. Fragments can be soil or environmental debris as well. Fragments may be more lethal at farther distances than the overpressure. This is due to the energy of these fragments being subjected to the inverse square rule of dissipation, whilst the energy of the shock wave rapidly diminishes more quickly as it is subject to the inverse cube rule of dissipation [21]. Fragments are likely to therefore injure more casualties and contribute a more significant portion of the burden of injury as the distance from the explosion increases.

Figure 2-6 shows one example for illustrative purposes and the injurious results are shown from a specific scenario.

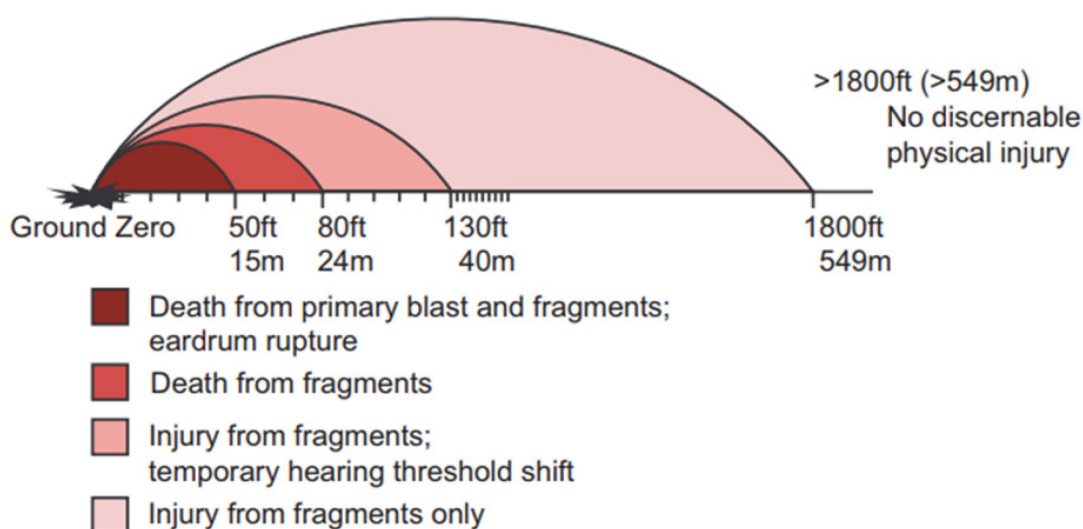


Figure 2-6: Injury and Death from Fragments as a Function of Distance from Detonation [22].

### **2.7.3 Tertiary Blast Injury**

Tertiary blast injuries relate to the displacement of the body (or solid objects into the body) due to the blast wind. Head injuries, fractures and crush injuries are common. The loading mechanism of tertiary blast is the strong blast winds that result from the explosive detonation violently displacing and throwing the body and other objects [20]. Tertiary blast injury may also occur by the blast wave collapsing a building or other objects and causing these objects to impact or fall on the body [23].

The force at which the subject impacts an object or is thrown correlates to the injury sustained. In severe cases, the strength of the blast wind may lead to limb amputations. Other injuries noted include fractures, brain injuries, crushing injuries, and injury from falling objects such as buildings and debris and blunt trauma [23]. Injury may occur due to impact of the body into solid objects, or through relative restraint of one part of the body compared to another.

### **2.7.4 Quaternary Blast Injury**

Quaternary blast injuries consist of a miscellaneous group of blast injuries not attributable to other groups. These include burns, inhalation injuries and toxic effects associated with the blast [24]. Quaternary blast injury is a result of heat, fires, and incapacitation from inhaled toxic gases from fires causing injury. The exposure to the high temperature resulting from an explosion damages tissue and causes injury. Certain chemicals such as powdered aluminum can be added to the explosive charge in order to increase the burn time, increasing the risk of quaternary injury [23].

Quaternary injuries include burns to the subject. As a result of the explosions the thermal effects along with the possibility of nearby objects combusting can inflict injury. Although fires are rare as the explosion consumes the nearby oxygen, the subject may be burned as a result of the exposure to thermal radiation. Burns to the external skin and burns to the airway passages of the individual may occur as the high temperature is breathed in through the lungs [25].

### **2.7.5 Quinary Blast Injury**

Quinary injury includes illnesses, injuries or diseases caused by chemical, biological or radiological substances such as dirty bombs. This can occur with the deliberate addition of biological, chemical, or nuclear products to an explosive device. The casualty may sustain a resultant radiation injury, bacteria, fungal or viral infection [26]. These chemicals can be an inherent result of the explosive or may be purposely added to the explosive charge to cause toxic injury effects [27]. Quinary blast injury is encountered due to the toxic effects in certain explosions and bombs. Quinary injury results in the individual becoming ill by absorbing or inhaling toxic chemicals. The type of chemical absorbed will determine injury; there have been cases reported where an individual suffered no external injury but was gravely ill because of the chemicals absorbed [27].

## **2.8 HUMAN BODY INTERACTION**

Primary blast injury to humans is caused by the pressure wave generated by an explosion or blast. The high-pressure wave delivers injury by impacting the body and transferring its energy into the body and organs. Air filled organs such as the lungs and gastrointestinal tract are the most susceptible to primary blast injury [28]. The eardrums are also very susceptible and have the lowest injury threshold. Depending on the size of the explosion and the location of the individual with respect to the explosion, serious or fatal injuries may occur.

The mechanism of injury from a blast may or may not be known but it is a factor of the blast wave pressure exerting a force on the area of the human body. The force exerted is transmitted to the internal structures by the movement of the tissue.

## 2.9 MOUNTED VS DISMOUNTED

A differentiation in injury pattern has been made between the mounted and dismounted casualty with pelvic blast injury. Singleton et al. [29] demonstrated an important difference between these two environments; casualties within a vehicle at the time of injury (mounted) are most likely to die from a CNS injury, followed by intra-cavity hemorrhage. The on foot (dismounted) casualty, however, was found to be more likely to die from extremity and junctional hemorrhage [30] (Figure 2-7).

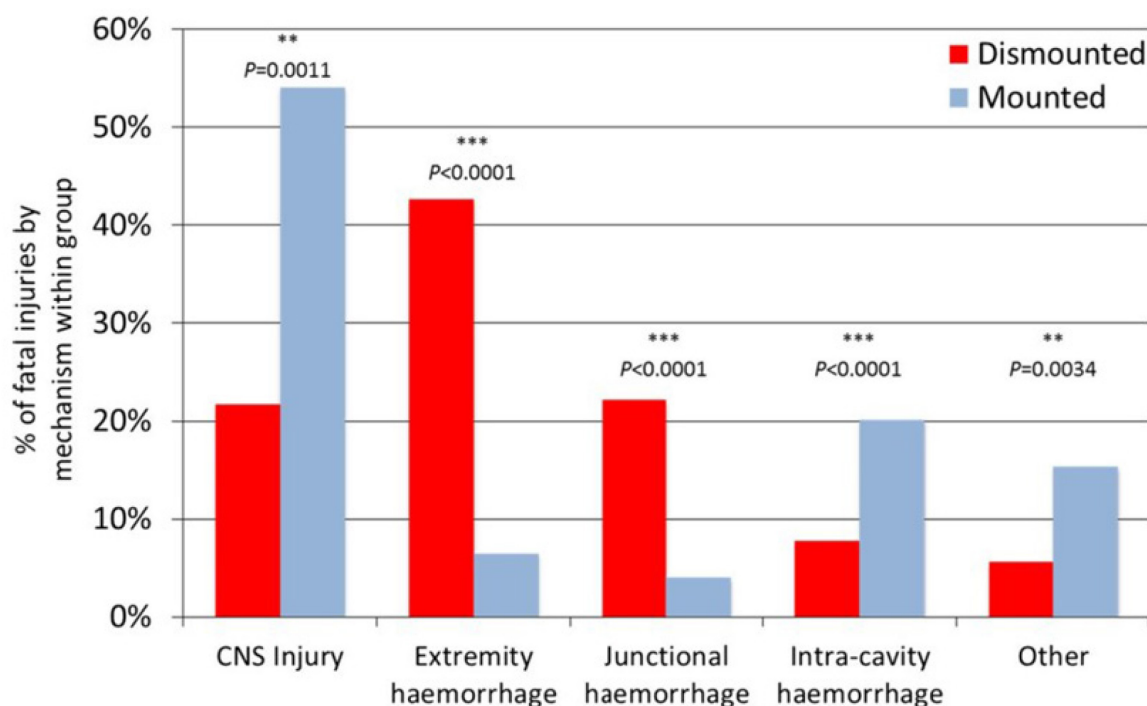


Figure 2-7: Differences in Incidence of Injury Patterns in the Mounted and Dismounted Casualty [30].

## 2.10 UNDERBODY BLAST VEHICLE LOADING FROM EXPLOSIVE DEVICE

The sequential effect that the vehicle and occupant mounted inside the vehicle undergoes following an UBB is shown in Figure 2-8. There are four types of effects in UBB, namely local effects; global effects; drop-down effects; and subsequent effects. Parallel to these sequential effects, there are three loading phases on the vehicle and its occupants, namely initial loading, global motion and Return To Ground (RTG).

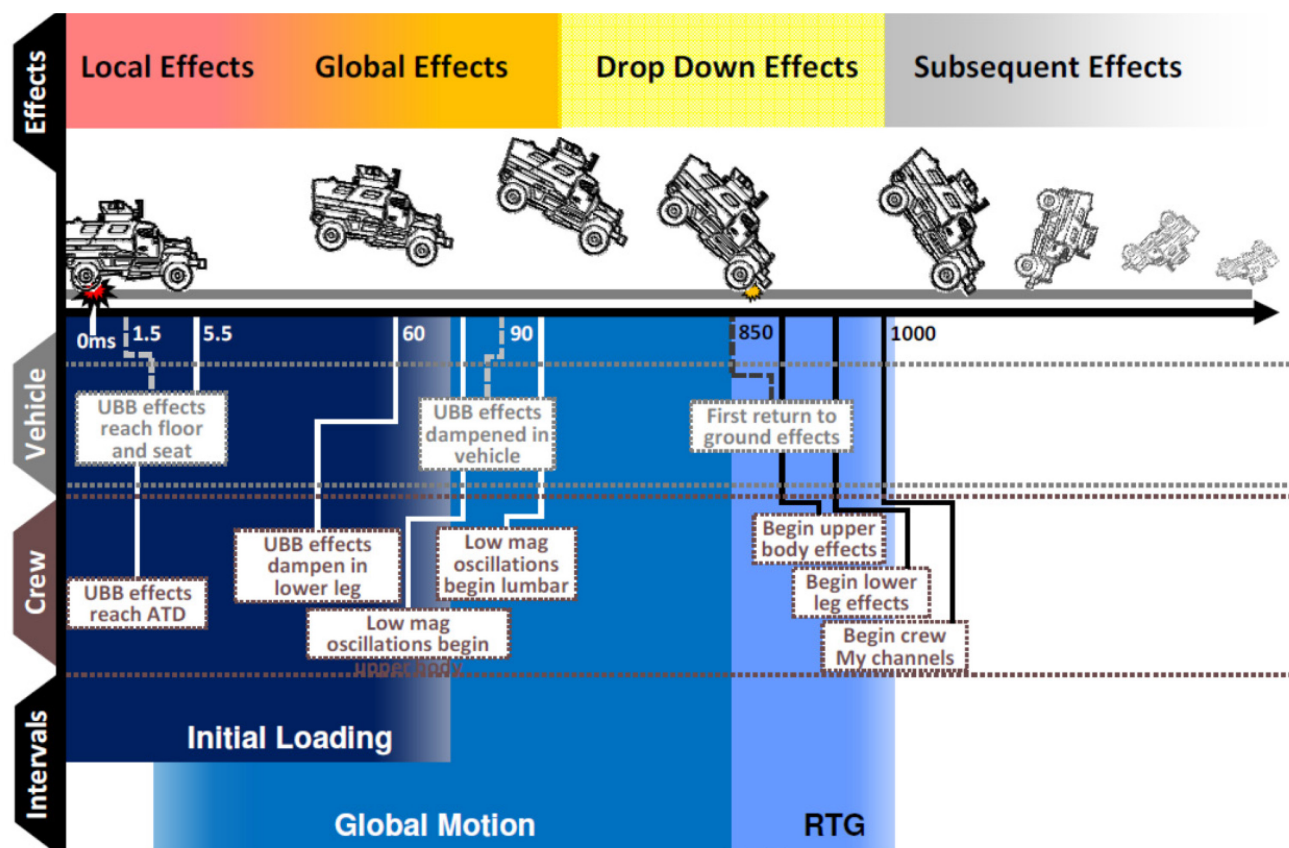


Figure 2-8: Vehicle Loading and Occupant Response Timeline from UBB [31].

## 2.10.1 Local Effects

After the detonation of an explosive under a vehicle, a high-pressure shock wave is formed and is rapidly transmitted into the surroundings, which propagate towards the vehicle. The magnitude and transfer of momentum of the shock wave depends primarily upon the size of the explosive charge and the depth of burial as well as the type of soil where it is buried. A shock wave accelerates rapidly until it reaches the vehicle floor and seat at 0 – 1.5 ms depending on the height of the hull from the ground. Upon contacting the hull, the shock wave is either deflected or reflected depending on the shape of the hull. The vehicle hull absorbs the reflected energy emitted by the shock wave and transmits local accelerations through the vehicle structure.

This loading causes rapid deformation of the floor of the vehicle and impact to the pelvis by seat and has been associated with distinctive injuries of the lower limb, pelvis, and lumbar spine [32].

## 2.10.2 Global Effects

After the high-magnitude response from the initial loading has passed, the global motion interval begins. This interval is dominated by dampened oscillation of the system which includes secondary effects such as blunt trauma from displaced stowage. These loads are typically insignificant compared to the initial local mechanical effect.

As the vehicle hull absorbs the reflected energy emitted by the shock wave, the vehicle weight may be offset causing the vehicle to leap completely or partially from the ground. The vertical height achieved is proportional to the explosive blast magnitude and inversely proportional to the weight of the vehicle [33].

### **2.10.3 Drop-down Effects**

If the explosion was large enough, the vehicle will be lifted by the blast, after some time, the vehicle will fall to the ground under the effect of gravity, potentially resulting in more injury, especially if the occupants are not appropriately restrained. The vehicle experiences a shock response as a result of the global motion being interrupted by the ground [31]. The magnitude of the drop-down impact is considerably less than the initial impact but may worsen structural failure or injury.

### **2.10.4 Subsequent Effects**

A vehicle attacked by a UBB is susceptible to additional events that may injure vehicle occupants, particularly if structural integrity is not maintained. These effects include vehicle rollover, toxic fumes, fire, heat effects, blast overpressure and fragment projectiles.

## **2.11 MODELING OF BLAST**

Modeling of blast and predicting blast related injuries can be achieved by various types of models using varying degrees of fidelity.

### **2.11.1 Analytical Models**

Analytical models are typically lower fidelity mathematical models that can be used to predict blast or injury. These models may be as simple as interpolating a history of experimental data or may be complex calculations that predict outcomes that have been calibrated to known responses. These models are often fast running tools and may not accurately model the physics of the problem but provide meaningful predictions.

### **2.11.2 Computational Fluid Dynamics**

Computational Fluid Dynamics (CFD) is a modeling tool that is often used to predict the blast wave and its progression through the environment. CFD is a tool that is applied to a wide range of engineering problems. It typically involves discretizing a domain into a number of cells and populating the cells with the appropriate material. As the simulation is performed the fluid is tracked in each cell and allowed to propagate according to the modeled physics. The simulations advances at each timestep to ensure errors are minimized and conservation laws are enforced. The result is a transient result that is capable of providing the user with a visualized fluid flow of an explosive event.

Simulations can either be performed in a two dimensional or three-dimensional domains. Two dimensional domains are often desired if the problem possess similarity as these drastically reduces the run time and more detailed models may be simulated. CFD simulations require grid convergence to ensure that the results are of sufficient quality to produce realistic predictions. CFD simulations can be combined with finite element analysis models to model the blast flow and resultant structural response.

### **2.11.3 Finite Element Analysis Models**

Finite Element Analysis (FEA) is a modeling tool that is used to predict the structural or biological material response of a model. These tools operate by dividing the structural object into a number of elements and defining the geometry with appropriate material and behavior models. The FEA solver relies on the defining and constitutive equations to form the basis of the model. Similarly to CFD the finite element analysis model will require and explicit time stepping approaches to calculate the response of the system over the selected time period. For accurate and realistic responses, the material model of the system needs to be well defined. FE Models allow for complex geometry and a high-fidelity solution to be computed. It can also allow for the prediction of stresses and strains inside the body which cannot be predicted in other manners.

### **2.12 CONCLUSION**

Blast injury is the key mechanism of wounding and death in recent conflicts. Increasing survivors in explosive events involves a thorough understanding of injury mechanisms. This chapter has described the physics of blast including the injury classification, mechanism, and resultant injury.

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## Chapter 3 – CHAIN FROM BLAST TO HUMAN EFFECTS

### 3.1 CONCEPT

#### 3.1.1 The Scenario to Human Effect Outcome

The goal of the framework is to provide a systematic method to assess the capabilities of computational models which fit in the blast to quality of life chain. This chapter presents the concept of the framework, which is based on a chain of processes, each process and subprocess can be described by a computational model. Ideally these models can be linked to predict the outcome for the human exposed to a blast insult. The links in this chain can be grouped by specific fields of science involved. The underlying thought concept is illustrated in Figure 3-1.



**Figure 3-1: The Thought Concept for the Chain Linking Blast to Final Outcome Relevant for the Human.**

Figure 3-1 shows a structured mind map of the blast-outcome process by a chain of items which lead sequentially the blast insult to the outcome for the human individual exposed to the blast insult. The chain contains the following elements:

- **The scenario:** a description of circumstances, e.g., infrastructure, stand-off to the threat, posture and orientation of the individual, car bomb or backpack explosive, etc., relevant for the blast exposure of the victim.
- **The threat:** the actual explosion resulting in a shockwave, debris, toxic gasses, heat, etc. This results in a biophysical response.

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- **Physical stress:** this is the parameter describing the load on or the stress experienced by the biological structure at risk. For instance, compression of the ribcage can lead to long injury [1], debris can cause blunt impact to the body which due to exceeding the mechanical strength of bone leads to fractures, heat exposure leads to burned skin.
- **The dose:** this is the level of load or stress the individual is exposed to. The dose and stress are an outcome of the scenario. An individual behind a wall will be exposed to a lower dose than an individual which is directly in sight of the blast source. Infrastructure components can lead to reflections increasing the dose and consequently increasing the stress on the human.
- **The victim:** the blast exposed individual is a victim if the stress dose exceeds certain injury severity tolerances.
- **Biomedical translation:** severity of the victim's trauma is indicated by a translation of the victim's physical condition to biomedical consequences.
- **Whole body/organ:** The injury assessment can be performed on whole body level of on a subsection of the body.
- **Physiological response:** describes the response of the organ functions to the sustained exposure.
- **Pathological evaluation:** leads to a description of injury symptoms.
- **Injury symptoms:** can be physical, psychological, or social.
- **Outcome parameter:** describes the relevance of the injury symptoms for the quality of live which enables to, ideally, quantify the severity for the QoL consequences.

The framework presented in this document aims at categorizing computational models which simulate one or more processes in the chain between blast insult and human consequence. Where output from one computational model is used as input for another model. Some models bridge multiple processes. This is illustrated by a modification of the gear box figure in Chapter 1 shown in Figure 3-2.

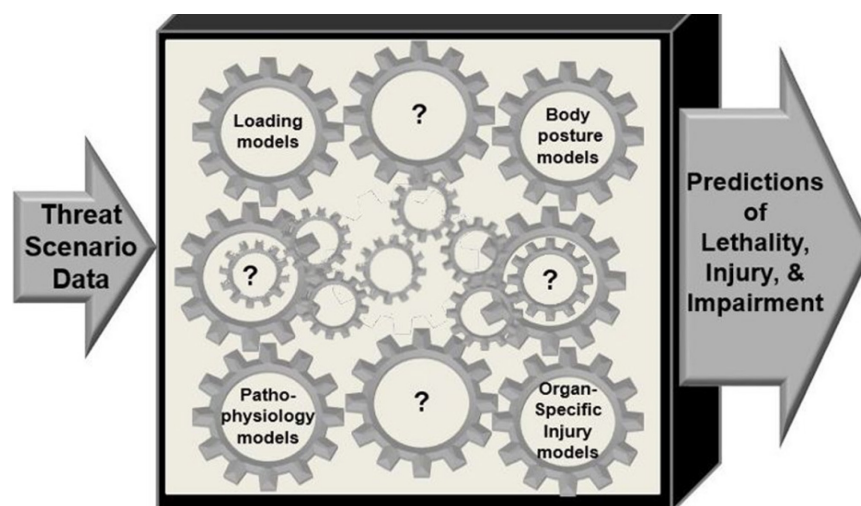


Figure 3-2: The Gear Box as Visualization of the Linkage of Computational Models Predict the Level of Quality of Live as a Consequence of a Blast Insult. One way of organizing the models is to start with loading module as first gear, linking to biomechanical models as second gear, in turn linking to pathophysiology and finally medical outcomes.

### 3.1.2 Computational Versus Non-Computational Models

Examples of non-computational method and a computational model to predict the risk of lethality as function is given below [2], [3].

An example of non-computational model are the Bowen curves. These curves give the lethality risk for a human exposed to a certain dose of overpressure. These curves can be used as a look up table given a specific overpressure and body posture. Where the dose is defined by the amplitude and the time duration of the incident overpressure [4]. These curves also include specific scenarios related to standing or prone position in front of a wall or in free field. These curves, shown in Figure 3-3, were updated later by Bass and Rafaels [5], [6].

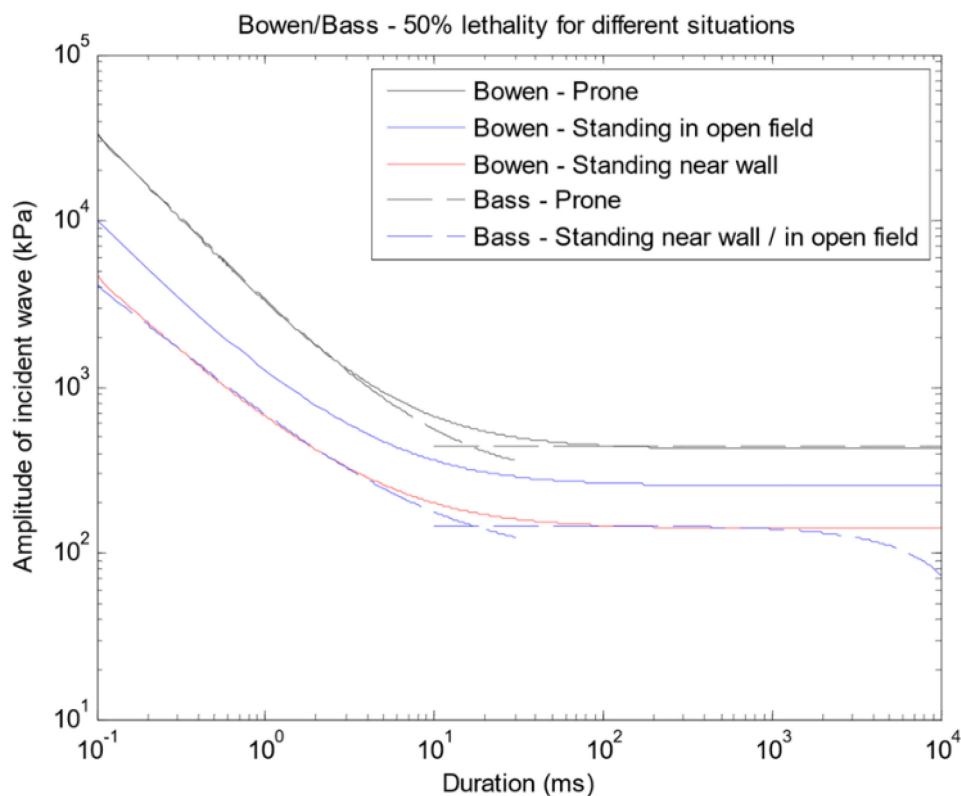


**Figure 3-3: The Bowen/Bass Curves Giving the 50% Lethality for Amplitude and Duration of the Incident Pressure.**

The curves are defined by a formula which needs no numerical (computational) techniques to solve.

$$P = P^* (1 + aT^{-b}) \quad (3-1)$$

Equation 3-1 specifies the lethality risk curves presented in Figure 3-3 as a function of peak overpressure and time duration of the positive phase.  $P^*$  is different for each level of lethality risk, but  $a$  and  $b$  remain the same. For 50% lethality risk  $P^* = 423$  kPa,  $a = 6.76$  and  $b = 1.064$

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Both the Bowen and Bass formulas have several limitations. First, they assume a free field blast wave and are therefore not applicable to complex blast waves that develop in a situation where the initial wave reflects against one or several walls/obstructions. So only applicable for a specific blast scenario. Secondly, they only consider lethality (probability of death) and not the severity of injury.

An example of a computational model predicting the human outcome due to blast exposure of the thorax is a mathematical model developed by Axelsson [1] (Figure 3-4). This model can take input for a blast wave of any shape and provide an injury prediction for a person exposed to this wave independent from the scenario.

The input is taken from the four-pressure measurement mounted in the so-called Blast Test Device (BTD) (Figure 3-5).

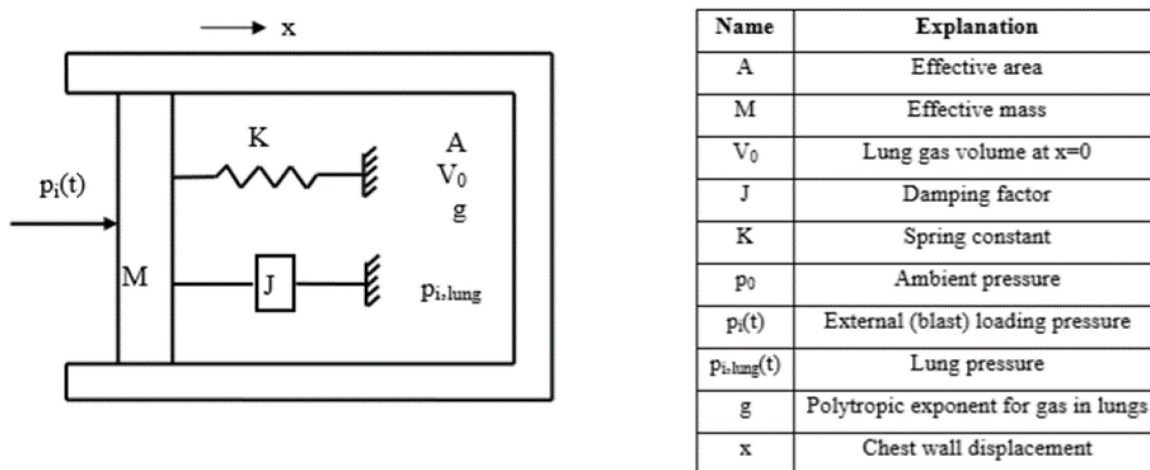


Figure 3-4: Mathematical Model of the Thorax According to Axelsson [1].

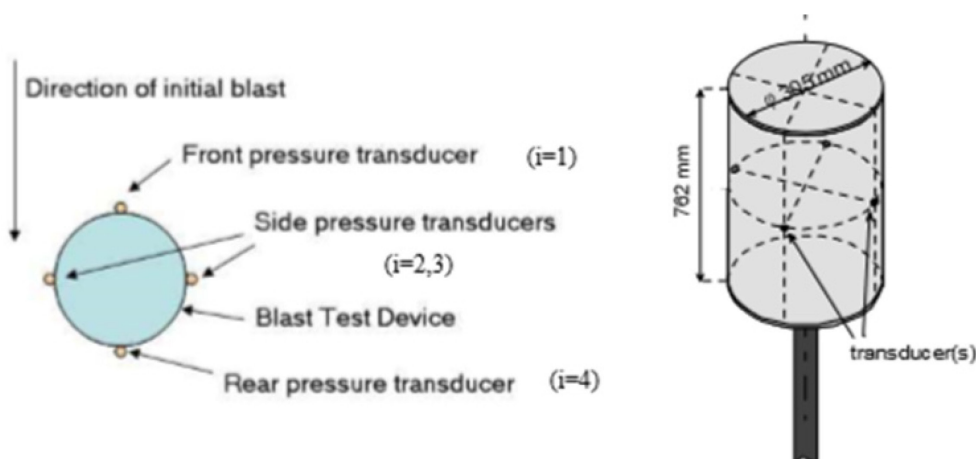


Figure 3-5: The Blast Test Device (BTD).

The mathematical formulas for the Axelsson BTM model are expressed in Equation 3-2 by four independent differential equations, one for each pressure transducer location.

$$M \cdot \frac{d^2 x_i}{dt^2} + J \cdot \frac{dx_i}{dt} + K \cdot x_i = A \cdot [p_i(t) - p_{i,lung}(t)] \quad i = 1,2,3,4 \quad (3-2)$$

$$p_{i,lung}(t) = p_0 \left( \frac{V_0}{V_0 - A \cdot x_i} \right)^2$$

The values of the model parameters can be found in Ref. [2], but are not relevant to be included explicitly here. However, it is not stated anywhere in Axelsson's original article [1] how these were derived.

For each of the four  $p_i(t)$  pressure histories measured on the BTM, the equation above can be solved for chest wall positions  $x_i(t)$ , chest wall velocities  $v_i(t)$  and lung pressure  $p_{i,lung}(t)$  using a specific computer code. There are no restrictions on the input pressure histories  $p_i(t)$ , so the Axelsson BTM model is not limited only to free field blast waves.

Axelsson found the following quantity, called the Chest Wall Velocity Predictor (V), to provide the best correlation as a measure for injury (Equation 3-3):

$$V = \frac{1}{4} \sum_{i=1}^4 \max(v_i(t)) \quad (3-3)$$

where the relation between V and the injury severity expressed in the Adjusted Severity of Injury Index (ASII) is given by Equation 3-4:

$$ASII = (0.124 + 0.17V)^{2.63} \quad (3-4)$$

The correlation between the injury level ASII and V is shown in Table 3-1.

**Table 3-1: Correlation Between Injury ASII and Vmax – BTM.**

| Injury Level          | ASII      | V(m/s)     |
|-----------------------|-----------|------------|
| No injury             | 0.0 – 0.2 | 0.0 – 3.6  |
| Trace to slight       | 0.2 – 1.0 | 3.6 – 7.5  |
| Slight to moderate    | 0.3 – 1.9 | 4.3 – 9.8  |
| Moderate to extensive | 1.0 – 7.1 | 7.5 – 16.9 |
| >50 % lethality       | >3.6      | >12.8      |

## CHAIN FROM BLAST TO HUMAN EFFECTS

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Thus, the Axelsson model including BTM and injury severity assessment forms three gears in the box:

- Quantification of the dose imposed on the body. The use of the BTM makes it scenario independent.
- Quantification of the “stress” sustained by the thorax by the chest wall, displacement, and velocity through a mathematical model. The equation of motion needs to be solved by a numerical algorithm which makes this part of the process the actual computational model.
- Linking the max chest wall velocity to the ASII injury severity scale, where a statistical procedure was used to correlate the Axelsson Vmax to injuries assessed in blast experiments with sheep.

Note that the statistical procedure could also involve a numerical algorithm to determine the best fit for the obtained data. The method used by Axelsson to link the BTM based Vmax to the ASII could not be retrieved within the time frame to create the report at hand. The statistical procedure could be a computational model also.

### 3.2 MODULES IN THE B2HE

Computational models are grouped with respect to the underlying expertise and application. The chain between blast threat and human consequence includes multiple disciplines, for example:

- Blast physics;
- Biomechanics;
- Biomedicine;
- Neurophysiology;
- Traumatology;
- Pathophysiology;
- Clinical medicine; and
- Rehabilitation, etc.

The disciplines have a certain overlap as results from one discipline is used as starting information for the other. Allocating the computational models to a position in Blast to Human Effects (B2HE). Each model is supposed to require a specific input and create an output, where the latter can be used as input for a model further in the B2HE chain. This is also the logic in the modules, which have a sequential order in the B2HE chain. Output created by model in module 1 can be used as input of models in module 2, etc. Modules overlap by the output-input parameters.

The Module chain is illustrated in Figure 3-6.

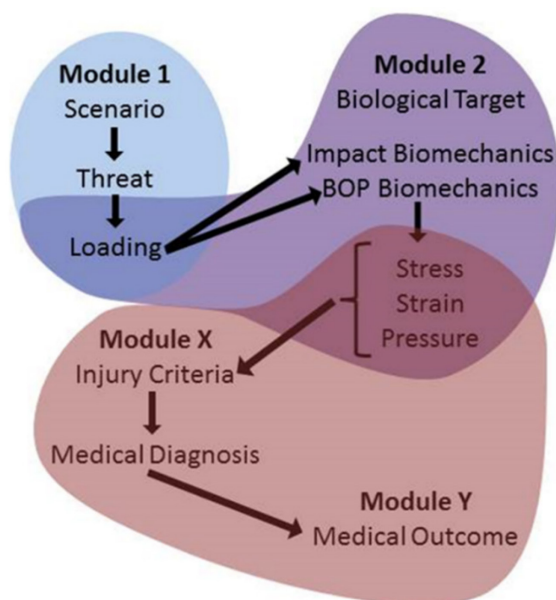


**Figure 3-6: Modules Defined for the BQoL Chain, Starting at the Threat Scenario in Module 1 and Ideally, the Medical Outcome of Module Y Classified the Level of QoL.**

## 3.3 THE FRAMEWORK

The actual frame work to categorize the computational models is a table reflecting the modules above.

The five identified modules are defined in Figure 3-7.

However, it is also possible that models bridge multiple modules. For instance, the Bowen curves are based on a statistical model correlating overpressure to lethality risk. The input for Bowen is the incident overpressure, which is the outcome of module 1. The lethality risk would be outcome of Module Y. The Axelsson model also uses overpressure, however determined by a specific device the BTD. A biomechanical model of the thorax produces the maximum chest wall velocity as injury criterion. Thus, the Axelsson thorax model fits into module 2: input = overpressure time history – output = maximum chest wall velocity. The correlation between the chest wall velocity and the ASII injury severity scale fits in Module X. The injury criterion *chest wall velocity* is correlated to an injury severity score based on pathophysiological findings and the medical consequences of these findings.

Available models are qualified by the following assessment criteria for inclusion in the framework:

| Model Name | Why Was the Model Developed? |   |   |   | Blast Classification | Prediction of ...? | Derivation (Source Data) | Validation | Is the Model Used? |
|------------|------------------------------|---|---|---|----------------------|--------------------|--------------------------|------------|--------------------|
|            | Module                       |   |   |   | Input                | Output             |                          |            |                    |
|            | 1                            | 2 | x | y |                      |                    |                          |            |                    |

## CHAIN FROM BLAST TO HUMAN EFFECTS

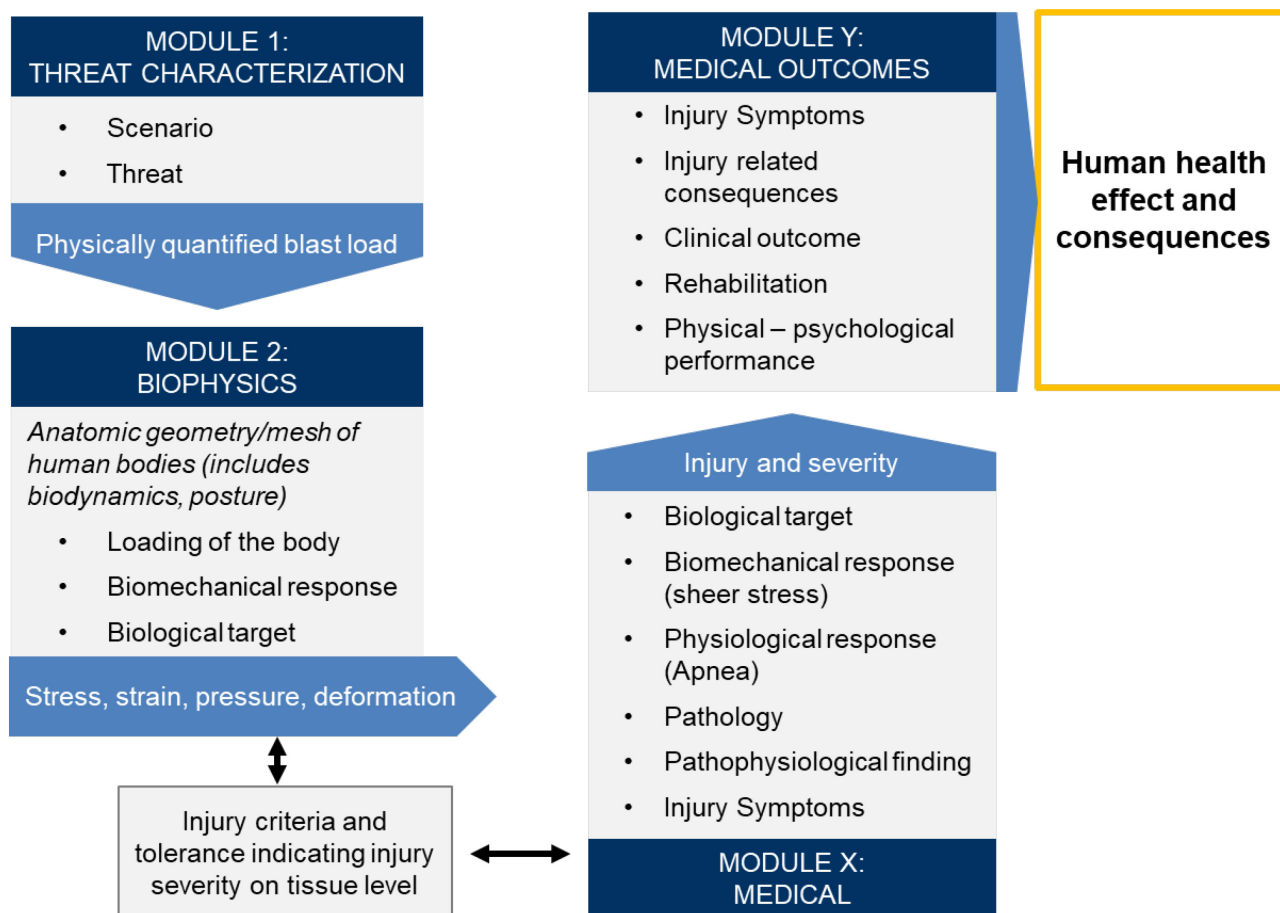


**Figure 3-7: Actual Framework Categorizing the Computational Models from Blast Exposure to Outcomes of Human Health Effects and Consequences.**

Models will be categorized by the modules as defined in Section 3.3.

The assessment criteria provide more information on the background and quality of the model:

- **Why was the model developed?**  
Background on the model development. Some models were developed for internal use, no intention to be linked to other models. Others are aiming at parameter variation studies with none or limited validation.
- **Blast classification**  
Indicates what component of the blast, (explosive source, overpressure, debris, heat, toxicity) or what bas injury category the model is dealing with.
- **Prediction of ... ?**  
Describes the output of the model, can be overpressure or impulse delivered by the explosion, or the load sustained by a biological structure, or the pathophysiology observed by an individual exposed to blast, etc.

- **Derivation (source data)**

Describes the data which were used to develop the model. Consequently, the model is tuned to line up optimal with that dataset.

- **Validation**

States to what extent the model is validated. Which means that datasets not used for derivation are used to verify the level of validity if the model.

- **Is the model used?**

Provides information on how the model is used and what the position of the model can have in the Blast-Human effects chain as well as the potential to be linked to other models.

### **3.4 REFERENCES**

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## **Chapter 4 – SCOPE AND BREADTH OF EXISTING COMPUTATIONAL MODELS (PAST, PRESENT AND IN DEVELOPMENT, FUTURE – APPLICATION OF THE FRAMEWORK)**

The NATO Human Factors and Medicine HFM-270 Research Task Group (RTG) titled “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats” recognizes the value of computational models in solving blast injury, prevention and treatment challenges and plans to develop a framework that integrates existing computational models and guide future ones to predict human lethality, injury, impairment, and long-term health effects across the spectrum of blast-related threats.

This framework will enable the evaluation of operational scenarios such as wargaming, assess the impact of innovative protection systems and devices, identify the needs for acute and long-term medical resources, and predict health outcomes and disabilities. The aim of RTG HFM-270 will be improved strategies to prevent, mitigate and treat blast injuries.

In creating the framework defined above, the task group started by evaluating existing computational models and modeling capabilities. This is where the member nations were requested in completing a questionnaire for each model developed within your organization, including both computational models and underlying experimental models.

The questionnaire used for the evaluation was composed by the attending members. It was delivered to scientific institutions, which are known to work on this topic.

The articles received with the questionnaires were submitted to the members of the group and reviewed to standard format (e.g., Annex I). The group members had the task of reading the work, creating a one-pager synopsis (Annex I) and classifying the work related to the needs and contents of the framework, which anatomical region is being edited and which established computational model (for example Finite Elements (FE) analysis) is used to simulate the blast effects.

Detailed analysis of each of these papers were presented by one or more reviewing expert, discussed by the technical team, and the final classification of the published models and studies was made with regard to the main topic. The technical team then decided on the final list of the models, concurred on the review and included the list for the framework. A complete list of the papers considered is too long to include here as the assessment was made at several RTG meetings. The findings can be seen in Annexes D, E, F, G and H.

### **4.1 SYSTEMATIC LITERATURE REVIEW: COMPUTATIONAL MODELS – BLAST**

The objective of the literature review was at first to capture all articles relevant to the topic and check their content (match search term for the key content) and relevancy, with regard to the scope of this group.

The database search was carried out by mesh terms (see below). This was followed by an appraisal of the search results regarding repetitions, duplicate publications, or incorrect assignment.

The implementation, identification, inclusion and exclusion of publications was carried out in accordance with the recommendations of the German Cochrane Society [1] and the PRISMA criteria published in PLoS [2].

### 4.2 ORGANIZATION OF THE SYSTEMATIC REVIEW

- 1) **Research question:** Systematic literature research on computational modeling of blast and blast injuries – current state of research.
- 2) **Databases:** Medline/PubMed and Embase; Cochrane Database of Systematic Reviews (CDSR); Google scholar, Web of Science, IEEE.org, Ei Compendex.
- 3) **Search strategy:** Search in Medline / PubMed and Embase (possibly searching clinicaltrials.gov → for studies that have not yet been published) stating the date of the search, limitation of date (1980-17.08.2017), German and English, French language.
  - a) “Blast injury” OR “blast injuries” OR “blast-induced” OR “blast wave” OR “blast injury model” OR “blast environment” OR “military blast” OR “blast related” OR “explosion” OR “overpressure” OR “explosions” OR “explosive agents” OR “bombs” OR “ballistic” OR “IED” OR “improvised explosive device” OR “trinitrotoluene” OR “blast-induced traumatic brain injury” OR “brain injury” OR “brain injuries” OR “traumatic brain injury” OR “craniocerebral trauma” OR “lung injury” OR “wounds and injury” OR “high-energy shock waves” OR “shock waves” OR “intracranial pressure” OR “intraocular pressure” OR “acceleration” OR “fragment” OR “fragmentation” OR “blast lung” OR “eardrum rupture” OR “middle ear damage” OR “abdominal haemorrhage” OR “eye rupture” OR “eye penetration” OR “blunt injuries” OR “crush injuries” OR “traumatic amputation” OR “fracture” OR “burns” OR “primary blast” OR “secondary blast” OR “tertiary blast” OR “quaternary blast” OR “quinary blast”.
  - b) “Computational simulation” OR “computer simulation” OR “computational model” OR “computational study” OR “computerized models” OR “computer-assisted” OR “numerical model”.
- 4) **Inclusion and exclusion criteria:**
  - a) Inclusion criteria: mesh term correct, full scientific paper.
  - b) Exclusion criteria: case report, duplicate, no computational model, only congress abstracts available.
- 5) **Number of studies identified in all databases**

284 published abstracts were identified in the included databases. In addition, 27 abstracts/papers were identified from other sources, so 311 abstracts were screened. After duplicates were excluded 306 abstracts remained. 264 studies were considered suitable for inclusion in the systematic review and why (e.g., systematic review, meta-analysis, double-blind study). Additionally, 42 studies were excluded based upon CAE reports. Citation management was done using EndNote X9.2. Details of the systematic review are provided in Annex J.

Figure 4-1 provides a diagram illustrating the systematic review.

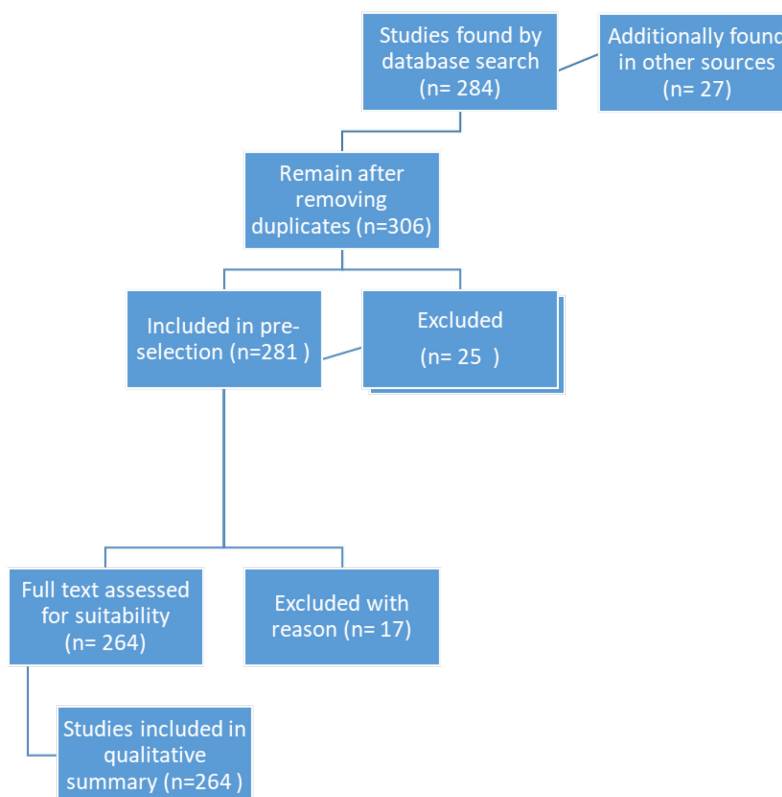


**Figure 4-1: Diagram Illustrating the Systematic Review.**

### 4.3 AIM OF THE FRAMEWORK

Under ideal conditions, an existing, established and validated computational model would allow the simulation of a scenario including defined location, time, exposure, personal protective equipment to get detailed information about mortality, injury patterns, recovery, and rehabilitation resources, and even return to duty or another study endpoint.

This model does not exist so far and will not be available in near future. There are various reasons for this, which can only be explained in a nutshell and simplified form here.

Existing computer models for the simulation of blast effects only deal with sub-aspects of the “chain of events” as defined by the expert group and described above. In addition, the most existing models usually only refer to one anatomical region or to one threat.

The underlying physical effects, laws and measured values are often not recorded and documented in a standardized manner and the validation of the computational models used for the simulation of an injury in the human being was in the past only rarely done.

At the same time there is the problem that e.g., commonly used Finite Element (FE) simulations the physical properties in individual tissues and anatomical segments of the human body and living conditions would need to be known to create a final validated simulation.

## SCOPE AND BREADTH OF EXISTING COMPUTATIONAL MODELS

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However, due to the reason that most of these experiments are not possible in human beings, FE simulation can only be performed using surrogate parameters e.g., the results of diagnostic imaging (ultrasound, MRI, and CT) to deduce the physical properties or to use the results of anatomical postmortem specimens.

This still limits the usability of the results, despite the steady and rapid progress made in improving the methodology over the past 10 years.

Therefore, it remains to be noted that there are competing simulation models relating to different anatomical regions, use different physical fundamentals and measurement methods and thus examine only point-like and therefore only partially all events in the human body after blast exposure.

They are thus only partial aspects of the “chain of events”. Lists all reviewed and published studies regarding the depicted sub-aspects to be a network or patchwork. This illustration is the framework developed by the expert group.

It shows existing and published studies and various computational simulation models on the effects of blast to the human body or parts thereof. By the color marking of respectively required input information and the output results, as well as e.g., the illustrated organ systems or anatomical structures allow answering the following questions in the most favorable case:

- 1) Which computational models are existing and what do they do?
- 2) How can they possibly be linked together in order to consistently depict the “chain of events”?
- 3) Where are the gaps for a successful link that simultaneously define future research priorities?
- 4) Which clinically or militarily relevant issues have not been considered?
- 5) Which combination and methodology of individual computational models is already available for answering a specific question and how can it be used?

Based on discussions around the chain diagram shown in Chapter 3, the TT members developed a matrix and worked through one example [3]. Table 4-1 provides a representative structure of the breakdown of the scope, contribution and impact of each technical publication, on how computational models are being used to model and simulate the effect of blast events, and how such events can affect the various organs of the human body:

- Threat = BOP.
- Loading = 30 psi.
- Biological Target = lung.
- Biomechanical = sheer stress.
- Physiological Response = apnea.
- Pathology = hemorrhage.
- Pathophysiological finding = local inflammation.
- Injury symptom = shortness of breath.
- Pathological finding = dyspnea, cyanosis.
- Outcome = ARDS, LOS on ICU.

## SCOPE AND BREADTH OF EXISTING COMPUTATIONAL MODELS

Table 4-1 provides a representative structure of the breakdown of the scope, contribution and impact of each technical publication, on how computational models are being used to model and simulate the effect of blast events, and how such events can affect the various organs of the human body.

**Table 4-1: Assessment Matrix to Represent Scope, Contribution and Impact of Each Technical Publication.**

| Scenario                     | Threat | Loading Characterization     | PPE | Biological Target | Biomechanical | Physiological Response | Pathology  | Pathophysiological Finding | Injury Symptom        | Pathological Finding | Outcome  |
|------------------------------|--------|------------------------------|-----|-------------------|---------------|------------------------|------------|----------------------------|-----------------------|----------------------|----------|
| 100 kg TNT, open field, 50 m | BOP    | 30 psi, $\Delta t$ , impulse | yes | lung              | shear stress  | apnea                  | hemorrhage | hypoxia                    | Short of breath/ ARDS | Dyspnoe, Cyanosis    | ICU stay |

Any model that addresses the simulation of blast effects on individuals can be analyzed and decomposed into the above cause and effect relationships shown above. As the example shows, each model then can identify its modeling capability, validation techniques and outcomes, and the human health effects and consequences. A list of all the papers describing these models is shown in Annex J.

Annex I shows a representative format used by this RTG to analyze the models and explains how each model can fit into the different modules introduced in Chapter 3. The format of the template used to develop the illustrative cases in Annex I should be construed as an example of a template, that can be modified and/or appended as appropriate to programmatic needs. Also, we note that the assessments are not unique and are as perceived by one or more members of the RTG.

Briefly, the template provides a summary of a model, identifies the computational modeling technique, assesses the assumptions and limitations of the model, and identifies the required data input for the model. An assessment was made of whether the model had been validated, together with the strength and circumstances of the validation. Finally, an overall assessment of the model was made, together with a determination of which of the framework's modules it aligned to as detailed in the next chapter. A complete end to end application of such individual models and how such models can be integrated into the framework developed by this RTG is described in Chapter 5.

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## **Chapter 5 – DESIGN OF AN INTEGRATED COMPUTATIONAL FRAMEWORK FOR MODELING AND SIMULATION OF WARFIGHTER INJURY, PERFORMANCE, AND PROTECTION**

### **5.1 INTRODUCTION**

A comprehensive modeling and simulation tool with an accurate human body model may help in better understanding of IED / mine blast effects on soldier survivability and in designing safety components to mitigate injuries sustained by warfighters. Because of the complex geometry of human anatomy and nonlinearities of tissue properties, an accurate simulation of a blast wave interaction with the human body and the resulting human body injury biomechanics is very challenging. The reported models of blast injury to a human body have typically focused mainly on individual part of the human body (head, torso, and pelvic) often using a simplified geometry and idealized blast loading (Friedlander shock wave), making them unsuitable for the analysis of the combat injury scenarios. The complicated kinematics and interaction between body parts due to the traveling blast wave loading are difficult to model without the use of whole-body finite element models. Furthermore, to the best of our knowledge, there are no existing models of combined blast wave and debris injury models. The existing whole human body biomechanics models have been developed mainly for simulating automotive crash injuries e.g., THUMS model [1] or the Global Human Body Modeling Consortium (GHBMC) [2].

Several scientific teams are conducting laboratory and clinical studies to elucidate injury mechanisms and to develop protective strategies. The majority of these efforts use an experimental approach of animal testing, *in vitro* study, and analysis of clinical data, all of which are useful and necessary but are slow, expensive, lack injury scaling and prediction capability. Better understanding of the blast wave injury mechanisms may be possible with a complementary experimental and computational modeling approach. Validated biomechanics and physiology-based mathematical modeling tools of blast head injury may reduce the need for trial-and-error tests involving laboratory animals, yet provide a capability to study brain injury mechanisms, perhaps accelerating the development of neuroprotective strategies and aiding in the development of improved protective armor [3], [4].

The computational framework for modeling of warfighter injury, performance, and protection should include the following components and capabilities:

- Blast load exposure scenarios encountered in combat and training.
- Blast “signatures” of various blast wave generating threats and weapons in training.
- Tools for automated generation of male/female human body anatomic external and internal geometries used for modeling blast loads and body biomechanical responses.
- Tools to set up blast exposure scenes involving blast threats and the exposed warfighters.
- High-fidelity and fast running models of human body biodynamics and injury biomechanics.
- Tools for computational evaluation of improved safety of warfighter protective equipment and operational protocols.
- Mathematical models and software tools simulating human body physiological responses to various modes of primary and secondary injury and recovery.

- Multiscale mathematical models of neuro-mechano-biology of brain mechanisms.
- Wearable Sensors for a dynamic collection of blast loads and body responses and mathematical models for translation of sensors signals to probability of human injury.
- Tools for model-based diagnostics, prediction of injury trajectory and body responses to treatments.

As shown in the previous chapter, Figure 5-1.

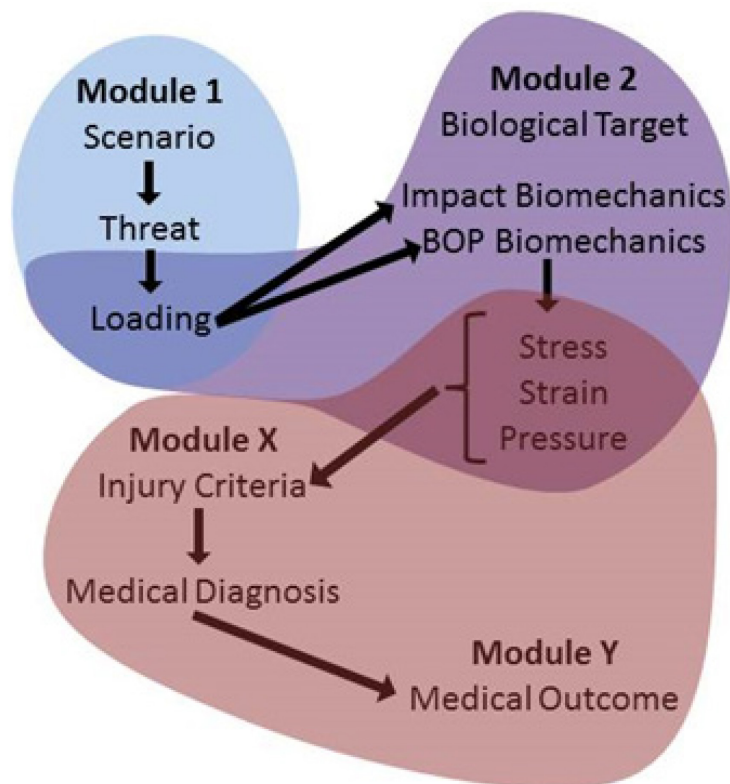


Figure 5-1: Modules Defined for the BQoL Chain, Starting at the Threat Scenario in Module 1 and Ideally, the Medical Outcome of Module Y Classified the Level of QoL.

## 5.2 MODULE 1

### 5.2.1 Threat Characterization

The first phase of an explosion is the *detonation*, a rapid chemical reaction and energy release generating high pressures and temperatures. The expansion of gases after detonation compresses the surrounding air into a pressure wave, *shock wave* that propagates at supersonic speed radially in all directions from the explosion site. The front of the shock wave is followed by a high-speed *blast wind*. The shock wave generated by an explosion blast is called the *blast wave*. If the explosion of a charge occurs at the ground surface the energy is released into a half hemisphere, so it generates almost two times larger effects as the free air explosion.

Detonation of high-energy explosives lasts few hundreds of microseconds and involves three consecutive phases:

- 1) Detonation of the explosive and release of combustion products,
- 2) Expansion of the detonation products and breakdown of the surrounding materials, and
- 3) Formation of the shock wave and the ejection of the debris and soil.

The entire process starts by the detonation wave within the explosive material transforming it into a mass of hot, high-pressure gaseous detonation products, which in turn set off mechanical deformation and a compressive/rarefaction stress waves in the soil. The released combustion products initiate the shock wave in the air and the fragmented soil is ejected forming a crater in the ground. The ejected soil is responsible for the majority of the explosion energy transferred to the target (human) in this stage of explosion. The trajectory of the ejected soil particles/fragments is generally in an upward direction in a conical direction and  $60 - 90^\circ$  angle [5], [6].

Mathematical modeling of blast detonation processes is extremely challenging as it involves strongly coupled and nonlinear chemistry, multiphase gas dynamics, and structures mechanics disciplines. Theoretical and computational models of blast detonation physics have been developed for decades [7], [8] and Chapter 2.

Theoretical and computational models often start with idealized explosion assuming the instantaneous release of energy from a point source in a free field. In such a case an analytical solution of the Sedov-Taylor problem [9] provides the pressure-time history in the form of the Friedlander curve, Figure 5-2. In practice, realistic impulses differ from the ideal Friedlander profile. The effects of reflecting surfaces such as ground or walls of sold objects produce secondary reflected waves and complex wave patterns. For example, an experimental pressure trace of a blast wave inside of a military vehicle, Figure 5-2 [10], typically exhibits complex patterns with several wave reflections.

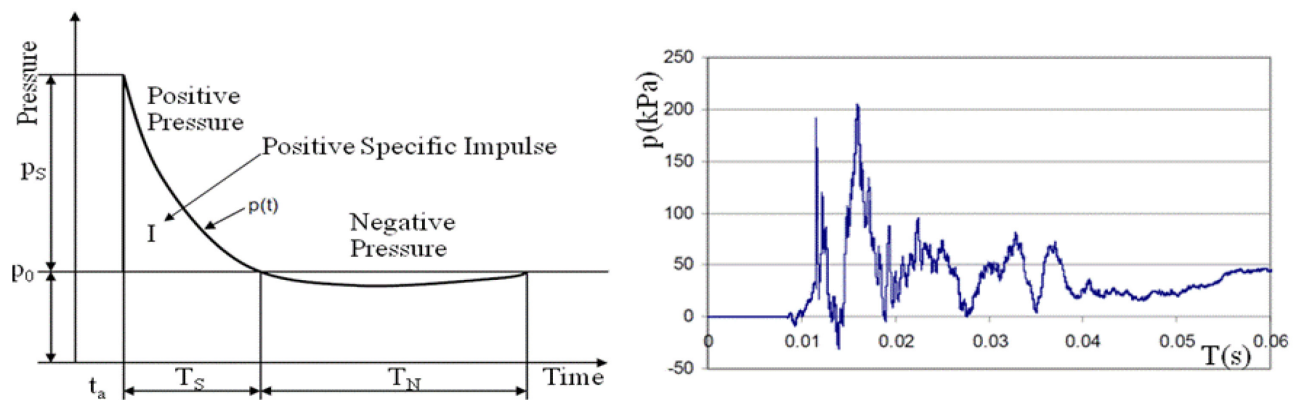


**Figure 5-2: Friedlander Curve – An Ideal Shock Wave Pressure Profile and Example of Complex Overpressure Pattern Inside a Vehicle Subjected to Blast Mine [10] Ideal Shock.**

Representative Warfighter threat scenarios (Figure 5-3) can be classified into two types including:

- a) Combat-related threat scenarios; and
- b) Training-related threat scenarios. Combat-related threat scenarios include threat scenarios with an IED located above/on/under the ground or with the use of grenade or artillery shells and others.

These are well-known threats to service members operating in potentially hostile environments on frontlines. Another classification includes blast threats during training operations. Recent evidence indicates that service members exposed to repeated low-level occupational blast exposure during military training (e.g., artillery, recoilless rifles, shoulder-mounted rocket launchers, and rocket miniguns) with blast wave generating weapons may be vulnerable to brain injury. The planned integrated computational framework should enable simulations for characterization and analysis of various combat and training-related threat scenarios. The different subcomponents are described below.



Figure 5-3: Combat and Training-Related Blast Threat Scenarios.

#### 5.2.1.1 Reconstruction of Training Scenario

The blast wave interaction and the subsequent loading is highly dependent on the warfighter posture and body measurements. This is impossible to model in combat scenarios where the posture is highly random. However, in training scenarios, with fixed training protocols, these postures are well established or can be obtained from high-quality photographs. The envisioned computational framework will include tools that can rapidly create different training setups based on soldier body scans or body measurements and high-quality photographs (posture and relative positioning).

#### 5.2.1.2 Threats and Loading Models

The planned framework may include computational tools that can reconstruct the threats from combat (e.g., IED, grenade, artillery shelling) and training (e.g., muzzle blast from miniguns, back-blast from shoulder-mounted assault weapons and others), as well as model the loads on the corresponding warfighter bodies. This computational suite will include a combination of high-fidelity CFD tools [11] as well as reduced-order analytical loading models (for rapid assessment). The corresponding dose on the body will be calculated using a combination of load propagation and the human body scene setup configurations.

#### 5.2.1.3 Weapon Signatures

Every weapon, especially newer ones, is introduced into training and combat operations with a known “weapon signature” that describe their overpressure conditions suggested safe zones and operational details (Figure 5-4). As new weapons are introduced, they can be first modeling and analyzed in training environment and then used for predicting combat operations impact. The envisioned computational framework could include inverse blast tools that can calculate and store “weapon signatures” (equivalent blast source models) for different heavy weapon systems. Some of the individual components were already developed as stand-alone tools by various institutions. The envisioned computational platform would integrate these different components to form a cohesive threat assessment platform. The physical loads (blast overpressure, force, impulse on the body) can be subsequently used to calculate the biodynamic/biomechanical response and characterize the injury.

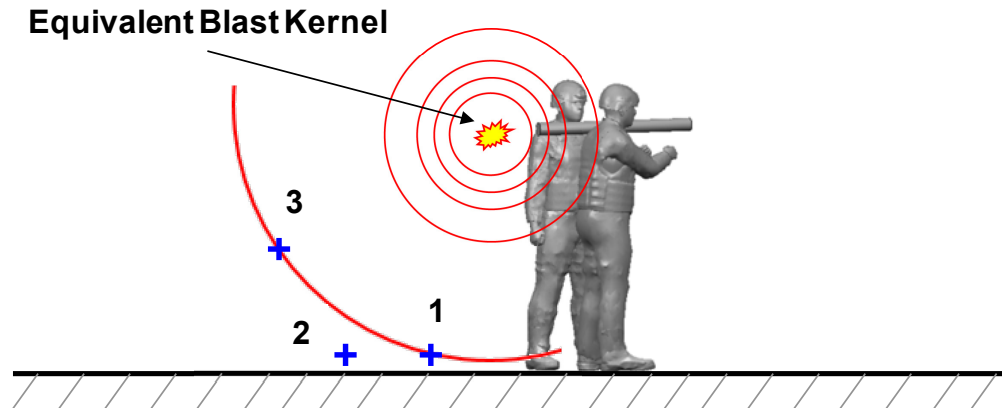


**Figure 5-4: Weapon Signature.**

## **5.3 MODULE 2**

### **5.3.1 Warfighter Body Model**

The human body is a complex system of different materials and complex interfaces. When the human body is exposed to the blast wave, different biological tissues/organs, respond differently. It is important to consider interaction of tissues with each other and on-coming blast wave including secondary and tertiary effects. The current idea of the reaction of the human body to blast exposure is that blast waves, interacting with the body, may transfer energy from the human body surface into the body interior such as the pelvic region (Figure 5-5). The interaction of the blast wave with the human body surface generates two types of waves: pressure waves and shear waves. As the pressure wave travels, the development of pressure differentials across the delicate structures, such as alveolar septa, causes disruption. When the stress wave passes from a solid into a gas filled tissue interface, a component of the compressive wave is reflected back as a tension wave. Most biological materials are weaker in tension than in compression and thus disruption and therefore damage at the tissue interface occurs. When the pressure wave compresses a gas containing structure such as an alveolus or bowel segment, the subsequent expansion causes damage to the wall of the structure. Shear waves are of long-time duration and low velocity causing the deformation of the body wall and compression of the visceral structures. The tearing of structures from their attachments and shearing of solid organs is caused by the asynchronous movements of tissues with differing inertia. The musculoskeletal system being solid is relatively resistant to the pressure waves while initial shock waves of sufficient intensity can cause long bone fracture. Because of these, the inclusion of whole human body (skin, skeleton, and organs) is important to accurately account for the propagation and spatial distribution of stress wave inside human body.

Computational simulations of warfighter blast injury require a detailed model of human body anatomy and computational mesh [4]. Whole human body skin anatomic geometry is needed to simulate blast loads on the body and the internal anatomy for modeling organ injury (brain, lungs, spine, and others). Several high-resolution Finite Element Models (FEM) of a whole human body have been developed for automotive crash analysis (e.g., GHBM [12] and THUMS [1], [13]) but there are no tools for modeling blast exposure and injury scenarios. It is recommended that a standard protocol and modeling tools should be developed to generate person-specific, and population human body anatomic geometry models based on anthropometric measurements. [14]. These tools should enable human body articulation, positioning, outfitting with protective armor and weapons and spatial positioning in the blast exposure scene. The main components of the body model are described below.



Figure 5-5: Explosion of a Shallow Buried IED.

#### 5.3.1.1 Anthropometry

Generation of personalized and population human body models using anthropometric measurements (height, weight, and others) or image/picture as inputs.

#### 5.3.1.2 Articulation

Tools to setup warfighter posture and interaction with equipment e.g., armor, sensors, weapons, vehicle seats and restraints.

#### 5.3.1.3 Skin Geometry

Obtained for anthropometry models or directly from a skin scan is needed to compute space-time-resolved blast wave loads (pressures and blast wind) on the warfighter body.

#### 5.3.1.4 Internal Anatomy

Computational FEM meshes of the whole human body and injury susceptible organs (brain, lung, spine) are needed for injury biomechanics simulations. There are no tools for automated generation of articulated human body anatomic geometry / mesh models. AI/ML based models that could use human skin geometry and high-resolution imaging as inputs to generate person-specific internal anatomical geometry. The anatomical models should enable simulations various forms of blast injury, including:

- 1) Brain, spine and neurotrauma;
- 2) Cardiovascular (compressible and non-compressible hemorrhage);
- 3) Pulmonary (edema, hemothorax, pneumothorax);
- 4) Skeletal spinal, extremities, thoracic);
- 5) Ocular;
- 6) Auditory; and
- 7) Skin burns and wounds.

### 5.3.1.5 Computational Mesh

Automated generation of human body computational meshes (external and internal) and material properties are needed to simulate blast loads on the body and injury biomechanics. These tools should account for warfighter posture, position in the blast scene, armor, and weapons.

### 5.3.2 Biodynamics and Biomechanics

An in-depth understanding of injury during military scenarios requires development and use of advanced computational models (Figure 5-6). These are much more than just biomechanics models. It involves an integrated framework with a range of disciplines (gas dynamics, structural biodynamics, biomechanics, physiology, pathology, biology, and biochemistry), time scales (microseconds to days) and space scales (micron size alveoli to meter size human body and distance from the blast) [15], [16]. It is recommended that the modeling of human body response should include a combination of these different disciplines. Furthermore, biodynamic/biomechanical response is critical to the design and development of better warfighter protective equipment.

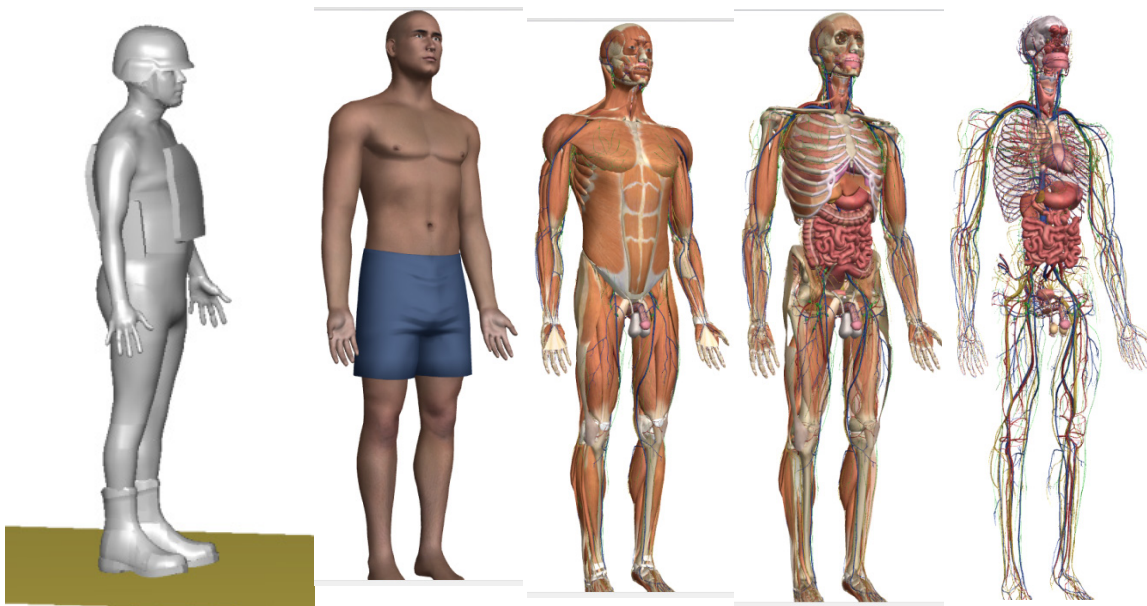


**Figure 5-6: Human Anatomic Geometry Models.**

### 5.3.3 Biodynamics

An integrated body dynamics models is required with components including:

- a) High-fidelity (Fluid-Structure Interaction (FSI)) model/reduced-order model of shock wave loading on the human body;
- b) Flexible human body biodynamics (translocation in space); and
- c) Impact on walls and ground.

Articulated human body biodynamics tools can capture the kinematics of full-body biodynamics response in multiple scenarios (e.g., soldier biodynamics under blast loadings, pilot biodynamics under emergency ejection and others) including the joint loads (forces and moments), translocation (joint displacements) and impacts. These biodynamics simulations can provide useful insights and detailed input conditions (accelerative or impact type) for different injury biomechanics models [17].

### 5.3.4 Biomechanics

The envisioned framework will include the development of an integrated suite of biomechanics tools that can accurately account for the *organ tissue biomechanics and pathophysiology of injury*. Organ tissue injury biomechanics tools should include capabilities for a detailed analysis of tissue stress/strains, deformation, changes in tissue perfusion, potential tearing of tissues of vasculature that can lead to hemorrhage, edema, emboli, hypoxia and ischemia, potential tissue damage and ablation due to thermal loads.

## 5.4 MODULE X

### 5.4.1 Injury and Trauma Trajectory

When a blast wave encounters an object of higher density, such as the human body, it reflects off the object, diffracts around it and passes through it in the form of elastic and shear waves [18], Figure 5-1. The reflected wave overpressure significantly exceeds the overpressure of the incident wave. The side walls, parallel to the shock propagation direction, are loaded with the free shock overpressure. The rear side loading begins after the blast wave passes the body and the diffracted waves meet at the center back side. In addition to the pressure loading, the body will also experience friction drag forces induced by the blast wind. This drag force appears after the primary wave front, but its duration is much longer. A person next to a solid wall may be exposed to not only the forward shock wave but also to even stronger reflected waves. Furthermore, blast injuries in a confined space may be more severe as the person is exposed to multiple reflected waves coming from various directions.

From the human injury viewpoint, the most important part of the wave energy is the one that is transmitted into the body in the form of both positive (compression) and negative (tension) stress waves as well as shear stress waves. In tissues, the steep gradient pressure waves are absorbed by viscoelastic damping and tissue plastic deformation (tearing and breaking), resulting in mechanical injury. When the pressure wave crosses material interfaces with different densities, large perturbations in stress and deformation take place. A wave impacting a denser material compresses it and when it emerges from denser to lighter material it creates tensile deformations. Therefore, in the human body, organs and tissues of different densities are accelerated at different relative rates, resulting in displacement, stretching, and shearing forces.

Results from computational biomechanics models, such as tissue stress and strain fields, could be used as inputs for modeling the injury. However, the prediction of injury solely using tissue biomechanics data is very challenging. A common approach is to establish injury threshold “risk curves” relating blast “dose” and body injury “response” in animal models and translating (scaling) them to humans [19], [20]. For correlating brain injury typical “dose” parameters typically involve incident blast wave parameters (the peak overpressure, blast impulse and duration of the positive phase) or overall body responses (head acceleration). Large number of experimental data is needed to develop such risk curves. New generation injury models are needed based on tissue/organ-specific parameters such as brain tissue local maximum strain rate, shear wave energy dissipation/absorption, and others. High resolution tissue histology and biomarker data from animal models could be used for validation of mathematical models. Development of mathematical models for repeated mild TBI, such as in military training with explosion generating weapons, is particularly challenging as there are no established animal models for this type of injury. We recommend that benchmark quality data of the “dose” (blast loads on the body) and “response” (biomarkers, physiological and cognitive symptoms) should be collected during military training that could be used for calibration and validation of either mechanistic or AI/ML models.

Mathematical models should be developed for both primary and secondary blast injury mechanisms:

- Primary blast biomechanics of the brain, lung, ear, eye, groin;
- Secondary injury (pathology) and recovery;
- Global and organ/tissue specific injury criteria and probability;
- Mathematical models of physiological responses and biomarker kinetics in body fluids;
- Models of trauma dynamics (hemorrhage, pulmonary contusions, spinal and skeletal injury, penetrating injury, skin burn); and
- Models and correlations to establish lethality, survivability and return to duty.

## **5.5 MODULE Y**

### **5.5.1 Medical Outcome, Diagnostics and Treatment**

A mild blast TBI is a complex, often chronic, and difficult to diagnose, pathophysiological process involving neurological, neurocognitive, and systemic responses, some of which are shared with other neurodegenerative and neuropsychiatric diseases. Fortunately, recent progress in high resolution imaging, detection of TBI specific biomarkers in body fluids, wearable sensors, AI/ML models and mobile computing may enable personalized diagnostics and treatment of blast brain injury patients. As the TBI has become a global challenge in both civilian and military population large number of clinical data is being generated which should be used for development, calibration, and validation of TBI diagnostic and treatment models. The biggest drawback of current human and clinical TBI studies, including military training with explosion generating weapons, is difficulty in correlating the blast dose and medical responses. Fortunately, recent developments in wearable blast sensors [21], multifunctional biomarkers [22] and fast running computational models of blast loads on a human body [23] provide foundation for more specific correlation of dose-response effects in mild TBI. The diagnostic protocols should collect the time-resolved data of:

- 1) Injury symptoms;
- 2) TBI biomarkers from available body fluids;

- 3) Data from portable diagnostics and wearable sensors, neuroimaging data, pharmacological treatment (drugs used, dosing and effects);
- 4) Exposure to physical, environmental, and psychological stressors. Mobile medical APPs and dynamic collection of personalized data in medical health records could provide valuable data for model development, personalized diagnostics, and predictive optimized treatment protocols.

Such an integrated computational framework could result in immense military relevant benefits in the form of better understanding of blast injury mechanisms, prevention of blast related injuries, warfighter protection, safer military training, and operations.

### 5.5.2 Warfighter Equipment

Integrated computational suite modeling the loading and human body response on a personalized basis can be extremely useful for design and development of better protective equipment (Figure 5-7).



Figure 5-7: Examples of Warfighter Protective Equipment.

#### 5.5.2.1 Automated Outfitting

The personalized human body generation tools, developed for reconstruction of training scenes, can be used to develop design recommendations for clothing, armor, helmet, weapon systems, wearable sensors, vehicle seats and restraints. The envisioned human body generator tools will include these additional design recommendation capabilities. Furthermore, these tools should account for the varying geometry and material properties of the different protective equipment and should be combined with human body biomechanics tools for comprehensive injury biomechanics simulations. In addition, these tools should also include model-based recommendation for optimal placement of body-worn sensors.

#### 5.5.2.1 Sensors

The envisioned platform will be including a computational framework that enables one to record and store the sensor data (Figure 5-8) with periodic uploads to a cloud-based data storage. This will be complemented by AI/ML based decision-making/support tools for personnel in military training scenarios. In addition, they can be complemented by portable diagnostic hardware tools for immediate on-field data access and display.



**Figure 5-8: Examples of Sensors on Soldier.**

## 5.6 INTEGRATED COMPUTATIONAL FRAMEWORK

An Integrated Computational Framework for Modeling and Simulation may provide a foundation for the development of a user-friendly framework, not only for a better understanding of blast injury mechanisms, but also for the development of personal protective armor, injury diagnostics, combat casualty care, and rehabilitation (Figure 5-9). Design of a simulation framework for multiscale modeling of explosion blast injuries involves not only mathematical modeling and numerical algorithms, but also technical specifications for software user scenarios and data analysis. The target applications include prediction of injury mechanisms, development of improved PPE, evaluation of injury severity and trauma care. Several challenges remain, such as better material properties for high strain rate tissue biomechanics, coupling between macro- and micro-scale tissue biomechanics, tissue damage models for the estimation of the injury location and severity (such as axonal injury and bone fracture), accurate models of penetrating injury, and model validation.

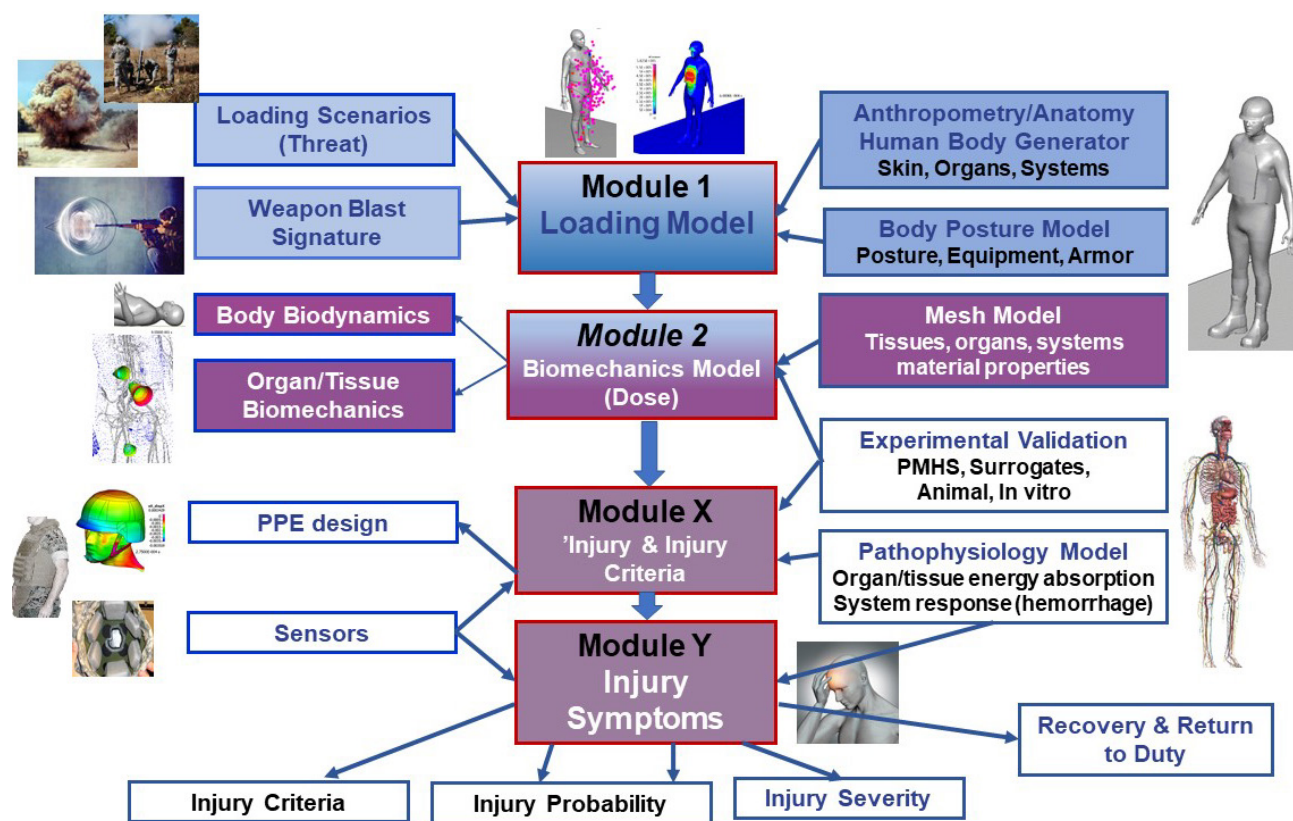


Figure 5-9: Schematic of an Integrated Computational Framework for Modeling and Simulation of Warfighter Injury, Performance, and Protection.

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## Chapter 6 – KEY FINDINGS AND GAPS

The RTG has reviewed computational models in published technical literature that claim to address simulation of blast injury effects both for whole body, specific organs and microscopically at tissue and cell levels. This review has led to the development of a framework that encompasses the computational modeling and simulation, as well as represent the gaps in the literature. The key findings and gaps are identified in this chapter.

### 6.1 KEY FINDINGS

The main findings from this literature search and review can be broken up into three sub-groups, and are described below:

- Formulation of a unified framework to address quantification of blast effects insult and characterization of the resulting injury.
- Summary of the published scientific and technical literature, and identification of their key characteristics.
- Establishing a need for an end-to-end modeling and simulation approach to consider the multiple modalities of trauma that can result from a blast incident.

#### 6.1.1 Formulation of a Framework to Quantify Blast Effects and Characterize the Resulting Injury

A representative blast incident produces multiple effects, such as overpressure, ballistic and blunt impact injuries. Using the US DOD classification system [1], these injuries have been partitioned into five groups: overpressure (primary effects), ballistic impact of the fragments and shrapnel (secondary effects), blunt impact or falls resulting from blast wind (tertiary effects), burns (quaternary effects) and chemical, biological and radiation injuries (quinary effects). While all these effects will not likely contribute to injury for each blast incident, consideration of all these effects allows the broadest and most generalized treatment of blast effects modeling and simulation.

The framework developed in this study and described in Chapters 3 and 4, is dependent on the interrelationship between the explosion and its threats to the human (civilian or Warfighter) through biophysical and biomedical models to lead towards clinical outcomes. The clinical elements derived from the modeling and simulation are linked to medical health care resources (e.g., role of care) and health care logistics. It is this interconnection between blast physics, biophysics and biomedical effects modeling, and clinical elements that has never been addressed in a comprehensive model.

A good way to understand the impact of this framework in analyzing blast incident effects is to consider a hypothetical scenario. In a typical IED incident, e.g., a roadside bombing intended for dismounted Warfighter, the buried explosion causes primary and secondary effects. In addition, in all likelihood, there will also be tertiary effects due to blast wind that can hurl one or more Warfighter to the ground or at nearby objects, such as trees or structures, or make larger objects to hit the Warfighter. There is a small likelihood of quaternary effects (burn injuries) if there are combustible materials in the vicinity, but it is unlikely to have quinary effects (chemical, biological injuries).

## KEY FINDINGS AND GAPS

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In this scenario, blast physics and computational fluid dynamics models can provide the overpressure history, and blast wind and buried fragments velocities to provide the quantitative loading data for biophysical model of the Warfighter. Biodynamic modeling and simulation provide a good representation of the overall motion of the Warfighter. Subsequent computational biomechanical modeling and simulation can predict the deformation and damages to the human body and, depending on situational needs and the fidelity of the model, can also predict the organ and/or tissue level effects. For any kind of structure modeling of the human body and its organs and tissues, the outcome will always be biomechanical measures, such as pressures, stress, strains, displacements, and accelerations. The connection between these measures and clinical assessment is through injury models established by relating biomechanical effects on the body with organs and tissue injuries through clinical assessment by the clinicians. Establishing this relationship is key to the prediction of injury, and the better the insult-injury model is, the better will the computational prediction of injury be. As these models are continuously refined and improved, they can also include organ and/or tissue recovery data, and thus also support prediction of recovery period to return to active service for the Warfighter (or return to normal life for the civilian). Improvement of the biophysics, biomechanical and the biomedical data will improve the fidelity of predicting the response of the human body (Warfighter or civilian) subjected to blast insults. Improvement of insult to injury models (and any recovery models) will help with enhance computational simulation-based injury prediction as well as provide data for medical health care resources, such as health care personnel, equipment and facilities need. The computational modeling and simulation will also support design of better strategy to minimize likelihood of Warfighter combat injury and design improved protective equipment and armor.

We refer the reader to Chapter 3 for a description of the framework and how it integrates computational models to create “a quality of life chain” that links blast effects with quality of life as a sequence of connected sequence of component modules. Chapter 4 extends the framework to design an integrated computational methodology for prediction of injury, and improvement of protective equipment design.

### 6.1.2 Literature Review

A detailed review of publicly available scientific and technical literature (archival and non-archival) was carried out by this RTG to assess the state-of-the-art in modeling and simulation for blast effects and injuries, and to determine how well these models could predict injuries due to blast incident effects. The literature analysis followed the four modules outlined in Chapter 3 covering blast threat characterization, Warfighter body model development including biodynamics and biomechanical simulation at full body, organ or tissue level simulation, injury and trauma clinical assessment, diagnosis and/or treatment, and medical outcome. Based on these assessments, the RTG believes that the compendium of simulation tools in this report (see Annex J) is current. Like other state-of-the-art technologies, additional modeling and simulation tools, and solver software packages continue to be developed continuously, and should be appended to this study from time to time.

The RTG analysis showed that:

- a) Most models and approaches address a small subset of the blast loading effects to the human, but they do not address a systems level solution that can be utilized to predict blast injury to the Warfighter in silico. We found no research demonstrating an integrated approach to simulate blast incident effects from threat modeling through clinical diagnosis and medical outcome. Most of the research on computational modeling concentrated on biomechanics or interpreting blast injury usually due to overpressure only. A few research groups attempted to integrate threat modeling with biological targets, but these models were not adequately validated.

- b) Although blast incidents produce multiple threats, only a very limited number of papers attempted to simulate both of these modalities, and that too they could only treat them as a simple superposition of the threat modes on the model. Coupled solutions for two or threats were not addressed in the literature.
- c) The models also either addressed the effect of the threat on the whole body or the head, but rarely as a multi-physics problem by addressing whole body, organ scale and tissue or cellular scale modeling of blast effects. A key limitation was the ability to integrate the scale effect, as well as establishing the mechanisms of injury at the micro-scale (tissue or cell) and mapping it to the organ and whole-body scale. The lack of availability of very large scale computers to create high resolution models that can span the multiple scales can be one of the reasons. However, the absence of such multi-scale high fidelity computational models also limits our understanding of blast loading effect to date.
- d) Research on biological tissue constitutive model development, especially for the range of strains and strain rates of relevance to blast loading, was very limited. The researchers generally often used quasi-static loading data or data with much lower strain rates than the measured blast loading rates. Further, most of the constitutive models are developed for tensile or compressive loading, and do not consider multi-axial loading, such as shear loading. Constitutive models are also available for isothermal loading conditions, mostly at room temperature, but this is probably a smaller order effect on simulation results than the rate dependency effects.
- e) The literature also has not addressed any attempts to simulate the effect of multiple smaller scale blast threats to the human. Our understanding of this type of loading is limited, because of our lack of understanding of how the brain changes due to this kind of loading. There were also no reported results on biomechanical properties or neurological response changes due to this kind of repetitive low level loading to the tissue.
- f) All of the simulation and results for blast loading in the literature are for acute conditions only, i.e., only at the instant the loading took place, and not for chronic conditions, i.e., after the lapse of time. This is an important aspect that is extremely important to predicting blast induced injury, because often the injuries are reported after a few hours or a few days of the incident(s). A key question here is to characterize how the constitutive model of tissue materials change over time due to initial blast overpressure or blunt impact loading.
- g) One of the key characteristics we looked for in the literature was validation of computational models and simulation results. Much of the literature provided only limited validation at best, and even when the validation was provided, the experimental conditions were not exactly the same as those used in constructing the simulation model. The degree of match between the simulation results and the experimental data also varied from one paper to another, and we realized the absence of a standardized approach to validation of the computational model, unlike for example the standard protocols for automotive crash analysis code verification and validation.

### **6.1.3 Systems-Based Approach to Blast Incident Effects Modeling and Simulation**

One of the key goals of this RTG was to apply the multiple cause and effect relationships described in the framework in Chapters 3 and 4 in an end-to-end simulation for blast incident loading. Based on the literature review and discussions with the subject matter experts, and additional research carried out by the RTG members, we concluded that such an end-to-end simulation of all the effects of blast loading on the Warfighter does not exist in the literature or in practice. Based on the RTG members prior work, Chapter 6 described how some of the different pieces of work that has been done by TNO in The Netherlands can be used to demonstrate the feasibility of the framework described in Chapters 3 and 4.

The framework described here can be demonstrated for an underbody blast incident for a vehicle and its effects on the Warfighters in the vehicle by integrating different tools from different projects to present a concept of the overall framework. This approach to combining different projects demonstrated the need for multiple disciplines working concurrently. A blast physicist and an explosives engineer can utilize research on explosive detonation models and blast dynamics modeling code to simulate the IED blast incident. A vehicle test engineer then uses the results from the IED blast simulation to perform a structural analysis using a commercial structural analysis finite element analysis package. The output of this structural analysis becomes the input loading profile to a Warfighter on a seat in the vehicle. A biomechanical finite element computational model of the human body in seated position can then be used to assess the response of the Warfighter, and, when combined with injury criteria, provide the likelihood of injury to the passenger.

This framework and the example in Chapter 6 demonstrate the feasibility of an end-to-end systems level simulation of the blast incident and its effects on the Warfighter. Such a systems level approach has not been found in published literature. This modeling and simulation can further be extended by transferring the individual stresses, strains, and pressure distribution from the whole-body analysis to organs and tissues of interest. Either a statistical or a deterministic biomechanical analysis with model fidelity for the organs and tissues can be utilized, and further injury analyses may be carried out.

## **6.2 GAPS**

This RTG also identified a number of scientific and technological gaps in the field that will allow a better use of the modeling and simulation tools to relate the blast incidents with Warfighter response, and to predict injury likelihood and protective equipment performance for a broader range of blast threats. The major gaps are:

- a) Computational modeling is done as a subset of the broader scope of the blast induced Warfighter injury problems, and often makes assumptions for either the input conditions or the results and their interpretation. Computational modeling needs to address a systems level end-to-end solution.
- b) Very few articles in the literature address multi-scale problems for blast loading to simulate not only the whole-body response, but also specific organs, e.g., brain, lungs, and heart, due to the same blast loading. The fidelity of the models used in the whole body response is limited and cannot address the organ and/or tissue level response. Further, the RTG found no model that addressed a true fluid-solid model of the biological system, and how that can affect the fidelity of the results, especially for blast effects. The framework proposed in this report is broad enough to cover this scale variation, but there is a need for available modules to provide the detailed simulation capabilities.
- c) Computational model validation is fairly limited and restricted to a small subset of the experimental data. A broader range of experimental data should be used, using material models and test conditions used in the experiments. Further, a standardize methodology for verification and validation of computational models and simulation techniques will be beneficial to the use of these simulation codes.
- d) The tissue material constitutive models used in computational simulation are quite limited and are not representative of blast incident conditions. For example, most of the data used in the literature is for quasi-static or very low strain rate conditions, although blast incidents produce strain rates in the range of 100 to 1000 s<sup>-1</sup> strain rates. Further, material data is only available for fresh harvested tissue and not live tissue, and only for uniaxial loading conditions and not a combined compression/tension and shear loading condition. Lastly, the material models are available for a single loading effect only, and not for repetitive loading. Low level repetitive blast loading due to heavy artillery fire and training exercise conditions, thus, cannot utilize these material models.

- e) Computational Warfighter body models, to date, are primarily in the area of biodynamics and biomechanics, and thus only address mechanical damage/injury to the tissue. These models do not address other mechanisms of injury, such as electrochemical changes or biochemical changes. Biomechanical simulation results show that for mild traumatic brain injuries, pressure rise in the brain may not be enough to cause biomechanical injuries but may trigger other modes of injury due to the presence of the large shear band from the pressure pulse passing through the brain. Existing models cannot address these factors as well as combination of multiple modes of injury at the tissue level or acute and chronic injury types.
- f) The blast research community has been addressing problems from different angles. There is limited coordinated effort to address multiple perspectives into a single focused direction to address the overall problem, as has been done, for example, by the automotive industry for crash simulation and testing. A joint effort to coordinate the blast effects research will benefit the community of interest, and provide better understanding of the causes of injury, its modeling and simulation for accurate prediction, and approaches to develop protective equipment to mitigate its effects.

### **6.3 REFERENCES**

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## KEY FINDINGS AND GAPS

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## Chapter 7 – SUMMARY AND RECOMMENDATIONS

### 7.1 SUMMARY

NATO recognized the value of computational modeling and the potential impact of a comprehensive, whole human blast effects modeling capability for NATO nations to counter rapidly emerging blast threats. To that effect, the NATO Human Factors and Medicine Panel established the HFM-270 Research Task Group (RTG) “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats”. The RTG consisted of 22 appointed members from 10 nations and would advance the capabilities developed by two preceding RTGs, HFM-207 and HFM-234.

The objective of the HFM-270 RTG was to leverage blast injury biomedical research and computational modeling efforts to develop a conceptual framework of computational models that can simulate the effects of blast on the human. The impact of this framework will be to predict the likelihood of injury due to blast and to support rapid development, testing and fielding of effective blast protection equipment to Service members.

A review of the publicly available technical literature (archival and non-archival) showed that comprehensive, threat-to-outcome computational modeling capability to support an agile and streamlined approach to designing, testing, and fielding blast protection equipment does not exist. Most of the modeling and simulation literature was focused on blast overpressure effects, and not on the other aspects of blast loading. The RTG also found that although there are many computational models, they are limited in their scope, either due to their assumptions and material models used, or the lack of adequate validation. Most of the models concentrated on either an organ or tissue, but not a multiple scale assessment of whole body, organs, and tissues. These models also only address a single blast threat and cannot model multiple, low-level events, and have limited human response data. The material models and injury criteria for blast loading is also sparse, thus limiting their capability to connect the computational biomechanical simulation results to organ or tissue injury effects. Overall, it was realized that the computational simulation and modeling efforts vary within NATO nations, and the models need to be better validated and integrated to provide a comprehensive approach. As a part of the literature review, the RTG compiled an extensive database on computational models and simulation and modeling capabilities in the participating NATO nations. It is suggested that this repository be updated periodically as new contributions relevant to this area are made.

Based on the literature review, the RTG developed a conceptual framework to show the interconnections between various aspects of an end-to-end systems-based modeling and simulation approach that does not exist currently. This framework is aimed to address all types of blast loading effects, primary, secondary, tertiary, quaternary and quinary, and both acute and chronic injuries. The framework consists of four modules, 1, 2, X and Y. Module 1 simulates the input produced by a blast incident and models the complete thermomechanical effect of the blast using blast physics. In Module 2, this simulated blast is used as the loading for biophysical simulation of a computational human model in the appropriate body position. As needed, secondary, multi-scale models and/or multi-physics model may be used to augment organ and/or tissue responses to emulate the known clinical assessments. At this point, Module X is used to develop the injury criteria from medical diagnosis data from clinical analysis and is applied to the biophysical results from Module 2 to identify the extent of injuries. Module Y follows Module X and formulates a medical outcome from the blast incident. Thus, it is a process of seamless integration between blast physics, biophysical modeling and simulation, clinical assessment of injured Warfighters and animal subjects, and detailed analysis jointly by medical professionals, engineers, and physicists. Since an integrated approach as formulated here does not exist, the RTG utilized three separate, but sequential, projects already carried out by TNO in The Netherlands to illustrate the application of the framework.

## SUMMARY AND RECOMMENDATIONS

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Lastly, the RTG identified the gaps in computational modeling and simulation of blast effects on humans based on both the review of literature, as well as input from the Subject Matter Experts who presented their perspectives to the Group. The major gaps identified are in tissue material constitutive models, suite of computational models that can cover the entire domain from blast modeling to medical outcome prediction, multi-threat, multi-scale and multi-physics modeling of organ and tissue response to blast loading, injury modeling and characterization, and adequate data and requirements for model calibration and validation.

This RTG's three-year effort produced a computational modeling framework that lays the groundwork for developing such a capability. The framework provides a comprehensive and logical structure within which individual models can interact to produce the desired threat-to-outcome modeling capability. The framework is unique because it reflects the knowledge, perspectives, and needs of the diverse communities and disciplines represented by the RTG members.

### 7.2 RECOMMENDATIONS

The general recommendation is that each nation should consider the gaps identified by this RTG when planning future investments in computational modeling efforts. Also, each nation as well as an organization, like the NATO, should designate resources to maintain and update the dynamic repository of existing models and modeling capabilities that are relevant to the framework. The framework as well as the repository can be a resource for advanced research, software, and hardware-based product development, advancing the state of science in related fields, and better mitigate blast injuries for Warfighters in participating nations.

More specifically, the RTG recommends that:

- a) Develop improved tissue material constitutive models for realistic stresses and strain rates relevant to blast loading, as well as for repeated low-level insults to the Warfighter.
- b) Create a methodology for proper verification of the simulation engines and validation of the computational models and simulation process based on independent assessment of both experimental and computational results and suggest how the differences should be documented.
- c) Develop tools and methodologies to establish a correlation or scaling between animal subjects testing and human body response assessment from combat and operational training data.
- d) Develop models to augment the capabilities of the current models to expand the scope of blast simulation and modeling.

## **Annex A – MINUTES FROM HFM-270 KICK-OFF MEETING OCTOBER 2016**

### **A.1 KICK-OFF MEETING SUMMARY OCTOBER 5 – 6, 2016, PARIS, FRANCE**

HFM-270 (RTG) “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats”.

#### **A.1.1 Background**

Explosive Weapons (EWs) are a continuing and significant source of casualties in NATO operations. The spectrum of operational scenarios involving these blast threats is broad and includes both mounted and dismounted operations. As EWs technology and deployment methods become more complex, so too are the resultant injuries, which now require increasingly sophisticated protective countermeasures and medical interventions. A novel approach is required to rapidly design and test protection systems that can mitigate or prevent the spectrum of the resulting blast injuries.

Blast injury research worldwide has demonstrated the power of computational modeling, tightly coupled with biomedical research, to elucidate tissue-level mechanisms of blast injury needed to design and test protection systems for individuals and occupants of combat platforms. Computational injury biomechanics, complemented with model-guided experimental testing, can provide valuable insight into blast injury mechanics, and support the development of personnel protective armor, injury diagnostics, combat casualty care techniques, and rehabilitation tools.

This new Human Factors and Medicine (HFM) – 270 Research Task Group (RTG) titled “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats” is a logical extension of previous HFM efforts, led by the United States of America (USA) Department of Defense (DoD) Blast Injury Research Program, that recognized the importance of a multidisciplinary approach and the value of computational models in solving blast injury prevention and treatment challenges. The HFM Research Symposium on Blast Injury (HFM-207) highlighted a requirement for an interdisciplinary scientific approach to address the entire spectrum of blast injuries and revealed a specific need for biomedically-valid computational models of blast injury that incorporate biomechanical and physiological responses. The follow-on HFM-234 (RTG) developed guidelines that can provide experimental data necessary to develop and validate computational models of mild Traumatic Brain Injury (mTBI) that will elucidate the tissue-level mechanisms of injury necessary to guide the development and testing of effective protection systems.

The Technical Activity Proposal for the present RTG was submitted to the NATO Science and Technology Organization (STO) in late 2015 and approved in the spring of 2016 (see Appendix A-1) which resulted in the establishment of a new NATO STO, HFM RTG with the objective to develop a framework for translating scientific information into the capability to prevent human lethality, injury, and impairment across the spectrum of blast-related threats with the aim of attenuating or preventing these problems by leveraging previous, ongoing, and planned blast injury biomedical research and computational modeling efforts and developing the framework for creating and evaluating effective systems that protect against these blast-related threats.

A kick-off meeting of the Technical Team (TT) for HFM-270 RTG was held on 5 – 6 October 2016 in Paris, France at the STO Collaboration Support Office (CSO). The purpose of the meeting was to review the Technical Activity Proposal (TAP) (Appendix A-1) and establish a Program of Work (PoW) for the next three years.

This document summarizes the deliberations of the HFM-270 (RTG) TT members at this kick-off meeting (see agenda (Appendix A-2)) and includes the developed PoW and list of the seventeen (17) appointed TT members (Appendix A-3) that represent eight (8) NATO nations; fifteen (15) of which were able to participate in the kick-off meeting. Dr. Levent Turhan participated by WebEx and Dr. Raj Gupta (USA), Executive Secretary, and Dr. Sarah Watts (UK) could not attend this kick-off meeting.

### **A.1.2 Welcome and Guidance for the HFM-270 (RTG)**

The NATO, STO-CSO, HFM Panel Executive, LtCol (Dr.) Frank Wessels welcomed all the appointed TT members and asked them to introduce themselves. After introductions, LtCol Wessels reviewed guidelines and recommendations from the STO-CSO for the HFM-270 (RTG). He noted that Mr. Mike Leggieri will be the Chair for the HFM-270 (RTG) and Dr. Maarten Nieuwenhuizen is the Panel Mentor.

LtCol Wessels started his presentation (copy in HFM-270 Meeting 1 folder on Science Connect website) by providing information on the NATO S&T organization and its role within the North Atlantic Council. He discussed the STO's business model, STO panels and groups, collaborative environment, and mission of the HFM panel to optimize the health, safety, well-being, and performance of the human in operational environments. LtCol Wessels highlighted the HFM panel management, requirements, TAD, and specific activities to be completed during the planning and working phases, roles of the RTG Chair, and TT members. He then reviewed the conditions that govern the participation of guests or external experts/as advisors and best practices and considerations for the RTG as well as several points to keep in mind:

- 1) Changes to TAP/TOR require approval.
- 2) Appoint editor and create outline for final report early.
- 3) Coordinate with STO-CSO publications early.
- 4) Keep Panel Executive and Panel Mentor informed.

LtCol Wessels enumerated the RTG deadlines as follows:

- 1) Meeting minutes are submitted to Panel Executive 2 – 3 weeks after each meeting.
- 2) First briefing to HFM Panel Business Meeting by the RTG Chair will take place in Fall 2017 (Brussels, BEL).
- 3) Technical Team report is due 45 days before HFM Panel Business Meeting.
- 4) Final technical report is due by October 2019.
- 5) Last briefing to HFM Panel Business Meeting by the RTG Chair will take place in Fall 2019.

LtCol Wessels gave an overview of resources available from the CSO to support the RTG including if changes need to be made to the PoW, financial support and how to request this support. He ended his presentation with a summary of the role of the Panel Executive and reminded everyone of the online resources available within the login section of the [www.cso.nat.int](http://www.cso.nat.int) website.

Mr. Marcin Kaminski, STO-CSO Publications Manager, reviewed the technical report publication process and highlighted the need for getting publication clearance from all participating nations early in the process. He encouraged the TT to use the library of templates (located on STO-CSO website under Authoring Support section under Publications <https://www.sto.nato.int/Pages/support-for-authors.aspx>) as guides when preparing their final report for publication. He emphasized the value of pre-releasing a draft final report for use by the participating nations prior to publication of the official final report.

Mr. Alan Shaffer, Director, STO-CSO, welcomed the TT members. He encouraged the team to include all forms of blast injury in their discussions and final report and consider conducting a demonstration of the framework concept; to publish in refereed journals, noting that STO has funding set aside to assist with publication costs; and to take advantage of the Science Connect site for data sharing and collaboration. He encouraged the TT members to become familiar with published STO reports, such as the recently published report on mTBI, that are pertinent to the objectives of this RTG, and to leverage ongoing efforts in each nation that illustrate modeling capabilities. He encouraged the team to utilize the tools for collaboration that STO-CSO has to offer, such as WebEx capability which can support up to 25 participants, and he suggested that team consider reoccurring one hour WebEx meetings to ensure ongoing momentum. He advised the team to take advantage of access to other nations' libraries and he ended by challenging the team to write a one paragraph "elevator pitch" on this effort that he can share with stakeholders. The TT members agreed to the following summary (Appendix A-4):

*HFM-270 (RTG) is a logical extension of previous HFM efforts that recognized the importance of a multidisciplinary approach and the value of computational models in solving blast injury, prevention and treatment challenges. The task group will develop a framework that integrates existing computational models and guides future ones to predict human lethality, injury, impairment, and long-term health effects across the spectrum of blast-related threats. This framework will enable the evaluation of operational scenarios such as war gaming, assess the impact of innovative protection systems, identify the needs for acute and long-term medical resources, and predict health outcomes and disabilities. The task group will evaluate existing computational models and modeling capabilities of the participating nations, identify those that can be used now to address current problems, gaps and future needs. The impact of HFM-270 (RTG) will be improved strategies to prevent, mitigate and treat blast injuries.*

In Mr. Shaffer's concluding remarks, he asked what he could do to help this RTG. Mr. Leggieri stated that the group could use his help facilitating the appointment of members from Australia, New Zealand, Israel, and Japan who have expressed an interest in joining the RTG. Mr. Shaffer agreed to help, and Mr. Leggieri agreed to send the contact information for the proposed TT members to LtCol Wessels. Dr. Cernak asked for advice on how to get better responses from nations on their capability for computational models using a survey tool that did not yield many responses when implemented in HFM-234 (RTG). Mr. Shaffer suggested that Dr. Cernak write a request in plain language that he can share with the Committee of the Chiefs of Military Medical Services in NATO (COMEDS) and S&T community.

Finally, Mr. Phil Reed from STO-CSO Information Management and Systems provided an overview of the new Science Connect resource ("Facebook for NATO") and the WebEx/VTC capabilities available to support the RTG as needed. LtCol Wessels is one of the administrators for the Science Connect site and will assist TT members with login difficulties or questions about the site.

### **A.1.3 Review of Technical Activity Description**

Mr. Leggieri presented background information on the HFM-270 (RTG) TAD. He discussed how EWs continue to be a source of casualties in NATO operations and that the spectrum of blast-related threats is broad and includes both mounted and dismounted operations. He explained that biomedical blast injury research has

demonstrated the power of computational modeling when tightly coupled with biomedical research to elucidate tissue-level mechanisms of blast injury. The resulting models can provide a capability for designing and testing protection systems for individuals and occupants of combat platforms and assessing health risks associated with the use of weapon systems. He described the RTG's objective to support this capability by developing a computational modeling framework that integrates existing models and guides future ones to predict human lethality, injury, impairment, and long-term health effects across the spectrum of blast-related threats.

#### **A.1.4 Review of the Proposed Plan to Achieve the TAD Objectives**

Mr. Leggieri described what constitutes a PoW, as highlighted below:

- 1) Description of specific efforts that achieve TAD objectives.
- 2) A schedule of workshops and meetings designed to:
  - a) Identify topics and hosts;
  - b) Describe host responsibilities for preparing workshop and meeting reports; and
  - c) Describe required workshop and meeting support from CSO.
- 3) List of specific deliverables from this three-year effort.
- 4) Description of information dissemination plans, such as NATO reports, scientific publications, etc.

To achieve the TAD objectives, Mr. Leggieri initiated the discussion by introducing a proposed plan:

- 1) Identify elements of the computational modeling Framework;
- 2) Identify existing, ongoing and planned models, databases, and injury criteria for each element;
- 3) Develop assessment criteria for inclusion in the Framework;
- 4) Identify gaps where no suitable models exist;
- 5) Develop the Framework (integration of models); and
- 6) Develop criteria for validating the Framework.

A summary of the TT discussion of each proposed element of the plan follows.

##### **1) Identify elements of the computational modeling Framework**

Elements of the computational modeling Framework can be categorized into prevent, treat, and rehab/repair. Within each of the three categories, the computational models can be divided into two major groups: i) Linear/immediate outcomes / fast/simple models; and ii) Long-term outcomes / complex models / high resolution and reliability / sophisticated models. The elements that fall within the linear/immediate outcomes/fast/simple models include threat scenarios such as fragment patterns, EW effects, and blast in underwater environments. The elements that fall within the long-term outcomes/complex models/high resolution and reliability/sophisticated models include available treatments and deterioration of the human system over time. In these situations, the team noted that there may be a need for more than one framework to address the end state.

**2) Identify existing, ongoing, and planned models, databases, and injury criteria for each element**

The TT members agreed that an effective mechanism for identifying and compiling existing, ongoing, and planned computational models from participating nations would be to use a survey based on the survey tool used in HFM-234 to identify each nation's research capabilities. Emphasis was placed on identifying and including both computational models and the underlying experimental models with associated material property, lethality, injury, and impairment data. Prioritization should be placed on the models that address the most important issues today and are translatable to future threats. The TT members will need to identify 5 – 10 questions that must be answered before a model can be considered for inclusion in the Framework. Mr. Leggieri noted that his office is establishing a working group that will help to identify relevant US DoD-sponsored computational models and modeling efforts. Mr. Phillipens noted that TNO is collecting information on the relevant computational models within the Netherlands.

**3) Develop assessment criteria for inclusion in the Framework**

The TT members discussed assessment criteria such as, biomedical validity (i.e., gender, age, etc.), suitability of assumptions, limitations/boundaries, intended use, development and maintenance cost, and clinical validity. The TT members indicated that a description of how the model was validated and what the validation means should be included as key information in the final report.

**4) Identify gaps where no suitable models exist**

The TT members agreed that the data compiled using the survey tool will identify gaps where there is a lack of suitable models; what research needs to be done to develop the required models; additional investment in existing models to further validate them; multinational collaborations; any incremental advances needed i.e., road map; and the ideal capability to include long-term outcomes. All agreed that gender and age are major gaps.

**5) Develop the Framework (integration of models)**

Prior to Framework development, the TT members agreed that they need to identify the components to include in the Framework; determine how to integrate the models (i.e., physiological, interfaces, data transfer, etc.) and identify Common Data Elements for each of model (i.e., computational, experimental, and clinical models).

**6) Develop criteria for validating the Framework**

The TT members discussed what criteria to use to validate the Framework. This effort will include validating the accuracy of individual and integrated computational model predictions (lethality, injury, and impairment) and identifying experimental evidence to support the resulting computational model prediction. A recommendation was made to identify a set of experimental/surrogate models to standardize computational models and that at least one demonstration should be conducted, as Mr. Shaffer suggested, to illustrate that the concept for the Framework is valid.

Based on the discussion above, the TT members finalized a list of proposed deliverables as follows:

- 1) Framework for Computational Models of Human Lethality, Injury, and Impairment from all Blast Threats, in Both Mounted and Dismounted Scenarios, and in all Threat Environments – this will be a standalone framework displayed in a vertical matrix.

- 2) Dynamic Repository of Existing Modeling Capabilities – which will be created with the information from the survey of all participating nations and include computational, experimental, clinical, and other models and be maintained as an active repository; a recommendation of how to maintain this repository will be included in the final report.
- 3) Gaps in Modeling Capabilities – gaps will become apparent as the existing modeling capabilities are identified in number 2 above.
- 4) Comprehensive Dictionary of Modeling and Simulation Terms – continuation of the dictionary created in HFM-234 (RTG).
- 5) TAP for new HFM which would develop standardization and validation criteria and approaches for implementing the Framework.
- 6) Publications in peer reviewed literature.
- 7) Final Report with Framework, Gaps and Recommendations and Comprehensive Dictionary and TAP as addenda – include discussion of confidence interval/accumulation of errors and utility of Framework using demonstration scenario outcomes in final report.

The TT members determined that at least nine meetings are needed to complete the proposed deliverables. The proposed schedule of future meetings and RTG activities are described in more detail in the PoW below.

### **A.1.5 Program of Work**

The team recognized the need for three in-person meetings every twelve months to facilitate the completion of the PoW and development of the deliverables for this RTG. Several TT members volunteered to conduct and/or host various activities, workshops, and meetings with the understanding that they needed to coordinate with their respective host nations and organizations to confirm their commitment to host various activities as listed in the proposed PoW. The TT members agreed that all workshops will be three days in duration. Invited guest scientists, clinicians, program managers, and/or Subject Matter Experts (SMEs) will be invited to give their talk and then leave; they will not be privy to any other guest presentations or TT discussions. Invited guest travel costs will be covered by the host organization for the specific meeting. If the host organization needs additional funding, STO-CSO may have funding to support guest travel; the host organizer will need to contact LtCol Wessels.

A group WebEx will be held midway between each in-person meeting and the duration of each call will be determined based on the objectives of the meeting.

The team agreed to maximize the use of the Science Connect website for information sharing, document development, etc.

**A.1.5.1 HFM-270 (RTG) Program of Work Schedule**

| Activity/<br>Workshop   | Month/Year        | Purpose                                                                                  | Host/Location                          | Point of Contact                        |
|-------------------------|-------------------|------------------------------------------------------------------------------------------|----------------------------------------|-----------------------------------------|
| 1 <sup>st</sup> Meeting | 5 – 6 Oct. 2016   | HFM-270 (RTG) Kick-off                                                                   | STO-CSO/Paris                          | LtCol (Dr.) Wessels                     |
| 1 <sup>st</sup> WebEx   | Mid-Nov. 2016     | Finalize Agenda and Invited Speakers for Next Meeting, and Finalize Survey               | WebEx                                  | Mr. Leggieri                            |
| 2 <sup>nd</sup> Meeting | 10 – 12 Jan. 2017 | Identify Elements of The Framework                                                       | USA/Frederick, MD                      | Mr. Leggieri                            |
| 2 <sup>nd</sup> WebEx   | Mid-Apr. 2017     | Finalize Agenda and Invited Speakers for Next Meeting                                    | WebEx                                  | Mr. Leggieri                            |
| 3 <sup>rd</sup> Meeting | 11 – 13 Jul. 2017 | Scope Breadth of Existing Models                                                         | GBR/Porton Down                        | Drs. Kirkman/Watts                      |
| 3 <sup>rd</sup> WebEx   | Mid-Sept. 2017    | Finalize Agenda and Invited Speakers for Next Meeting                                    | WebEx                                  | Mr. Leggieri                            |
| 4 <sup>th</sup> Meeting | 7 – 9 Nov. 2017   | Overview of Existing Computational Models                                                | NLD/Rijswijk                           | Mr. Philippens                          |
| 4 <sup>th</sup> WebEx   | Mid-Jan. 2018     | Finalize Agenda and Invited Speakers for Next Meeting                                    | WebEx                                  | Mr. Leggieri                            |
| 5 <sup>th</sup> Meeting | 6 – 8 Mar. 2018   | Overview of Existing Computational Models                                                | DEU/Koblenz                            | Drs. Franke/Bieler                      |
| 5 <sup>th</sup> WebEx   | Mid-May 2018      | Finalize Agenda and a List of Assessment Criteria to Use at Next Meeting                 | WebEx                                  | Mr. Leggieri                            |
| 6 <sup>th</sup> Meeting | 10 – 12 Jul. 2018 | Apply Assessment Criteria                                                                | Suffield Research Center, Alberta, CAN | Drs. Bouamoul/Sawyers                   |
| 6 <sup>th</sup> WebEx   | Early Oct. 2018   | Finalize Agenda                                                                          | WebEx                                  | Mr. Leggieri                            |
| 7 <sup>th</sup> Meeting | 4 – 6 Dec. 2018   | Finalize the Framework and Develop Blast Scenarios                                       | TUR/Ankara                             | Drs. Turhan/Huri and Mr. Kurtoglu/Erdik |
| 7 <sup>th</sup> WebEx   | Mid-Feb. 2019     | Finalize Agenda                                                                          | WebEx                                  | Mr. Leggieri                            |
| 8 <sup>th</sup> Meeting | 3 – 5 Apr. 2019   | Review Demonstration Results, Identify Gaps and Finalize Dictionary, TAP and Manuscripts | SWE/Stockholm                          | Dr. Risling                             |
| 8 <sup>th</sup> WebEx   | Late Jun. 2019    | Review Draft Final Report Revisions                                                      | WebEx                                  | Mr. Leggieri                            |
| 9 <sup>th</sup> Meeting | 4 – 6 Sept. 2019  | Finalize All Deliverables                                                                | STO-CSO/Paris                          | LtCol (Dr.) Wessels                     |

### **A.1.5.2 Program of Work, Schedule, and Milestones**

#### **1<sup>st</sup> Meeting: Kick-off (5 – 6 October 2016 – Paris, FRA)**

Refer to meeting summary write up in this document.

#### **1<sup>st</sup> WebEx: Mid-November 2016**

- 1) Discuss the draft agenda for the 2<sup>nd</sup> meeting, including proposed presentations by SMEs.
- 2) Finalize survey questions for existing computational, experimental, and supporting models from participating nations and discuss the design of the data repository on the STO-CSO Science Connect site.

#### **2<sup>nd</sup> Meeting: Identify Elements of the Framework (10 – 12 January 2017 – Fort Detrick, Frederick, MD, USA)**

- 1) Identify elements of the computational modeling Framework displayed in a vertical matrix to populate with existing computational models.
- 2) Dictionary Working Group – provide strategy update.
- 3) Publications Working Group – provide strategy update.
- 4) TAP Working Group – provide strategy update.
- 5) Dr. Gupta will provide overview of DoD Computational Modeling Expert Panel findings and recommendations.
- 6) Presentations from USA DoD SMEs.

#### **2<sup>nd</sup> WebEx: Mid-April 2017**

Discuss the draft agenda for the 3<sup>rd</sup> meeting, including proposed presentations by SMEs.

#### **3<sup>rd</sup> Meeting: Scope Breadth of Existing Models (11 – 13 July 2017 – Porton Down, Salisbury, Wiltshire, GBR)**

- 1) Scope the breadth of existing computational models based on responses to survey.
- 2) Categorize computational models by type:
  - a) Threat;
  - b) Lethality;
  - c) Injury (blunt/impact, burns, brain, ballistic); and
  - d) Impairment.
- 3) Presentations from computational modeling SMEs.
- 4) Develop plan that will include criteria to assess model capabilities in Meetings 3 – 5.
- 5) Dictionary Working Group – provide update.
- 6) Publications Working Group – provide update.
- 7) TAP Working Group – provide update

**3rd WebEx: Mid-September 2017**

Discuss the draft agenda for the 4<sup>th</sup> meeting, including proposed presentations by SMEs.

**4th Meeting: Overview of Existing Computational Models (7 – 9 November 2017 – TNO, Rijswijk, NLD)**

- 1) Evaluate technical capabilities of existing models based on plan established in 3<sup>rd</sup> meeting.
- 2) Presentations from SMEs on selected existing computational models.
- 3) Dictionary Working Group – provide update.
- 4) Publications Working Group – provide update.
- 5) TAP Working Group – provide update.

**4th WebEx: Mid-January 2018**

Discuss the draft agenda for the 5<sup>th</sup> meeting, including proposed presentations by SMEs.

**5th Meeting: Overview of Existing Computational Models (6 – 8 March 2018 – Koblenz, DEU)**

- 1) Evaluate technical capabilities of existing models based on plan established in 3<sup>rd</sup> meeting.
- 2) Presentations from SMEs on selected existing models.
- 3) Dictionary Working Group – provide update.
- 4) Publications Working Group – provide update.
- 5) TAP Working Group – provide update.
- 6) Executive Secretary will present a draft outline of the final report for discussion and assign responsibly for writing sections of the final report to the TT members.

**5th WebEx: Mid-May 2018**

- 1) Discuss the draft agenda for the 6<sup>th</sup> meeting, including proposed presentations by SMEs.
- 2) Discuss draft list of assessment criteria developed and coordinated virtually prior to the WebEx to use at the 6<sup>th</sup> meeting.

**6th Meeting: Apply Assessment Criteria (10 – 12 July 2018 – Suffield Research Center, Alberta, CAN)**

- 1) Apply assessment criteria developed in the 5<sup>th</sup> WebEx to determine which models should be included in the Framework.
- 2) Incorporate existing models into the Framework including strengths and weaknesses of each model.
- 3) Dictionary Working Group – provide update.
- 4) Publications Working Group – provide update.
- 5) TAP Working Group – provide update.
- 6) Executive Secretary provide status update on draft final report.

**6th WebEx: Early October 2018**

Discuss the draft agenda for the 7<sup>th</sup> meeting.

**7th Meeting: Finalize the Framework and Develop Blast Scenarios (4 – 6 December 2018 – Ankara, TUR)**

- 1) Finalize the Framework.
- 2) Finalize integration of models into Framework and identify gaps.
- 3) Develop several blast threat scenarios for demonstration of Framework applicability using selected mature computational models.
  - a) Identify points of contact for selected mature computational models to be used and any associated cost for running the scenarios developed before the 8<sup>th</sup> meeting.
  - b) Designate TT member(s) to take on task of having demonstrations run on selected models and presenting outcomes at 8<sup>th</sup> meeting.
- 4) Dictionary Working Group – provide update.
- 5) Publications Working Group – provide update.
- 6) TAP Working Group – provide update.
- 7) Executive Secretary provide status update on draft final report.

**7th WebEx: Mid-February 2019**

Discuss the draft agenda for the 8<sup>th</sup> meeting.

**8th Meeting: Review Demonstration Results, Identify Gaps and Finalize Dictionary, TAP and Manuscripts (3 – 5 April 2019 – Stockholm, SWE)**

- 1) Evaluate concept of the Framework.
  - a) Selected TT member(s) present output of blast threat scenarios run through selected mature computational models to demonstrate Framework feasibility.
  - b) Explore cumulative and propagation of errors.
- 2) Identify gaps and research needed to close the gaps.
- 3) Finalize dictionary.
- 4) Finalize new TAP.
- 5) Finalize draft manuscripts for publication in peer reviewed journals.
- 6) Executive Secretary provide status update on draft final report.

**8th WebEx: Late June 2019**

- 1) Review any revisions to draft deliverables.
- 2) Executive Secretary will review process for requesting clearance from each participating nation i.e., NATO Form 13-3E.

**9th Meeting: Finalize Deliverables (4 – 6 September 2019 – Munich, DEU)**

Finalize all deliverables:

- 1) Framework for Computational Models of Human Lethality, Injury, and Impairment from Blast Threats, in Both Mounted and Dismounted Scenario in any Threat Environment.
- 2) Dynamic Repository of Existing Modeling Capabilities.
- 3) Gaps in Modeling Capabilities.
- 4) Comprehensive Dictionary of Modeling and Simulation Terms.
- 5) Draft TAP for new HFM which would develop a standardization and validation criteria and approaches for the Framework.
- 6) Publications in peer reviewed literature.
- 7) Final Report with Framework, Gaps and Recommendations and addenda.
- 8) Executive Secretary provide status update on progress of participating nations clearance.

**A.1.6 Outcomes of Kick-Off Meeting**

In addition to developing a PoW, three working groups were established and will continue their work for the three-year duration of this RTG. These working groups are as follows:

- 1) **Dictionary Working Group** to develop a dictionary of commonly used computational modeling terms with definitions (i.e., Comprehensive Dictionary of Modeling and Simulation Terms). They will start with the dictionary developed during HFM-234 (RTG) and use literature to identify new terms and definitions. The working group members are:
  - a) Dr. Ibolja Cernak;
  - b) Col (Dr.) Philippe May;
  - c) Dr. Emrys Kirkman.
- 2) **Publication Working Group** to identify and guide publication of articles in appropriate peer reviewed journals throughout the duration of this RTG. They will consider an array of publication types including simulation and medical journals. The working group members are:
  - a) Dr. Dan Bieler;
  - b) Mr. Ilker Kurtoglu;
  - c) Dr. Mårten Risling;
  - d) Dr. Amal Bouamoul;
  - e) Dr. Axel Franke;
  - f) Dr. Raj Gupta.
- 3) **TAP Working Group** to draft a Technical Activity Proposal (TAP) for a new HFM activity which will develop standardization and validation criteria and approaches for the Framework. The working group members are:
  - a) Dr. Ibolja Cernak;
  - b) Dr. Amit Bagchi;

- c) Dr. Thomas Sawyer;
- d) Dr. Sarah Watts or Dr. Emrys Kirkman.

A summary paragraph (Appendix A-4) on this effort was developed by the team that can be used by Mr. Shaffer and all participating nations for this RTG.

The action items from this Kick-off meeting are as follows:

- 1) All TT members must confirm access to the HFM-270 (RTG) site on Science Connect at <https://www.sto.nato.int/>.
- 2) Meeting summary:
  - a) Chair to post draft on Science Connect site Friday, 21 October 2016.
  - b) Technical Team to provide feedback using track changes by Monday, 31 October 2016.
  - c) Chair to deliver final meeting summary to Panel Executive on Friday, 4 November 2016.
- 3) Dictionary Working Group to review HFM-234 dictionary and develop strategy for adding terms and definitions related to computational modeling and simulation.
- 4) Publication Working Group develop a strategy for coordinating publications over the duration of this RTG.
- 5) TAP Working Group develop a strategy for developing this new TAP.
- 6) Chair responsible for setting up WebEx for mid-November 2016:
  - a) Coordinate a time for the WebEx that will work for the TT members for the participating nations.
  - b) Prepare a draft agenda including:
    - i) Suggestions for speakers.
    - ii) Overview of DoD Computational Modeling Expert Panel findings and recommendations – Dr. Gupta.
    - iii) Working Group reports.
  - c) Finalize survey tool:
    - iv) Review draft survey questions and design of repository developed and coordinated virtually prior to WebEx.
    - v) Finalize survey.
    - vi) Propose and finalize survey dissemination plan.
    - vii) Set a deadline for initial survey responses that will be used to inform guest presentations for meetings 3 – 5.
    - viii) Present draft recommendation of how to maintain this repository.

**A.1.7 List of Nations**

Canada (CAN)  
France (FRA)  
Germany (DEU)  
Netherlands (NLD)  
Sweden (SWE)  
Turkey (TUR)  
United Kingdom (GBR)  
United States (USA)

**A.1.8 National and STO Resources Needed**

- National resources needed: Manpower, travel funds, national data, technical and administrative support for organizing and conducting workshops and writing reports.
- Document translation and funding for invited participants to the workshops.
- Hardware and Software: Microsoft Office and use of STO Science Connect website and WebEx resources.

**A.1.9 Technical Team Leader and Team Members (No Ranks)**

Mr. Mike Leggieri (USA), Chair  
Dr. Raj Gupta (USA), Executive Secretary and SME  
Dr. Dan Bieler (DEU)  
Dr. Amal Bouamoul (CAN)  
Dr. Ibolja Cernak (USA)  
Mr. Atil Erdik (TUR)  
Dr. Axel Franke (DEU)  
Dr. Pinar Huri (TUR)  
Dr. Emrys Kirkman (GBR)  
Mr. Ilker Kurtoglu (TUR)  
Dr. Philippe May (FRA)  
Mr. Mathieu Philippens (NLD)  
Dr. Mårten Risling (SWE)  
Dr. Thomas Sawyer (CAN)  
Dr. Levent Turhan (TUR)  
Dr. Sarah Watts (GBR)

**A.1.10 Appendices**

Appendix A-1: Technical Activity Proposal.

Appendix A-2: HFM-270 Kick-off Meeting Agenda.

Appendix A-3: HFM-270 Appointed Technical Team Members.

Appendix A-4: HFM-270 (RTG) Summary.

## Appendix A-1: HFM-270 TECHNICAL ACTIVITY PROPOSAL (TAP) AND TERMS OF REFERENCE (TOR)



PUBLIC RELEASE

### Technical Activity Proposal (TAP)



|                                        |         |                                                                                                             |                                |
|----------------------------------------|---------|-------------------------------------------------------------------------------------------------------------|--------------------------------|
| <b>Activity reference number</b>       | HFM-270 | <b>Activity Title</b>                                                                                       | <b>Approval</b><br>2015        |
| <b>Type and serial number</b>          | RTG     | Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats | <b>Start</b><br>May 2016       |
| <b>Location(s) and Dates</b>           |         | Kick-off meeting CSO Paris                                                                                  | <b>End</b><br>May 2019         |
| <b>Coordination with other bodies</b>  |         | COMEDS                                                                                                      |                                |
| <b>NATO Classification of activity</b> |         | Public Release                                                                                              | <b>Non NATO Invited</b><br>Yes |
| <b>Publication Data</b>                |         | TR                                                                                                          | PR                             |
| <b>Keywords</b>                        |         | Blast injury, biomedical research, computational modeling, modeling and simulation, blast injury prevention |                                |

#### I. Background and Justification (Relevance to NATO):

Explosive weapons are a continuing source of casualties in NATO operations. The spectrum of operational scenarios involving these blast threats is broad, and includes both mounted and dismounted operations. A novel approach is required to rapidly design and test protection systems that can mitigate or prevent blast injuries. Biomedical blast injury research in the U.S. has demonstrated the power of computational modeling, tightly coupled with biomedical research, to elucidate tissue-level mechanisms of blast injury needed to design and test protection systems for individuals and occupants of combat platforms. The proposed effort will leverage previous, ongoing, and planned blast injury biomedical research and computational modeling efforts among the participating nations. This effort is a logical follow-on to HFM-207/SYM (2011) and HFM-234/RTG (2013-2016) which highlighted requirements for biomedically-valid computational models of blast injury that incorporate both biomechanical and physiological responses.

#### II. Objective(s):

To leverage previous, ongoing, and planned blast injury biomedical research and computational modeling efforts among the participating nations to develop a framework for translating scientific information into the capability to model the mechanisms of human lethality, injury, and impairment across the spectrum of blast-related threats. The proposed RTG will also develop the framework for creating and evaluating effective systems that protect against these blast-related threats.

#### III. Topic To Be Covered:

- Computational modeling of human lethality, injury, and impairment from blast threats, in both mounted and dismounted scenarios;
- Previous, ongoing, and planned blast injury biomedical research and computational modeling efforts, and how these fit into overarching frameworks for understanding mechanisms of injury and development of protective systems;
- Identification of the gaps that remain in the mechanisms of blast-related injury and in understanding how to adequately protect from these injuries.

#### IV. Deliverable (e.g. S/W Engage Model, Database,...) and/or end product (e.g. Final Report):

Technical Report, other deliverable(s) : none

#### V. Technical Team Leader And Lead Nation:

Chairman : To Be Determined.

Lead Nation: United States



PUBLIC RELEASE

**Technical Activity Proposal (TAP)**



**VI. Nations Willing/Invited to Participate:**

NATO Nations and Bodies : Canada, Estonia, France, Germany, Netherlands, Norway

PfP Nations : all PfP invited

MD Nations : all MD invited

ICI Nations : none

Global Partners : Australia, Japan, New Zealand, Republic of Korea

Contact / Other Nations : Singapore

**VII. National And/Or NATO Resources Needed (Physical and non-physical Assets):**

Members of this RTG will be funded by their nations

**VIII. STO/CSO Resources Needed:**

CSO meeting room for kick-off meeting

Funding for 2 consultants

**Additional Information**

**Limited Participation Technical Team:**

No



PUBLIC RELEASE

**Terms Of Reference (TOR)**



**HFM-270, RTG  
on**

**Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats**

**I. Origin**

**A. Background**

**B. Justification (Relevance for NATO)**

**II. Objectives**

**III. Resources**

**A. Membership**

Chairman : To Be Determined.

Lead Nation: United States

Nations Willing/Invited to Participate: Canada, Estonia, France, Germany, Netherlands, Norway

**B. National And/Or NATO Resources Needed :**

Members of this RTG will be funded by their nations

**C. STO/CSO resources needed**

CSO meeting room for kick-off meeting

Funding for 2 consultants

**IV. Security Classification Level**

The security level will be Public Release

**V. Participation By Partner Nations**

PfP Nations : all PfP invited

MD Nations : all MD invited

ICINations : none

Global Partners : Australia, Japan, New Zealand, Republic of Korea

Contact / Other Nations : Singapore

**VI. Liaison**

## Appendix A-2: HFM-270 – KICK-OFF MEETING AGENDA

| Wednesday October 5, 2016 |                                              |                                                                         |
|---------------------------|----------------------------------------------|-------------------------------------------------------------------------|
|                           |                                              |                                                                         |
| <b>0900</b>               | Welcome                                      | Mr. Leggieri                                                            |
|                           | Introductions                                | Team Members (TM)                                                       |
|                           | Guidelines and Recommendations (50 min)      | LtCol (NLD) Frank Wessels<br>HFM Panel Executive                        |
|                           | Break                                        |                                                                         |
|                           | Technical Report process (20 min)            | Mr. Marcin Kaminski<br>Publication Manager                              |
|                           | CSO SharePoint site overview (20 min)        | Mr. Phil Reed, Information<br>Management and System                     |
|                           | Challenge for Technical Team (30 min)        | Mr. Alan Shaffer<br>Director, NATO Science &<br>Technology Organization |
|                           |                                              |                                                                         |
| <b>1200</b>               | <b>Lunch</b>                                 |                                                                         |
|                           |                                              |                                                                         |
| <b>1300</b>               | Technical Activity Description (TAD)         | Mr. Leggieri/TM                                                         |
|                           | Development of HFM-270 Program of Work (PoW) | Mr. Leggieri/TM                                                         |
|                           | Break                                        |                                                                         |
|                           | Development of HFM-270 PoW (cont.)           | TM                                                                      |
|                           |                                              |                                                                         |
| <b>1900</b>               | <b>Dinner</b>                                | <b>TM</b>                                                               |

| Thursday October 6, 2016 |                                    |                                                  |
|--------------------------|------------------------------------|--------------------------------------------------|
|                          |                                    |                                                  |
| <b>0900</b>              | Development of HFM-270 PoW (cont.) | TM                                               |
|                          | Break                              |                                                  |
|                          | Development of HFM-270 PoW (cont.) | TM                                               |
|                          |                                    |                                                  |
| <b>1200</b>              | <b>Lunch</b>                       |                                                  |
|                          |                                    |                                                  |
| <b>1300</b>              | Development of HFM-270 PoW (cont.) | TM                                               |
|                          | Final Guidance                     | LtCol (NLD) Frank Wessels<br>HFM Panel Executive |
|                          | Next Steps                         | Mr. Leggieri/TM                                  |
|                          |                                    |                                                  |
| <b>1500</b>              | <b>Adjourn</b>                     |                                                  |

### **Appendix A-3: HFM-270 (RTG) APPOINTED TECHNICAL TEAM MEMBERS PRESENT AT HFM-270 KICK-OFF MEETING 5 – 6 OCTOBER 2016**

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### **Appendix A-4: HFM-270 (RTG) SUMMARY**

HFM-270 (RTG) is a logical extension of previous HFM efforts that recognized the importance of a multidisciplinary approach and the value of computational models in solving blast injury, prevention, and treatment challenges. The task group will develop a framework that integrates existing computational models and guides future ones to predict human lethality, injury, impairment, and long-term health effects across the spectrum of blast-related threats. This framework will enable the evaluation of operational scenarios such as war gaming, assess the impact of innovative protection systems, identify the needs for acute and long-term medical resources, and predict health outcomes and disabilities. The task group will evaluate existing computational models and modeling capabilities of the participating nations, identify those that can be used now to address current problems, gaps, and future needs. The impact of HFM-270 (RTG) will be improved strategies to prevent, mitigate and treat blast injuries.

## **Annex B – MINUTES FROM HFM-270 PANEL MEETING JANUARY 2017**

### **B.1 MEETING #2, JANUARY 10 – 12, 2017, FREDERICK, MARYLAND, USA,**

HFM-270 (RTG) “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats”.

#### **B.1.1 Background**

Explosive Weapons (EWs) are a continuing and significant source of casualties in NATO operations. The spectrum of operational scenarios involving these blast threats is broad and includes both mounted and dismounted operations. As EWs technology and deployment methods become more complex, so too are the resultant injuries, which now require increasingly sophisticated protective countermeasures and medical interventions. A novel approach is required to rapidly design and test protection systems that can mitigate or prevent the spectrum of the resulting blast injuries.

Blast injury research worldwide has demonstrated the power of computational modeling, tightly coupled with biomedical research, to elucidate tissue level mechanisms of blast injury needed to design and test protection systems for individuals and occupants of combat platforms. Computational injury biomechanics, complemented with model-guided experimental testing, can provide valuable insight into blast injury mechanics, and support the development of personnel protective armor, injury diagnostics, combat casualty care techniques, and rehabilitation tools.

The Human Factors and Medicine HFM-270 Research Task Group (RTG) titled “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats” is a logical extension of previous HFM efforts that recognized the importance of a multidisciplinary approach and the value of computational models in solving blast injury prevention and treatment challenges. The HFM Research Symposium on Blast Injury (HFM-207 (SYM)) highlighted a requirement for an interdisciplinary scientific approach to address the entire spectrum of blast injuries and revealed a specific need for biomedically-valid computational models of blast injury that incorporate biomechanical and physiological responses. The follow-on HFM-234 (RTG) developed guidelines that can provide experimental data necessary to develop and validate computational models of mild Traumatic Brain Injury (mTBI) that will elucidate the tissue-level mechanisms of injury necessary to guide the development and testing of effective protection systems.

The objective of the HFM-270 (RTG) is to develop a framework for translating scientific information into the capability to prevent human lethality, injury, and impairment across the spectrum of blast-related threats with the aim of attenuating or preventing these problems by leveraging previous, ongoing, and planned blast injury biomedical research and computational modeling efforts and developing the framework for creating and evaluating effective systems that protect against these blast-related threats.

A second meeting of the Technical Team (TT) for HFM-270 (RTG) was held on 10 – 12 January 2017 in Frederick, Maryland, USA. The main focus of the meeting was to “Identify Elements of The Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats.”

This document summarizes the deliberations of the TT members at the second HFM-270 (RTG) meeting (see agenda (Appendix B-1)); 10 TT members (see attendance roster (Appendix B-2)), representing eight NATO

nations, participated in the second meeting, and three invited Subject Matter Experts (SMEs) presented briefings on the first day to provide a basic understanding of computational modeling to all the TT members.

### **B.1.2 Welcome and Introductions**

Mr. Michael Leggieri welcomed all TT members and the three invited SMEs and requested that everyone introduce themselves.

Mr. Leggieri suggested starting off each HFM-270 (RTG) meeting with a review of the overall objectives and goals of the HFM-270 (RTG) and then for the specific meeting. He reviewed the United States (US) Department of Defense (DoD) definition of blast injuries as defined in DoD Directive 6025.21E (primary, secondary, tertiary, quaternary, and quinary) noting that the modeling and simulation framework should consider the entire spectrum of blast-related injuries and injury mechanisms. He reintroduced the concept of the fragmented uncoordinated state of computational models represented by a black box and that laid the groundwork for this TT by identifying the elements of the framework for computational models of human lethality, injury, and impairment from all blast threats, in both mounted and dismounted scenarios, and in all threat environments, and noted that without developing a framework, we will never fill in the black box. This framework will allow evaluation of the existing models and help identify any gaps. This directly ties into the task set out for the second meeting in the Program of Work (PoW) – identify elements of the computational modeling framework. This task will form the basis for the future tasks in the PoW. Mr. Leggieri reminded the TT of the 7 deliverables laid out in the PoW (reproduced below), the first one being “Framework for Computational Models of Human Lethality, Injury, and Impairment from all Blast Threats, in Both Mounted and Dismounted Scenarios, and in all Threat Environments” and reiterated that this will be a standalone framework displayed in a vertical matrix.

- 1) Framework for Computational Models of Human Lethality, Injury, and Impairment from all Blast Threats, in Both Mounted and Dismounted Scenarios, and in all Threat Environments – this will be a standalone framework displayed in a vertical matrix.
- 2) Dynamic Repository of Existing Modeling Capabilities – which will be created with the information from the survey of all participating nations and include computational, experimental, clinical, and other models and be maintained as an active repository; a recommendation of how to maintain this repository will be included in the final report.
- 3) Gaps in Modeling Capabilities – gaps will become apparent as the existing modeling capabilities are identified in number 2 above.
- 4) Comprehensive Dictionary of Modeling and Simulation Terms – this will be a continuation of the dictionary created in HFM-234 (RTG).
- 5) Technical Activity Proposal (TAP) for new HFM which would develop standardization and validation criteria and approaches for implementing the Framework.
- 6) Publications in peer reviewed literature.
- 7) Final Report with Framework, Gaps and Recommendations, and Comprehensive Dictionary and TAP as addenda – this will include discussion of confidence interval/accumulation of errors and utility of Framework using demonstration scenario outcomes in final report.

Also, from the PoW, the objectives for the second meeting include:

- 8) Identify elements of the computational modeling Framework displayed in a vertical matrix to populate with existing computational models.

- 9) Dictionary Working Group – provide strategy update.
- 10) Publications Working Group – provide strategy update.
- 11) TAP Working Group – provide strategy update.
- 12) Dr. Gupta will provide an overview of DoD Computational Modeling Expert Panel findings and recommendations.
- 13) Presentations from USA DoD SMEs.

He emphasized that the HFM-270 (RTG) has committed to an ambitious schedule of face-to-face meetings and teleconferences. Mr. Leggieri reviewed the agenda focused on identifying the elements of the framework for modeling and simulation of human lethality, injury, and impairment from blast-related threats. In addition, he mentioned that all invited SMEs are requested to leave after the last of their presentations.

### **B.1.3 Set of Presentations on “Basic Understanding of Computational Modeling”**

Dr. Raj Gupta introduced four presentations as requested by the TT members to provide a basic understanding of computational modeling.

- 1) Animal Trauma Pathophysiology and Animal Models and Behavior.** Presentation by Dr. Mårten Risling (Karolinska Institutet), who presented on behalf of Dr. Agoston (USUHS).

Dr. Risling noted that the problem we face with the blast wave is that the primary component of the blast, the shock wave, uniquely interacts with biological structures. We have different anatomical structures in the head with different acoustic impedances. We have some understanding of how a shock wave interacts with various anatomical structures, but it is a very complex situation because the brain is a highly vascularized organ; blood has a very different acoustic impedance than the brain parenchyma. Also, the gray matter and the white matter that contains the axons embedded in lipid sheet (myelin) have different acoustic impedances. Some clinical data exists on primary blast-induced TBI which also points to the importance of impedance mismatch at boundaries, i.e., at blood-brain boundary. We do not have all the data about what happens when the shock wave travels through the different structures of the brain. Lots of attention is paid to monitoring serum levels of vascular biomarkers because the function of the endothelium is quite crucial. We will probably end up with a panel of markers that will be indicative of the mechanism of the injury, i.e., if it is caused by the primary component or other – like kinetic components. Determining the exact time course of the various pathologies is also very important but we only have approximate timelines for a few pathologies and many of them are mostly hypothetical. We also have limited, if any, understanding of how the different pathologies are related to each other.

Vascular injury and cell damage lead to mechanisms that get rid of dying cells by triggering the inflammatory response. Vascular injury can also trigger inflammation. The exact timelines of the various pathological processes are currently not well known, even in animal models, and they are difficult to translate into human injuries. Rodents have very different timelines of normal biology – their metabolism is higher, and lifespan is shorter than humans – and for pathological processes, such as inflammation. But timelines are important because we need to know what we are going to model, i.e., unique shockwaves may result in unique biology requiring specific essential elements for modeling the blast physics, model, and biology. Dr. Cernak noted that Dr. Agoston emphasizes the point that currently there is no good way of translating data from animal models to human injury because we have little information about the temporal pattern of changes of, for example serum biomarker levels, in animals versus in humans. Thus,

what we are creating in animals can be different from what occurs in humans. For example, if we see long-term neurodegeneration in humans as consequence of blast-induced TBI, we must find an animal model that shows the same long-term outcome. To be able to better identify essential elements of blast-induced TBI, it is important to compare the exact biological outcomes (behavior, histology, proteomics) of various TBI models, e.g., Acceleration/Deceleration (A/D) and penetrating type of TBIs with blast-induced TBI. Such comparison will help to determine how similar or dissimilar blast-induced TBI is to other forms of TBI and will also help determine the physical components of blast-induced TBI, e.g., shock wave versus A/D. **In summary:** modeling must be driven by the physics, and species differences must be taken into account so as to mimic the biomechanics as closely as possible; outcome measures must be clinically relevant, which will enable direct comparison between experimental and clinical data; monitoring, i.e., determining time-dependent changes in the biological outcomes, is critical to identify the exact pathobiology of blast-induced TBI.

TT members discussed if kinetic energy plays a role in blast effects and suggested that ground reflection is the source of the kinetic energy that is responsible for the secondary effects. This was followed by a discussion of what models reproduce – primary, secondary, tertiary effects or all three? Additional specifics to be considered when designing or evaluation models include: the goal of the model or experimental design, using high-speed video to document kinetic effects of blast, position of target – mounted or dismounted, and the geometry of the rodent models (the animal models used must resemble the human anatomy and physiology as closely as possible). This last point led to animated discussion of whether it is possible to exactly replicate the human anatomy and physiology in a blast injury model; the conclusion was that the focus should be on how to scale and understand each model's specific limitations. In addition to these challenges, the response to the initial injury must be accounted for, e.g., inflammation. All agreed that the long-term outcomes of blast exposure are not studied in current models. Mention was made of the historical research conducted at Albuquerque on blast but that the brain was ignored, and the assumption was that gas filled organs were injured first; however, with soldiers now wearing personal protective equipment, resulting injuries are different. The discussion turned to toxicity and injury thresholds, and the enormous lack of data on these two components.

## **2) Blast Physics.** Presentation by Dr. Suthee Wiri, Applied Research Associates Inc. (ARA)

Dr. Wiri is a chemical engineer by training but knows a bit about medicine and biology as he also took premed classes in college. He spoke about simulating blast environments, experimental data, and exposures, and he would like to think he is addressing the loading model gear of the black box graphic. He appreciates the multidisciplinary approach of HFM-270 (RTG) as he believes that you need physicists, engineers, biologists, and neurologists to make any headway in this field. A simulation is great but only reliable when it has been validated. Twenty years ago, there was no field exposure data to use in validating models, but that has changed; we now have blast gauges to measure exposures in both field and laboratory. Typically, there is not enough data in published reports on blast injury to reproduce or validate a simulation; publications really need to include this basic information (i.e., standoff distance, driver pressure, shock tube length/diameter, etc.). All this and more information are needed to reproduce a scenario. ARA received a collection of combat scenarios in Afghanistan from DARPA which fielded a small blast gauge and collected the data from each gauge in these scenarios. Dr. Wiri led a team to try to understand this collection of data which includes intelligence data, blast gauge data, and limited medical report information for each scenario. They performed analyses and simulations to reconstruct the blast fields for each of the approximately 20 scenarios with hundreds of pressure traces. This is important because it gives us an idea about the threats experienced in that operational environment. They reconstructed each scenario from 3 points, but was this a truly validated simulation? No because we don't know the charge size. There was only one good example (slide 8):

- a) Blast under vehicle.
- b) Six individuals, one was wearing a gauge.



One important point to remember is that the blast is more than peak overpressure, most publications report this but the blast wave is also an impulse, positive phase duration, number of peaks (waveform shape), etc. Real life blast exposures do not look like “ideal” free field blasts; one must consider operational yields (grams to kilotons of TNT equivalent). When designing your experiment, it is important to consider blockage events, orientation, mounting, and any ground reflection.

A suggestion was made that ARA may be a good candidate for a dry run of the scenario to test the Framework after the HFM-270’s 7th meeting.

Some discussion followed about noise in blast gauge readings and how multiple gauges are needed for each event to accurately recreate it in a simulation.

All the terms on slide 10 should be added to the terms for the dictionary including “incident,” “reflected,” and “shielded” pressure.

Dr. Wiri continued his presentation by discussing the PREVENT shock tube. It is important to understand the type of exposure in your experiment. This shock tube/facility does not always give a nice free field blast wave form; ARA has found that there is a very complex blast environment within the PREVENT shock tube. A Friedlander waveform is the simplest form of a blast wave, but this is not what happens in the middle of the PREVENT shock tube; there are two peaks, a “one-two punch” for smaller charge sizes (0.48 kg and 0.61 kg charge size). CFD simulations capture multiple peaks in an empty tube. What are the implications on correlations with injury? The bottom line is if you just look at wall data within the shock tube, the peaks look ideal whereas interior pencil gauges record two peaks. Any target inside the tube is exposed to multiple reflections.

Discussion followed on how reflections from the walls lead to multiple peaks and the necessity to include all dimensions of the tube and where the gauges are located in presentations and publications.

Discussion of the details of charge type, use of a diaphragm, how the design of the tube and location of the target need to be optimized, and the location of the gauges in the blast tube to measure exposure across the full length and in the middle of the diameter of the shock tube. It was suggested that when designing a new experiment, a CFD simulation should be performed first and then the design of the biological model finalized. No one is sure if this was included in the recommendations from HFM-234. Dr. Wiri indicated that the essential information needed to simulate an exposure includes the following: dimensions, charge size (mass, shape, destination point, etc.), gauge locations, and subject location (not reported in 90% of publications).

Dr. Wiri continued by saying it is important to fully characterize your shock tube/facility and model. There is a study by King<sup>1</sup>, funded by USAMRMC, looking at front, side, and rear exposure; there are many differences in exposure levels and discrepancies in medical effects. To summarize:

- 1) CFD tools have been used for decades to study air blast.
- 2) Experimental data is important to validate simulations.
- 3) Publish enough details for others to reproduce results.
- 4) Multidisciplinary teams are important to study TBI.

When asked how he would define validation, Dr. Wiri suggested using the ASME standards (he provided the IEEE<sup>2</sup> and ASME<sup>3</sup> standards as well the Oberkampf<sup>4</sup> citation which is the “de facto standard” for computational fluid dynamics).

### **3) Biomechanics Models and Injury Threshold Severity.** Presentation by Dr. Namas Chandra (New Jersey Institute of Technology (NJIT))

Why are we interested in modeling? Dr. Chandra’s perspective is that the prediction is the most important part of modeling. The big data and personalized medicine era are here whether we like it or not. Tertiary effects (A/D) are well developed using cadaver testing and head injury criterion based on more than 50 years of study on motor vehicle accidents; secondary effects (penetrating) are reasonably available; primary effects are not available for brain/neck, though blast lung injuries were well studied in the 60s in both small and large animals. Blast is different from blunt, where mass-based scaling is not valid for blast TBI (no Bowen curve). For general numerical modeling issues for biomechanical response, we need the right loading conditions, and tissue mechanical properties. Immediately after blast, the injury is caused by the biomechanical loading conditions for which the fidelity of tissue mechanical properties may be less critical. MRI/CT enables anatomically accurate models. If needed, blood vessels, muscles, and joints can be included in the models. For major fractures / massive bleeding / large scale injury, a simplified model is OK. For more subtle changes, vascular/tissue level biochemistry causing secondary and substantive changes, the present models are incapable so we need to develop them, i.e., develop modular organs that can be fine or coarse-grained and multi-scaled. For many problems in physical science there is coupling between low- and high-level structures.

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<sup>1</sup> <http://www.dtic.mil/docs/citations/ADA620348>.

<sup>2</sup> <https://standards.ieee.org/findstds/standard/1012-2012.html>.

<sup>3</sup> <https://www.asme.org/products/codes-standards/v-v-20-2009-standard-verification-validation>.

<sup>4</sup> Oberkampf, W.L. and T.G. Trucano, 2002. “Verification and Validation in Computational Fluid Dynamics”. Prog. Aero. Sci., 38, 209-272.

If what happens at the fine level affects the coarse level or vice versa, then it is called two-way coupled problem. In one-way coupled problems, we can assume that the effect of smaller scales (tissues) does not affect what happens at the larger scale (organ level). As a first approximation, we can adapt this approach.

There was a suggestion of the need to address multilevel scale as well as morphological or functional changes at organ level.

Dr. Chandra continued with a slide on trauma analysis with Insult-Injury-Medical Outcomes; for insult  $t = 0$ , injury has a time aspect, and medical outcomes such as physical, cognitive, and behavioral/emotional symptoms occur at chronic times ( $t > 0$ ). If we do not align these axes, then we will never understand the problem. Dr. Chandra designed the parameters of the shock tubes used at NJIT; they are capable of reproducing ConWep<sup>5</sup> profiles in the 70 – 400 kPa range. ConWep (Conventional Weapons Effects) is software developed by the US Army Corp of Engineers based on conventional weapons effects calculations from the equations and curves of TM 5-855-1. Can we think of this as a “creep” problem, related to the timescale of the injury? In a creep situation, the long-term effects are local whereas biological effects are systematic.

A discussion of how ConWep is well validated and considered the gold standard although the data do not incorporate ground reflections and does not incorporate the real-life restrictions, i.e., ConWep is a simple simulation of blast without any interference.

Dr. Chandra continued if we do not understand the simple situation then we will never be able to understand situations that are more complicated. Even though ConWep profiles do not represent reality, we still need to understand these ideal situations before moving on. For the validation of shock tubes (any design) (slide 5) use 1 MHz sensor system as close to animal as possible; assure the wave is shock; no side reflections from tube; duration is between 3 – 7 microseconds; very minimal to no pressure beyond the duration; and animal is adequately restrained with no clamping. Note that a Friedlander wave is not necessarily a shock wave. Lessons from failed clinical trials show that ~30 TBI clinical trials have failed. Clearly progesterone did something in animals but failed in human trials. For better human success, a thorough understanding of animal (dosing, window, route, age, and sex) needs to be modeled and optimized. Can the model be predictive? Otherwise, the model will not work.

The TT members discussed the need to focus on modeling humans and how well an animal model replicates human injury. There was agreement that computational models should be used to guide animal model design to replicate human injury and that computational models could be the middle node in a modeling paradigm, i.e., link experimentally validated computational model with human injury, such as inflammation.

Dr. Chandra continued with the idea that computational models provide a link between experimentally validated animal models and observations in humans. Also, need to scale the physiology, not just the morphology from animal to human. For proper biomechanical loading model, we cannot scale simply based on mass, but must use multi-levels of modeling. Neurochemical mechanisms (secondary effects) of a neurovascular unit (mTBI) includes oxidative stress, neuroinflammation, blood-brain barrier disruption (vasculature), neuronal apoptosis/necrosis, and excitotoxicity/edema. These strain gauges will tell you that something is happening in the body, even if no injury has occurred. These natural gauges will be initiated by different exposures. Different combinations and how much will affect the biokinetics leading to secondary injury cascades should be used as a guide. In spatio-temporal dissection of the model, we must categorize the model from organ to sub-organ level. What is meant by sub-organ level? Start by looking at

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<sup>5</sup> <https://pdc.usace.army.mil/software/conwep/>.

hippocampus or other substructures within the brain. In many organs you have functionally independent systems. In neurochemical to medical outcome models, the scalability issue in animal models is paramount.

The pros, cons, and must haves include:

- Pros:
  - Graded exposures (increasing Blast Overpressure (BOP), intensity;  $n > 1$  for statistics).
  - Examine cognitive, pathophysiological, sensorimotor and behavior changes post-injury, time effects.
  - Probe injury mechanisms and bio-chemical pathways.
  - Identify new diagnostic tools, interventions, and therapeutic strategies.
  - Use different animal species, age, gender, health status (normal, induced disease).
- Cons:
  - Difference in anatomical, functional, and behavioral patterns from humans.
  - Complex scaling models required from animal to human – needed for different insults, injury and outcomes.
  - Exposure event (injury event) different in terms of loading, animal restraints, and anesthetics.
  - Biology different for therapy-tools and medicine may not be scalable.
- Must:
  - Accurate replication of injury event, e.g., primary blast versus jet.
  - Comparable restraints and protections (orientation, body armor, head gear).
  - Proper measurement of physical, pathological, immuno-histochemical, behavior parameters.
  - Replication of injury at the tissue level, and time effect.

Numerical models must rely on animal models (slide 12); most soldiers come home after 5 years of service meaning they did not sustain a single debilitating injury, rather it was multiple low-level exposures.

Dr. Chandra commented that the Center for Injury Biomechanics, Materials, and Medicine (CIBMM), where he is director, has reviewed all the facilities' shock tubes and that these days they are looking at the biochemistry of many animal models. Their approach is summarized in a recent publication in Scientific Reports<sup>6</sup>.

- 1) Understand the neuro-pathophysiology in animal models at different blast over pressures, showed a survival curve with mild, moderate, severe, and lethal exposure levels.
- 2) Develop a spatio-temporal pattern of pathophysiology and biomechanics; in most publications, there is a narrow view of one region. Dissection of brain to study spatial resolution of pathology and biomechanical loading in different brain structures.

NADPH Oxidase (NOX) IF in different brain injuries. Is a shock wave changing differently?

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<sup>6</sup> Mishra, V. et al. 2016. "Primary Blast Causes Mild, Moderate, Severe and Lethal TBI with Increasing Blast Overpressures: Experimental Rat Injury Model". Sci. Rep. 6, 26992; doi: 10.1038/srep26992.

At CIBMM, we are testing and validating helmets and goggles; a certain helmet may reduce the exposure, but it might not reduce the injury, any modifications we make have to be as good as the previous versions. It is difficult to anticipate the ramifications of the protective equipment.

**4) Injury Models and Injury Criteria.** Presentation by Dr. Andrzej Przekwas (CFDRC)

Dr. Przekwas started with an outline of his presentation:

- Computational Blast TBI: Models and Resolutions.
- Framework for Multiscale IED Blast Injury Simulations.
- Components: Blast scene, Human Body, Loading, Injury, Protection.
- Validation: Model components, PMHS, Surrogates, Animals, *in vitro*.
- Injury Criteria and Scores: Global versus Local.
- Recommendations and Discussion: Future Mobile Computing and “Personalized” Protection.

High fidelity models are based on detailed anatomical geometry, tissue properties; the price you pay determines the kind of mesh, High Performance Computing (HPC) hours and tools.

Dr. Wiri commented that over the past 5 – 10 years DoD has built extensive resources that can be utilized and there are several HPC computing centers, e.g., in Mississippi, Ohio, and Maryland. These days we can get almost anything done.

Dr. Przekwas indicated that DHP users have unlimited and unconstrained access to custom software tools such as SHAMRC or CoBi. Access to commercial tools for parallel computing may be limited due to number of licenses and active users.

There was a question about the accessibility to these DoD HPC resources. Based on information from [www.hpc.mil](http://www.hpc.mil), those who may run on HPCMP resources are:

- DoD researchers and engineers.
- DoD contractors.
- University staff working on a DoD research grant.

Note: Non-US Citizens may have access to HPCMP resources.

***High Fidelity Multiscale Models***

Needed to understand tissue/cell injury mechanisms to design/evaluate Personal Protective Equipment (PPE) (helmet, vest, eyewear). He indicated that high fidelity models are typically used by experts, academia, etc. Reduced order models based on analytical or ODE equations, e.g., ConWep for blast, (Injury-8) spring-mass-damper for biomechanics, require experimental data for calibration, run in sec/min on everything: PC, laptop, web and mobile App; Fast running models are a rapid “back of the envelope” assessment of load-response corridors, evaluation of PPE, forensics, etc.; and can be used by engineers, etc. and individual (personalized) warfighters. Current blast injury models are disparate and non-reproducible: very few 3-D Finite Element Models (FEM) whole human body injury models exist. Examples of human body models are APL/JHU, Thums, and GHBM. Best example of a human surrogate (dummy) is Hybrid III. Standard 3-D

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human body models are needed for: modeling Underbody Blast (UBB) injury, Improvised Explosive Device (IED) blast – body response, Behind-Armor Trauma (BABT) evaluation of various injury mechanisms e.g., thoracic TBI hypothesis.

Several brain (head) models have been developed for TBI biomechanics, (Kleiven, Zhang, Radovitzky, Gilchrist, Willinger, Kraft, Chandra, Moss, Ji, etc.) but are still not reproducible. Potential reasons: different anatomy, mesh resolution, material models used, loading pattern, etc. Many authors claim that their models are “validated.” This certainly is not the case for blast TBI. Further model improvements and validation are needed to evaluate effects of different blast loads, brain shear waves, treatment of CSF between the brain and the skull. At some point, we need a benchmark test case and experimental data to evaluate these effects. In blast TBI studies, authors apply different loads and there are many unknowns.

Multiscale models of TBI biomechanics are the new trend; a couple of recent publications demonstrated brain scale biomechanics with neuron/axon-scale mechano-biology. The goal is to understand injury mechanisms and develop “local” injury criteria. One of the main challenges is how to use macro-scale results as “loads” for micro-scale simulations (macro-to-micro coupling)? Such a coupling model has yet to be formulated and validated.

Dr. Przekwas discussed the requirements for the development of blast brain injury criteria in terms of the representative injury parameters and dose-response type clinical data. As a first step such injury criteria could be evaluated using complementary computational and laboratory animal models. They would enable better understanding of the link between primary (biomechanics) and secondary (neurobiology) injury mechanisms. Benchmark animal, e.g., rat, and *in vitro* blast injury “models” would also help in animal to human “Extrapolation” (iv-IVE) of injury criteria.

Dr. Przekwas indicated that several models of various elements of TBI have already been developed and could be reused. An integrated computational framework for coupling primary and secondary blast brain injury mechanisms and development of injury criteria is needed. We would need to identify interfaces between the models so that data can be passed from one model to the next. For example, a blast CFD code could provide space-time resolved pressure loads to the human body/head as inputs to a head/brain biomechanics model. The concept was presented as a Multiscale Modeling Framework of blast injury (slide 5) and includes:

- 1) Representative loading scenarios (threat), loading model – blast with and without debris, blunt, fall, crash, ballistic.
- 2) Anatomic model of a human body and body posture model – human body shape/mesh, equipment, PPE.
- 3) Energy absorption – in the form of human body biodynamic response (body falling on the ground) and “under the skin” biomechanics of various organs including the brain.

During the presentation there was a question if a pure blast wave can cause body translocation. Is there enough blast wave “kinetic energy” at a distance from the blast center? Dr. Przekwas indicated that persons at a distance may lose balance and fall due to vertigo. This potential cause can be seen in the Boston bombing videos. Dr. Przekwas discussed the protective role of military helmets in blast TBI; in the military, there are several standard helmets with various designs of retention and suspension systems available.

There was a question about whether pads for helmets are standard, Dr. Przekwas answered in the affirmative and that there is a military standard, e.g., Zorbium helmet pad system from Team Wendy.

***Blast Event (Threat) Reconstruction Model***

Includes IED threats and blast scenes such as side road shallow buried IED threats, vehicle carried explosives, human suicide bombers, pressure cookers, and other devices. People have not looked at complex effects of suicide bombers such as infection caused by exploding infected body. Models of IED detonation, blast wave and debris include First Principles Models (FEM) which are computationally intensive and semi-analytical models of detonation/fragmentation. Detonation models provide initial conditions for blast wave dynamics models, such as CFD models and reduced order analytical models of blast wave and debris propagation/impact.

There was a question if the ARA model is available to anyone in the US government? Dr. Wiri responded that yes, the ARA model, called SHAMRC, is US government owned. The UK has the code but is not sure how to obtain this tool. Defense Threat Reduction Agency (DTRA) is the agency that distributes the code to government contractors and other government agencies ([http://www.dtra.mil/Portals/61/Documents/dispatch\\_v3\\_i2\\_web.pdf?ver=2014-09-26-104733-797](http://www.dtra.mil/Portals/61/Documents/dispatch_v3_i2_web.pdf?ver=2014-09-26-104733-797)). POCs at DTRA are Jackie Bell [jacqueline.l.bell2.civ@mail.mil](mailto:jacqueline.l.bell2.civ@mail.mil) and Jeff Davis [jeffery.j.davis18.civ@mail.mil](mailto:jeffery.j.davis18.civ@mail.mil).

***How to Reconstruct Field IED Threats in the Lab***

He was impressed with Dr. Chandra's work in making this happen. Field blasts generate complex load profiles, blast, and debris; shock tubes generate idealized profiles, but tube modifications are possible. One way to address this is to use the "inverse problem" approach: with known pressure traces measured on the target, e.g., human body, reconstruct IED charge mass, distance, and direction.

Dr. Przekwas reviewed existing Human Body/Brain Models which include 3-D body/brain anatomic geometry. Such models are being developed using anatomical data from NIH/NLM Visible Human ([https://www.nlm.nih.gov/research/visible/visible\\_human.html](https://www.nlm.nih.gov/research/visible/visible_human.html)), Duke University XCAT database (<https://olv.duke.edu/xcat>), or the Virtual Population (ViP) models from IT'IS foundation in Zurich, Switzerland (<https://www.itis.ethz.ch/virtual-population>). These anatomical data are used to generate human body/head FEM biomechanics models, examples include: NRL-Simpleware, APL/JHU, CFDR CoBi. The human body model should be "morphable" to enable setup of body posture and body armor / seat interaction. For blast TBI simulations the detailed brain model should include not only the cerebrum but also axonal tracks, gray/white matter interface, CSF layer, cranial bone, and facial structures. Computational mesh for blast and biomechanics, such as human skin mesh embedded in the air, for blast loading, e.g., using adaptive octree mesh (refined near body); good quality hexahedral mesh for whole body/brain. One example is the head/brain hexahedral mesh model developed at Pennsylvania State University (PSU) by Dr. Kraft's team. Dr. Przekwas suggested that a standard human body geometry/mesh is needed for benchmarking. In modeling IED blast loading of the human body one can assume the body is rigid for the first few microseconds. Need standard human body geometry/mesh to be in blast injury study including lung, ear, groin, eye, and others. IED Threats: blast pressure loading on human (slide 8) shows different human body pressure wave patterns from ground shallow buried IED animation versus in air 1.2 meters above ground.

The TT members discussed how similar results have been seen in ARA simulations, and suggested need to start adjusting animal model experiments based on these loading profiles/signatures, i.e., starting from below versus straight on, as computational simulations guide animal models injury criteria and inform experimental models.

***Joint-Based Human Body Biodynamics Model: (Slide 9)***

Dr. Przekwas showed an animation of a soldier falling down after the blast wave impact. Each joint is calibrated based on its degree of movement. He indicated that a repeated TBI is feasible when the soldier was hit by a primary blast and then hit the head on the ground again. In the animation of the soldier falling, it looks like the soldier has no tension in the body; this is due to the simulations showing the first few hundred milliseconds when the nervous system will not have time to respond yet.

***Blunt And Penetrating Injury: (Slide 10)***

Dr. Przekwas identified additional types of loads caused by IEDs. FEM models can be used for blunt non-penetrating impact to the body/head – organ, vascular, skeletal injury (BABT). Such models could be used to compute parameters needed for injury criteria for various organs such as: brain, thoracic, lung, neck, and others. FEM models can predict not only effects on tissue but also bone and vascular system. FEM and joint-based models can be used for inertial loads e.g., due to head movement. For a given head movement, Dr. Przekwas' team looked at the inertial effects on various brain structures including brain stem and cerebellum.

Discussion of the relationship between the mechanical parameters and the whiplash injury, concluded with not much has been done on neck injuries.

In penetrating injury (terminal ballistics), the CFDRC team found that FEM models are not reliable and time consuming while empirical models are fast, calibrated on experimental data (gelatin, pig), and can be used to assess penetrating injury scores. For these experiments steel spheres and cylinders were used.

***Blast TBI Models – Surrogates (Rats and Physical Phantoms): (Slide 10)***

Dr. Przekwas' team validated the rat blast biomechanics model against a live animal in a shock tube; model compared to experimental tests by Chavko et al 2011<sup>7</sup> and Shoge et al 2011<sup>8</sup>, incident pressure wave and intra-ventricular pressure profiles, and rat biomechanics. Simulations showed different blast TBI biomechanics and pressure propagation patterns in rats exposed to shock tube waves impacting the rat body from the front, back, and side. The CoBi blast TBI model has been validated with data obtained from DARPA projects and APL/JHU field tests (explosive charge 1.2 meters above the ground). CoBi simulated Intracranial Pressures (ICP) qualitatively agree with shock tube test data very well<sup>9</sup>. Negative pressure first in contrecoup then higher peak ICP at contrecoup than at coup; maximum principal strains develop later and higher value at the contrecoup; and model results also used to provide data for *in vitro* testing (Dr. Adam Willis, AFRL).

A discussion of exposure thresholds that are relevant to operational exposures, also taking into account that the reflective pressure can more than double compared to primary wave pressure, e.g., 250 kilopascal = 50% lung injuries. He also confirmed that in the APL/JHU test the incident overpressure was < 200 kilopascal. A question was raised to explain negative pressures at the back of the head and how it is due to deformation of cranium.

<sup>7</sup> Chavko, M., Watanabe, T., Adeeb, S., Lankasky, J., Ahlers, S.T., McCarron, R.M., 2011. "Relationship Between Orientation to a Blast and Pressure Wave Propagation Inside the Rat Brain". *Journal of Neuroscience Methods*, 195(1), 30 January 2011, 61-66.

<sup>8</sup> Shoge, R.O., Tong, L.C., Riccio, C.A., Atkins, J.L., VanAlburt, S.A., Edwards, A.A., et al. 2011. "Experimental Evaluation of Blast-Induced Traumatic Brain Injury in Rats Using a Cylindrical Shock Tube". *ATACCC Conference*, Frederick.

<sup>9</sup> Goeller, J., Wardlaw, A., Treichler, D., O'Bruba, J., Weiss, G. "Investigation of Cavitation as a Possible Damage Mechanism in Blast-Induced Traumatic Brain Injury". *Journal of Neurotrauma*. July 2012, 29(10): 1970-1981. doi:10.1089/neu.2011.2224.

***Blast TBI Models – Human Multiscale Macro-Micro: (Slide 13)***

Need for local axonal injury – correlate to *in vitro* or animal data and tissue biomechanics provides loading conditions for axonal micromechanics. Discussed how axonal structures respond to mechanical loading including formation of axon varicosity due to axon-oligodendrocyte link, microtubule-tau interactions such that in high-rate stretching there are microtubule-tau, tau-tau, and microtubule-microtubule failures.

There was some discussion of the oligodendrocytes connecting axonal structures and if the axon varicosity observation was based on experimental data or could it be due to mechanical shear stress disrupting microtubules, or could something else like inflammation be responsible for the injury? Dr. Przekwas responded that this is a good question; his team is just starting to look at the mechanobiology effects on axonal and synaptic structures.

Skipped slides 14 and 15.

***Framework for Injury Criteria and Tolerance: Blast, Blunt and Acceleration Loading to the Head May Cause Brain Injury: (Slide 16)***

Brain injury is caused by both: primary micro-damage to brain microstructures and secondary biological cascade of both injury and repair. Brain injury mechanisms are not fully understood. Head injury criteria use “dose-response” type correlations.

The Dose is either measured or computed from head macroscale kinematics (acceleration, velocity, etc.). Several parameters used for head injury criteria e.g., HIC and BrIC:

$$HIC = \left( (t_2 - t_1) \cdot \left[ \frac{\int_{t_1}^{t_2} a(t) dt}{t_2 - t_1} \right]^{2.5} \right)_{\max}$$

$$BrIC = \sqrt{\left(\frac{\omega_x}{\omega_{xC}}\right)^2 + \left(\frac{\omega_y}{\omega_{yC}}\right)^2 + \left(\frac{\omega_z}{\omega_{zC}}\right)^2}$$

where **a** is the linear head acceleration and **ω** is the angular acceleration (**ω<sub>C</sub>** is the “critical” value)

The Response is measured by clinical outcome and can include long-term, moderate/severe, age, etc. Tolerance curves have been established and include probability of various levels of injury measured by injury scales: AIS, GCS, ISS, RISS, etc.

Discussion of injury scores concluded the need to use a morphological and functional scoring system.

***Comparing Global Kinematic Versus Computation Tissue-Specific Injury Criteria (IC): (Slide 17)***

Kinematic based IC (HIC) can use readily available sensors for parameter measurements; simple to simulate; most kinematic IC models use 3DOF parameters (acceleration or rotation); 6DOF models recently proposed show better prediction of injury; HIC is not injury-specific, does not relate to injury severity, does not take into account variations in the brain mass or load direction, etc. In biomechanics and mechanobiology right now, people start looking at the microstructure level; the challenge is difficult to reconstruct and measure head loads; requires benchmark head anatomy, FEM tools, and material models (computationally intensive); tissue based injury criteria (animal, *in vitro*, clinical); for cellular scale models not clear how to impose micro-scale BCs from macro-scale

FEM mesh; models of local  $\mu$ -neuro structures; CFDRC-PSU team developed the whole brain FEM models with entire white matter with embedded axonal tracts model; which will better correlate data with injury predictors<sup>10</sup>.

For tissue-cellular level injury criteria the most common is the criteria based on axonal injury. For modeling axonal biomechanics simple spring-mass models are used, typically for a local segment of an axon/node of Ranvier damage. Coupled mechanical and electrophysiological models of entire axon have been developed (PSU-CFDRC). Such models provide the foundation for novel mechanobiology based IC including percent of Cumulative Volume Damage (CVD) of white matter  $f(t)$  using different injury criteria; shear strain injury criterion predicted the max amount of CVD; an element is “damaged” if it experiences a strain/stress greater than the threshold specified during the simulation.

### ***Recommendations and Discussion: (Slide 18)***

Great progress reported in the development of FEM TBI models, much less in whole body IED blast injury; duplication in all aspects of models – anatomy, FEM tools, material property, load patterns; standard open source “benchmark” models are needed; there is no “Computational Framework” for blast injury; benchmark animal models are needed for understanding of injury mechanisms and validation tissue/cellular IC; improved models of neuro-axonal mechanobiology; need to establish use scenarios for computational tools; and can we use fast running models and mobile computing for “personalized” blast protection?

A discussion ensued related to the different brain regions having different relationships of axons to oligodendrocytes, and the modeling of injury and repair to counteract the injury, e.g., tauopathy and CTE. Also discussed was the fact that the damaged biological structure in an injury is accompanied by changes in its mechanical properties. Attention was directed to the elasticity or compensation responses from fluid surrounding an organ and the huge compensatory response of the vascular system, which is very resistant and highly elastic in the brain. There was general agreement of the admonishment to avoid the same mistakes as the 30 failed TBI drug trials.

### **B.1.4 Working Group Updates**

- 1) **Dictionary Working Group** to develop a dictionary of commonly used computational modeling terms with definitions (i.e., Comprehensive Dictionary of Modeling and Simulation Terms). They will start with the dictionary developed during the HFM-234 (RTG) and use literature to identify new terms and definitions.
  - a) The working group members are:
    - i) Dr. Ibolja Cernak (Chair);
    - ii) Col (Dr.) Philippe May;
    - iii) Dr. Emrys Kirkman.
  - b) Phone conference held on 29 November 2016.
    - i) Selected Chair – Dr. Cernak.
    - ii) Confirmed approach will be the same as for HFM-234 dictionary:

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<sup>10</sup>Garimella, H.T., and Kraft, R.H., 2016. “Modeling the Mechanics of Axonal Fiber Tracts Using the Embedded Finite Element Method”. Int. J. Numer. Meth. Biomed. Engng., doi: [10.1002/cnm.2823](https://doi.org/10.1002/cnm.2823).

- Establish template with generalizable terms based on presentations and discussions (model, validation, etc.).
    - Add specific terms used in SME presentations.
    - Choose terms that will have a crucial role.
  - c) Send draft terms to SME presenters and TT to provide definitions.
  - d) Chair will coordinate Working Group meetings.
- 2) **Publication Working Group** to identify and guide publication of articles in appropriate peer reviewed journals throughout the duration of this RTG. They will consider an array of publication types including simulation and medical journals.
- a) The working group members are:
    - i) Dr. Dan Bieler (Chair);
    - ii) Dr. Axel Franke (co-Chair);
    - iii) Mr. Ilker Kurtoglu;
    - iv) Dr. Marten Risling;
    - v) Dr. Amal Bouamoul;
    - vi) Dr. Raj Gupta.
  - b) Discussion to select Chair and co-Chair – consensus to appoint Dr. Bieler as Chair and Dr. Franke as co-Chair.
  - c) Develop strategy for topics and types of publications for next meeting.
  - d) Suggest TT members to co-author these manuscripts and which journals to submit them to.
  - e) Collaborate via email/teleconference.
  - f) Chair to coordinate Working Group recommendations.
  - g) Chair to contact Dr. Emrys Kirkman regarding the Journal of Royal Army Medical Corp Blast supplement.
- 3) **TAP Working Group** to draft a Technical Activity Proposal (TAP) for a new HFM activity which will develop standardization and validation criteria and approaches for the Framework.
- a) The working group members are:
    - i) Dr. Amit Bagchi (Chair);
    - ii) Dr. Ibolja Cernak;
    - iii) Dr. Thomas Sawyer;
    - iv) Dr. Sarah Watts or Dr. Emrys Kirkman;
    - v) Dr. Raj Gupta.
  - b) Discussion to select Chair – consensus to appoint Dr. Bagchi as Chair.

- c) Develop strategy and timeline to present at next meeting.
- d) Use TAP from HFM-270 as a guide.
- e) Chair will coordinate Working Group meetings.

### **B.1.5 Overview of Computational Modeling Expert Panel Findings and Recommendations Presented by Dr. Raj Gupta**

Dr. Gupta's presentation focused on the findings and recommendations from the DoD Brain Injury Computational Modeling Expert Panel from 2012 which was assembled to assess the state-of-the-art computational modeling efforts aimed at understanding the injury mechanism of non-impact, blast-induced mTBI, with the ultimate goal of accelerating prevention and treatment strategies. The following summary highlights the most pertinent information for this meeting.

Dr. Gupta started by discussing the incidence of TBI and mTBI, noting that TBI affects both the civilian and military sectors, and is the leading cause of death and disability among children and young adults. More than 1.4 million US civilians suffer TBIs on an annual basis, with 50,000 deaths and 235,000 hospitalizations. By 2012, the DoD Military Health System had documented 233,425 US Service Members diagnosed with TBI from combat and non-combat related causes since 2000. More than 76% of these individuals presented with mTBI. mTBI is currently diagnosed by the event and through self-reporting of symptoms and was specifically defined in 2009 as: "any post-event exposure alteration of mental state (i.e., dazed or confused) at the time of injury, any loss of consciousness lasting 30 minutes or less, post-traumatic amnesia lasting less than 24 hours, and structural brain imaging (MRI or CT scan) yielding normal results."

Overview of computational modeling of mTBI includes physiology-based computational/mathematical modeling tools of blast head injury that may provide a framework to understand injury mechanisms, guide experimental testing, interpret data, and scale animal data to humans to study both blast wave TBI mechanisms and the effectiveness of protective or treatment strategies. Computational modeling of non-impact, blast-induced mTBI is very difficult, involving a range of disciplines, e.g., biomechanics, physiology, biology, lengths (subcellular to macroscopic), and time scales (microseconds to weeks). Validated multidisciplinary models are needed that integrate blast explosion physics, anatomical- and image-based human body geometrical models, human body biodynamics, tissue biomechanics, and several physiological models. Overall, data from the engineering/physical world has to be connected with data from the medical world. The DoD Brain Injury Computational Modeling Expert Panel was established in March 2010 as an outcome of the 2009 International State-of-the-Science meeting on non-impact, blast-induced mTBI. The Expert Panel members included clinicians, engineers, experimentalists, mathematicians, modelers, neuroscientists, and physicists. Several focused and theme-based meetings were held from March 2010 to September 2011. Overall, the Expert Panel felt that the computational model should accurately predict non-impact, blast-induced mTBI. Specifically, they noted that the computational model should:

- Be anatomically and pathophysiologically correct (i.e., biofidelic model).
- Exhibit consistent material and biological properties.
- Answer the problem as proposed.
- Be based on experimental data using animal models.
- Be field consistent.
- Have a well-defined framework (including carefully defined nomenclature and taxonomy).

- Be scalable to humans and eventually multi-scaled (nested hierarchical model).
- Predict injury (in animals).
- Corroborate *in vitro* and *in vivo* models.
- Incorporate input/guidance from the medical community.
- Include the concept of coupling fields (weak and strong coupling).
- Have the ability to capture empirical data.

Computational modeling validation schematic – there were so many issues to address. For simplicity, the expert panel developed a schematic comprised of five major categories. Dr. Cernak added that the whole point of this is that the structure would allow flow, so that if you start with clinical data / observations you can work backwards to predict dose-damage-outcome, etc.

### ***Blast Exposure Characterization***

Blast exposure characterization involves measuring and documenting the effects of blast exposure on the human body – still need to define the environment and the effects the environment has on humans, especially on the brain. The effects of the blast wave on the human brain should be the first step in the development of an end-to-end predictive computational model. Mr. Leggieri added that we do not know what the actual blast exposures are and it might be several years until we do know; he cautioned against being hung up on getting the blast exposure right.

Blast physics starts with a blast that results from the rapid conversion of a solid or liquid into a gas. The heated gas expands into the surrounding air faster than the speed of sound, which compresses the air and creates a peak overpressure (shock) wave that radiates from the point of detonation. Following the shock wave, a blast wind radiates from the point of detonation. As the gas expands, the pressure drops and creates a vacuum or negative-pressure wave.

Skip to slide 15 – current understanding of blast wave interaction with the human brain and the resultant injury is very limited. Scientists believe that mechanical stresses from blast exposure create primary cellular injury in brain tissue, and then subsequent biochemical, metabolic, and neurological processes lead to neurocognitive dysfunction and adverse clinical outcomes.

Components of blast relevant to mTBI include pathways into the brain – migration through skull/penetration through soft tissues / acceleration of skull / distortion of skull / blood entering from some other part of the body; internal damage such as electromagnetic effects / pressure gradients / differential, local stretch to axons and damage to microtubules, and cavitation (formation and then immediate implosion of cavities in a liquid); and the outcomes such as loss of consciousness, memory loss, and other neurological/psychological/physiological outcomes.

Challenges identified by the Expert Panel include:

- 1) Need experimental blast injuries to closely approximate those observed in soldiers in the field – the inflicted injury should be reproducible, quantifiable, and comparable to human conditions (long-term memory and motor impairments);
- 2) Need an objective method and validated instrumentation to measure and document the effects of blast exposure on the human brain;
- 3) Need to determine damage thresholds for different types of brain tissue, e.g., white matter is more

vulnerable than gray matter; and

- 4) Need to be able to measure and define the ‘dose’ required to cause mTBI – dose requires standardization in terms of overpressure (expressed as kilopascal) and duration experienced at the skull surface in several axes (fronto-orbital, laterally and posteriorly).

Once parameters are defined, computer modeling can be effectively employed. Discussed focusing on computational models of eardrum rupture since it is a simple system. Once we have the simple, system worked out, we can move to a more complex system like the brain. The group noted that eardrum rupture is significantly influenced by the placement of the body, and it is not as simple as it might seem; there are still a lot of unknowns with regard to involvement of the brain; and that there is clinical data showing that even without eardrum rupture there are long-term effects on hearing.

Work in Progress at the time of the Expert Panel meetings included:

- 1) Developing shock tubes that allow scientists to experimentally recreate and closely monitor blast conditions (JHU/APL, Wayne State, WRAIR, others);
- 2) Designing blast dosimeter sensors that change color when exposed to blast waves (LLNL);
- 3) Designing and testing inexpensive, disposable, single-use gauges that can measure the peak pressure of blast waves;
- 4) Filing a provisional patent on a simple helmet-mounted antenna that can provide quantitative measures of skull stress and primary blast exposure (MIT);
- 5) Identifying upper and lower thresholds for material failure at the neuronal level. (University Nebraska/NJIT); and
- 6) Investigating the structural changes to the brain at sub-lethal BOP exposures in non-human primates (DSO Labs, Singapore).

At the end of each theme based focused meetings, the Expert Panel identified challenges and made recommendations that could be accomplished in near-, mid- and far-term.

For Blast Exposure Characterization, the Near-Term (1 – 2 years) recommendations included:

- 1) Collect and analyze historical (in-theater) and experimental blast exposure data;
- 2) Compare these data and compile incident lists of mTBI-inducing events including information about charge type and size, detonation type and point, distance to target, position of the target, terrain, electromagnetic impulse, blast only injury, and blast plus impact injury;
- 3) Test the identified scenarios in well-instrumented laboratory-scale experiments using well-characterized models;
- 4) Validate basic blast-material coupling and response in in-theater conditions;
- 5) Provide a set of laboratory-scale experiments to test the blast coupling with head/body surrogates of increasing complexity and measure the chemical, mechanical and physiological responses at different locations to test the influence of geometry; and
- 6) Perform field experiments of realistic blast exposures of instrumented surrogate models of head and whole body, and measure mechanical, chemical and physiological correlates to blast.

Mid-Term (2 – 5 years) recommendations include performing field experiments of realistic blast scenarios of instrumented biological and animal subjects and measure mechanical, chemical, and physiological that correlates to blast.

Far-Term (>5 years) recommendations include:

- 1) Complete validation studies; and
- 2) Design and assess preventive and treatment strategies.

Additional Expert Panel Recommendations were to:

- 1) Define an appropriate injury metric for the development of a valid computational model – one approach is to elucidate the important metrics of pressure waves (rate of change, duration, peak, area under the curve, tension versus compression) and determine how these metrics relate to total energy deposition in the tissue;
- 2) Gather detailed calibration, measurement, and reporting of loading conditions over the entire duration of the event;
- 3) Determine the minimum number of tests needed using accepted statistical approaches such as power analysis;
- 4) Perform base tests in a relevant (blast) loading paradigm to establish injury signature before simulation in the laboratory, establish load range for humans, test un-scaled and scaled on models, and refine laboratory tests to reproduce blast injury.

The Holy Grail would be to “establish load range for humans, test un-scaled and scaled on models.”

Brain Injury Computational Modeling involves the mathematical mapping and computerized simulation of the structural connectivity and biological response in the brain following exposure to a blast wave.

Different types of modeling include *in vitro* testing and modeling, animal testing and modeling, human surrogates/material modeling, and human simulation/mathematical modeling.

The Expert Panel’s MODELING TREE (slide 26) captures the whole picture in one view. It has a lot of detail, but it summarizes the proceedings of the panel. All the elements are still valid (Dr. Cernak developed the schematic tree).

### ***in vitro Testing and Modeling***

Requires relevant biological materials characterization (skull, brain, dura, blood vessels, CSF); one of the main things that came out of the proceedings is that we really do not understand the physical properties of the brain; even years later we still do not know. One hurdle is the techniques used to measure physical properties. First you need to develop a technique to measure high strain rates which is critical for computational models. Dr. Cernak added that once the mechanical factor is transmitted to the brain (causing strain, stretch), how does the brain react? We have limited knowledge about the biomechanical properties of the tissues in the brain and how they react.

It involves analyzing the injurious effects of blast waves, e.g., effects on the neuronal cytoskeleton or organelles, changes to the ability of calcium ions to enter neurons, axonal stretch injuries, using brain cell cultures, brain tissue slices, and physical brain phantoms, e.g., Hoffman 2-D and 3-D Brain Phantoms™. The ultimate goal is to develop *in vitro* models from which data can be captured that can feed the development of a

## ANNEX B – MINUTES FROM HFM-270 PANEL MEETING JANUARY 2017

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computational/mathematical model of non-impact, blast-induced mTBI. The advantage of *in vitro* models is they allow researchers to control the mechanical injury and reduce other potentially complicating factors.

Challenges specified by the Expert Panel were as follows:

- 1) *in vitro* tissue characterization of mammalian tissue (bovine, porcine) is needed;
- 2) The microscopic and macroscopic levels have to be bridged, and force-injury correlations are needed at the microscopic level;
- 3) Data is needed that will help guide the experimentalists and will validate models at the tissue level; and
- 4) Shock tubes must be designed, and experiments staged carefully to generate proper blast simulations.

Work in Progress as of 2012 includes:

- 1) Developing *in vitro* assays that are amenable to benchtop work and high-throughput screening (Harvard) and that can mimic diffuse axonal injury and vascular injury prior to vasospasm in these *in vitro* models;
- 2) Observed a rapid influx of calcium in neurons when axons were stretched in a blast *in vitro* model, which may be related to damage of the sodium-calcium gate (U Penn);
- 3) Developed an *in vitro* model featuring primary cortical rat neurons that can be used to determine the mechanisms of TBI (Duke);
- 4) Measuring the biomechanical properties of human brain tissue under high strain rate hydrostatic compression and shear loading using a modified split-Hopkinson pressure bar (JHU/APL);
- 5) Developed novel methods to characterize the compression responses of soft tissues (including brain) at low to high strain rates using the split-Hopkinson pressure bar (Purdue);
- 6) Developed a platform for high strain testing of live brain tissue slices relevant to blast TBI that may aid in the validation of mathematical models of brain deformation (University of Florida);
- 7) Developed an *in vitro* model of TBI in which rat brain tissue slices are cultured on a stretchable substrate and exposed to deformation on a fine scale at pre-selected strain rates (Columbia U);
- 8) Studying damage to astrocytes following neurotrauma (UCSD) – found that intermediate filaments in reactive astrocytes may serve as potent inhibitors of neuroregeneration following neurotrauma;
- 9) Using a Kolsky bar to measure inertial effects in soft and nearly incompressible materials (ARL);
- 10) Embedded rat cortical neurons and astrocytes in a 3-D collagen matrix to create a more biofidelic *in vitro* injury model (MIT); and
- 11) Studying the response of living brain slices to BOP, using a specially designed barochamber (Wayne State University).

Proposed Roadmap for *in vitro* Testing (slide 32) was included in the National Research Action Plan developed by the DoD, Department of Veterans Affairs, Department of Health and Human Services, and Department of Education in response to the Executive order “Improving Access to Mental Health Services for Veterans, Service Members and military Families.”

Near-Term (1 – 2 years) recommendations include:

- 1) Develop well-controlled, reproducible, and reliable *in vitro* models for military relevant stressors, and for combined stressor-blast injury paradigms – establish protocols to quantify subcellular primary and secondary response to load, and establish several “standard” reproducible models for neuro-axonal cell cultures and brain slices;
- 2) Establish injury mechanisms, e.g., determine kinetics, thresholds;
- 3) Model FEM biomechanics of cell culture/tissue; and
- 4) Model primary injury to microscopic structures – axonal, synaptic, cytoskeleton, membrane, ion channels, etc.

Mid-Term (2 – 5 years) recommendations include develop short- and long-term secondary injury models for neuron homeostasis (metabolism, electrophysiology, etc.) and injury (depolarization, edema, transport, beading, etc.).

Far-Term (>5 years) recommendations include develop predictive, validated mathematical and computational models based on experimental *in vitro* findings.

Additional Expert Panel Recommendations are as follows:

- 1) Consider a systems engineering Design of Experiments approach to the experimental design of *in vitro* studies – this would provide an articulated plan to explore the clinical impact of multiple possible injury mechanisms, rapidly reject those that have little or no impact, and develop those that do have impact.
- 2) Establish criteria for inclusion/rejection of experimental and developmental plans.

### ***Animal Testing and Modeling***

Animal testing for non-impact, blast-induced mTBI involves the use of animals, e.g., rats, pigs, non-human primates, in research experiments aimed at determining the mechanism and anatomic distribution of injury – animal tests provide the means to observe brain damage and behavioral outcomes that are accepted as clinically relevant to mTBI/concussion in humans. Animal modeling involves the computer simulation of animal tests and provides the estimate of mechanical dose that correlates to the brain damage. This is very challenging, since every aspect of the system (geometry, material properties, and strengths) is complex. Add ferrets as they are better than mice or rats and closer to human cognition/behavior, e.g., food choice. Whatever animal we use the point is to create an injury that is similar to a human, i.e., model should predict or correlate with human injury.

The challenges specified by the Expert Panel are as follows:

- 1) Need *in vivo* tissue characterization of mammalian tissue (bovine, porcine, ovine);
- 3) There are limited animal models that measure the common blast-related impairments (cognitive, motor, auditory, etc.);
- 4) *in vitro* and *in vivo* data often disagree with each other, which emphasizes the need for more accurate *in vivo* characterization;
- 5) Scaling – researchers need to ensure that tissue strain rates in animal models are equivalent to those observed in humans exposed to blast;

- 6) Need clinical confirmation that the damage produced in an animal correlates with what causes mTBI in humans; and
- 7) Need to define the environment for animal experiments to determine that the relevant parameters are being measured.

Animal species to test/model: small animal models are genetically more uniform and cheaper, but do not have the same biomechanics as human, require simpler shock tube exposure facilities (but shock tubes can provide non-representative exposures), and **should be used as exploratory indicators**. Large, non-primate model (pigs, etc.) have larger head/brain size allowing for instrumentation, physiological/blood chemistry, anatomical differences require validated mathematical model to interpret results, need to identify mTBI/concussion correspondence, and are **best candidates for determining mechanical-to-damage relations**. Non-human primates provide least ambiguous mTBI/concussion measures, but only small numbers will be allowed; they are the **best candidate for clinical buy-in**.

Work in progress as of 2012 includes:

- 1) Assessing the effects of low-intensity shock waves on the rat head through a combination of neurocognitive testing, imaging, and histopathology (Wayne State);
- 2) Using a combination of imaging, electron and light microscopy, and behavioral tests to identify structures in the rat head that are mechanically damaged by blast (L-3 Communications);
- 3) Collecting a variety of data (pressure readings, histological, etc.) on rats exposed to blast in shock tubes (WRAIR);
- 4) Developed a weight drop mouse impact model of mTBI (Sanford Burnham);
- 5) Developed a rat model to simulate vehicle underbelly blast attacks (Naval Surface Warfare Center);
- 6) Developing an anisotropic finite element rat head model (Royal Institute of Technology);
- 7) Developed a rodent model of blast injury that includes exposure to stress (USUHS);
- 8) Developing a rat computational model of primary TBI (CFDRC);
- 9) Developing a ferret model of blast-induced brain injury (Duke) – axonal injury staining patterns may indicate a different injury mechanism for blast TBI than for traditional blunt TBI;
- 10) Developing a FEM of the mini-pig head to scale between pig and human and conduct longitudinal studies (Virginia Tech);
- 11) Developed a constitutive model that can capture the key features of tissue response over four orders of strain rate magnitude (MIT) – can measure the *in vivo* response of biological tissue at high strain rates in Yorkshire pigs; and
- 12) Developed a non-human primate model of blast injury that can replicate the emotional and higher cognitive deficits seen in humans (DSO National Laboratories, Singapore).

***Proposed Roadmap for Animal Testing: (Slide 43)***

Animal Simulation: model elements to consider are: assume that anatomy can be modeled completely – does vascular and CSF need to be modeled? Nested, hierarchical models are needed; how will animal simulation be validated? Can we instrument the animal in a meaningful way? How will the damage be modeled? Do we need microstructure models? Do we need physiological models? Do we need biochemical/ultrastructural

models? If magnetic resonance / Diffusion Tensor Imaging (DTI) is a biological measure of injury, how will that be related to mechanical calculations? How important are material properties to the simulation? Do we need additional testing? *in vivo*? *in vitro*? What range of strain/strain rate is meaningful? These elements should be considered as we identify the elements of the framework during this meeting.

***Proposed Roadmap for Animal Modeling: (Slide 45)***

Scaling of the model is a complex task – what types of scaling are needed? Ideal scaling would reproduce injury symptoms (biology, physiology, cognitive); scale down from IED blast impact on humans **to** shock tube wave parameters for surrogates or animals; scale down from mechanical stress/strain fields in human brain **to** animal **to** *in vitro*; scale up to reproduce “mechanical load-to-injury outcome” correlations **from** *in vitro* **to** animal **to** human (challenging); and scale by induction – if mathematical models can predict load-injury relations *in vitro* and in small animals and in large animals, can we predict injury in humans? Scale up/down of primary biomechanical parameters may be doable – strains, strain rates, impulse, irreversible energy absorbed, other? Potentially no scaling is needed at the microscale *in vivo* (i.e., mechanical damage to cells/tissue may cause similar injury events).

Near-Term (1 – 2 years) recommendations include:

- 1) Conduct comprehensive literature review on experimental blast-induced TBIs and neurological deficits in relation to – exposure characteristics (type, manifestation, and temporal profile of symptoms);
- 2) Localization of identifiable pathological changes in the brain (relationship between exposure characteristics and lethality as well as organ damage dependent on type or species (animal’s size, mass, and position related to and distance from the charge), and time after exposure);
- 3) Establish a detailed experimental database;
- 4) Perform a detailed comparison with clinical data and establish similarities and differences between clinical and experimental data;
- 5) Develop protocols for joint clinical-experimental databases and cross-search these databases;
- 6) Develop highly-controlled, reproducible, and reliable rodent (rat and mouse) models utilizing militarily relevant exposure conditions that are capable of reproducing symptoms of human non-impact blast TBI – compare the overlap between the rat and mouse models, and provide guidelines for their utilization;
- 7) Validate the rodent models using a pig model and validate all models using a non-human primate model.

Mid-Term (2 – 5 years) recommendations include:

- 1) Conduct multi-level, multi-species experiments based on and guided by clinical findings – define the importance of whole-body exposure versus isolated head exposure in the development, intensity, and temporal profile of deficits linked to blast mTBI;
- 2) Establish the temporal profile of cardiovascular and cerebrovascular changes after blast, and identify the underlying mechanisms;
- 3) Identify the pathobiology of cellular/sub-cellular/molecular changes due to blast including axonal pathology (astrocyte, glial, and microglial-dependent mechanisms, channelopathies, mitochondrial dysfunction, and proteinopathies, among others);

- 4) Develop well-controlled, reproducible, and reliable multi-species experimental models for military relevant stressors, and for combined stressor-blast injury paradigms;
- 5) Establish the importance of genetic and epigenetic changes for non-impact blast TBI development, progress, and outcome using multi-species experimental models;
- 6) Develop militarily relevant, well-controlled, reproducible, and reliable multi-species experimental models combining primary, secondary, and tertiary blast effects and compare the development, progress, and outcome of related morphological and functional deficits; and
- 7) Conduct intervention experiments targeting the identified mechanisms.

Far-Term (>5 years) recommendation to develop predictive mathematical and computational models based on experimental findings.

Additional Expert Panel recommendations are as follows:

- 1) Conduct parallel examination of alternative injury mechanisms – rodent studies examining multiple intervals between blast exposures and studies of acceleration and head rotation in an animal with appropriate head size and neck structure;
- 2) Gather animal experimentation data specifically relevant to computational model validation, e.g., shear waves by conducting swine experiments with multiple fibers (wires) inserted into the brain that are sensitive to shearing movements;
- 3) Cavitation studies by injecting ultrasound microbubbles in rodent to accentuate the possibility of cavitation and look for obvious injury; and
- 4) Pressure to evaluate head movement as the possible cause of coup/contrecoup in non-human primates.

No one species can provide all the information required to determine the mechanism of injury and validate that the results are clinically valid to human mTBI – need a spectrum of animal models, each with a specific contribution. In other words, need a set of standardized experiments for validation, and overall, need animal models that reproduce the battlefield injury.

### ***Human Surrogates and Material Modeling: (Slide 50)***

Human surrogates are used for studying blast-related injury and are physical models that typically consist of a skull, brain, facial structure, and skin – the various parts of the surrogate are fabricated using biosimulants and researchers embed miniature pressure sensors at various points on the surrogate to track brain displacement, measure acceleration and pressure, etc. Material modeling for non-impact, blast-induced mTBI involves capturing the behavior of the *in vivo* brain as a material, which includes determining the material properties for various regions of the brain and identifying biologically relevant interfaces, e.g., skull/CSF/soft tissue. It is important to capture the connection of different body parts (brain + thorax). Do the surrogates incorporate biomechanical properties? The TT members discussed the importance of the interface between the different components of the brain, e.g., clinically see microhemorrhages between gray and white matter; so, the interfaces are functionally important, and assumptions of material properties of the target organ must include connection to the rest of the body to be more accurate.

The challenges specified by the Expert Panel include:

- 1) Develop validated constitutive models for material properties of skull, CSF, and brain tissue, particularly for large strain rates and for perfused tissue;
- 2) Solve brain biomechanics equations using FEM solvers for soft tissue;
- 3) Elucidate the geometry, loading, and material properties required to predict the trauma that may occur;
- 4) Conduct biological testing aimed at providing insight into injury thresholds;
- 5) Examine response to appropriate input modes (linear/angular, rigid/penetrating, etc.), response on an appropriate scale, geometry and important structures, and response at appropriate rates; and
- 6) Develop higher fidelity models that capture effects of hydration, fatigue, temperature, stress, etc.

Work in progress as of 2012 includes:

- 1) Developed the Realistic Explosive Dummy Head (RED Head) to aid in answering questions about how brain damage occurs. (University of Nebraska/NJIT) – as a blast wave hits the RED Head, tiny fiber-optic sensors record the event;
- 2) Conducting research on inverted cadaver heads using high-speed biplane x-rays (Virginia Tech);
- 3) Studying the response of the human brain to BOP using post-mortem brains (Wayne State University) – also characterizing how the blast wave propagates across the human head;
- 4) Developed human head and neck surrogate models that can record the mechanical correlates of blast-induced TBI (JHU/APL);
- 5) Generated a cervical spine model to predict response and injury in multi-directional loading (University of Waterloo);
- 6) Developed a geometrically detailed FE head model within a Simulated Injury Monitor (SIMon) to model TBI (NHTSA) – SIMon uses biomechanical measures and dynamic head responses from crash tests to assess head injury;
- 7) Developing a reusable manikin that is equipped with sensors for baseline studies to determine reference criteria with respect to human injury (Naval Surface Warfare Center and Office of Naval Research); and
- 8) Developing novel polymer gels of tunable mechanical properties to act as reliable tissue surrogates for Army applications (JHU/APL) – goal is to make the gels mechanically behave like tissues under impact loading.

Elements to consider for Human Surrogates include:

- 1) A human anthropometric model (body + head) including anatomical characteristics (eyes, ears, nose, neck, major vessels);
- 2) Facilitate incorporation of helmets and PPE;
- 3) A complementary computational “twin” model;
- 4) Well-defined instrumentation of the dummy and PPE – pressures, accelerometers, video;
- 5) Field representative blast loads such as shock tube, free field, and reflected blasts;

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- 6) Material properties – use “best available” first; and
- 7) Short- and long-term physiological responses.

Near-Term (1 – 2 years) recommendations include:

- 1) Conduct a comprehensive literature review of the existing viscoelastic properties of the skull, scalp, and brain tissue, vasculature, CSF, etc., for typical exposure conditions;
- 2) Determine necessary material (mechanical, chemical and physiological), new testing techniques, e.g., split-Hopkinson bar, stress-relaxation, vibration (what next?);
- 3) Conduct material testing under the homogeneous and isotropic assumption as the first approximation;
- 4) Conduct a comprehensive material validation study, preferably with the help of a third party;
- 5) Investigate the influence of the material properties variability (and experimental errors) on the response and tolerance to exposure conditions (for example stress/strain-time fields developed inside the brain); and
- 6) Investigate the influence of homogeneity and anisotropy of tested materials on the stress/strain-time fields developed inside the brain.

Mid-Term (2 – 5 years) recommendation to investigate the influence of homogeneity and anisotropy of tested materials on the chemical and physiological response and tolerance inside the brain.

Far-Term (>5 years) recommendation to develop an atlas (map) of material (mechanical, chemical, and physiological) properties.

Additional Expert Panel recommendations are as follows: obtain reliable experimental data across a spectrum of surrogates (and animals) and develop validation standards for human models – physical model component, cadaveric/human test component, material level validation and development of acceptable prototypes.

### ***Human Simulation and Mathematical Modeling: (Slide 59)***

Human simulation involves performing computational simulations of well-characterized experimental laboratory blast exposure tests, with the goal of identifying variations in pressure, stress, cavitation, etc. Mathematical (computational) modeling involves sophisticated computer modeling of fluid dynamics and biomechanical data to digitally predict what each region of the human brain experiences during a blast.

Challenges specified by the Expert Panel include:

- 1) Need to account for three responses – cerebral, systemic, and local – that often occur at the same time following blast injury;
- 2) Develop tissue-specific constitutive models that account for all relevant response mechanisms – nonlinear visco- and poro-elasticity, anisotropy, rate-dependency, and cavitation;
- 3) Reproduce the most frequent symptoms observed in mTBI patients (issues with vision, balance/hearing, sleep, cognition, etc.);
- 4) Merge three criteria – biological, biomechanical, and wave dynamics – for the modeling to work;
- 5) Capture physics and mechanics at the neural level; and

- 6) Overall, computational modeling is needed to bridge the gap between understanding the dynamics of microstructure on the engineering side and cellular/functional disruption on the clinical side.

Work in progress as of 2012 includes:

- 1) Developing biologically relevant models of the human head, neck, and torso that incorporate complex physics (MIT/DVBIC) – the goal is to develop a hierarchy of models from engineering relevance to medical relevance;
- 2) Developing simulation models that can model the skull, CSF, and brain with sufficient detail to identify deformation mechanisms and differences between blast and impact (LLNL);
- 3) Creating the full body “Digital Warrior,” which is constructed with a finite element mesh and captures many injury locations in one model (ARL);
- 4) Developing an anisotropic FE head model, which will be connected to a microscale model (KTH – Royal Institute of Technology);
- 5) Human Connectome Project – A NIH-funded comprehensive white matter mapping project that provides axonal-based material models for performing mechanics-based simulations and gathering information on tissue damage;
- 6) Developing an articulated human body model and a variety of head anatomical/geometric models (skin, cranium, CSF, brain structures, axonal tracks, and vasculature) (CFDRC);
- 7) Created a FE human head model with ~130,000 elements (JHU/APL) and will use the model to predict intracranial pressures and relative brain-skull displacements and will apply the stresses developed in the model to the CFDRC’s vascular model to calculate the pressures in the vascular system.

The TT members discussed current status of the “digital warrior” projects, e.g., digital astronaut (NASA project), Oak Ridge National Laboratories (in the 90s). Dr. Gupta offered to give a brief update on the current status of all digital human projects at the third meeting in Porton Down, GRB.

***Proposed Approach/Roadmap for Computational Human Modeling: (Slide 64)***

Elements to consider when designing human simulation include establish human anatomical (geometric/mesh) models:

- 1) For the body – skin versus protected (helmet, PPE);
- 2) For the head – skin, skull, CSF, resolved brain, vascular, eyes, ear, nose (olfactory, sinuses?); and
- 3) For the whole body – vascular, spinal cord/CSF, etc.

Primary Biomechanics – blast transfer to brain and the role of helmet. Is “face-on” exposure to blast sufficient to cause TBI? Need to simulate brain-CSF? Primary macro injury to micro injury – brain tissues and vascular microstructure injury; secondary injury mechanism – myriad of injury mechanisms – identify the most important ones; material properties – use “best available” first; and physiological responses – short/long-term.

Near-Term (1 – 2 years) recommendations include:

- 1) Conduct a comprehensive literature review of the existing human models, analyze advantages, limitations, successes, and failures;

- 2) Conduct a CT and MRI study on the head/brain geometry to determine the “average” age-dependent head/brain geometry along with the error bounds;
- 3) Develop an “average” FE head model based on average geometry along with the lower and upper bounds;
- 4) Develop a full body model with vasculature to define possible interactive pathways;
- 5) Exercise all models at the conditions relevant to the problem at hand (based on exposure data);
- 6) Determine if the geometry affects the stress/strain, chemical, and physiological responses;
- 7) Determine if material, chemical, and physiological variability affects response and tolerance inside the brain;
- 8) Simulate test conditions used in the clinical approach, tune up the models, and provide feedback to the test labs if necessary;
- 9) Conduct a battery of validation tests based on test conditions different from those used in the development of the models; and
- 10) Develop injury criteria.

Mid-Term (2 – 5 years) recommendations include:

- 1) Conduct parametric analyses and identify variables that significantly influence the injury outcome; and
- 2) Investigate influence of brain homogeneity and anisotropy on the mechanical, chemical, and physiological injury outcomes field inside the brain.

Far-Term (>5 years) recommendation to implement material map (including mechanical, chemical, and physiological properties) into one multi-physics model and fine tune injury criteria if necessary.

***Dose-Damage-Outcome Correlations: (Slide 68)***

These correlations refer to linking external blast exposure to the mechanical dose within the brain, to neural damage, and to clinically relevant outcomes, e.g., behaviors that are clinically accepted as indicative of mTBI.

***Proposed Sequence for Dose-Response Testing: (Slide 70)***

Desired outcome effects of the animal models:

- 1) Relevant behavioral outcomes – are there any small animal behaviors that correspond to mTBI? Declarative memory? Medical imaging findings representative of humans (i.e., MRI anomalies using DTI, MRS). Reliable biomarkers such as in CSF or serum, similar response to treatment – clinical candidates such as progesterone and pregnenolone, and sleep and rest as per DoD protocols.

Challenges specified by the Expert Panel include:

- 1) Develop an integral damage model that includes size of injury, time parameters, rates, and time to manifestation of injury (milliseconds to months), and verify the model in animals and human cadaver tests;
- 2) Develop mechanical dose-response models of brain tissue dysfunction related to non-impact, blast-induced mTBI;
- 3) Correlate “dose” (stress, strain, work, etc.) at the brain tissue level with the “damage” that causes the neurological outcomes;

- 4) Delineate tissue-specific thresholds for damage; and
- 5) Develop definitions of physical failure and functional failure.

Work in Progress as of 2012 includes:

- 1) Determining the mechanical signaling pathways activated by blast waves and elucidating the cellular mechanisms that potentiate the injury cascade following blast injury (Harvard University) – built a series of vertically integrated models of blast injury to try to understand the scaling laws of injury forces from the micron to the millimeter scale;
- 2) Generated an *in vitro* model of TBI using rat brain tissue slices that allows for the correlation of input mechanical parameters with the degree of cell death expected in specific brain regions (Columbia University) – found that cell death does not occur immediately after injury and that there are significant regional differences in tolerance to injury;
- 3) Identifying upper and lower thresholds for material failure at the neuronal level using a human surrogate (the RED Head; University of Nebraska-Lincoln/NJIT);
- 4) Characterizing effects of BOP exposure on brain function and physiology in an unanesthetized animal model (Naval Medical Research Center) – BOP exposure at 75 kilopascals produced mTBI devoid of any overt pathology, and BOP at 120 kilopascals or higher could produce mild, moderate, or severe TBI accompanied by systemic injury;
- 5) Developing a dosimeter containing photonic nanocrystals that break when exposed to a very fast shock wave, resulting in a change of color (University of Pennsylvania in collaboration with Naval Medical Research Center); and
- 6) Developing a rat blast injury model that includes exposure to stress – to identify molecular targets for diagnosis, prognosis, and mitigation of blast-induced TBI by:
  - a) Replicating the neurobiological changes seen in humans; and
  - b) Determining the cellular and molecular pathologies contributing to the neurobehavioral abnormalities (USUHS) – exposure to a single blast after stress resulted in chronic memory impairment, transient increase in anxiety, chronic neuronal and glial cell losses, chronic astrogliosis, chronic neuroinflammation, lasting vascular damage, and increased rate of de novo hippocampal neurogenesis.

Near-Term (1 – 2 years) recommendations include:

- 1) Identify observables in small animals that correlate to behaviors that are clinically accepted as mTBI;
- 2) Identify damage mechanisms that correlate with observables; and
- 3) Identify large animal candidates and tissue level stress/strain instrumentation.

Mid-Term (2 – 5 years) recommendations include:

- 1) Conduct large animal tests to measure pathway dynamics;
- 2) Mechanical “dose”, and desired observables; and
- 3) Confirm findings in non-human primate tests.

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Far-Term (>5 years) recommendation to use understanding of mechanism to explore therapeutic options in small animal models.

Additional Expert Panel recommendations are as follows:

- 1) Develop a new “Bowen curve” establishing a correlation between exposure and functional deficits as seen in humans;
- 2) Establish initial dose-response curves of at least two species;
- 3) Include multiple exposures and head acceleration and/or rotation;
- 4) Use detailed calibration, measurement, and reporting of sensors/gauges to record the response of the target specimen – should include information about the type of gauge used, location, and placement method; and
- 5) Link the environment to biological and cognitive function.

### ***Clinical Data/Observations: (Slide 77)***

The clinical data and observations are the neurocognitive, physiological, and behavioral information gathered when humans are exposed to blast.

Challenges specified by the Expert Panel include the following:

- 1) Obtain guidance from medical community professionals to help blast injury researchers know where to focus their efforts;
- 2) Obtain improved clinical histories of soldiers exposed to blast to develop an integrated clinical descriptor of the injury that is accurate and not encumbered by security concerns;
- 3) Collect and save data at the field immediately after blast injury, including pre-injury conditions and relevant environmental information;
- 4) Identify the neurobiology underlying blast-induced mTBI functional deficits/symptoms in soldiers;
- 5) Identify biomarkers that are indicative of exposure to hazardous levels; and
- 6) Characterize the human neuropathology related to blast exposure.

Work in progress as of 2012 includes:

- 1) Conducting clinical trials on humans focused on examining blast-induced damage to the brain, and performing parallel biomarker studies (UCSD, Traumatic Brain Injury Clinical Trial Collaboration);
- 2) Conducting neurologic, neurocognitive, and behavioral assessments on Operation Iraqi Freedom (OIF) veterans with mTBI (University of Washington) which demonstrated that compared to community (civilian volunteer) controls, OIF test subjects showed hypometabolism in the medial temporal lobe and thalamus;
- 3) Studying the long-term effects of blast-induced mTBI in OIF / Operation Enduring Freedom (OEF) veterans using DTI and neurobehavioral tests (Baylor College of Medicine) which found significant differences in learning between the OIF/OEF test subjects and controls (non-blast exposed veterans) using the Verbal Selective Reminding Test;

- 4) Conducting neurocognitive assessments and functional neuroimaging in Breachers who have repeated exposure to low level blast (WRAIR) and found a pattern of decreased neurocognitive performance in the instructors on exposure days but not on later days and instructors also showed reduced efficiency in neural processing on a memory task;
- 5) Studying the clinical symptoms observed in soldiers with mTBI following deployment (VA Hospital Colorado) – found that post-traumatic stress disorder (PTSD) and mTBI can co-occur, and that PTSD or other anxiety disorders are twice as likely to develop when TBI is mild;
- 6) Developed an accelerometer package that will enable the acquisition of rotational acceleration data about the superior-inferior axis of the head (Wake Forest University) – data collection recently began on the Wake Forest football team, and preliminary data have shown strain in the brain to be most correlated to the maximum rotational velocity of the impact;
- 7) Screening veterans of OEF/OIF for TBI. (Department of Veterans Affairs) – preliminary data show 7.5% of veterans as having had mTBI; and
- 8) Conducted a clinical study in which DTI was used to detect damage to axons in the brains of Soldiers diagnosed with mTBI (Washington University School of Medicine) – significantly more DTI abnormalities than would be expected by chance in 18 of the 63 mTBI subjects (conventional MRI and CT missed these abnormalities completely).

Near-Term (1 – 2 years) recommendations include:

- 1) Conduct a comprehensive literature review on blast induced TBI and neurological deficits in relation to type, manifestation, and temporal profile of symptoms including localization of identifiable pathological changes in the brain, co-existing exposure to military relevant stressors, and pre-existing conditions that might influence susceptibility toward TBI, in relation to well-characterized exposure conditions;
- 2) Establish detailed and inter-linked databases that provide information about exposure characteristics such as type, manifestation, and temporal profile of symptoms, localization of identifiable pathological changes in the brain, co-existing exposure to military relevant stressors, and pre-existing conditions that might influence susceptibility toward TBI, in relation to well-characterized exposure conditions;
- 3) Perform well-characterized clinical studies identifying type, manifestation, and temporal profile of symptoms, localization of identifiable pathological changes in the brain, co-existing exposure to military relevant stressors, and pre-existing conditions that might influence susceptibility toward traumatic brain injury, in relation to well-characterized exposure conditions; and
- 4) Validate existing human models and identify gap(s).

Mid-Term (2 – 5 years) recommendations include:

- 1) Continue with well-characterized clinical studies identifying type, manifestation, and temporal profile of symptoms, localization of identifiable pathological changes in the brain, co-existing exposure to military relevant stressors, and pre-existing conditions that might influence susceptibility toward TBI, in relation to well-characterized exposure conditions;
- 2) Fine tune and connect clinical databases, and consolidate them into one;
- 3) Design and perform longitudinal, prospective studies for diagnostic, treatment, and rehabilitation methods; and
- 4) Validate human model with dose-injury relation against data from theater.

Far-Term (>5 years) recommendations include:

- 1) Develop predictive mathematical models based on clinical information; and
- 2) Use validated simulations of improved protective strategies to design improved military PPE.

***Computational Blast-induced mTBI Modeling Enterprise: (Slide 86):***

According to the Expert panel the main purpose of the Enterprise is to develop a computational model of non-impact, blast-induced mTBI. It is envisioned that the Enterprise will:

- Set the broad research agenda and prioritize specific research challenges;
- Set a framework for sharing information and resources and provide quality assurance;
- Minimize duplication of effort, which should free up resources for more novel research;
- Keep the work focused on the solution; and
- Allow research to evolve as new capabilities are brought online and we learn new things.

Notably, the Enterprise will *not* dictate how specific research is conducted or any specific approach to that research. The research framework will include a national database at its center, numerous Centers of Excellence (CoEs), and a program integrator. Each CoE will have expertise in a specific scientific area, and CoEs will share data for iterative refinements and corroboration. While there may be some permanent CoEs, it is envisioned that CoEs will be formed on a dynamic basis as new capabilities come online or as we learn more about mTBI. The program integrator is a key aspect of the framework. The program integrator will control the flow in and out of the national database as well as around the CoEs to facilitate the sharing of information. The program evaluator will also control the quality of the data in the database and ensure that a set of standards is being followed that everyone agrees is reliable.

Why hasn't this been done? A lot of investment went into the clinical side of the house with the idea that we will return to computational models. Mr. Leggieri added that PCO is currently standing up a working group of program managers who are funding/developing these computational models' efforts. Step 1 will be information sharing, and Step 2 will be to find duplicative efforts and collaborative opportunities as appropriate this information from this working group will be shared with the HFM-270 TT members. Drs. Bieler and Franke shared information about the EU wide (civilians and military) medical registry specific to blast and ballistic injuries (like the "trauma registry"), the module for explosions captures data from terrorist attacks and suicide bombers. This was followed by a discussion on how to incorporate the modeling capability information from each nation into the framework and identify the gaps and the expected data to be collected by the survey. The group then discussed the definitions of "framework," "elements," and "roadmap."

### **B.1.6 Finalize Survey Questions**

Mr. Leggieri reiterated that this survey is critical to identify what models are out there. To finalize the draft survey questions, our approach will be to review those questions that still need work. Discussion started with selecting which word to use in Question 10, "material/properties/law." Some dialogue on the how detailed or how far to drill down into specific model types as written the survey mainly focused on FE models. The TT members agreed to start at the beginning of the survey and review each question sequentially.

After Question 2, add a new Question 3: "What is the basic type of your model?" Discussed suggestion to include examples i.e., finite element model, computational fluid, rigid body, motion of equation, multibody dynamics, and other (please specify); question finalized by consensus.

Questions 3 – 5: Consensus on leaving these as is.

Question 6: “What assumptions were made in developing your computational model?” Discussed suggestion to include examples, i.e., threat, materials, boundaries/interfaces, or injury criteria or leave it open ended; question finalized by consensus.

Question 7: “What input data are required for your computational model?” Discussed suggestion to move this question to after the next question and rewording it to clarify the intent; question finalized by consensus.

Question 8: “What is the solving software used in your model?” Discussed suggestion to take out examples; consensus on removing the examples.

Question 9: “What operating system does your model run on?” Discussed suggestion to remove the OS examples; consensus on removing the examples.

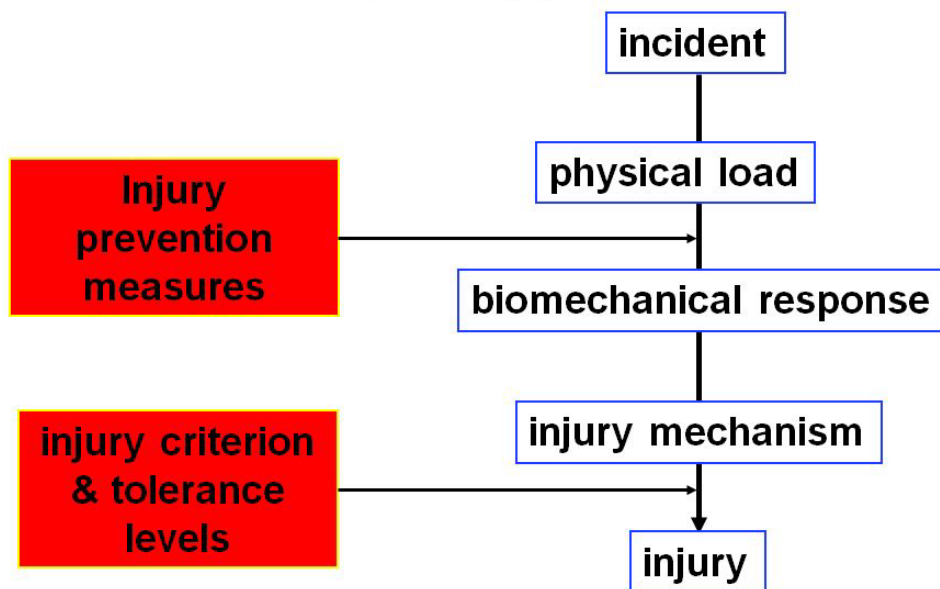
Question 10: “What are the material/properties needed for your computational model?” Discussed suggestions to delete examples; consensus to cut examples.

Question 11: “What underlying experimental model(s) or data support your computational model?” Consensus on leaving this one alone.

Question 12: “What injury mechanism does your computational model simulate?” Discussed concern with “injury mechanism” here and then later in Question 14 use “loading mechanism,” could use “threat/loading mechanism” as per Mr. Philippens’ slide below. Some concern expressed with using “simulate;” consensus on changing this to “address” because many models do not “simulate.”

## Injury Biomechanics

### The Load – Injury model



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Question 13: “What injury criteria does your computational model utilize/can utilize?” Looked for definition of “injury criteria” is defined in the HFM-234 Dictionary of Blast Injury Terms and suggested including dictionary with the survey, however “injury criteria” was not defined. Discussed various possible substitutions but concern that only considering the biomechanical parameters; the goal is to eventually model the physical, biological, and chemical effects of blast exposure and long-term outcomes. After much discuss, the TT members agreed to taking the example parameters out; question finalized by consensus.

Question 14: “What threat/loading mechanism does your computational model address?” Discussion about what modeling capabilities to focus on, aspects of blast or the whole picture, and agreed that focused on models of the effects of the blast. Recommendation to add “temperature” to the options; question finalized by consensus.

Question 15: “What blast-related threat exposure or loading mechanism does your computational model simulate?” Discussed suggestion to move this question up to before Question 13 and reword to ask if model simulates threat; consensus on deleting Question 15.

Question 16: “What is the primary exposure measurement used in your computational model?” Consensus to delete this question as it is covered by Question 15.

Question 17: “What is the injury target of your computational model?” Discussed suggestions to reword question to clarify the intent; question finalized by consensus.

Question 18: “What is the body response simulated by your computational model, e.g., loss of consciousness, lung contusion, fractures, sprains, tissue rupture, etc.?” Consensus on no changes.

Question 19: “What is the secondary injury simulated by your computational model? Micro-level injury or Macro-level injury” Discussion regarding the meaning of this question, cellular level is implied by micro-level and tissue level by macro-level. Consensus on deleting Question 19.

Question 20: “What is the state of development of your computational model?” Discussion regarding the meaning of this question, final consensus wording is “Is your computational model fully developed? Yes/No. If no, indicate which stage of development (i.e., prototype, being proved out, interim design tool, etc.).”

Question 21: “What, if any, additional effort is needed to fully validate or develop your computational model?” Discussed suggestions to reword question to clarify the intent; question finalized by consensus.

Question 22: “What data were used to validate your computational model?” Discussed suggestions to reword question to clarify the intent; question finalized by consensus.

Question 23: “What experimental model was used to create your computational model?” Discussion regarding the intent of this question, focused on the sources of the data used in developing the model, suggestion to delete the bullets and just ask what the sources are; question finalized by consensus.

Question 24: “What methods were used for loading animals or *in vitro* models in the underlying experimental models?” Question deleted by consensus.

Question 25: “Does your model include distribution of: size, shape, gender, age, and other?”

Discussion to clarify meaning of this question by rewording it; question finalized by consensus.

Question 26: “What type of geometry is used in the model?” Discussion regarding removing the bullets and rewording to clarify the meaning; question finalized by consensus.

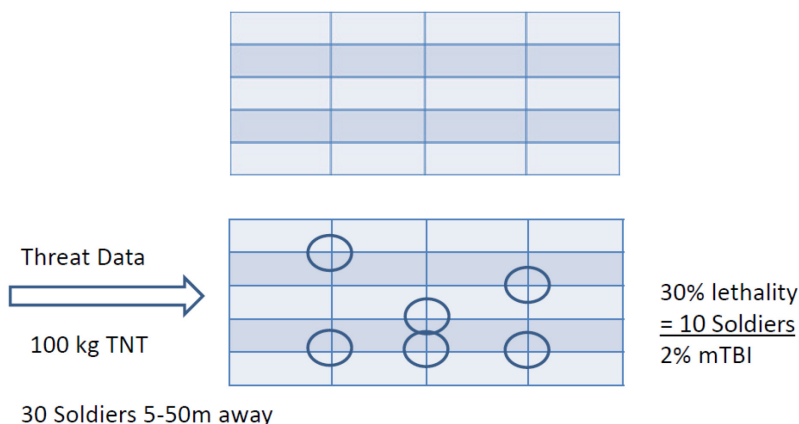
Question 27: “What is the time frame modeled (please specify in hours, days, months and/or years)?” Discussion to clarify immediate is  $t = 0$  and acute is  $t > 0$ . Question finalized by consensus.

Question 28: “What are the outcome measures?” Discussion around using the “Other” option to indicate outcomes other than lethality, survival, etc.; question finalized by consensus.

The final survey is attached in Appendix B-4. Note that “Survey” will be replaced with “Questionnaire” to comply with US regulations on the use of surveys.

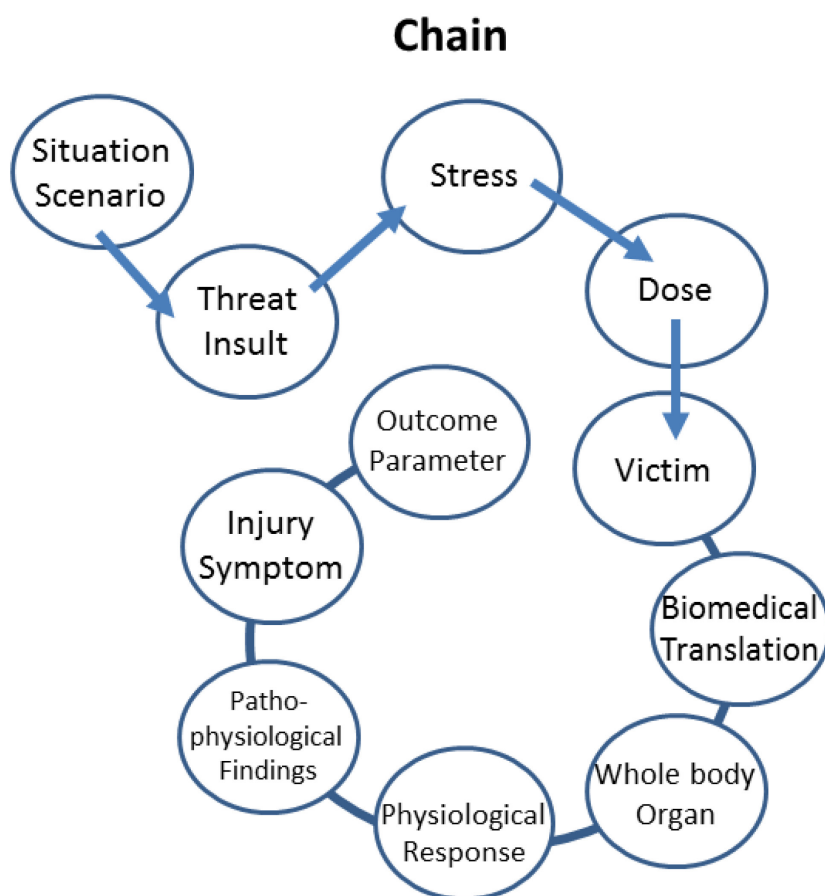
### B.1.7 Identify Elements of the Framework

Mr. Leggieri initiated discussions by reviewing the slides from the HFM-270 (RTG) Kick-off meeting titled “Identify Elements of the Computational Model Framework” and suggested that the framework would be displayed as a matrix. He suggested that the TT members define what an “element” is. He believes that elements are types of models, e.g., loading model, similar to the cogs in the black box. Others think of elements as building blocks, broad categories of models, or threats as illustrated in the black box. Discussion around what the Framework should encompass ensued with a suggestion that the Framework will identify what kinds of models are necessary in order to predict the human response to blast. Discussion continued about what the relationships should be between the models within the overall framework and what will be the input needed, with the ultimate input being threat data. The matrix encompasses computational models only, it does not incorporate animal models; once populated the matrix will help identify gaps and therefore what computational models are still needed. All agree that there are models of various threats and body systems or organs; the question is how to integrate the various models of various systems/organs into the Framework. With threats being multidimensional (temperature, gas, pressure), there will be multiple models that will be needed to model these dimensions, the difficulty will be in integrating them to represent the human as represented by a system of components and the degree of their connections/integration. Dr. Bieler illustrated an example of a threat scenario (100 kg TNT, 30 Soldiers distance to blast 5 – 50 m) and the predicted responses: 30% die immediately, at a certain pressure the brain will be affected with 2% experiencing mTBI in this example.



At various intersections there are connections between the models within the Framework; there may be multiple models involved to predict the outcomes. Consensus that experimental models that support the computational models, such as a pig or rodent model, must be incorporated into the Framework in some way to ensure that when there is a computational model related to pigs, but someone wants to know what is going on in mice, can easily see gaps. Taking the elements discussed at the kickoff meeting in Paris, TT members used a biomechanical model to identify clinical observations and the resulting response. TT members will first define the chain from insult to impact and then work through a schematic of the model.

Linked threat → External stress or insult → Outcome



Based on discussions around the chain diagram, the TT members developed a matrix and worked through one simple example (Table B-1).

- Threat = BOP
- Loading = 30 psi
- Biological Target = lung
- Biomechanical = sheer stress

- Physiological Response = Apnea
- Pathology = hemorrhage
- Pathophysiological finding = local inflammation
- Injury symptom = shortness of breath
- Outcome = ARDS

Note that not every threat will lead to an entry in each element column. TT members worked through a real experiment from DSLT with 2 kg TNT (primary blast injury) and a bolt (secondary blast injury); this example would need multiple models for both primary and secondary injuries and the pathophysiological response, with the target being to model to predict the whole body response (Table B-2).

- Scenario = 2 kg EDC, 2 m
- Threat = BOP
- Loading = 30 psi, blood loss
- Biological target = whole body
- Biomechanical = sheet stress, compression, increased internal pressure, fragments
- Physiological response = cardiovascular response
- Pathology = hemorrhage
- Pathophysiological finding = ischemia, reperfusion injury, hypotension
- Injury symptom = shock
- Outcome = coagulopathy

Some discussion on the timeframe of models, i.e., blast to survivability or injury severity; ideal would be to be able to go forward and backwards within the matrix. For instance, based on several symptoms can predict overpressure, and if overpressure known, can predict additional symptoms. Another example, epidemiology study that asks soldiers if they have shortness of breath then can connect the response and go backwards and forward from threat to outcome. Loading is an important parameter that must be accounted for, and discussions included use of PPE and loading behind such equipment, making for complex modeling requirements. Suggestion to have multiple lines for each scenario to account for loading and target, within each there will be multiple responses. TT members referred to the HFM-234 report (reproduced below) for the framework elements. A lot of discussion ensued on what the models need to predict, i.e., injury threshold exceeded or not, soldier needs to be sent for evaluation following exposure, or long-term outcomes; this meeting is not focused on individual models rather identifying the elements of the framework. All agreed to focus on biophysical models and translating clinical outcomes, and how to transfers back and forth between the two using thresholds, injury assessment scores, and loading scenarios. Plan to flesh out a computational model framework tomorrow; adjourned for the day.

## ANNEX B – MINUTES FROM HFM-270 PANEL MEETING JANUARY 2017

**Table B-1. Example of Framework Matrix Using a Lung Model as a Biological Target.**

| Scenario                     | Threat | Loading Characterization     | PPE | Biological Target | Biomechanical | Physiological Response | Pathology  | Pathophysiological Finding | Injury Symptom       | Outcome  |
|------------------------------|--------|------------------------------|-----|-------------------|---------------|------------------------|------------|----------------------------|----------------------|----------|
| 100 kg TNT, open field, 50 m | BOP    | 30 psi, $\Delta t$ , impulse | Yes | Lung              | Shear stress  | Apnea                  | Hemorrhage | Hypoxia                    | Short of breath/ARDS | ICU stay |

**Table B-2. Example of Framework Matrix Using a Whole Body Response Model as a Biological Target.**

| Scenario       | Threat | Loading Characterization | PPE | Biological Target | Biomechanical                                                     | Physiological Response  | Pathology  | Pathophysiological Finding                | Injury Symptom | Outcome      |
|----------------|--------|--------------------------|-----|-------------------|-------------------------------------------------------------------|-------------------------|------------|-------------------------------------------|----------------|--------------|
| 2 kg EDC1, 2 m | BOP    | 30 psi, bl loss 30%/wt   | No  | Whole body        | Shear stress, compression, increased internal pressure, fragments | Cardiovascular response | Hemorrhage | Ischemic reperfusion injury, Hypotension, | Shock          | Coagulopathy |

| <b>Blast Injury Toxicology Framework from HFM-234</b>                                                |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Toxicology methods relevant to understanding blast exposure effects + Toxicology methods and metrics | <p>End product – Dictionary of commonly used terms with definitions.</p> <ul style="list-style-type: none"> <li>• Factors influencing threshold-dose levels, functional, morphological, anatomical, biological (cellular, tissue, organ, biochemical).</li> <li>• Blast effect on human from outside (whole body-cellular) failure due to stress, strain, pressure, force, etc.</li> </ul>                                                                                                                                                                                                                                                         |
| Define the exposure                                                                                  | <p>Define the threat (environmental circumstances for blast).</p> <ul style="list-style-type: none"> <li>• How we are going to define – free field.</li> <li>• Understand existence.</li> <li>• Awareness of different consequences of wave complexities.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                               |
|                                                                                                      | <p>Understanding of Exposure (starting point-incident) – define the environment.</p> <ul style="list-style-type: none"> <li>• What component of blast exposure (Primary, secondary, etc.)</li> <li>• Which parts of the body.</li> <li>• Any concomitant injuries, e.g., hemorrhage or any physiological stress.</li> <li>• Dosimetry pattern.</li> <li>• Dose-exposure to what.</li> <li>• Route of exposure.</li> <li>• Injury/impairment Threshold –biological, physiological, or psychological.</li> <li>• Thresholds and components of threshold as appropriate (mechanical, biological, biochemical, physiological, male/female).</li> </ul> |
|                                                                                                      | Blast exposure monitoring methods and metrics                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|                                                                                                      | Loading mechanism (what is environment doing to body) and how the body reacts                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| Response                                                                                             | <p>Injury Threshold (scale) – dose driven curve; biological, mechanical, physiological, or psychological, Performance, no injury, define threshold at cellular, tissue or organ level.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|                                                                                                      | When –acute to chronic.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
|                                                                                                      | Physical/physiological or combination (Target organs, tissues, cellular).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|                                                                                                      | Psychological and behavioral.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|                                                                                                      | Systemic – neuroendocrine, immune, epigenetic (changes because of environment), genetic.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |

| <b>Blast Injury Toxicology Framework from HFM-234</b>                     |                                                                                                                                                                           |
|---------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Determine Outcome                                                         | Consequence/outcome for example performance, return to duty, preventive, treatable, short/long-term consequences.                                                         |
|                                                                           | Matrices i.e., list of components (physical/physiological) with weight for each component.                                                                                |
|                                                                           | Criteria for above parameters in regard to operational parameters (when they become serious enough to cause injury) -Provide information to risk assessors (operational). |
|                                                                           | Where they can be used (PPE, operational or modeling purposes).                                                                                                           |
| Identify community                                                        | Vehicle designers, mechanical, medical, material, test and evaluation as applicable.                                                                                      |
| Advancing the state of practice in Computational Modeling of blast injury | Leverage work already done by US DoD Computational Modeling Expert Panel.                                                                                                 |

**From HFM-234 (RTG) “Environmental Toxicology of Blast Exposures: Injury Metrics, Modeling, Methods and Standards” Kick-Off Meeting Summary and Program of Work.**

Initial discussion based on scenarios discussed yesterday, will need to build the next layer of computational model engines for each – biomechanical, physiological, and pathological, and then a third layer translating these into medical findings/outcomes. TT members agreed to start with the outcomes and work backwards to identify the elements of the Framework, including a fourth dimension of time.

Noted that the definitions of “immediate”, “short-term”, “mid-term” and “long-term” need to be defined because they are related to the operational environment. Extensive discussion of the outcome categories to include in the framework ensued and included how to capture “roles of care,” the medical resources needed, medical outcomes, medical health care resources, and predicting probability of performance decrement and impairment. Consensus is that the medical element is the driver and must be linked to the operational environment within the Framework.

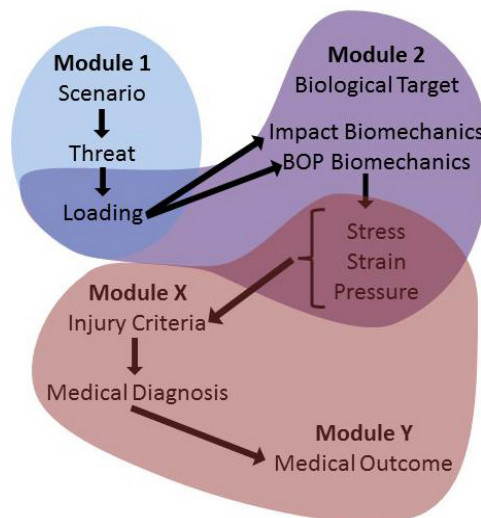
- Operational element:
  - Return to duty.
  - Fit to fight (physical and cognitive performance).
  - Injury Prevention.
- Medical Health Care Resources (role of care):
  - Sanitary burden (cost of care).
  - People.
  - Equipment.
  - Facilities.

Ongoing discussion centered around how animal experiments and clinical data/outcomes will be addressed by the models. TT members started developing modules (a module is made up of elements). The table developed

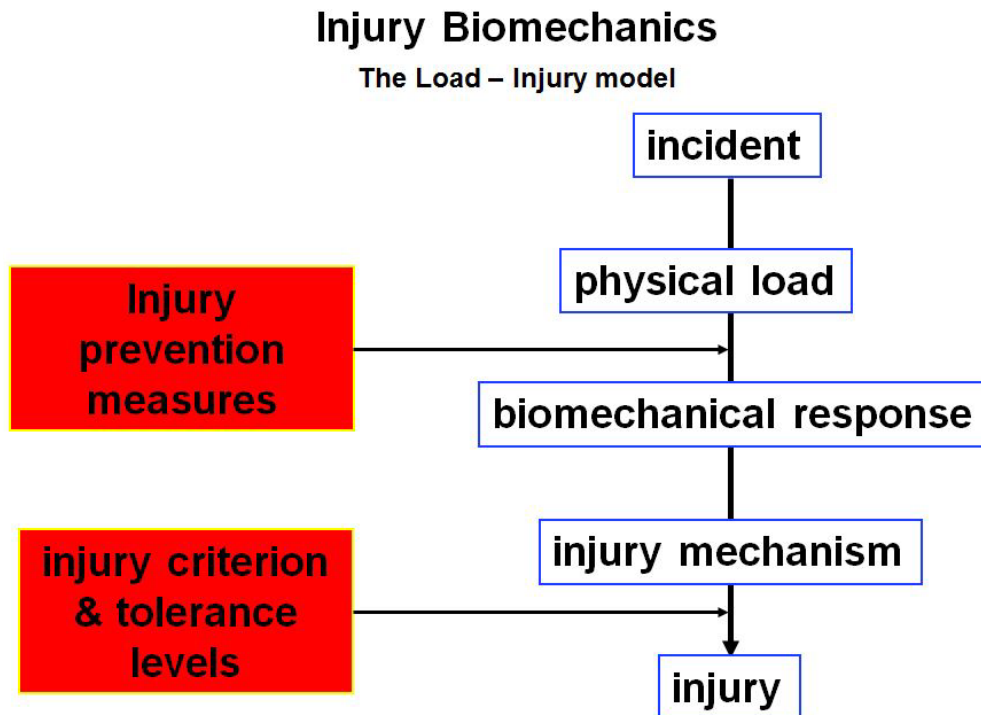
yesterday, identifies individual elements and the individual elements could be incorporated into different modules. The first module could be threat characterization, and the second module could be biomechanical response, and so on; and module 1 must talk to module 2, etc.

### MODULES (composed of Elements)

- Module 1 – Threat Characterization
  - Scenario
  - Threat
  - Loading
- Module 2 – Biomechanical (includes biodynamics, posture)
  - Loading
  - Biomechanical
  - Biological target
- Module X – Injury
  - Biological target
  - Biomechanical response
  - Physiological response
  - Pathology
  - Pathophysiological finding
  - Injury Symptoms
- Module Y – Outcomes
  - Injury Symptoms
  - Injury related Consequences



Discussed how different elements will feed into different modules (projected a slide), for example injury prevention measures will modulate/change the physical load, injury criterion and tolerance levels affect injury mechanism; and not all the elements should be addressed within each module.



Categorize Outcomes – these are generalizable:

- Medical
- Military Loss
- Return to Duty
- Economic loss
- Operational
- Prevention

This list led to a discussion about the definition of outcome and consequences; such that “outcome categories” renamed to framework “result categories” (computational modeling capability will support these results categories). All agreed that time is accounted for in the injury related consequences. TT members realized that Module X and Y are not necessarily related to blast, i.e., a fracture is a fracture and length of stay in a hospital, such that individual models incorporated into the Framework do not have to be blast specific.

**B.1.8 Action Items**

The action items from this meeting are as follows:

- 1) Questionnaire for collecting existing computational models and modeling capabilities has been finalized:
  - a) Convert word document into a fillable PDF document.
  - b) Chair to distribute to all TT members by email and post on the Science Connect site.
  - c) TT members to administer the Questionnaire to identify existing computational models and modeling capabilities within each participating nation before next HFM-270 (RTG) meeting in July 2017.
  - d) TT members to present an overview of the existing computational models and modeling capabilities within their respective nations at the next HFM-270 (RTG) meeting at Porton Down in July 2017.
- 2) All TT members are to use the HFM-270 (RTG) site on Science Connect at <https://www.sto.nato.int/>, but documents for review and comment will continue to be shared by email as some of the TT members are unable to access Science Connect.
- 3) All TT members were requested to review future meeting and teleconference dates (see Appendix B-3), identify any potential conflicts, and confirm participation.
- 4) Dictionary Working Group to develop list of generalizable terms and send out to TT members and SMEs and report out on progress at the Porton Down meeting.
- 5) Publication Working Group to develop a strategy for coordinating publications over the duration of this RTG and report out on the strategy at the Porton Down meeting.
- 6) TAP Working Group to develop a strategy for developing this new TAP and report on the strategy and timeline at the Porton Down meeting.
- 7) WebEx capability is proving too great a hurdle for some of the TT members, therefore HFM-2709 (RTG) will use teleconferences going forward.
- 8) Use the DOCS feature in Science Connect for preparing, collaborating, and finalizing HFM-270 (RTG) documents.
- 9) Next teleconference on 19 April 2017: The goal will be to review draft agenda for the Porton Down meeting prepared by the meetings hosts, including:
  - a) Review of overall objectives and goals for HFM-270 (RTG), and specific goals for Porton Down meeting by Mr. Leggieri (NEW).
  - b) Scope the breadth of existing computational models and modeling capabilities in each of the eight participating nations, based on responses received to the questionnaire as presented by the TT members (~30 minutes for each nation).
  - c) Categorize computational models by type:
    - i) Threat.
    - ii) Lethality.
    - iii) Injury (blunt/impact, burns, brain, ballistic).
    - iv) Impairment.

- d) Presentations from computational modeling SMEs.
- e) Dr. Gupta will provide an overview of the current status of past and on-going US human model projects (NEW).
- f) Develop plan that will include criteria to assess model capabilities in Meetings 3 – 5.
- g) Dictionary Working Group – provide update.
- h) Publications Working Group – provide update.
- i) TAP Working Group – provide update.
- 10) Confirmed date and location for next meeting titled “Scope Breadth of Existing Models” is 11 – 13 July 2017 at Porton Down (near Salisbury), Great Britain, hosted by Drs. Sarah Watts and Emrys Kirkman, Defence Science and Technology Laboratory (Dstl).

Note all presentation slide decks, meeting agenda, and other meeting documents are archived in the Meeting 2 folder in the HFM-270 File Share location on the Science Connect collaboration site (<https://scienceconnect.sto.nato.int/>).

#### **B.1.9 List of Nations**

Canada (CAN)  
France (FRA)  
Germany (DEU)  
Netherlands (NLD)  
Sweden (SWE)  
Turkey (TUR)  
United Kingdom (GBR)  
United States (USA)

#### **B.1.10 National and STO Resources Needed**

- National resources needed: Manpower, travel funds, national data, technical and administrative support for organizing and conducting workshops and writing reports.
- Document translation and funding for invited participants to the workshops.
- Hardware and Software: Microsoft Office and use of STO Science Connect website and WebEx resources.

#### **B.1.11 Technical Team Leader and Team Members (No Ranks)**

Mr. Mike Leggieri (USA), Chair  
Dr. Raj Gupta (USA), Executive Secretary  
Dr. Dan Bieler (DEU)  
Dr. Amal Bouamoul (CAN)

Dr. Ibolja Cernak (USA)

Mr. Atil Erdik (TUR)

Dr. Axel Franke (DEU)

Dr. Pinar Huri (TUR)

Dr. Emrys Kirkman (GBR)

Mr. Ilker Kurtoglu (TUR)

Dr. Philippe May (FRA)

Mr. Mathieu Philippens (NLD)

Dr. Marten Risling (SWE)

Dr. Thomas Sawyer (CAN)

Dr. Levent Turhan (TUR)

Dr. Sarah Watts (GBR)

#### **B.1.12 Appendices**

Appendix B-1: HFM-270 (RTG) Second Meeting Agenda

Appendix B-2: HFM-270 (RTG) Attendance Roster

Appendix B-3: HFM-270 (RTG) Future Meeting Dates

Appendix B-4: Questionnaire of Existing Computational Models and Modeling Capabilities

**Appendix B-1: HFM-270 (RTG) – FINAL AGENDA FOR SECOND MEETING**

| Tuesday January 10, 2017 |                                                                                         |                                            |
|--------------------------|-----------------------------------------------------------------------------------------|--------------------------------------------|
|                          |                                                                                         |                                            |
| <b>0900</b>              | Welcome                                                                                 | Mr. Leggieri                               |
|                          | Introductions                                                                           | Team Members (TM)                          |
| <b>0930</b>              | Introduction to Set of Presentations on “Basic Understanding of Computational Modeling” | Dr. Gupta                                  |
| <b>0935</b>              | Animal Trauma Pathophysiology and Animal Models and Behavior                            | Dr. Marten Risling (for Dr. Denes Agoston) |
| <b>1035</b>              | <b>Break</b>                                                                            |                                            |
| <b>1050</b>              | Blast Physics                                                                           | Dr. Suthee Wiri                            |
|                          |                                                                                         |                                            |
| <b>1200</b>              | <b>Lunch</b>                                                                            |                                            |
|                          |                                                                                         |                                            |
| <b>1315</b>              | Biomechanics Models and Injury Threshold Severity                                       | Dr. Namas Chandra                          |
| <b>1500</b>              | <b>Break</b>                                                                            |                                            |
| <b>1515</b>              | Injury Models and Injury Criteria                                                       | Dr. Andrzej Przekwas                       |
| <b>1615</b>              | Dictionary Working Group Strategy Update                                                | Working Group (WG)                         |
| <b>1620</b>              | Publications Working Group Strategy Update                                              | WG                                         |
| <b>1625</b>              | TAP Working Group Strategy Update                                                       | WG                                         |
| <b>1630</b>              | Adjourn                                                                                 |                                            |
|                          |                                                                                         |                                            |
| <b>1900</b>              | <b>Dinner at Monocracy Crossing</b>                                                     | <b>TM</b>                                  |

| Wednesday January 11, 2017 |                                                                                      |              |
|----------------------------|--------------------------------------------------------------------------------------|--------------|
|                            |                                                                                      |              |
| <b>0900</b>                | Overview of Computational Modeling Expert Panel Findings and Recommendations (cont.) | Dr. Gupta    |
| <b>1000</b>                | Finalize Survey Questions                                                            | Dr. Gupta/TM |
| <b>1045</b>                | <b>Break</b>                                                                         |              |
|                            | Identify elements of the Framework (cont.)                                           | TM           |
|                            |                                                                                      |              |
| <b>1200</b>                | <b>Lunch</b>                                                                         |              |
|                            |                                                                                      |              |

| <b>Wednesday January 11, 2017</b> |                                            |    |
|-----------------------------------|--------------------------------------------|----|
| <b>1315</b>                       | Identify elements of the Framework (cont.) | TM |
| <b>1500</b>                       | <b>Break</b>                               |    |
|                                   | Identify elements of the Framework (cont.) | TM |
|                                   |                                            |    |
| <b>1630</b>                       | <b>Adjourn</b>                             |    |

| <b>Thursday January 12, 2017</b> |                                            |                 |
|----------------------------------|--------------------------------------------|-----------------|
|                                  |                                            |                 |
| <b>0900</b>                      | Identify elements of the Framework (cont.) | TM              |
| <b>1045</b>                      | <b>Break</b>                               |                 |
|                                  | Identify elements of the Framework (cont.) | TM              |
| <b>1200</b>                      | Action Items                               | Mr. Leggieri/TM |
|                                  |                                            |                 |
| <b>1300</b>                      | <b>Adjourn</b>                             |                 |

Appendix B-2: HFM-270 (RTG) APPOINTED TECHNICAL TEAM MEMBERS  
(10 – 12<sup>th</sup> January, 2017)

**In attendance:**

Dr. Amit Bagchi  
Naval Research Laboratory  
[amit.bagchi@nrl.navy.mil](mailto:amit.bagchi@nrl.navy.mil)

Dr. Dan Bieler  
Central Hospital of the German Federal Armed Forces  
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Dr. Ibolja Cernak  
University of Alberta  
[Cernak@ualberta.ca](mailto:Cernak@ualberta.ca)

LtCol (Dr.) Axel Franke  
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Dr. Raj Gupta (Executive Secretary)  
US Army Medical Research and Materiel Command  
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Mr. Mike Leggieri (Chair)  
US Army Medical Research and Materiel Command  
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Mr. Mathieu Philippons  
TNO Defence, Security and Safety  
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Dr. Marten Risling  
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Dr. Levent Turhan  
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Dr. Sarah Watts  
Biomedical Sciences Department  
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**Absent:**

Dr. Amal Bouamoul  
Defence Research and Development Canada  
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Col (Dr.) Philippe May  
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Dr. Thomas Sawyer  
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**Subject Matter Experts**

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### Appendix B-3 – HFM-270 (RTG) PROGRAM OF WORK SCHEDULE

| Activity/<br>Workshop   | Month/Year        | Purpose                                                                                  | Host/Location                          | Point of Contact                        |
|-------------------------|-------------------|------------------------------------------------------------------------------------------|----------------------------------------|-----------------------------------------|
| 1 <sup>st</sup> Meeting | 5 – 6 Oct. 2016   | HFM-270 (RTG) Kick-off                                                                   | STO-CSO/Paris                          | LtCol (Dr.) Wessels                     |
| 1 <sup>st</sup> Telecon | 16 Nov. 2016      | Finalize Agenda and Invited Speakers for Next Meeting, and Finalize Survey               | Teleconference                         | Mr. Leggieri                            |
| 2 <sup>nd</sup> Meeting | 10 – 12 Jan. 2017 | Identify Elements of The Framework                                                       | USA/Frederick, MD                      | Mr. Leggieri                            |
| 2 <sup>nd</sup> Telecon | 19 Apr. 2017      | Finalize Agenda and Invited Speakers for Next Meeting                                    | Teleconference                         | Mr. Leggieri                            |
| 3 <sup>rd</sup> Meeting | 11 – 13 Jul. 2017 | Scope Breadth of Existing Models                                                         | GBR/Porton Down                        | Drs. Kirkman/Watts                      |
| 3 <sup>rd</sup> Telecon | 13 Sept. 2017     | Finalize Agenda and Invited Speakers for Next Meeting                                    | Teleconference                         | Mr. Leggieri                            |
| 4 <sup>th</sup> Meeting | 7 – 9 Nov. 2017   | Overview of Existing Computational Models                                                | NLD/Rijswijk                           | Mr. Philippens                          |
| 4 <sup>th</sup> Telecon | 17 Jan. 2018      | Finalize Agenda and Invited Speakers for Next Meeting                                    | Teleconference                         | Mr. Leggieri                            |
| 5 <sup>th</sup> Meeting | 6 – 8 Mar. 2018   | Overview of Existing Computational Models                                                | DEU/Koblenz                            | Drs. Franke/Bieler                      |
| 5 <sup>th</sup> Telecon | 16 May 2018       | Finalize Agenda and a List of Assessment Criteria to Use at Next Meeting                 | Teleconference                         | Mr. Leggieri                            |
| 6 <sup>th</sup> Meeting | 10 – 12 Jul. 2018 | Apply Assessment Criteria                                                                | Suffield Research Center, Alberta, CAN | Drs. Bouamoul/Sawyers                   |
| 6 <sup>th</sup> Telecon | 3 Oct. 2018       | Finalize Agenda                                                                          | Teleconference                         | Mr. Leggieri                            |
| 7 <sup>th</sup> Meeting | 4 – 6 Dec. 2018   | Finalize the Framework and Develop Blast Scenarios                                       | TUR/Ankara                             | Drs. Turhan/Huri and Mr. Kurtoglu/Erdik |
| 7 <sup>th</sup> Telecon | 13 Feb. 2019      | Finalize Agenda                                                                          | Teleconference                         | Mr. Leggieri                            |
| 8 <sup>th</sup> Meeting | 3 – 5 Apr. 2019   | Review Demonstration Results, Identify Gaps and Finalize Dictionary, TAP and Manuscripts | SWE/Stockholm                          | Dr. Risling                             |
| 8 <sup>th</sup> Telecon | 27 Jun. 2019      | Review Draft Final Report Revisions                                                      | Teleconference                         | Mr. Leggieri                            |
| 9 <sup>th</sup> Meeting | 4 – 6 Sept. 2019  | Finalize All Deliverables                                                                | STO-CSO/Paris                          | LtCol (Dr.) Wessels                     |

### Appendix B-4: QUESTIONNAIRE FOR HFM-270 (RTG)

The NATO Human Factors and Medicine HFM-270 Research Task Group (RTG) titled “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats” recognizes the value of computational models in solving blast injury, prevention and treatment challenges and plans to develop a framework that integrates existing computational models and guide future ones to predict human lethality, injury, impairment, and long-term health effects across the spectrum of blast-related threats. This framework will enable the evaluation of operational scenarios such as war gaming, assess the impact of innovative protection systems, identify the needs for acute and long-term medical resources, and predict health outcomes and disabilities. The impact of HFM-270 (RTG) will be improved strategies to prevent, mitigate and treat blast injuries.

In creating the framework defined above, the task group would like to start by evaluating existing computational models and modeling capabilities. This is where your support is requested in completing this survey for **each** model developed within your organization, including both computational models and underlying experimental models. For clarity below is a definition of what is intended by the word “model” and “validation” for the purposes of this questionnaire.

#### MODEL

- 1) Graphical, mathematical, physical, biological, or verbal representation or simplified version of a concept, phenomenon, relationship, structure, or system(s).
- 2) The objectives of a model include:
  - a. To facilitate understanding by eliminating unnecessary components;
  - b. To aid in decision making by simulating ‘what if’ scenarios;
  - c. To explain, control, and predict events on the basis of past observations. Since most objects and phenomenon are very complicated (have numerous parts) and much too complex (parts have dense interconnections) to be comprehended in their entirety, a model contains only those features that are of primary importance to the model maker’s purpose.

**VALIDATION** is a critically important aspect of all models.

- 1) The model should generate/simulate the injury or a component of the injury that it is supposed to model. Thus, the model is an accurate representation of the real-life injury.
- 2) The injury mechanism should in most cases be the same as in human injuries or diseases, but there might be exceptions to this rule.

Note: Validation of animal models is difficult if the pathology of the human condition is not clearly defined. For example, due to the complexity of the blast environment and its interactions with human body, the similarities and differences between the mechanisms underlying mild TBI and PTSD are still under debate, could still arise from variable pathology. In such intricate pathological conditions, the model could be validated to replicate a specific component of either a cause or process of the impairment. For example, when focusing on pathologies caused by primary blast only, care must be taken to be explicit about the focus to avoid over-interpretation of the findings by those reading the report.

Please complete the questionnaire for **each** model developed within your organization, including both computational models and underlying experimental models.

**Questions:**

- 1) Do you have an existing computational model that predicts some aspect of human lethality, injury, impairment, or long-term health effects?  
☐ Yes  
☐ No
- 2) What is the name of your computational model?
- 3) What is the basic type of your model?  
☐ Finite Element Model  
☐ Computational Fluid  
☐ Rigid Body  
☐ Motion of Equations  
☐ Multibody Dynamics  
☐ Other (please specify)
- 4) Who is the Owner and Developer of your computational model? Please include organizational affiliation.
- 5) Who is the principal investigator for the computational model? Include full name and email address.
- 6) What is the intended use of your computational model?
- 7) What assumptions were made in developing your computational model concerning threat, materials, boundaries/interfaces, or injury criteria?
- 8) What are the sources of the data used to create your computational model?
- 9) What input data are required to run your computational model?
- 10) What is the solving software used in your model?
- 11) What Operating System (OS) does your model run on?
- 12) What are the material models/properties needed for your computational model?
- 13) What underlying experimental model(s) or data support your computational model?  
☐ Biological  
☐ Physical  
☐ Mathematical  
☐ Other (please specify)

14) What threat/loading mechanism does your computational model address?

- ☐ Blast Overpressure
- ☐ Acceleration/Deceleration
- ☐ Toxic Gas Inhalation
- ☐ Penetrating Fragments
- ☐ Temperature
- ☐ Other (please specify)

15) What parameters correlate with the biological effect that your computational model predicts?

16) What part of the body does your computational model address?

- ☐ Whole body
- ☐ Body part
- ☐ Organ
- ☐ System

17) What is the body response simulated by your computational model, e.g., loss of consciousness, lung contusion, fractures, sprains, tissue rupture, etc.?

18) Is your computational model fully developed?

- ☐ Yes
- ☐ No

If no, indicate which stage of development, i.e., prototype, being proved out, interim design tool, etc.

19) What, if any, additional effort is needed to fully develop your computational model?

20) Is your computational model validated?

- ☐ Yes
- ☐ No

If yes, and to what level and what data were used?

21) Does your computational model address the modifying effect of the target's:

- ☐ Size
- ☐ Shape
- ☐ Gender
- ☐ Age
- ☐ Other (please specify)

- 22) What is the source of the geometry used in the model? For example, Atlas, CT scan/MRI, anthropometric database, etc.
- 23) What is the time frame modeled (please specify in hours, days, months and/or years)?
- ☐ Immediate [text field for time frame (300 characters)]
  - ☐ Acute [text field for time frame (300 characters)]
  - ☐ Sub-acute [text field for time frame (300 characters)]
  - ☐ Chronic [text field for time frame (300 characters)]
  - ☐ Other (please specify)
- 24) What are the outcome measures?
- ☐ Lethality
  - ☐ Survival rate
  - ☐ Injury probability
  - ☐ Injury severity (please specify the measuring tool/score)
  - ☐ Other (please specify and provide the measuring tool)
- 25) How does the principal investigator for the computational model assess the strengths/weaknesses/limitations of the model?

**Thank you for your time in completing this questionnaire!**



## **Annex C – MINUTES FROM THE HFM-270 PANEL MEETING JULY 2017**

### **C.1 MEETING #3, 11 – 13 JULY 2017, DEFENCE SCIENCE AND TECHNOLOGY LABORATORY, PORTON DOWN, SALISBURY, WILTSHIRE, ENGLAND**

HFM-270 (RTG) “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats”.

**Meeting called by** Michael J. Leggieri, Jr.

**Date:** 11<sup>th</sup> to 13<sup>th</sup> July 2017

**Note taker** Emma Stott, Dstl Associate Project Manager

| <b>ATTENDEES</b>                                                 |                                                                   |
|------------------------------------------------------------------|-------------------------------------------------------------------|
| <b>Members</b>                                                   |                                                                   |
| Mr. Mike Leggieri (Chair) (USA) (ML)                             | Dr. Marten Risling (SW) (MR)                                      |
| Dr. Raj Gupta (USA) (RG)                                         | Dr. Ibolja Cernak (CAN) (IC) (12-13th)                            |
| Dr. Emrys Kirkman (UK) (EK)                                      | Mr. Mathieu Philippens (NL) (MP)                                  |
| Dr. Sarah Watts (UK) (SW)                                        | Mr. Thanyani Pandelani (SA) (TP)                                  |
| Dr. Dan Bieler (DE) (DB)                                         |                                                                   |
| <b>Observers</b>                                                 |                                                                   |
| Dr. Charmaine Richman (USA) (CR),                                | Mark Bates (MB)                                                   |
| Rayeesa Ahmed (SA) (RA),                                         | Polly Williams (PW)                                               |
| Tim Westerhof (NL) (TW)                                          | Emma Stott (ES)                                                   |
| <b>SMEs</b>                                                      |                                                                   |
| Dr. S. Wilson (Loughborough University) (SWi)                    | Surg Cdr T. Scott (RN and Nottingham University) (TS)             |
| Dr. Alec Milne and Dr Andy Milne (Fluid Gravity) (ALM) and (ANM) | Mr. W. McGeehin and Ms. N. Dukes-Hemming (Frazer-Nash) (WM) (NDH) |
| Dr. R Fryer (Dstl) (RF)                                          | Dr. G. Grigoriadis (Imperial) (GG)                                |
| <b>Apologies</b>                                                 |                                                                   |
| Dr. Amit Bagchi (ABa)                                            | Mr. Ilker Kurtoglu (IK)                                           |
| Dr. Amal Bouamoul (ABo)                                          | Col (Dr.) Philippe May (PM)                                       |
| Mr. Atil Erdik (AE)                                              | Dr. Thomas Sawyer (TS)                                            |
| LtCol (Dr.) Axel Franke (AF)                                     | Dr. Mattias Skold (MS)                                            |
| Dr. Pinar Huri (PH)                                              | Dr. Levent Turhan (LT)                                            |
| Mr. David Reinecke (DR)                                          |                                                                   |

## ANNEX C – MINUTES FROM THE HFM-270 PANEL MEETING JULY 2017

|              |
|--------------|
| <b>Links</b> |
| N/A          |

|                                         |
|-----------------------------------------|
| <b>1 Minutes from previous meetings</b> |
| N/A                                     |

|                                         |
|-----------------------------------------|
| <b>2 Actions from previous meetings</b> |
| N/A                                     |

|          | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Actions |
|----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| <b>3</b> | <p><b>Introduction</b></p> <p>The Chair welcomed everyone to the meeting and thanked all members for their efforts in supporting the group. The chair updated the members that the working group now has 21 official members from 9 different nations, with a possible addition of one more nation: Israel.</p> <p>The Chair briefed the definitions of blast injuries from the Department of Defense (DoD). The term the “black box” was briefed as the aim of the group with a timeframe of three years to develop the framework for the capability to be based on. The “black box” is a combination of computational models of human lethality, injury, and impairment from blast threats in both mounted and dismounted scenarios.</p> <p>The objectives of the meeting were listed as the following:</p> <ol style="list-style-type: none"> <li>1) Scope the breadth of existing computational models and modeling capabilities in each of the eight participating nations, based on responses received to the questionnaire.</li> <li>2) Categorize computational models by type: <ul style="list-style-type: none"> <li>• Threat.</li> <li>• Lethality.</li> <li>• Injury (blunt/impact, burns, brain, ballistic).</li> <li>• Impairment.</li> </ul> </li> <li>3) Presentations from UK computational modeling SMEs.</li> <li>4) Overview of the current status of past and on-going US human model projects – Dr. Gupta.</li> <li>5) Develop plan that will include criteria to assess model capabilities in meetings 3 – 5.</li> <li>6) Working Group Updates: <ul style="list-style-type: none"> <li>• Dictionary Working Group.</li> <li>• Publications Working Group.</li> <li>• TAP Working Group.</li> </ul> </li> </ol> |         |

|   | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Actions |
|---|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
|   | <p>The chair updated members that the reports resulting from NATO HFM-234 Panel<sup>1</sup> that was being put together by the US was expected to be released to NATO in the near future as it is currently going through internal review at DoD.</p> <p>All members were reminded that the next meeting would be taking place in November in the Netherlands, with a teleconference planned for 13 September 2017. The focus of the fourth meeting will be to gain an overview of the modeling capabilities available, as will be the focus of the fifth meeting.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |         |
| 4 | <p><b>USA Questionnaire Responses</b></p> <p>RG briefed the responses for the USA, mainly the results were supplied by the DoD but some other US departments had been included. The National Institute of Health is doing some of the human modeling work.</p> <p>Each nation's response to questionnaires will be put on the Science Connect website.</p> <p>Suggestion from RG that more time would be required to get more in depth detail on models, should the questionnaire responses not be sufficient.</p> <p><b>Comment:</b> Models should be qualified depending on the scale that they model i.e., macro, meso, micro as these are terms referred to in the modeling community. (MP)<br/>Post meeting comment these terms should be added to the Dictionary if not already included. (SW)</p> <p><b>Comment:</b> Models should be defined according to the level that it has been validate. (MP)</p> <p><b>Comment:</b> The range of exposures or threat could be the same starting point and the range of outcomes or injuries could be the same end point but the bit in between is the technical approach and can vary hugely. (MP)</p> <p><b>Comment:</b> How they validate the model in comparison to development of the model is important to capture. Another way to validate a model is to keep part of the data set aside to test the model once it has been built (forward and backward verification). (EK)</p> <p>RG suggested that ideally models are validated using animal experimental data. EK commented that the number of replicates is key to the validation (a statistically significant sample size should be chosen).</p> <p>RG commented that there were lots of computational models of rodent brain injury for mild brain injury but that they were missing the extreme stress/strain of blast.</p> <p><b>Comment:</b> The purpose of the model should be explicitly stated in the questionnaire, which may require going back to the model developers at a later date for further information. (MP)</p> <p><b>Comment:</b> Some models are missing the link back to injury and predictions of how badly a person would be injured. (EK)</p> <p>RG suggested that models may not be null and void just because they don't currently address the requirements of the "black box" and that with some steering by the group they could be adapted.</p> |         |

<sup>1</sup> HFM-234 Environmental Toxicology of Blast Exposures: Injury Metrics, Modeling, Methods and Standards.

## ANNEX C – MINUTES FROM THE HFM-270 PANEL MEETING JULY 2017

|   | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Actions   |
|---|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
|   | <p><b>Comment:</b> It was agreed amongst the members that the model's assumptions should be included in the assessment criteria for the models.</p> <p>RG commented that biomechanics assume deceleration and acceleration are the same. Modeling capability currently assumes linear injury and doesn't address the circular/angular injury from blast.</p> <p><b>Comment:</b> Research has shown that there is a response from the brain to injury which is increased when a helmet is worn if the exact resonance of the brain is induced by the presence of the helmet.</p> <p><b>Question:</b> Are we judging the models and coming up with the best model? (EK)</p> <p><b>Answer:</b> No, we are identifying the gaps (asking whether or not the model does what we need it to do for this working group). This will require careful communication with those providing responses to questionnaires. (ML)</p> <p>RG commented that the US models available of the spine were missing the thoracic and lumbar region.</p> <p><b>Comment:</b> MP suggested that the University of Strasbourg has completed a large database of wound injury but not for the purpose of blast injuries.</p> <p>RG advised that the list of models presented was not an exhaustive list and more models are available that will need to be taken into account.</p> |           |
|   | <b>Action:</b> Send a copy of the questionnaire responses to CR.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | All       |
|   | <b>Action:</b> Upload all questionnaire responses to a separate area of the Science Connect website.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | CR        |
|   | <b>Action:</b> Highlight terms used in the questionnaire so that they can be added into the dictionary terms.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | All       |
|   | <b>Action:</b> Upload all presentations onto Science Connect.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | CR        |
|   | Email presentations held by Dstl to CR.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | SW        |
|   | <b>Action:</b> UK to include burn models. Ask NIHR if they have any models.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | SW and EK |
| 5 | <p><b>Canada Questionnaire Responses</b></p> <p>SW went through the four questionnaire responses from TS (Canada).</p> <p><b>Comment:</b> MP suggested that there are several modifications available of the lung injury model briefed.</p> <p><b>Comment:</b> The rapid city planner was missing the complex blast element.</p> <p><b>Comment:</b> At the Mild Traumatic Brain Injury forum there was a model that was briefed but this is missing from the list. MP is currently using this model.</p> <p><b>Action:</b> Contact Amal about the missing model from the list (briefed at MTBI)</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | MP        |
| 6 | <p><b>France Questionnaire Responses</b></p> <p>France is having issues with communication lines and did not receive an email about the third meeting.</p> <p>No responses received from France.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |           |

|           | <b>Day 1</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | <b>Actions</b>               |
|-----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------|
|           | <b>Action:</b> USA to contact France to resolve comms issues.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | IC and RG                    |
| <b>7</b>  | <b>Germany Questionnaire Responses</b><br>DB completed a literature review of models available and has created a spreadsheet of the results broken down according to the organ affected. It was suggested that this could be used to amalgamate all models found/direct each country.<br>DB noted that there is no blast program for the military in Germany.<br><b>Action:</b> Send spreadsheet of papers to CR.<br><b>Action:</b> Send out spreadsheet of papers to all members.                                                                                                                                                              | <br><br><br><br><br>DB<br>CR |
| <b>8</b>  | <b>Netherlands Questionnaire Responses</b><br>MP went through the questionnaire responses for the Netherlands, all responses were from TNO as the military and universities are not working in this area. Lots of models relate to vehicles.<br>MP suggested that those who were asked to fill out the questionnaire weren't sure how much detail to go into. They were also worried as to who was seeing the responses to the questionnaire.<br>MP was unable to share all details of the models with the HFM-270 Group as approval would need to be sought from other parties involved.<br>MP will include more models in the fourth meeting. |                              |
| <b>9</b>  | <b>Sweden Questionnaire Responses</b><br>MR went through the responses from the two questionnaires.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                              |
| <b>10</b> | <b>Turkey Questionnaire Responses</b><br>SW went through the responses from Turkey as they were not present at the meeting. Turkey still collecting and collating responses – to be presented either at next Teleconference or Panel meeting.                                                                                                                                                                                                                                                                                                                                                                                                   |                              |
| <b>11</b> | <b>UK Questionnaire Responses</b><br>SW went through the responses from the UK.<br>SW advised that some presenters on day two will be going over the models discussed in more detail, so can answer technical questions relating to their models.<br>Other requests to fill out the questionnaire didn't come back with a response before this meeting.                                                                                                                                                                                                                                                                                         |                              |
| <b>12</b> | <b>South Africa Questionnaire Responses</b><br>TP presented 1 questionnaire response related to mTBI.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                              |

## ANNEX C – MINUTES FROM THE HFM-270 PANEL MEETING JULY 2017

|    | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Actions |
|----|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| 13 | <p><b>Discussion</b></p> <p>Three main criteria for assessment suggested as the following:</p> <ol style="list-style-type: none"> <li>1) Assumptions/boundaries</li> <li>2) Data</li> <li>3) Where the model fits into the framework proposed (start and end/input and output)</li> </ol> <p>Suggestion from MP that the starting point would be to categorize the models according to the chain decided on page 39 of the HFM-270 RTG Meeting 2 Summary document. This can then be shown to the modelers and they could categorize their model. An alternative was suggested and agreed that actually the members should attempt to start putting the models into groups.</p> <p>After some discussion it was agreed amongst the members that the way forward would be to collect the following information:</p> <ul style="list-style-type: none"> <li>• Input and output of the model</li> <li>• Detail about the boundaries of the physical parameters might be useful to aid decisions (plus boundary conditions)</li> </ul> <p>Then, with the above information assess the gaps and decide the best model of the group using criteria such as how they are validated.</p> |         |
|    | <b>Action:</b> Include assumptions in assessment criteria.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | HFM-270 |
|    | <b>Action:</b> Include micro or meso or macro level in assessment criteria.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | HFM-270 |
|    | <b>Action:</b> Include how the model is being (is someone else using the model ‘in anger’) used in assessment criteria.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | HFM-270 |
|    | <b>Action:</b> Include input and output in assessment criteria.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | HFM-270 |
|    | <b>Action:</b> Include any specific unique test devices needed to feed into the model (boundaries of the input) in the assessment criteria.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | HFM-270 |
|    | <b>Action:</b> How “generalizable” the model is should be included as an assessment criterion. This will show whether or not the model can be adapted to the blast framework.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | HFM-270 |
|    | <b>Action:</b> Availability of the model should be included as an assessment criterion (no commercial restrictions to use).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | HFM-270 |
|    | <b>Action:</b> Experience required to use the model should be included in the assessment criterion.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | HFM-270 |
|    | <b>Action:</b> Finalize the model criteria on day 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | HFM-270 |

|    | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Actions |
|----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| 14 | <b>Introduction</b><br>The Chair briefed the SMEs on the aim of the group and initiated introductions around the table.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |         |
| 15 | <b>Fluid Gravity Engineering (FGE) – ALM and ANM</b><br>ALM suggested that the key to success is to coordinate the work of the modeling community. ML commented that there is a lot of computational modeling taking place in the US but no coordination is currently present, to achieve the goal of the “black box” we must be coordinated.<br>ML suggested that he thought blast lung has been nailed down by the modeling community but the same couldn’t be said for blast brain. IC commented that we have partitioned the problem and taken lung and brain separately and we may need to move to a model of whole body injury for blast. ML commented that the US Congress focus is the brain.<br>ALM suggested that the focus of research historically has been on mortality but now the focus is on long term impact. ML agreed and suggested that in the US now the focus needs to include repeated low level exposures (such as weapon systems). |         |
|    | <b>Action:</b> Send dictionary terms from IC to SME presenters for input and additions of modeling terminology.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | SW      |
| 16 | <b>Imperial College – GG</b><br>The work presented by Imperial College has been funded by the Royal British Legion.<br>IC commented that the TBI model doesn’t show a typical blast response and clinical signs as it shows blunt trauma from sports injuries. GG suggested that this is the starting point and can be worked up.<br>RG suggested that the leg model was missing vasculature, muscle, etc. which will modify the bones response to blast.<br>GG confirmed that the model for vehicles does not show the size of blast that will cause injury.                                                                                                                                                                                                                                                                                                                                                                                               |         |
| 17 | <b>Dstl – RF</b><br>RF presented a range of models developed at Dstl.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |         |
| 18 | <b>Dstl – EK</b><br>EK presented the blast poly-trauma animal model developed at Dstl.<br>EK advised that the rates of blood loss will massively affect the physiological response and this will need to be integrated into any modeling.<br>SW commented that there is a group in Europe looking into physiological models as they aren’t really in existence. See <a href="http://www.vph-institute.org/">http://www.vph-institute.org/</a> for more information.<br>EK advised that a “reality” check is required of models in comparison to clinical or experimental data.<br>After the presentation by EK members were taken for a tour of the range and the LA blast arena.                                                                                                                                                                                                                                                                           |         |

## ANNEX C – MINUTES FROM THE HFM-270 PANEL MEETING JULY 2017

|    | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Actions |
|----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| 19 | <p><b>Frazer-Nash – NDH and WP</b></p> <p>NDH gave an overview of the work that takes place in Frazer-Nash.</p> <p>WP gave a presentation about the models developed alongside Dstl.</p> <p>WP advised that approaches used to create ODIN (extension of PALETTE) might be useful for the group to apply to their aggregation of models together into the black box.</p> <p><b>Question:</b> Can the solver code leave Frazer-Nash? (RG)</p> <p><b>Answer:</b> Always possible to make open source if there is a requirement to do so. (WP)</p> <p><b>Question:</b> The blast lung models you refer to, what are they? (EK)</p> <p><b>Answer:</b> Empirical based PI/Bowen curve related to survivability.</p>                                                                                                                                                 |         |
|    | <p><b>Action:</b> Provide a list of Dstl funded models provided by Frazer-Nash.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | WP      |
| 20 | <p><b>Royal Navy and Nottingham University – TS</b></p> <p><b>Question:</b> Will the studies you are completing on CPAP inform the design of a new first aid device / buddy-buddy system as Frazer-Nash have worked with DSA division at Dstl under a CDE call? (NDH)</p> <p><b>Answer:</b> Possibly. (TS)</p> <p><b>Question:</b> Are any other factors (e.g., orthopedic) being taken into account in your model? (IC)</p> <p><b>Answer:</b> Not taken into account. (TS)</p>                                                                                                                                                                                                                                                                                                                                                                                |         |
| 21 | <p><b>Discussion</b></p> <p><b>Question:</b> How do we future proof models and make sure that they aren't used outside of their bounds? (EK)</p> <p><b>Answer:</b> You could provide a fidelity report (parametric validity form will accompany all models) and indicators for TRLs. (WP)</p> <p><b>Question:</b> How do you assess TRL? (RG)</p> <p><b>Answer:</b> For ODIN it was assessed for the purpose of the model. It would be a good idea to include a warning to the user when they are using it outside the bounds of the scope. (WP)</p> <p><b>Question:</b> How easy is it to integrate models using different codes or operating systems?</p> <p><b>Answer:</b> It isn't impossible (it would require multiple APIs) but it is easier if they are all in the same language, it might not take much to re-code models into the same language.</p> |         |

|  | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Actions |
|--|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
|  | <p><b>Question:</b> Is there an industrial standard for TRLs? (EK)</p> <p><b>Answer:</b> NASA TRL is a good place to start or DoD. (ANM)</p> <p>Suggestion from RG that the NASA ones could be repurposed for the working group's purpose. Post meeting note FGE (ANM) could provide information regarding a 'model maturity framework'.</p> <p>ML advised that the US process is V, V and A (verification, validation, and accreditation) and accreditation will be for use in a very specific application.</p> <p>In the software industry validation and verification mean something else;</p> <p>Validation = requirements are right.</p> <p>Verification = does the software address the requirements (MP).</p> <p>Validation might not be possible in some areas as experimental/clinical data might not be available.</p> <p>MP questioned if the level of granularity is required as a question in the questionnaire. IC suggested that it depends on the question and the HFM-270 needs to advise the modelers and not the other way around.</p> <p>ALM suggested that you need to give the modelers a broad boundary so that they can fix it, otherwise if you are too specific then it will become impossible.</p> <p>NDH suggested that the focus should possibly be on short, mid, and long term aims with an architect overseeing the coordination of the model. The architectural principles should be established from the beginning. (WP)</p> <p>WP advised that it might be best to start with an abstract interface first and take two/three models to roadmap and see if they work. A step by step process would be best from their experience.</p> <p><b>Question:</b> How do you cope with amalgamated uncertainty? (EK)</p> <p><b>Answer:</b> No uncertainty in engineering models. However, no reason why you can't start from scratch and add in codes to include uncertainty. (WP)</p> <p>ALM advised that it is very difficult to do uncertainty of each element or model but not impossible, best established up front.</p> <p><b>Question:</b> Would funding be available from NATO to take on support to this work? (NDH)</p> <p><b>Answer:</b> Never say never, might be available indirectly to address the gaps in modeling capability. (ML and RG)</p> <p>Need to be open to possible commercial use or running and maintenance that will be involved in running the "black box".</p> <p>SMEs advised the HFM-270 that the assessment criteria looked good but the derivation data was missing (that you use to verify the model against).</p> |         |

## ANNEX C – MINUTES FROM THE HFM-270 PANEL MEETING JULY 2017

|    | Day 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Actions |
|----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| 22 | <p><b>Discussions</b></p> <p>EK raised the subject of publishing reports from HFM-234. EK has spoken with the Editor of the blast supplement in the Journal of Royal Army Medical Corps (JRAMC) and he is keen to include the output from the HRM234 working group. The editor has requested a 2,000 word summary of for each report to be included in the printed version of the Journal by the end of July/beginning of August. Access to the full reports will be via the online Journal.</p> <p>ML advised that the Office of the Secretary of Defense has approved the reports from HFM-234<sup>i</sup>. The final document will be available on the Science Connect website under the HFM-270 folder next week. This is a pre-release copy.</p> <p><b>Question:</b> Will others be able to have a copy of this? (IC)</p> <p><b>Answer:</b> It will be public release as it is an unclassified document. (RG and ML)</p> <p>Stephen Bjarnason (Canada) has agreed to make any changes required to the Guidelines for Reproducing Blast Exposures in the Lab.</p> <p><b>Question:</b> Does anyone have a possible back up paper that could be used in the Supplement? (EK)</p> <p><b>Answer:</b> Suggestion that a summary of the final report is submitted to go with the other 4 document or it will look disjointed. (ML)</p> <p><b>Question:</b> How to best do the author list? (DB)</p> <p><b>Answer:</b> All agreed that those who put in the main efforts should be listed as the first, second, third and last authors with the rest of the members listed in between in alphabetical order (with an asterisk to denote that they are HFM-234 working group members). The order of the main effort authors will be discussed amongst those main effort parties.</p> <p>Main efforts for each area agreed as follows:</p> <p>Dictionary of Blast Injury Terms; IC, MP, SW, EK</p> <p>Guidelines for using Animal Models in Blast Injury Research; SW, EK, MR, IC</p> <p>Guidelines for Conducting Epidemiological Studies of Blast Injury; RG, IC, DB</p> <p>Guidelines for Reproducing Blast Exposures in the Lab; Stephen Bjarnason, Tyson Josey, Simon Ouellet, Lucy Martineau, IC</p> <p>TS's paper briefed in the presentation on day two could be included in the publications. EK will ask if a first draft can be shared amongst the NATO group as it will also be part of the supplement.</p> <p>EK listed the papers already confirmed for the Supplement. It is still possible to include more papers and RG could include his paper if EK can agree later delivery with the journal as the delivery of the paper is most likely at the end of August. RG will confirm the scope of the paper by the end of next week (21<sup>st</sup> July).</p> |         |
|    | <b>Action:</b> Email Steve about making changes to Guidelines for Reproducing Blast Exposures in the Lab.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | DB      |
|    | <b>Action:</b> Size down epidemiological studies document to 2,000 words.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | DB      |

|           | <b>Day 3</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | <b>Actions</b> |
|-----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
|           | <b>Action:</b> Size down animal model document to 2,000 words.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | SW             |
|           | <b>Action:</b> Size down dictionary document to 2,000 words.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | IC             |
|           | <b>Action:</b> Confirm above actions by email and authors of each paper.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | DB             |
|           | <b>Action:</b> Write summary of final report.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | ML and RG      |
|           | <b>Action:</b> Check with Jeff if a summary of the final report would be acceptable.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | EK             |
|           | <b>Action:</b> IC to confirm authors of Guidelines for Reproducing Blast Exposures in the Lab via email.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | IC             |
|           | <b>Action:</b> Provide a list of likely publications to NATO panel.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | EK             |
| <b>23</b> | <b>Concept – RG</b><br><p>The purpose of the concept work was to test the theory of being able to integrate currently available models into a “black box”. The models weren’t necessarily fit for purpose for the actual “black box” for the HFM-270 group.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                |
| <b>24</b> | <p>Discussion on Assessment Criteria – ML</p> <p>The next two meetings should be used to assess the models for their suitability in the black box, based on the following:</p> <ol style="list-style-type: none"> <li>1) Input.</li> <li>2) Output.</li> <li>3) Validation method and evidence of validation.</li> </ol> <p>DB commented that you may need to categorize the input and output in order to distinguish between models, perhaps on a color basis. You need to know about the data used to develop the model and to validate the model.</p> <p>Boundaries for the original purpose would be useful.</p> <p>Each nation should review the questionnaires received against the agreed spreadsheet (with categories) generated during the meeting. ML will ask for an update at the next teleconference in September. Outcomes of analysis against the spreadsheet will need to be sent to Mat ahead of the November meeting.</p> <p>The criteria were refined, agreed, and collated in a spreadsheet for use by Panel members. An explanation of the spreadsheet is given below.</p> <ul style="list-style-type: none"> <li>• Column A = state the abbreviated name of the model.</li> <li>• Column B = see response to Q6 of questionnaire.</li> <li>• Column C = primary, secondary, tertiary, etc.</li> <li>• Column D = see response to Q15 of questionnaire.</li> <li>• Column E = see response to Q16 of questionnaire.</li> <li>• Column F = see response to Q9 of questionnaire.</li> <li>• Column G = see response to Q24 of questionnaire.</li> </ul> |                |

## ANNEX C – MINUTES FROM THE HFM-270 PANEL MEETING JULY 2017

|    | Day 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Actions |
|----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
|    | <ul style="list-style-type: none"> <li>Column H = see response to Q8 of questionnaire.</li> <li>Column I = see response to Q20 of questionnaire.</li> <li>Columns K-W = see Input / Output within the Framework page 39 of Meeting 2 Summary document. Color Input BLUE and Output GREEN.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |         |
|    | <b>Action:</b> Each nation to provide their spreadsheet results for the questionnaires.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | All     |
|    | <b>Action:</b> Provide CR with a copy of the agreed assessment criteria spreadsheet.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | SW      |
|    | <b>Action:</b> Upload agreed assessment criteria spreadsheet to Science Connect.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | CR      |
| 25 | <p><b>Updates from Working Groups</b></p> <p><b>Dictionary – IC</b></p> <p>IC plans to make a template with the most frequently used terms for blast. This will be sent out to all the questionnaire responders. In addition, the presenters for HFM-270 meetings will be asked for their own list of terms to add in. SW/EK/IC will come up with a simple 1 page of terminology to be sent around members before being sent to questionnaire responders (by the end of August).</p> <p><b>Publications</b></p> <ol style="list-style-type: none"> <li>1) Review article/overview of available models by DB.</li> <li>2) Methodology for the way to assess models available.</li> </ol> <p><b>Question:</b> Is a systematic review required of available models in the area of blast as this is the most robust way of completing a search for all available models? (EK)</p> <p><b>Answer:</b> All suggested that this might be useful. DB has a contact in the German Army that might be able to do a quick looksee to determine the scope of a Systematic Review.</p> <p><b>Question:</b> Should we go back to the model developers that responded to the questionnaires and ask for their published papers relating to those models? (CR)</p> <p><b>Answer:</b> All agreed yes.</p> <p><b>TAP</b></p> <p>Latest information was that ABa was to go to RG and ML for the format of the HFM-270 working group.</p> |         |
|    | <b>Action:</b> Check all terms used in the assessment criteria spreadsheet are in the dictionary template document.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | IC      |
|    | <b>Action:</b> Check with contact at German Army to see if they can complete a systematic review “looksee” of available models in the blast area.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | DB      |
|    | <b>Action:</b> Go back to questionnaire responders and ask for published papers on their models.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | All     |
|    | <b>Action:</b> Provide Steve Bjarnason with the information on the HFM-234 set up.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | RG      |
|    | <b>Action:</b> Provide list of contact details for each member on Science Connect website.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | CR      |
| 26 | <p><b>Date of Next Meeting</b></p> <p>7 – 9th November 2017 – TNO, Rijswijk, Netherlands</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |         |

| Action | Description                                                                                                                                                    | Person    |
|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| 1      | Send a copy of the questionnaire responses to CR.                                                                                                              | All       |
| 2      | Upload all questionnaire responses to a separate area of the Science Connect website.                                                                          | CR        |
| 3      | Highlight terms used in the questionnaire so that they can be added into the dictionary terms.                                                                 | All       |
| 4      | Upload all presentations onto Science Connect.<br>Email presentations held by Dstl to CR.                                                                      | CR<br>SW  |
| 5      | UK to include burn models. Ask NIHR if they have any models.                                                                                                   | SW and EK |
| 6      | Contact Amal about the missing model from the list (briefed at MTBI)                                                                                           | MP        |
| 7      | USA to contact France to resolve comms issues.                                                                                                                 | IC and RG |
| 8      | Send spreadsheet of papers to CR.                                                                                                                              | DB        |
| 9      | Send out spreadsheet of papers to all members.                                                                                                                 | CR        |
| 10     | Include assumptions in assessment criteria.                                                                                                                    | HFM-270   |
| 11     | Include micro or meso or macro level in assessment criteria.                                                                                                   | HFM-270   |
| 12     | Include how the model is being (is someone else using the model ‘in anger’) used in assessment criteria.                                                       | HFM-270   |
| 13     | Include input and output in assessment criteria.                                                                                                               | HFM-270   |
| 14     | Include any specific unique test devices needed to feed into the model (boundaries of the input) in the assessment criteria.                                   | HFM-270   |
| 15     | How “generalizable” the model is should be included as an assessment criterion. This will show whether or not the model can be adapted to the blast framework. | HFM-270   |
| 16     | Availability of the model should be included as an assessment criterion (no commercial restrictions to use).                                                   | HFM-270   |
| 17     | Experience required to use the model should be included in the assessment criterion.                                                                           | HFM-270   |
| 18     | Finalize the model criteria on day 3.                                                                                                                          | HFM-270   |
| 19     | Send dictionary terms from IC to SME presenters for input and additions of modeling terminology.                                                               | SW        |
| 20     | Provide a list of Dstl funded models provided by Frazer-Nash.                                                                                                  | WP        |
| 21     | Email Steve about making changes to Guidelines for Reproducing Blast Exposures in the Lab.                                                                     | DB        |
| 22     | Size down epidemiological studies document to 2,000 words.                                                                                                     | DB        |
| 23     | Size down animal model document to 2,000 words.                                                                                                                | SW        |

## ANNEX C – MINUTES FROM THE HFM-270 PANEL MEETING JULY 2017

| Action | Description                                                                                                                        | Person    |
|--------|------------------------------------------------------------------------------------------------------------------------------------|-----------|
| 24     | Size down dictionary document to 2,000 words.                                                                                      | IC        |
| 25     | Confirm above actions by email and authors of each paper.                                                                          | DB        |
| 26     | Write summary of final report.                                                                                                     | ML and RG |
| 27     | Check with Jeff if a summary of the final report would be acceptable.                                                              | EK        |
| 28     | Confirm authors of Guidelines for Reproducing Blast Exposures in the Lab via email.                                                | IC        |
| 29     | Provide a list of likely publications to NATO Panel.                                                                               | EK        |
| 30     | Each nation to provide assessments of their questionnaires using agreed assessment criteria spreadsheet.                           | All       |
| 31     | Provide CR with a copy of the agreed assessment criteria spreadsheet.                                                              | SW        |
| 32     | Upload agreed assessment criteria spreadsheet to Science Connect.                                                                  | CR        |
| 33     | Check all terms used in the assessment criteria spreadsheet are in the dictionary template document.                               | IC        |
| 34     | Check with contact at German Army to see if they can complete a systematic review “looksee” of available models in the blast area. | DB        |
| 35     | Go back to questionnaire responders and ask for published papers on their models.                                                  | All       |
| 36     | Provide Steve Bjarnason with the information on the HFM2-34 set up.                                                                | RG        |
| 37     | Provide list of contact details for each member on Science Connect website.                                                        | CR        |

## **Annex D – MINUTES FROM THE HFM-270 PANEL MEETING NOVEMBER 2017**

### **D.1 MEETING #4, 7 – 9 NOVEMBER 2017, TNO RIJSWIJK, THE NETHERLANDS**

HFM-270 (RTG) “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats”.

**Meeting called by** Michael J. Leggieri, Jr.

**Date:** 7<sup>th</sup> to 9<sup>th</sup> July 2017

**Note taker** Marieke Verheijden (TNO) / Tim Westerhof (TNO)

| <b>ATTENDEES</b>                          |                                  |
|-------------------------------------------|----------------------------------|
| <b>Members</b>                            |                                  |
| Mr. Michael Leggieri (Chair) (USA) (ML)   | Mr. Mathieu Philippens (NL) (MP) |
| Dr. Raj Gupta (USA) (RG)                  | Dr. Mårten Risling (SWE) (MR)    |
| Dr. Amit Bagchi (USA) (ABa)               | Dr. Thomas Sawyer (CAN) (TS)     |
| Dr. Dan Bieler (DEU) (DB)                 | Dr. Mattias Skold (SWE) (MS)     |
| Dr. Tomer Erlich (ISR) (TE)               | Dr. Sarah Watts (UK) (SW)        |
| Dr. Axel Franke (DEU)                     |                                  |
| <b>Observers</b>                          |                                  |
| Dr. Charmaine Richman (USA) (CR)          | Mr. Tim Westerhof (NLD) (TW)     |
| Dr. Marieke Verheijden (NLD) (MV) (7 Nov) |                                  |
| <b>SMEs</b>                               |                                  |
| Mr. Ricolt Boeschoten (NLD) (RB)          | Mr. Yoeng Sin Khoe (NLD) (YSK)   |
| Dr. Hans van Dommelen (NLD) (HvD)         | Mr. Bart de Jong (NLD) (BdJ)     |
| Mr. Wim van den Heuvel (NLD) (WvdH)       | Dr. Jimmy Verreault (NLD) (JV)   |
| <b>Apologies</b>                          |                                  |
| Dr. Amal Bouamoul (CA) (ABo)              | Col (Dr.) Philippe May (FR) (PM) |
| Dr. Ibolja Cernak (CAN) (IC)              | Mr. Thanyani Pandelani (SA) (TP) |
| Mr. Atil Erdik (TR) (AE)                  | Dr. David Reinecke (SA) (DR)     |
| Dr. Pinar Huri (TR) (PH)                  | Dr. Levent Turhan (TR) (LT)      |
| Dr. Emrys Kirkman (UK) (EK)               | Dr. Avraham Yitzhak (ISR)        |
| Mr. Ilker Kurtoglu (TR) (IK)              |                                  |

## ANNEX D – MINUTES FROM THE HFM-270 PANEL MEETING NOVEMBER 2017

|   | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Actions |
|---|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| 1 | <p><b>Opening address and welcome</b></p> <p>Opening address and welcome to TNO Defence, Safety and Security by Dr. Louk Absil, Director of TNO's Force Protection Program (presentation 1). Dr. Louk Absil gave an introduction to TNO and stated why the work of the HFM270 is relevant.</p> <p>Next Mike Leggieri welcomed the group to the HFM-270 Meeting 4. He stated the scope and objectives of the group, as well as the objectives of Meeting 4 (presentation 2). Furthermore, the agenda was confirmed.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |         |
| 2 | <p><b>Status</b></p> <p>Mat Philippens provided an overview of the progress of HFM-270 and the results of the previous three meetings (presentation 3).</p> <p>Based on the discussion following Mat's presentation, the TAD objectives (as noted in the minutes of the kick-off meeting) were rephrased as follows:</p> <ol style="list-style-type: none"> <li>1) Identify elements of the computational model Framework.</li> <li>2) Develop screening tool for inclusion of models in the Framework.</li> <li>3) Identify existing, ongoing, and planned models, databases, and injury criteria for each element.</li> <li>4) Use of the screening tool to populate models into the framework.</li> <li>5) Identify gaps where no suitable models exist.</li> <li>6) Identify the gaps in integrating the models.</li> <li>7) Demonstrate the Framework by running example scenarios.</li> </ol> <p>The assessment criteria (excel spreadsheet) was renamed as the screening tool.</p> <p>Another point that was left for discussion at a later point was whether 'open' accessibility should be a screening criterion? Or possibly just the possibility to have ones' data processed by someone else in the group having access to the models.</p> <p>One of the next steps will be to develop more specific assessment criteria, so when populating the framework, the gaps will become obvious. This may be an iterative process.</p> <p>The discussion continued as to what was meant by validating the framework and how a framework could be validated. Differentiation was made between validation of the framework and validation of each model. The 7<sup>th</sup> TAD objective was changed to "Demonstrating the Framework."</p> |         |
| 3 | <p><b>Action items and minutes from previous meetings</b></p> <p>Dr. Raj Gupta reviewed the action items from the previous meeting:</p> <ul style="list-style-type: none"> <li>• Actions 1 and 2 were completed.</li> <li>• Action 3 is ongoing.</li> <li>• Actions 4 through 13 were completed.</li> <li>• Action 14: postponed to the next meeting, specific criteria for input needs to be developed.</li> <li>• Actions 15 through 18: completed.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |         |

|            | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Actions |
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|            | <ul style="list-style-type: none"> <li>Action 19: ongoing.</li> <li>Action 20: unknown.</li> <li>Action 21 through 26: Almost all documents have been submitted to the journal. Raj will send the final document after his return.</li> <li>Action items 27 through 29 were completed.</li> <li>Action item 30: This will be discussed further during Meeting 4.</li> <li>Action item 31 and 32: completed.</li> <li>Action item 33: unknown.</li> <li>Item 34: review status is discussed in this meeting on the second day.</li> <li>Item 35: completed, the available papers were uploaded on science connect.</li> <li>Item 36: Completed.</li> <li>Item 37: Completed. The list will also be updated during the current meeting. Tomer Erlich has not been able to connect to the Science connect website. Dr Charmaine Richman will help solving this.</li> </ul> <p>There were no other comments on the action items or minutes.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |         |
| <b>4</b>   | <b>Update on computational models and assessments by participating nations</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |         |
| <b>4.1</b> | <p><b>USA</b></p> <p>Dr. Raj Gupta started with a list of additional questions for the models. By reviewing the information in the questionnaires that were completed, the following additional questions may be required for populating the models in the framework:</p> <ol style="list-style-type: none"> <li>1) Are there any current users of the model? If yes, who is the POC?</li> <li>2) Is the computational model being actively updated and maintained? (software code, current state of the art, ...)</li> <li>3) How are assumptions and constraints for the module captured?</li> <li>4) Is the model based upon deterministic (cause) or stochastic (random probability) concepts?</li> <li>5) Is there a license fee associated with the computational models use?</li> <li>6) Additional software solutions, such as databases, visualization software, numerical solvers, etc.</li> <li>7) Installation of computational models in other organizations.</li> <li>8) How does the computational model execute?</li> <li>9) Is the computational model designed to be federated with other computational models to be executed within such a federation? (Or is it designed to stand alone, without possibility to be integrated with other models?)</li> </ol> <p>Dr. Raj Gupta continued with a discussion of the US models listed in the screening tool:</p> <ol style="list-style-type: none"> <li>10) Information on each individual model was presented briefly.</li> </ol> |         |

## ANNEX D – MINUTES FROM THE HFM-270 PANEL MEETING NOVEMBER 2017

|     | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Actions |
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|     | <p>Based on the models that were presented, some discussion on the scope of the models took place. It was concluded that the scope is broad, focusing on all injuries (including for example infections, blood transfusion, etc.).</p> <p>A difference was noted between output (which any model will render) and outcome (which needs to be relevant to the scope of the group).</p> <p>The discussion continued on would it be worthwhile to (within countries) ‘validate’ the assessment in the screening tool by an independent other? To see if there are differences in interpretation and if so, to discuss these differences and come to a conclusion. Several members had already done this, and it was useful.</p>                                                                                                                                                                                                                                |         |
| 4.2 | <p><b>Israel</b></p> <p>Dr. Tomer Erlich presented with Prof Yoram Epstein and Prof Amit Gefen (via Skype) their ongoing work on the development of a computational modeling framework which facilitates evaluation of protective gear with regards to a variety of non-penetrating and/or thermal threats (presentation 4). They presented three examples:</p> <ol style="list-style-type: none"> <li>1) A 3D head model, that can be combined with a protective helmet;</li> <li>2) The same 3D head model with eye protection against combusting fuel; and</li> <li>3) Example of a work in progress: a torso model.</li> </ol> <p>The geometry of the models is based on CT/MRI data of the visible human project. The goal of the model is to predict injury.</p> <p>The models presented were entered into the questionnaires for Israel and the information was submitted to Dr. Charmaine Richman.</p>                                              |         |
| 4.3 | <p><b>USA (continued)</b></p> <p>Dr. Charmaine Richman continued with the US models, presenting them briefly. The information in screening tool was based only on the information that was provided to the team by the owners/authors of the model. The USA input was verified by discussing possible differences in opinion until consensus was reached.</p> <p>Discussion took place around models that may or may not be within the scope of the group’s current effort (i.e., blast-related models). Also, the relevance of models regarding treatment of blast-related injuries for the current scope was discussed (i.e., whether this fits in model Y).</p> <p>Initially one change was made to the information on the MBTS model in the excel sheet. Subsequently some changes were also made to the models. It was also agreed on that for multiple models the information provided in the questionnaire is insufficient to screen the models.</p> |         |
| 4.4 | <p><b>Canada</b></p> <p>The excel sheet was not ready in time to be presented during this meeting.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |         |
| 4.5 | <p><b>Germany</b></p> <p>Germany presented their progress on systematic review of computational blast models in literature on day 2.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |         |

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| <b>4.6</b> | <b>Netherlands</b><br><p>Tim Westerhof provided an update on the Dutch computational blast models. The relevant models from TNO's Department of Explosions, Ballistics, and Protection are currently included in the sheet. Models from other departments (such as: protection against CBRN threats) are not yet included in the excel sheet. This is possible in the future.</p> <p>Information on each individual model was presented briefly. Based on the discussions, some additional information was added to the sheet and some changes were made.</p>                                            |         |
| <b>4.7</b> | <b>Sweden</b><br><p>Dr. Mårten Risling provided an update on the Swedish computational blast models. Sweden does not have many models reported in the excel sheet yet. They are still waiting for additional response from other organizations, which should start coming in any time soon now that the relevant person has come back from maternity leave.</p> <p>A brief presentation was given on the work of Jacobo Antona-Makoshi's doctorate thesis entitled: "Traumatic Brain Injuries: Animal Experiments and Numerical Simulations to Support the Development of a Brain Injury Criterion".</p> |         |
| <b>4.8</b> | <b>UK</b><br><p>Dr. Sarah Watts continued with an update of the UK models. Most models presented in the table are not from Dstl and therefore the information in the excel sheet is subject to interpretation of the data in the questionnaire. Also, in some cases, sufficient information to screen the model was missing. Information on each individual model was presented briefly. Based on the discussion some changes will be made to the sheet (e.g., GRIM and EAGLE models).</p>                                                                                                               |         |
|            | <p>Some of the models mention a certain body part or organ as the topic of study. Further specification is necessary in these cases. For example: is it lung tissue, is it a lung, is it the thorax, is it a lung in a torso? This may differ per model but was not yet consistently specified in the excel sheet.</p>                                                                                                                                                                                                                                                                                   |         |
|            | <p><b>Action:</b> go back to the excel sheets and makes changes based on today's discussions.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | HFM-270 |

|            | Day 2                                                                                                                                                                                                                                                                                                                                                                                                    | Actions |
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| <b>5</b>   | <b>Introduction</b><br><p>The introduction of the HFM-270 work for the SMEs was postponed to the afternoon discussion, since not all SMEs were present in the morning.</p>                                                                                                                                                                                                                               |         |
| <b>6</b>   | <b>Local symposium computational modeling</b>                                                                                                                                                                                                                                                                                                                                                            |         |
| <b>6.1</b> | <b>COMbined Metal Plywood ASSessment (COMPASS) – Ricolt Boeschoten</b><br><b>Abstract:</b><br><p>Defensive Aid Suites (DAS) consists of sensors and countermeasures to defeat incoming threats like Anti-Tank Rockets (ATR) and Anti-Tank Guided Missiles (ATGM). A Hard Kill DAS (HK-DAS) directly impacts the incoming threat with the aim to avoid a hit or to reduce its penetration capability.</p> |         |

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|     | <p>STANAG 4686 “Procedures for the Assessment of DAS for Land Vehicles “and the underlying Allied Engineering Procedures (AEP) aim at providing the foundation to analyze and evaluate DAS for land vehicles in a standardized way. AEP-62 Volume 5 “DAS event collateral damage” describes the methodology to assess collateral damage by fragments and blast effects on the unprotected human caused by a so-called HK-DAS event.</p> <p>The COMbined Metal and Plywood ASSESSment (COMPASS) tool has been jointly developed by the Netherlands and United States for assessing risk of injury to dismounted personnel located around a HK-DAS event. COMPASS automates the assessment of collateral damage by fragments on the unprotected human as described in Volume 5.</p> <p><b>Q&amp;A:</b></p> <p>Motivation for the used types of witness plates? <i>Plywood is traditionally used starting in early 80s.</i></p> <p>What type of fragment are included? <i>16 mg – 80 g</i></p>                                                                                                                                    |         |
| 6.2 | <p><b>Modeling IEDs – The TNO toolbox – Yoeng Sin Khoe</b></p> <p><b>Abstract:</b></p> <p>The TNO toolbox for modeling and analyzing consequences of IEDs aims to address the complete chain of events. This chain starts at the characterization of the threat.</p> <p>Through experimental techniques and modeling tools, 3 main threat mechanisms are described. These are the fragmentation (describing the direction and distribution), the overpressure (magnitude) and secondary effects (e.g., glass, sand, and grit).</p> <p>The next step in the chain is to combine the impact conditions and the effectiveness of PPE. This results in physical damage on the human body and an injury assessment.</p> <p>Finally, the last step in the chain uses the injury assessment as a basis to perform a functional assessment. For the fragment threat, this complete chain is implemented in TNO’s ICARUS tool. For overpressure injury, separate models (e.g., Bass, Axelsson) are applied. Our objective is to gain insight in the effectiveness of PPE and the consequences of injury for functional performance.</p> |         |
|     | <p><b>Q&amp;A:</b></p> <p>Do you have medical experts involved for injury assessment? <i>TNO has contacts with medical staff of the Dutch MoD but also through international cooperation.</i></p> <p>For the ICARUS tool, are combined loads of fragments and overpressure simulated? <i>No, it is done separately, we are working on it. The model is at the moment good for single hits, but multiple hits are not possible (yet).</i></p> <p>How can you validate such full chain of models? <i>No validation possible as it requires test series capturing every part of the model, verification is the best that can be done.</i></p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |         |
| 6.3 | <p><b>NLD Occupant Modeling of Vehicle IED Underbelly Blast – Tim Westerhof</b></p> <p><b>Abstract:</b></p> <p>Aside from detailed FE models, TNO also uses fast running engineering models to simulate the vehicle and occupant response after a military vehicle underbelly blast event.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |         |

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|     | <p>For the vehicle response, the vehicle global motion model is used, which simulates the 3D global motion of a rigid body due to IED loading. This is a loading model and does not include injury.</p> <p>To simulate the occupant response, the lumbar spine model is used to assess injury risk for 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> percentile anthropometries. The model is a MDOF system, derived from the Madymo human body model.</p> <p>These models may have a low fidelity but provide first order answers for the users and fill a gap. How do such models fit into the framework?</p> <p><b>Q&amp;A:</b></p> <p>The compression response of the lumbar spine is an order of magnitude larger than the IED loads, why is this? <i>The IED loads the lumbar spine through contact interfaces such as tissue, seat cushioning, seat frame. These damp out the loading on the lumbar spine.</i></p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |         |
| 6.4 | <p><b>FE Analysis to Assess the Protective Capabilities of Helmets Against Mild Blast Loads – Mat Philippens</b></p> <p><b>Abstract:</b></p> <p>The BI<sup>2</sup>PED physical headform developed by DRDC was evaluated in a shocktube study. The BI<sup>2</sup>PED consists of a skull covered by a soft skin. A gel type brain simulant is floating in water in the skull. Pressure sensors embedded in the brain simulant and pressure sensors as well as strain gauges on the outer surface of the skull provide the mechanical response of skull and brain when exposed to a shockwave. The bare headform, and headform with a standard open and a full-face helmet was exposed to a Friedlander type of shockwave with static peak pressures of 70 and 160 kPa and positive phase of 10 ms. Further study of the transition of the air shock into the headform was performed using a Finite element model of the BI<sup>2</sup>PED also provided by DRDC. It was concluded that three phases are observed in the pressure response of the brain. Where the largest pressure is seen during the first phase on the bare headform. A helmet reduces the peak pressure in the first phase but increases the peak pressures in the third phase. The air shockwave is transferred to the brain through modal deformation of the skull. Initially by a high order mode which develops into a first order modal deformation in the third phase.</p> <p>The increase in peak pressure by application of a helmet is caused by a sudden acceleration of the skull which impacts the floating brain and excites the brain simulant in its modal resonance frequency, which by coincidence is close to the first order modal frequency of the skull. It is not known if the model brain response of the surrogate brain will also occur in the real human brain. Conclusion: A helmet shielding the skull decreases the peak pressure in the first phase of the pressure response but intends to increase the pressure in the third phase. However peak pressures with helmet are significantly lower than without helmet. The modal frequencies of skull and brain are significant in the load transfer from the shockwave to the brain and need to be incorporated in any blast – tbi head surrogate. The latter should also be mounted without restraints or on a neck which allows initial motion to enable inertial loading of the brain.</p> <p><b>Q&amp;A:</b></p> <ul style="list-style-type: none"> <li>Should pressure sensor in BiPED shock tube trials give a mirror result if orientation of sensors is mirrored? <i>No static vs dynamic pressure and side on pressure.</i></li> </ul> |         |

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|            | <ul style="list-style-type: none"> <li>What pressure do you get when you applied only rigid body motion? <i>Will be discussed later in presentation</i></li> <li>What is the displacement occurring by the pressure load? <i>15 – 20 mm</i></li> <li>Is there a vibration of the brain in the vibration of the skull? <i>Yes</i></li> <li>How to validate for actual human? <i>Simon Ouellet (DRDC) has done this with PMHS and published.</i></li> <li>How to check for cavitation due to under pressure? <i>Possible in BiPED model, but not real human.</i></li> <li>What material is used in the BiPED test model? <i>Silguard, similar to gelatin.</i></li> <li>What are expected differences between tethered or free brain in skull? <i>Water cannot pull on brain, only compress. Air bubble is present in BiPED model otherwise it would pop open. The air bubble on top is critical and functions as a cushion.</i></li> <li>Can Silguard be used for brain? <i>Sufficient for modeling.</i></li> </ul>                                                                                                                                                                                                                |         |
| <b>6.5</b> | <p><b>Numerical Modeling of Blunt Head Impact – Mat Philippens</b></p> <p><b>Abstract:</b></p> <p>The injury risk of blunt impacts to the head can be assessed by the application of Finite Element models. There are models available which are validated for Diffuse Axonal Injury. Two methods to assess the injury risk for combat helmet behind armor blunt trauma are presented, and a method to assess the DAI risk for inertial loads of the head by for instance vehicle crashes, impact to objects or a hard floor, etc.</p> <p>The first BABT method applies contact forces on the skull surface to a FE human head model. The forces are measured by a head surrogate equipped with force load cells. A second method applies the 3D back face deformation of a combat helmet induced by a bullet impact to a FE head model. The first method showed that there is significant risk that the tolerance for under pressure is exceeded due to the pressure wave induced by the impact of the skull. The second method shows that the DAI injury risk is highly sensitive to the stand-off of the helmet by a stand-off variation study. A difference of 1 mm in stand-off can change the DAI risk from 6 to 86 %.</p> |         |
|            | <p>Drop tests equivalent to crash helmet tests performed on four different helmet configurations show that the DAI risk exceeds 63 % and goes up to 100 % for most cases for realistic impact velocities of 4.5 and 5.5 m/s. DAI gives a higher resolution on consequences like unconsciousness than traditional injury criteria like Head Injury Criterion or peak g.</p> <p><b>Q&amp;A:</b></p> <p>What is the basis for axonal strain? <i>Real axonal, model is based on brain geometry and several tissues.</i></p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |         |

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| 6.6 | <p><b>Micromechanics of Traumatic Brain Injury – Dr. Hans van Dommelen</b></p> <p><b>Abstract:</b></p> <p>A wide range of length scales from several micrometers at the cellular level to several decimeters at the head level are concerned with the development of TBI. Macro-level FE head models often predict the response of the head based on a geometrically homogeneous macro-level anatomical structure. These models often ignore the effect of the heterogeneous substructure of the brain. This work developed and combined a macro-, meso- and micro-level model of the head.</p> <p>A nonlinear viscoelastic model has been developed to describe the mechanical response of brain tissue. The model is validated using the mechanical behavior of brain tissue in both shear and compression. This model is used with a macro-level finite element head model to systematically investigate the consequences of incorporating constitutive nonlinearities for the assessment of injury.</p> <p>To investigate the mechanical influences of the convolutions of the cerebral cortex during a mechanical load on the head, meso-level models connecting the head level to the tissue level have been developed. Stress concentrations with respect to the homogeneous reference situation have been quantified.</p> <p>A microstructural model bridges the tissue level to the cellular level. At this level, a model has been developed that is based on pathological observations of local axonal injury in case of Diffuse Axonal Injury. The results indicate that cellular level heterogeneities have an important influence on the axonal strain, leading to an orientation and location dependent sensitivity of the tissue to mechanical loads.</p> <p><b>Q&amp;A:</b></p> <ul style="list-style-type: none"> <li>• Is CSF used in the model? <i>Yes, but not as fluid material.</i></li> <li>• Porcine brain tissue is used within 6 hours after extracting to make sure shear modules has not changed.</li> </ul> |         |
| 6.7 | <p><b>Blast Source Modeling – Jimmy Verreault</b></p> <p><b>Abstract:</b></p> <p>Several TNO simulation modeling strategies, best practices as well as examples of previous studies are presented for the following topics:</p> <ul style="list-style-type: none"> <li>• Air explosion, conventional warheads.</li> <li>• Fragmentation of warheads (natural fragmentation, pre-fragmented warheads).</li> <li>• Fragment impact on armor systems (ballistic protection improvements, prediction of pressure load).</li> <li>• Air blast (explosion in urban environment).</li> <li>• Other examples (MH-17, muzzle blast from a ship gun).</li> <li>• Air explosion, unconventional warhead (afterburn in internal explosions, thermobaric explosives, BLEVE).</li> <li>• Mine blast loading on vehicles.</li> <li>• Under-water explosions.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |         |

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|     | <b>Q&amp;A:</b> <ul style="list-style-type: none"> <li>Are these loading models used with injury models? <i>Yes, for vehicles and ship studies currently available injury models are used. There are no direct injury models developed at Structural Dynamics.</i></li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |         |
| 6.8 | <b>Armored Vehicle and Occupant Modeling Under Mine Blast Loading – Bart de Jong</b><br><b>Abstract:</b><br><p>Mine blast can heavily damage armored vehicle and can cause injury to the occupants of the vehicle. TNO has developed a method to model structural damage and occupant injury. This method consists of 3 different models which are fully coupled in the final simulation.</p> <p>The first model is the TNO mine blast subroutine. The model is based on the Westin model and applies a triangular time pressure profile on the bottom of the vehicle. Extensive test campaigns have been established to calibrate this model.</p> <p>The second model consists of the structural part, this is modeled in LS-Dyna. The structure of the armored vehicle is modeled in detail in LS-Dyna. Care is taken to model parts which play a key role in the blast transfer, such as the floor and the chair system.</p> <p>The final model is Madymo, which is used to model the occupant response. Madymo makes use of a multi-body system to represent the occupant of the vehicle. Chance of injury is predicted based on failure criteria such as HIC and DRI.</p> <b>Q&amp;A:</b> <ul style="list-style-type: none"> <li>Are longer solution times possible? <i>Yes, when you are willing to wait longer. 0.5 s takes 6 days to solve for full vehicle with Madymo ATD.</i></li> <li>Where do the Madymo injury limits originate from? <i>HFM groups such as 093, 198, 271, automotive injury criteria, etc.</i></li> <li>Are soldier worn sensors being used in theatre, such as accelerometers on vehicle occupants in UBB incidents? <i>No, however there are examples of blast gauges which contain accelerometers and pressure gauges. However better signal interpretation and how to use the sensors are critical the get useful data.</i></li> <li>Is the mine blast model linked to the vehicle model and human model? <i>Yes, at current state they are already connected.</i></li> <li>How can you validate your models? <i>This must be done for each scenario separately with experimental data and learn from there. There are many differences for each model, vehicle + geometries.</i></li> </ul> |         |
| 6.9 | <b>SME Discussion</b><br><p>The discussion started with defining the scope of the framework. The scope of the framework is very broad and is applicable to multiple scenarios and multiple threats. A possible outcome could be that the first version of the framework only works for a few scenarios, but we can build from there to include other scenarios as well.</p> <p>The discussion continued with the question as to who would use the framework? It might be mostly applicable at a political/management level, and not so much for modelers itself since the modelers usually know what is available in their field. The framework can have multiple users.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |         |

|   | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Actions |
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|   | <p>When the framework is filled with models, it should be clear what the limitations are from the models, otherwise it is not possible to know what models are applicable for a future user. Furthermore, model fidelity is not a selection criterion for the framework, the usage of the tool determines the level of required fidelity.</p> <p>Another topic addressed in the discussion by the SMEs is that it is important to speak the same language. For example, some see blast as only overpressure, while it can include more types of threats. This point is acknowledged by the group and is addressed in the dictionary working group.</p> <p>The next topic is the validation of computational models and the framework. The question was raised as to whether there were any standards/references on validating computation models (e.g., ISO standards for automotive industry). If so, the group can use these for the framework. Validation methods which are available are different for each domain. Furthermore, it was discussed as to what the definition of validation was, how well should a model be validated and how should the experiment data match with results of validated computational models. It was not decided if this was within the scope of the current group. It may be that there is no standard way to validate models for the framework due to the diversity in goals of the models. The goal of the model may result in no test data being available for validation.</p> <p>However, in these cases a better understanding of the physics may improve the model validity. Therefore, it is important to identify the POC of the model.</p> <p>The setup of the framework and current work of the group is the starting point. Future work may result in changes of the framework. Suggestion of the SMEs is to start with a specific case for which the framework can be used, since it is difficult to specify details if the goal of the framework is kept too general.</p> |         |
| 7 | <p><b>Systematic literature review</b></p> <p>Dr. Dan Bieler provided an update and the plan of the systematic literature review. The main topics were how and where literature will be searched for the review.</p> <p>The suggested literature databases are Medline, PubMed, Embase and CDSR. However, these are (bio)medical databases. Suggestions are made for additional (national) databases, such as google scholar, conference proceedings (e.g., MABS, PASS), IEEE, Scopus, Springer, ScienceDirect, Bicompendix, TNO literature database and the paper database of Dr. Amit Bagchi.</p> <p>Better results may be achieved if multiple group members perform a search. There is no general database for engineering or physics where everything is included.</p> <p>If the classification of the literature is NATO restricted, abstract may be included. This can be sufficient for the literature review.</p> <p>Search languages will be German and English. Suggestion of the group is to include French.</p> <p>The list of mesh words was discussed and extended. The current mesh words are based on key words found in the literature. It was agreed to categorize the mesh words to the framework and include the terms of the framework as well. Dr. Bieler will send out an update of the mesh words.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |         |

## ANNEX D – MINUTES FROM THE HFM-270 PANEL MEETING NOVEMBER 2017

|  | Day 2                                                                                                                                                                                                                                        | Actions |
|--|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
|  | <p>Two to four independent reviewers are required for the literature review. More reviewers are not allowed for a systematic review.</p> <p>The panel agreed with the presented plan of Dr. Bieler for the systematic literature review.</p> |         |

|    | Day 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Actions |
|----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
|    | <p>The group reformulated some of the TAD objectives for clarification and to prevent future confusion. These were updated to:</p> <ol style="list-style-type: none"> <li>1) Identify elements of the computational modeling Framework.</li> <li>2) Develop screening tool for inclusion of models in the Framework.</li> <li>3) Identify existing, ongoing, and planned models, databases, and injury criteria for each element.</li> <li>4) Use the screening tool to populate models into the Framework.</li> <li>5) Identify gaps where no suitable models exist.</li> <li>6) Identify the gaps of integrating the models within the Framework and formulate recommendations to close the gaps.</li> <li>7) Demonstrate the Framework by running example scenarios.</li> </ol> <p>The intent of the group is not to assess the validity of the models.</p> |         |
| 9  | <p><b>Action items</b></p> <p>The new actions items were discussed, which are listed at the end of this document.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |         |
| 10 | <p><b>TAP working group update – Dr. Amit Bagchi</b></p> <p>Dr. Amit Bagchi acknowledged that the validation and verification of the framework is an important topic. A list of methods to validate models will be useful. The TAP working group will focus on what is required to validate the framework, from engineering, biological and medical points of view. The TAP working group can provide information which will be discussed in a next meeting.</p>                                                                                                                                                                                                                                                                                                                                                                                               |         |
| 11 | <p><b>Dictionary working group update – Dr. Sarah Watts</b></p> <p>No updates, they will be provided at the next teleconference.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |         |
| 12 | <p><b>Publications working group update – Dr. Sarah Watts</b></p> <p>No updates, they will be provided at the next teleconference.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |         |
| 13 | <p><b>Closing words – Mike Leggieri</b></p> <p>Mr. Mike Leggieri thanked the group for their contributions and the hosts for their part on organizing the meeting. The 5<sup>th</sup> meeting will take place in Koblenz, Germany on the 6 – 8<sup>th</sup> March 2018. The agenda will be discussed at the next telcon. The location of the 6<sup>th</sup> meeting has to be confirmed.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |         |
| 14 | <p><b>Date of 5th meeting</b></p> <p>6 – 8th March 2018 – Koblenz, Germany</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |         |

| Action                                       | Description                                                                                                                        | Person                    |
|----------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|---------------------------|
| <b>Meeting 3, May 2017, Dstl Porton Down</b> |                                                                                                                                    |                           |
| <b>3-3</b>                                   | Highlight terms used in the questionnaire so that they can be added into the dictionary terms.                                     | <b>All</b>                |
| <b>3-14</b>                                  | Include any specific unique test devices needed to feed into the model (boundaries of the input) in the assessment criteria.       | <b>HFM-270</b>            |
| <b>3-19</b>                                  | Send dictionary terms from IC to SME presenters for input and additions of modeling terminology.                                   | <b>SW</b>                 |
| <b>3-20</b>                                  | Provide a list of Dstl funded models provided by Frazer-Nash.                                                                      | <b>WM</b>                 |
| <b>3-30</b>                                  | Each nation to provide assessments of their questionnaires using agreed assessment criteria spreadsheet.                           | <b>All</b>                |
| <b>3-34</b>                                  | Check with contact at German Army to see if they can complete a systematic review “looksee” of available models in the blast area. | <b>DB</b>                 |
| <b>Meeting 4, Nov 2017, TNO Rijswijk</b>     |                                                                                                                                    |                           |
| <b>4-1</b>                                   | Fill in models in the spreadsheet of the screening tool before meeting 5 (formerly addressed as assessment criteria).              | <b>TS, AB, IC, TE, MR</b> |
| <b>4-2</b>                                   | Follow up on the screening tool with members who were not present at meeting 4 at TNO. Deadline at the next telcon.                | <b>ML</b>                 |
| <b>4-3</b>                                   | Update the models already filled in the spreadsheet of the screening tool.                                                         | <b>All</b>                |
| <b>4-4</b>                                   | Upload screening tool spreadsheet on Science connect website.                                                                      | <b>All</b>                |
| <b>4-5</b>                                   | Combine all screening tool spreadsheets of all members.                                                                            | <b>SW</b>                 |
| <b>4-6</b>                                   | Send out list of questions which may be required to populate the framework with the models.                                        | <b>RG</b>                 |
| <b>4-7</b>                                   | Review question list of action nr 4 – 6 and add questions if required.                                                             | <b>All</b>                |
| <b>4-8</b>                                   | Send out mesh words for literature review.                                                                                         | <b>DB</b>                 |
| <b>4-9</b>                                   | Provide information how the literature review should be performed at next telcon.                                                  | <b>DB</b>                 |
| <b>4-10</b>                                  | Confirm the location of meeting 6.                                                                                                 | <b>ML</b>                 |



## **Annex E – MINUTES FROM THE HFM-270 PANEL MEETING MARCH 2018**

### **E.1 MEETING #5 –06 – 08 MARCH 2018, KOBLENZ, GERMANY**

HFM-270 (RTG) “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats”.

**Meeting called by** Michael J. Leggieri, Jr.

**Date:** 6<sup>th</sup> to 8<sup>th</sup> March 2018

**Note taker** Dan Bieler (DEU) / Maximilian Völlmecke (DEU)

| <b>ATTENDEES</b>                 |                                  |
|----------------------------------|----------------------------------|
| <b>Members</b>                   |                                  |
| Dr. Raj Gupta (USA) (RG)         | Dr. Sarah Watts (UK) (SW)        |
| Dr. Amit Bagchi (USA) (ABa)      | Mr. Mathieu Philippens (NL) (MP) |
| Dr. Dan Bieler (DEU) (DB)        | Dr. Mårten Risling (SWE) (MR)    |
| Dr. Axel Franke (DEU)            | Dr. Mattias Skold (SWE)          |
| Dr. Emrys Kirkman (UK) (EK)      | Dr. Thomas Sawyer (CAN)          |
| <b>Observers</b>                 |                                  |
| Dr. Sidney Hinds (USA)           |                                  |
| <b>Apologies</b>                 |                                  |
| Dr. Amal Bouamoul (CA) (ABo)     | Dr. David Reinecke (SA) (DR)     |
| Dr. Ibolja Cernak (CAN) (IC)     | Dr. Avraham Yitzhak (ISR)        |
| Dr. Charmaine Richman (USA) (CR) | Mr. Tim Westerhof (NLD) (TW)     |
| Col (Dr.) Philippe May (FR) (PM) |                                  |

|          | <b>Day 1</b>                                                                                                                                                                                                                                                                                                                                                                                | <b>Actions</b> |
|----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| <b>1</b> | <b>Opening address and welcome</b><br>Opening address and welcome to German Armed Forces Hospital by Brigadier General Dr. Norbert Weller, Commander of the German Armed Forces Hospital Koblenz.<br>Next Raj Gupta was bidding the group welcome to HFM-270 meeting 5. Objectives of the group, as well as the objectives of meeting 5 were stated. Furthermore, the agenda was confirmed. |                |
| <b>2</b> | <b>Action items and minutes from previous meeting 4 at Rijswijk, NL</b>                                                                                                                                                                                                                                                                                                                     |                |

## ANNEX E – MINUTES FROM THE HFM-270 PANEL MEETING MARCH 2018

|     | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Actions |
|-----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| 3   | Dr. Raj Gupta reviewed the action items from the previous meeting:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |         |
|     | Fill in models in the spreadsheet of the screening tool before meeting 5 (formerly addressed as assessment criteria). TS, AB, IC, TE, MR                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |         |
|     | Follow up on the screening tool with members who were not present at meeting 4 at TNO. Deadline at the next telcon. ML                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |         |
|     | Update the models already filled in the spreadsheet of the screening tool. All                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |         |
|     | Upload screening tool spreadsheet on Science connect website. All                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |         |
|     | Combine all screening tool spreadsheets of all members. SW                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |         |
|     | Send out list of questions which may be required to populate the framework with the models. RG                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |         |
|     | Review question list of action nr 4-6 and add questions if required. All                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |         |
|     | Send out mesh words for literature review. DB                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |         |
|     | Provide information how the literature review should be performed at next telcon. DB                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |         |
|     | Confirm the location of meeting 6. ML                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |         |
|     | There were no other comments on the action items or minutes.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |         |
| 4   | <b>Discussion in working groups</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |         |
| 4.1 | <b>Dictionary working group – Dr. Emrys Kirkman</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |         |
| 4.2 | <b>Publications working group update – Dr. Dan Bieler</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |         |
| 4.3 | <b>TAP working group– Dr. Amit Bagchi</b><br>Validation of models. Most models refer to 5 – 10 standard papers from 70's to 2010. Amit Bagchi says that most models lack details.<br>S. Hinds says that research can be standardized; often details such as distance body armor is not mentioned in publications. S. Hinds mentions differences in the models of diffuse axonal injury and intracranial hemorrhage.<br>mTBI is there a threshold model for impact on the cranium. Especially for patients who don't fit in the clinical diagnosis of a brain concussion.<br>Amit Bagchi suggests providing standardized models in order to have models for blast injuries. Different models for different types of injuries. |         |
| 4.4 | <b>Systematic literature review update – Dr. Dan Bieler</b><br>Talking about publications, publication on modeling, publication on medical issues<br>PDF suggests checking whether papers are according to the guidelines. DB suggests that guidelines need to be cross checked.<br>Establish “NATO” Guidelines suggested by Hinds, PDF suggests recommendations regarding Blast injury.<br>DB suggests giving them a certain name for the guidelines.                                                                                                                                                                                                                                                                       |         |

|            | <b>Day 2</b>                                                                                                                                                                                                                                                                                                                                   | <b>Actions</b> |
|------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| <b>5</b>   | <b>Local symposium Part 1</b><br><b>What Computational Modeling must achieve – clinical aspects</b>                                                                                                                                                                                                                                            |                |
| <b>5.1</b> | <b>Introduction – facts, figures, and clinical challenges after blast injury</b><br><b>Völlmecke</b><br>A computational model needs to be able to describe and assess the link between injury and needed treatment in order to give advice to the clinician which treatment at what time.                                                      |                |
| <b>5.2</b> | <b>Behavioral and neurosurgical changes after Blast injury – What computational model does the neurologist need?</b><br><b>Hinds</b><br>Mentioning the problems of mild traumatic brain injury and the challenges in a computational model and the way to describe the biomechanical aspects of the brain in a computational model.            |                |
| <b>5.3</b> | <b>Neurosurgical aspects of blast trauma – What computational model does the neurosurgeon need?</b><br><b>Stettin</b><br>Focusing on clinical aspects and challenges in the treatment of blast trauma in a neurosurgical setting. Stettin was mentioning the problems of the brain in the skull and how to describe the biomechanical aspects. |                |
| <b>6</b>   | <b>SME Discussion</b>                                                                                                                                                                                                                                                                                                                          |                |

|            | <b>Day 3</b>                                                                                                                                                                                                                                                                                                                                                                                     | <b>Actions</b> |
|------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| <b>7</b>   | <b>Local symposium Part 2</b><br><b>What Computational Modeling must achieve – clinical aspects</b>                                                                                                                                                                                                                                                                                              |                |
| <b>7.1</b> | <b>Reconstructive surgery after blast-related wounds and fractures – What computational model do we need?</b><br><b>Kollig</b><br>Most computational models are based on biomechanical aspects. There is a lack of regarding the influence of infection and prolonged treatment due to sepsis.                                                                                                   |                |
| <b>7.2</b> | <b>Outcome prediction – How to evaluate clinical function, quality of live and self-assessment tools of veterans?</b><br><b>Völlmecke</b><br>So far there is no proper tool to evaluate the outcome of veterans after blast. Only regarding the clinical function is not enough to assess the quality of live and outcome after a blast injury. A tool is needed in order to assess the outcome. |                |
| <b>8</b>   | <b>Working Group updates</b>                                                                                                                                                                                                                                                                                                                                                                     |                |
| <b>8.1</b> | <b>Dictionary working group update – Dr. Emrys Kirkman</b>                                                                                                                                                                                                                                                                                                                                       |                |
| <b>8.2</b> | <b>Publications working group update – Dr. Dan Bieler</b>                                                                                                                                                                                                                                                                                                                                        |                |

## ANNEX E – MINUTES FROM THE HFM-270 PANEL MEETING MARCH 2018

|     | Day 3                                                                                                                                                                                                                                                                                                              | Actions |
|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| 8.3 | TAP working group update – Dr. Amit Bagchi                                                                                                                                                                                                                                                                         |         |
| 9   | Revisit the framework – create an example scenario                                                                                                                                                                                                                                                                 |         |
| 10  | Action items<br>The new actions items were discussed, which are listed at the end of this document.                                                                                                                                                                                                                |         |
| 11  | Closing words – Raj Gupta<br>Mr. Mike Leggieri thanks the group for their contributions and the hosts for their part on organizing the meeting. The 6 <sup>th</sup> meeting will take place in Suffield, Canada on the 10 <sup>th</sup> – 12 <sup>th</sup> July 2018. The agenda will be discussed at next telcon. |         |
| 12  | Date of 6 <sup>th</sup> meeting<br>10 – 12 <sup>th</sup> July 2018 – Suffield, Canada.                                                                                                                                                                                                                             |         |

| Action                                         | Description                                                                                                                                                                                                                  | Person           |
|------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| <b>Meeting 5, March 2018, Koblenz, Germany</b> |                                                                                                                                                                                                                              |                  |
| 5-1                                            | RG will send general articles to DB; he will select 5 – 10 articles and send those articles to TT. Every TT is supposed to review and identify strength and weaknesses of those articles for discussion in the next meeting. | RG / DB / All TT |
| 5-2                                            | At the next meeting we will revise the screening tool based on the information gained from <b>Action Item 1</b> .                                                                                                            | All TT           |
| 5-3                                            | RG convert additional information into questions and send it to TT members for their input, incorporate feedback and send out final questions to TT members. TT will coordinate responses for the respective nations.        | RG               |
| 5-4                                            | RG contact Philippe May and ask him for continued cooperation on dictionary working group.                                                                                                                                   | RG / PM          |
| 5-5                                            | DB will coordinate a list of proposed publications with his working group. Send a final list to TT.                                                                                                                          | DB               |
| 5-6                                            | TAP working group AB. AB will coordinate draft of TAP with his working group. Send revised draft to TT.                                                                                                                      | AB               |
| 5-7                                            | DB and AF will give a proposal concerning the proposed publications in Action item 5. (At meeting 7, South Africa)                                                                                                           | DB / AF          |
| 5-8                                            | Enquire France and Turkey regarding their computational model questionnaire and assessment status.                                                                                                                           | SW               |
| 5-9                                            | SW will send RG a list of nations who need to submit their screening tool to the science connect website.                                                                                                                    | SW               |
| 5-10                                           | DB will send EK three finalized papers.                                                                                                                                                                                      | DB / EK          |
| 5-11                                           | RG will resend introduction JRMC to SW.                                                                                                                                                                                      | RG / SW          |

| Action | Description                                                                                                                                  | Person  |
|--------|----------------------------------------------------------------------------------------------------------------------------------------------|---------|
| 5-12   | TT need to provide input for the draft final report to RG. RG will send out the word version of the draft outline of the final report to TT. | All TT  |
| 5-13   | EK will send out a copy of the current dictionary to extended dictionary group.                                                              | RG / SW |
| 5-14   | Update the models already filled in the spreadsheet of the screening tool. All TT                                                            | All TT  |
| 5-15   | Combine all screening tool spreadsheets of all members. SW                                                                                   | SW      |



## Annex F – MINUTES FROM THE HFM-270 PANEL MEETING JULY 2018

### F.1 MEETING #6 – 10 – 12 JULY 2018, DRDC SUFFIELD RESEARCH CENTRE, CANADA

HFM-270 (RTG) “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats”.

**Meeting called by** Michael J. Leggieri, Jr.

**Date:** 10<sup>th</sup> to 12<sup>th</sup> July 2018

**Note taker** Thomas W. Sawyer (CAN)

| ATTENDEES                         |                             |
|-----------------------------------|-----------------------------|
| <b>Members</b>                    | <b>SMEs</b>                 |
| Mr. Michael Leggieri (USA) (ML)   | Dr. Akio Yoshinaka (CAN)    |
| Dr. Raj Gupta (USA) (RG)          | Dr. Julian Lee (CAN)        |
| Dr. Amit Bagchi (USA) (AB)        | Dr. Fan Zhang (CAN)         |
| Dr. Tomer Erlich (ISR) (TE)       | Mr. David Ritzel (CAN)      |
| Dr. Levent Turhan (TR) LT         |                             |
| Dr. Mathieu Philippens (NLD) (MP) |                             |
| Dr. Thomas Sawyer (CAN) (TS)      |                             |
| <b>Apologies</b>                  |                             |
| Dr. Amal Bouamoul (CAN)           | Dr. Dan Bieler (DEU) (DB)   |
| Mr. Tyson Josey (CAN)             | Col (Dr.) Philippe May (FR) |
| Dr. Ibolja Cernak (CAN)           | Dr. David Reinecke (SA)     |
| Dr. Charmaine Richman (USA)       | Dr. Avraham Yitzhak         |
| Dr. Mårten Risling (SWE)          | Mr. Tim Westerhof (NLD)     |
| Dr. Mattias Skold (SWE)           | Dr. Sarah Watts (UK) (SW)   |
| Dr. Axel Franke (DEU)             | Dr. Emrys Kirkman (UK) (EK) |

|   | Day 1                                                                                                                                                                                                                                                                                                                                                         | Action |
|---|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|
| 1 | <b>Opening address and welcome</b><br>An opening address and welcome to Defence Research and Development Canada – Suffield Research Centre (DRDC-SRC) was provided by Dr. John Anderson, Acting Centre Director. Dr. Anderson provided an overview of DRDC-SRC research activities, concentrating on blast work and wished the group well in their endeavors. |        |

## ANNEX F – MINUTES FROM THE HFM-270 PANEL MEETING JULY 2018

|   | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Action |
|---|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|
|   | ML welcomed the group to HFM-270 meeting 6. The objectives of the group were overviewed. It was noted that changes to the original agenda were necessary. AB suggested that the extra time available be used to discuss the TAP of the follow-on RTG and the TT agreed. It was also noted that the group was on schedule to meet their deliverables.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |        |
| 2 | <p><b>Action Items from Meeting 5, Koblenz, 06th – 08th March 2018</b></p> <p>RG reviewed the action items from the previous meeting:</p> <p><b>Action items</b></p> <ol style="list-style-type: none"> <li>1) RG will send general articles to DB; he will select 5 – 10 articles and send those articles to TT. Every TT is supposed to review and identify strengths and weaknesses of those articles for discussion in the next meeting. RG / DB / All TT. <ul style="list-style-type: none"> <li>• Articles sent to DB.</li> </ul> </li> <li>2) At the next meeting we will revise the screening tool based on the information gained from <b>Action Item 1</b>. All TT.</li> <li>3) RG to convert additional information into questions and send it to TT members for their input, incorporate feedback and send out final questions to TT members. <ul style="list-style-type: none"> <li>• Revised questions and updated questionnaire sent.</li> <li>• TT will coordinate responses for the respective nations.</li> </ul> </li> <li>4) RG to contact Philippe May and ask him for continued cooperation on dictionary working group. RG / PM <ul style="list-style-type: none"> <li>• No response. MP to coordinate with French (mil/civ community) about possible models for inclusion.</li> </ul> </li> <li>5) DB will coordinate a list of proposed publications with his working group <ul style="list-style-type: none"> <li>• A final list was sent to the TT.</li> </ul> </li> <li>6) TAP working group: AB will coordinate draft of TAP with his working group and send revised draft to TT. <ul style="list-style-type: none"> <li>• Draft TAP shared with TT members last Telecon.</li> </ul> </li> <li>7) DB and AF will give a proposal concerning the proposed publications in Action item 5 (at Meeting 7, South Africa).</li> <li>8) Enquire of France and Turkey regarding their computational model questionnaire and assessment status. <ul style="list-style-type: none"> <li>• LT described difficulties obtaining information. There is a requirement to follow up with the FR member.</li> </ul> </li> <li>9) SW will send RG a list of nations who need to submit their screening tool to the science connect website. <ul style="list-style-type: none"> <li>• Follow-up required.</li> </ul> </li> </ol> |        |

|          | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Action |
|----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|
|          | <p>10) DB will send EK three finalized papers.</p> <ul style="list-style-type: none"> <li>3 of 4 articles published in JRAMC. Status of Dictionary of Terms needs to be ascertained.</li> </ul> <p>11) EK will send to all TT the confirmation that papers were accepted.</p> <ul style="list-style-type: none"> <li>Articles published in JRAMC.</li> </ul> <p>12) RG will resend introduction JRAMC to SW.</p> <ul style="list-style-type: none"> <li>The HFM-234 overview article was published and resent (one of the four articles).</li> </ul> <p>13) TT needs to provide input for the draft final report to RG. RG will send out the word version of the draft outline of the final report to TT.</p> <ul style="list-style-type: none"> <li>Comments received and incorporated in draft 2.</li> </ul> <p>14) EK will send out a copy of the current dictionary to the extended dictionary group.</p> <ul style="list-style-type: none"> <li>Follow-up required.</li> </ul> <p>15) Update the models already filled in the spreadsheet of the screening tool. All TT</p> <p>16) Combine all screening tool spreadsheets of all members. SW</p> <ul style="list-style-type: none"> <li>Follow-up required.</li> </ul> <p>Action Items 1 and 2 (see below) were promulgated during discussion.</p> |        |
| <b>3</b> | <p><b>SME Discussion</b></p> <p>The topic of personal blast gauge use came up with respect to their utility in providing blast exposure data. There was consensus that this issue was a good example of technology being developed without a good idea of the requirements to solve the problem at hand (i.e., blast overpressure induced TBI). Personal blast gauges are only useful in extremely controlled situations because overpressure depends on not only the location of the gauge, but also the orientation of the gauge with respect to the explosion, and it is not clear what their outputs actually mean in terms of the potential injury outcome. The group noted that it is important that decision makers understand the limitations of the current technology.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |        |
| <b>4</b> | <p><b>Screening Tool Exercise with Example Model</b></p> <p>An exercise was carried out where the TT applied the screening tool to a computational model describing lung injury. The TT reviewed the sample paper:</p> <p>A Model for Predicting Primary Blast Lung Injury<br/> L.N. MacFadden, P.C. Chau, K.H.-H. Ho and J.H. Stuhmiller<br/> J. Trauma Acute Care Surg. 73(5), 1121-1129 (2012)</p> <p>A wide ranging discussion surrounded this exercise. MP stated that the input, output, and validation portions of the assessment tool as applied to a given computational model are the most important aspects of the tool.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |        |

## ANNEX F – MINUTES FROM THE HFM-270 PANEL MEETING JULY 2018

|   | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Action |
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|   | <p>It was generally noted that interpretation of the paper(s) surrounding a given model was difficult and that often such interpretation is the result of the individual's expertise and experience. The balance between a detailed analysis of the work predicated on one's experience, and what is actually referred to in the paper is difficult to determine.</p> <p>TE noted that the paper did not actually include any functional endpoints of lung, but rather only gross pathology; TE further stated that there are no thresholds identified for blast lung based on functional injury to facilitate equipment development. AB mentioned that assigning injury thresholds are very difficult, partially due to the very real consequences that these values have on personal protection development. MP stated that a major problem is that almost all data for this kind of work is derived from non-human animals.</p> <p>The TT agreed that the model as described in the paper was not actually validated, although the authors state that their work was validated by the sheep data that was used. The TT noted that their model was simply "fit" or correlated to the sheep data, not validated.</p> <p>The subsequent issue of validation resulted in extended discourse whose conclusion was that it was obvious that validation is an extremely difficult process. In the absence of human data, can animal data be used, or for example do measure mechanical changes translate to injury severity? Can they be used in personal protection development?</p> |        |
| 5 | <p><b>TAP Working Group – Dr. Amit Bagchi</b></p> <p>In the absence of the other group leaders at this meeting, only the progress of the Working Group responsible for the Technical Activity Proposal (TAP) for the follow-on work to HFM-270 was briefed. AB noted that the next TAP should focus on the validation of the computational models compiled by this TT. This is important because without this validation, there is no assurance of the quality of the output and/or predictions from them. Review of the literature suggests that validation is not adequately addressed with the majority of published models. The deliverable from the next TAP will be a robust methodology for the validation of computational models, with an exercise to illustrate proof-of-concept. The WG also provided a number of key issues that they considered important in the eventual make-up of the validation methodology. This TAP needs to be discussed in detail at the next meeting in December 2018 (Meeting 7) in South Africa to enable its submission to NATO STO for review by the RTG in 2019.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |        |

|            | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Actions |
|------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| <b>6</b>   | <b>Local symposium Part 1</b><br><b>Applications of Computational Modeling</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |         |
| <b>6.1</b> | <b>Underwater Blast and Lung Injury</b><br><b>Dr. Julian Lee and T Josey</b><br><p>The presentation covered ongoing research at DRDC Suffield on mechanisms and models for underwater blast injury. The fundamental differences between underwater and air blast were discussed, followed by experiments on modifying underwater blast histories using foam-encased charges. The application of underwater blast to study primary blast effects on brain cell aggregates was briefly mentioned. The development of a calculator for underwater blast standoff distances was then presented, showing the approach to predicting underwater blast properties through a ray-tracing method, then applying the predicted blast to injury criteria. Next, the topic of underwater blast injury modeling was discussed, including a range of physical models, biological (e.g., Animal) models, semi-empirical models, and numerical simulation models. The range of different types of underwater blast injury, increasing in severity from eardrum rupture to lung hemorrhage, to gastrointestinal tract hemorrhage was covered, followed by different initiatives to develop both experimental and numerical lung injury models. Finally, the use of historical human case studies for producing underwater injury criteria was discussed, along with a methodology for applying these criteria to blast standoff calculations.</p>                       |         |
| <b>6.2</b> | <b>Blast Injury Using Surrogates in Experimental Trials (Blast Injury Assessment Tools)</b><br><b>Dr. Akio Yoshinaka</b><br><p>Air blast injuries can be categorized into four types:</p> <p><b>Primary blast injury:</b> Injuries are the direct result of shock exposure. Air filled organs and passageways are typically vulnerable (e.g., lungs, gastrointestinal tract, upper respiratory tract, ears), although Traumatic Brain Injury (TBI) is also included.</p> <p><b>Secondary blast injury:</b> Injuries resulting from airborne debris including fragmentation from either explosive charge or surrounding environment. This includes both blunt and penetrating fragments.</p> <p><b>Tertiary blast injury:</b> Injuries resulting from drag induced by air flow downstream of shock front. Examples include blunt impact from full body displacement and traumatic amputation of the extremities.</p> <p><b>Quaternary blast injury:</b> Burn injuries, crush injuries (e.g., from structure collapse) and all other injuries not included in the first three types.</p> <p>In this presentation, a number of injury criteria and models were discussed in the context of their use in evaluating the threat from blast in field experimental settings, namely: ear drum rupture, blast lung/chest, lethality/incapacitation/skin penetration from fragment impact. This presentation will briefly review the related methodologies.</p> |         |

|  | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Actions |
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|  | <p><b>Ear drum rupture</b></p> <p>As quoted in Hirsch [1968] and Kerr [1978], classic values for Tympanic Membrane (TM) rupture have a threshold value of 34 kPa (5 PSI) and a complete rupture value of 100 kPa (15 PSI). The systematic study by James [1982] provides pressures at the ear drum which result in free field values slightly different from those of Hirsch and Kerr. Although TM rupture seems to provide a simple means to evaluate ear injury, it does not appear to be a good indicator of more serious injuries (blast lung for example, see Radford [2011]).</p> <p><b>Blast lung/chest</b></p> <p>Bowen [1968] curves have been the benchmark for decades. Questions have been raised about the interpretation of the original data. Bass [2008] reviewed blast lung injury for large mammals and provided a correction to the Bowen curves. Axelsson [1996] developed a Single-Degree-Of-Freedom (SDOF) chest model to assess intrathoracic injury from complex blast exposure based on trials performed on sheep within rigid enclosures. The Axelsson approach requires the use of a rigid cylinder instrumented with four static pressure gauges which is located where personnel are expected to be standing within the test structure. Pressure histories from these gauges are used a forcing function to determine the response of the SDOF chest wall whose peak velocity is related to a level of injury. Little is said about the origin of the various model constants (spring, damping, etc.) and whether they came from the monitoring of real animal chest motion. The fact that SDOF models do not capture the wave dynamics occurring within the chest wall also raises questions.</p> <p><b>Fragmentation</b></p> <p>Probability of survival from fragment or debris impact is weighed by the probability of being hit. If multiple hits are considered, a simple assumption is that injury is cumulative, not synergistic. Given a hit, the probability of injury is model/criterion dependent. The 79 J(58 ft·lb) lethality criterion has been used as rule of thumb for a long time but its origin (Rohne [1906]) is not based on solid evidence. Janzer [1982] proposed lethality criteria that are a function of Kinetic Energy (KE) and body part hit (i.e., head, thorax, abdomen, limbs) for non-penetrating fragments. Swisdak [2007] shows lethality vs. KE on a single curve but does not mention whether it is for penetrating fragment or blunt impact. Louis [1978] (steel cubes) and Sperrazza [1968] (steel spheres) have produced relations between fragment KE and probability of skin penetration. Kokinakis [1965] published incapacitation criteria for spheres, cubes, and flechettes, relating the probability of incapacitation as a function of projectile mass, velocity, and tactical scenario. This study was based on the firing of projectiles in anatomical components of goats, whereby the physiological effect that could arise from a random strike on a soldier was evaluated by a medical assessor and categorized into wound classes. Assessor and combat personnel then related wound classes with the expected decrease in soldier task performance, which is commensurate to a level of incapacitation.</p> <p><b>Conclusions</b></p> <p>Although the above injury assessment methodologies can be easily implemented during field experimentation, one needs to recognize the limitations or questions surrounding those criteria/models. In the short term, it is recommended that injury assessments be provided with the implied caveat of specific models/criteria (e.g., <i>50% Bass lung injury</i> instead of simply <i>50% lung injury</i>).</p> |         |

|     | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Actions |
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| 6.3 | <p><b>Rapid City Planner: An Explosion Assessment Tool for Urban Environments</b></p> <p><b>Dr. Fan Zhang</b></p> <p>The accurate and fast analysis of weapon/IED effects in urban areas or complex terrains is critical to both timely battle planning with low collateral damage and force protection. As the complex urban environment represents multiple, close proximity lethal/loading scenarios, most fast modeling and war gaming tools would be incapable of this type of prediction. Secondly, the real-time large data of both urban population and structures pose a challenge to an accurate modeling tool to be capable of fusing multiple sources of information in a timely fashion.</p> <p>Rapid City Planner (RCP) is an M&amp;S tool developed to overcome these challenges (TRL 8). It provides a fast and accurate real urban/complex terrain weapon effects simulation and analysis capability on a portable laptop, based on next generation Computational Fluid Dynamics (CFD) using GPUs and automatic urban scenario setup, with a build-in virtual Globe platform for real-world coordinate modeling and fusion of multiple sources of geographic data with both online and off-the-grid capability for poor/no network activities. Benchmark comparisons demonstrate 100 times faster than the existing CFD software (e.g., Chinook). RCP has a weapon library including direct and indirect firepower weapons, missiles, IED/booby traps, VBIED, UAV IED, air bombs, and CBRE multi-threats. Users can input their own weapons into the RCP weapon library through a robust built-in Threat GUI, as well as input their own scenarios by a built-in target GUI with structural models. RCP fast and accurate computation provides a holistic outcome for building/structure damage, human injuries from both blast and fragments, frangible glazing fragmentation and secondary debris threats in real urban areas, and Collateral Damage Evaluation (CDE) in dense and crowded environments.</p> |         |
| 6.4 | <p><b>Understanding Blast Injury Biomechanics</b></p> <p><b>Mr. David Ritzel</b></p> <p>An overview of blast injury biomechanics was given, as well as the critical importance of understanding its complexity in the design of not only computational predictive models, but also biological models of blast. The challenge of modeling blast injury was discussed, with the observation that the most valuable data source – the soldier, was the most complex, the most vulnerable and the most difficult to study empirically. There is relatively little blast expertise in the biomedical research community and great care needs to be taken when developing models (computational/animal/in vitro) of blast. Both blast lung and blast-induced traumatic brain injury are distinct from injuries caused by impact/whiplash. Several examples of incorrect blast simulation were overviewed and it was noted that “correlation” does not imply a valid cause-and-effect for a given animal model system.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |         |
|     | <p>Attention to and understanding of blast physics was noted as being essential to the development of animal models of blast. Inclusion of data from invalid animal models of blast into computational models renders their predictive value invalid. Likewise, increased geometric detail in a computational model does not translate into increased predictive value if the biomechanics are incorrect.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |         |

## ANNEX F – MINUTES FROM THE HFM-270 PANEL MEETING JULY 2018

|   | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Actions |
|---|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| 7 | <b>Blast Facility Tour</b><br>DRDC blast facilities were toured and the TT was briefed on the development and use of the Advanced Blast Simulator located in Bldg 19, as well as the model systems used with it. The group was then transported to the Ritzel Centre complex in the Suffield Experimental Proving Ground. The large blast tube and Underwater Explosive Pond were toured. The plans to modify the large blast tube to enable it to generate IED-level blast waves were overviewed. |         |

|    | Day 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Actions |
|----|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| 8  | <b>Meeting 7 Preparation Update – Dr. Reinecke</b><br>Dr. Reinecke joined the meeting by telephone with an update of HFM-270 Meeting 7 to be held in Stellenbosch, South Africa. Flights to South Africa should be to Capetown International Airport, although there may be linking flights to Stellenbosch from Johannesburg. Stellenbosch is 20 km from Capetown. He will send an information package in the next month.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |         |
|    | <b>Group Discussion</b><br>Distribution of the computational models included in the framework will be carried out by RG and DB (see Action 3). It was identified that ~80 models populate the framework, with additional models likely to be included once DB completes his literature search. It was noted by the TT that discussion and application of the framework to one sample computational model took over 90 minutes. Although the overviews of these assessments to be given in Meeting 7 will be significantly shorter (~20 min), it was recognized that briefing of the 80-plus models so far included in the framework will be a major undertaking. The technical team thus agreed that Meeting 7, to be held in Stellenbosch, South Africa, should be extended from 4 – 6 December to 3 – 7 December 2018. It was also noted that if member countries appoint representatives to the panel, they should turn up to the meetings. ML suggested and the TT agreed that based on the current membership of the panel (23), each TT member should be assigned 4 models, with a secondary assessment by another member. This means that each member will be responsible for 8 models, to be completed by mid-November 2018. This will allow distribution and review by the TT prior to Meeting 7. AB noted that some individuals will lack the specific expertise to fully assess their assigned models. ML stated that this will partially be made up for by the secondary assessment, as well as when they are briefed during Meeting 7. |         |
|    | MP stated that it would be useful if a “summary statement” column was included in the assessment tool. This would highlight information not covered in the other topic columns and include reviewer-specific insight of the model not necessarily included in the assessed paper(s). There was general agreement to add this. AB and RG were actioned to provide the format and an example of this to the TT (Action 4).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |         |
| 10 | <b>Action items</b><br>The new action items were discussed and are listed at the end of this document.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |         |

|           | Day 3                                                                                                                                                                                                                                                                                                   | Actions |
|-----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| <b>11</b> | <b>Closing words – Dr. Gupta</b><br>Mr. Mike Leggieri thanked the group for their contributions and the host for his part in organizing the meeting. The 7 <sup>th</sup> meeting will take place in Stellenbosch, South Africa on 3 – 7 December 2018. The agenda will be discussed at the next telcon. |         |
| <b>12</b> | <b>Date of 7<sup>th</sup> meeting</b><br>3 – 7 December 2018 – Stellenbosch, South Africa                                                                                                                                                                                                               |         |

| Action                                                | Description                                                                                                                                                                          | Person       |
|-------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|
| <b>Meeting 6, 10 – 12 July 2018, Suffield, Canada</b> |                                                                                                                                                                                      |              |
| <b>6-1</b>                                            | MP to ask French colleagues as to the existence of computational model papers in French literature.                                                                                  | <b>MP</b>    |
| <b>6-2</b>                                            | AB to query contacts at the Southwest Research Institute in San Antonio whether they have computational models that would be appropriate for inclusion in the data base.             | <b>AB</b>    |
| <b>6-3</b>                                            | By 31 Aug 2108, RG to work with DB to divide and then assign the Technical Team members their allocation of computational models from the framework, for screening tool application. | <b>DB/RG</b> |
| <b>6-4</b>                                            | AB and RG to provide Technical Team a format and example summary of the McFadden paper (J. Trauma Acute Care Surg. 73, 1121-1129 (2012).                                             | <b>AB/RG</b> |
| <b>6-5</b>                                            | MP to ask CSO whether they can create a database of the reference papers identified in the framework.                                                                                | <b>MP</b>    |
| <b>6-6</b>                                            | TS to provide RG a summary of the SME presentations.                                                                                                                                 | <b>RG/TS</b> |
| <b>6-7</b>                                            | Technical Team members to send their assigned computational model assessments to RG by 16 November 2018.                                                                             | <b>RG/TT</b> |



## Annex G – MINUTES FROM THE HFM-270 PANEL MEETING DECEMBER 2018

### G.1 MEETING #7, 3 – 7 DECEMBER 2018, CSIR, NRE BUILDING, STELLENBOSCH SOUTH AFRICA

HFM-270 (RTG) “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats”.

**Meeting called by** Michael J. Leggieri, Jr.

**Date:** 3<sup>rd</sup> to 7<sup>th</sup> Dec 2018

**Note taker** David Reinecke and Rayeesa Ahmed (SA)

**Minutes** Thanyani Pandelani (SA)

| ATTENDEES                         |                                  |
|-----------------------------------|----------------------------------|
| <b>Members</b>                    |                                  |
| Mr. Michael Leggieri (USA) (ML)   | Dr. Dan Bieler (DEU) (DB)        |
| Dr. Amit Bagchi (USA) (AB)        | Dr. Mårten Risling (SWE) (MR)    |
| Dr. Mathieu Philippens (NLD) (MP) | Dr. Mattias Skold (SWE) (MS)     |
| Dr. David Reinecke (SA) (DR)      | Mr. Thanyani Pandelani (SA) (TP) |
| Dr. Axel Franke (DEU) (AF)        |                                  |
| <b>SMEs</b>                       | <b>Skype:</b>                    |
| Mr. Phumlane Nkosi (SA) (PN)      | Dr. Sarah Watts (UK) (SW)        |
| Ms. Rayeesa Ahmed (SA) (RA)       | Dr. Emrys Kirkman (UK) (EK)      |
| Mrs. Zelldra Schutte (SA) (ZS)    |                                  |
| <b>Apologies</b>                  |                                  |
| Dr. Thomas Sawyer (CAN) (TS)      | Dr. Ibolja Cernak (CAN) (IC)     |
| Dr. Levent Turhan (TR) (LT)       | Dr. Charmaine Richman (USA) (CR) |
| Dr. Tomer Erlich (ISR) (TE)       | Col (Dr.) Philippe May (FR) (PM) |
| Dr. Raj Gupta (USA) (RG)          | Dr. Avraham Yitzhak (AY)         |
| Dr. Amal Bouamoul (CAN) (ABO)     | Mr. Tim Westerhof (NLD) (TW)     |
| Mr. Tyson Josey (CAN) (TJ)        |                                  |

## ANNEX G – MINUTES FROM THE HFM-270 PANEL MEETING DECEMBER 2018

|   | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Action |
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| 1 | <p><b>Opening address and welcome</b></p> <p>An opening address and welcome to Council for Scientific and Industrial Research (CSIR) was given by Dr David Reinecke. Dr. Reinecke provided an overview of CSIR research activities on blast.</p> <p>A CSIR safety induction was given by CSIR NRE employee.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |        |
| 2 | <p><b>Introduction – ML</b></p> <p>ML welcomed the group to HFM-270 meeting 7. ML presented on the framework for modeling and simulation of human lethality, injury, and impairment from blast-related threats, just to remind everyone about the objectives of the TG.</p> <p>The spectrum of blast-related injuries is as defined in DoD directive 6025.21E. This covered the primary, secondary, tertiary, quaternary and quinary injuries and injury mechanisms. Even if a model does not address primary aspects, it can address secondary aspects such as blunt impact and penetrative injuries.</p> <p>The approach is to develop a black box of computational modeling capability which can predict lethality, injury and impairment and help with weapon system health risks, rapidly design protection concepts, and cost reduction. This approach will enable the development and testing for individual and vehicle occupant blast protection concepts in virtual environment.</p> <p><b>Deliverables (RTG in final year): Final report</b></p> <p><b>Focus for this meeting</b></p> <ol style="list-style-type: none"> <li>1) To review papers and see how they fit in the model.</li> <li>2) Receive updates on dictionary and publications.</li> <li>3) Receive updates on TAP working group.</li> <li>4) Assignment of responsibilities on the report.</li> </ol> <p><b>Last Meeting 6 Action Items</b></p> <ol style="list-style-type: none"> <li>6.1 Computational models in France: MP followed with Denis Lafont (DL) and does not know of any computational models. DL says ML need to contact HFM 270 FR member (Phillippe). ML to request Raj Gupta to locate representative (Action 7-9).</li> <li>6.2 AB has contacted Southwest Research Institute and Sandia Labs in USA on inputs on computational models. AB waiting for instruction from ML and RG to review. These labs are willing to share within the US only and not NATO. AB will use open work to summarize computational models from Sandia Labs but not so clear on Southwest Research Institute (Action 7-1).</li> <li>6.3 This action is completed. Papers were assigned to each TG member for review.</li> <li>6.4 This action has been completed. AB sent a format and example summary review example.</li> <li>6.5 Not done, CSO to do database for papers, MP to report on progress in the next meeting.</li> </ol> |        |

|          | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Action |
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|          | <p>6.6 Not done, TS still needs to provide summary on subject matter expert presentations in Suffield. TS still to action (Action 7-2).</p> <p>6.7 This action will be completed during this meeting (no. 7).</p> <p><b>Final report</b></p> <ul style="list-style-type: none"> <li>• Report structure updated in meeting 6.</li> <li>• TP is the only one who gave feedback on the report structure.</li> <li>• ML to ask for volunteers for report portions all the TG members to contribute to the report (Action 7-11).</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |        |
| <b>3</b> | <p><b>Review of papers</b></p> <p>The papers of models that were assigned to each TT member were reviewed and presented to the group.</p> <p><b>SW</b></p> <p>5.0 Head Injury Prediction Model for Space Flight</p> <ul style="list-style-type: none"> <li>• This covers tertiary injuries.</li> <li>• Accelerative loading and related to Head Injury Criterion (HIC).</li> <li>• This model was not on the summary spread sheet and was added including the modules filled in.</li> <li>• MP notes that HIC can also give what type of injury can be expected.</li> </ul> <p>5.1 Acoustic Injury Prediction Model for Impulse Noise</p> <ul style="list-style-type: none"> <li>• Used Cat and Chinchillas data to build model Auditory Hazard Assessment Algorithm for the Human (AHAH).</li> <li>• Used historical GE rifle fire as input.</li> <li>• Use pressure data and predicts auditory injury.</li> <li>• This is update of existing model based on human study using animals.</li> <li>• It has its own injury risk/prediction/assessment called Auditory Risk Unit (ARU).</li> <li>• ARU is correlated to hearing loss.</li> <li>• It is being used by US DoD to assess weapons system health risk. Also used in NL for shooting range.</li> </ul> <p><b>AB</b></p> <p>5.2 Hierarchical Model Validation of the Falx Cerebri and Tentorium Cerebelli</p> <ul style="list-style-type: none"> <li>• Model with movement of membranes around the brain.</li> <li>• Has material test <i>in situ</i> and excised specimens (on the membrane) loading materials up to 100 mm/s. Poked the membrane that folds into the brain. This membrane holds the brain in the skull.</li> <li>• Model FEA called Hyper Mesh Altair Engineering.</li> </ul> |        |

|  | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Action |
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|  | <ul style="list-style-type: none"> <li>MR/MS agree that the model has some value however tissue has issues such as risks, thus possibly supportive of modeling. DB noted this is important reference for FEA.</li> </ul> <p>5.3 Bayesian Analysis and Risk assessment of Selected Medical Events in Support of the Integrated Medical Model Effort.</p> <ul style="list-style-type: none"> <li>There is nothing relevant to the panel however the method / what they did: <ul style="list-style-type: none"> <li>Risk of any medical event occurring in persons partaking in space flight such as stroke to dental carries.</li> <li>They have a computational system to determine these risks and probability of events.</li> </ul> </li> </ul> <p>5.4 Multi Scale Modeling of Blast induced TBI: Problems and Challenges</p> <ul style="list-style-type: none"> <li>Range of models.</li> <li>No detail on the data summarized, it is a presentation.</li> <li>TP has reviewed the paper that the presentation was based on. (See his review).</li> </ul> <p><b>TP</b></p> <p>5.5 Integrated Medical Model a Probabilistic Simulation Model Predicting In-Flight Medical Risks</p> <ul style="list-style-type: none"> <li>Probabilistic model to predict human spaceflight mission medical risk.</li> <li>Not relevant to the group.</li> </ul> <p>5.6 Mathematical Models of Blast Induced TBI: Problems and Challenges</p> <ul style="list-style-type: none"> <li>Not relevant to the group but the references are important to be reviewed.</li> </ul> <p>5.7 Human Surrogate Head Response to Dynamic Overpressure Loading in Protected and Unprotected Conditions</p> <ul style="list-style-type: none"> <li>Used HIII head with cast in surrogate brain.</li> <li>Uses Human Surrogate Head Model (HSHM).</li> <li>Uses Monte Carlo approach to predict possible medical scenarios in flight.</li> <li>Use Integrated Medical Evidence Database using analogue in-flight and terrestrial data.</li> <li>Out of our framework but can be used to further add value to the injury data that we produce.</li> </ul> <p><b>DR</b></p> <p>5.8 Method for Obtaining Simple Shear Material Properties of the Intervertebral Disc Under High Strain Rates</p> <ul style="list-style-type: none"> <li>Material data for IVD material model as developed/applied by the user.</li> <li>Uses SHPB with force cells (piezo electric) and double lap shear test specimen.</li> <li>Uses fresh frozen samples.</li> <li>Does not take orientation of annulus fibers into account.</li> </ul> |        |

|      | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Action |
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| 5.9  | <p>Chapter 18: Determination of Simple Shear Material Properties of the Brain at High Strain Rates</p> <ul style="list-style-type: none"> <li>Simple shear data for freshly harvested brain tissue given. Notes higher strain rate results in lower shear modulus values.</li> <li>Only two specimens one tested at slightly higher strain rate than the other.</li> <li>Brain split into three sections (lobe, Midbrain/Pons, Cerebellum); however not investigated as part of the study; strong correlation.</li> </ul>                 |        |
| 5.10 | <p>Experimental Determination of Pressure Wave Transmission to the Brain During Head-Neck Blast Tests</p> <ul style="list-style-type: none"> <li>Biomechanical model that utilizes loading as input to characterize biomechanical parameters and injury scoring that can be utilized for product (e.g., protective equipment) assessment.</li> <li>Incident external pressure as well as ICP sensors, skull strain gauges and neutral density beads to measure brain motion.</li> </ul>                                                   |        |
|      | <b>AB</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |        |
| 5.11 | <p>Anthropometry Model Generation based on ANSURII (Anthropometric Surface – ANSUR) Database</p> <ul style="list-style-type: none"> <li>From US Marine Corps and commercial company.</li> <li>Software tool for automatic anthropometric generation from US Army database.</li> <li>Uses large pool of male and female anthropometric scans.</li> <li>Uses data base to generate statistical key anthropometry landmarks.</li> <li>Supporting data for generation of statistical anthropometry as part of models or scenarios.</li> </ul> |        |
| 5.12 | <p>Impact of Big Data Decision Support Tool on Military Logistics: Medical Analytics Meets the Mission</p> <ul style="list-style-type: none"> <li>Good case study of how big data decision support tool can support military logistics by helping medical analytics to meet the mission objectives.</li> <li>Beyond this effort but has value for additional post processing value add of the data generated by the modeling.</li> </ul>                                                                                                  |        |
| 5.13 | <p>Multi Scale Computational Modeling of Lung Blast Injuries</p> <ul style="list-style-type: none"> <li>Overview of the groups own work overestimated 15 years.</li> <li>Related to COBi software.</li> <li>Good overview of general issues such as blast wave, human anatomy, etc.; good information for introduction section of TG report.</li> </ul>                                                                                                                                                                                   |        |
|      | <b>AF</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |        |
| 5.14 | <p>Biomechanical Response of Blast Loading to the Head using 2D and 3D Cineographic Registration</p> <ul style="list-style-type: none"> <li>Same as paper 3 of DR, frozen head with a shock tube and 1000 kPa.</li> <li>Measure motion (x-ray) and local deformation.</li> </ul>                                                                                                                                                                                                                                                          |        |

## ANNEX G – MINUTES FROM THE HFM-270 PANEL MEETING DECEMBER 2018

|  | Day 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Action |
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|  | <ul style="list-style-type: none"> <li>Fluids are not human fluids.</li> <li>Replicates tertiary loading (global motion).</li> <li>Lot of discussion around applicability of this loading as not representative thus not useable even for helmet protection. Looking a gross motion of the head and neck complex.</li> <li>AB noted that a human will not survive a 1000 kPa pressure. Lung damage starts at 480 kPa (70 Psi).</li> </ul> <p>5.15 Particle Deposition in a Multi Path Model of Human Lung</p> <ul style="list-style-type: none"> <li>Mathematical representation.</li> <li>Use different theoretical lung models.</li> <li>For toxicological inhalation.</li> <li>Noted smaller particles are more distributed than larger particles.</li> <li>Has two lung models one statistical.</li> <li>Ternary and quinary phase injurious, thus limited.</li> </ul> <p>5.16 Modeling of Particle Distribution in the Pig Respiratory Tract</p> <ul style="list-style-type: none"> <li>For distribution in pigs (this is 15 years after the work above was done).</li> <li>Relevant need to do correlation with humans and pigs.</li> <li>The model was added to the framework.</li> </ul> |        |

|   | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Action |
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| 4 | <p><b>Welcome</b></p> <p>ML welcomed everyone to the day 2 of the meeting. ML noted that the US has many modeling efforts, but these are fragmented and disparate. The DoD got all project managers together and got them to list what they are doing. There is a DoD working group with the purpose of shaping, focusing, and coordinating the computational modeling efforts.</p> <p>The DoD want to know what the computational capability will deliver to the soldiers. The working group consist of both engineering and medical research communities working together.</p> <p>ML want this TG to develop a framework that goes from threat scenario to outcome. The developed framework must be correct thus cover all the items the TT reviewed. The TT will not cover all the possible programs/models; thus, the framework must be correct to be updated as and when new models and research are discovered as we progress.</p> |        |

|          | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Action |
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| <b>5</b> | <p><b>Review of papers</b></p> <p>Continuation of the paper reviews and presentation.</p> <p><b>ML</b></p> <p>5.1 Response of Individual Thoracolumbar Spine Ligaments under High Strain Rates</p> <ul style="list-style-type: none"> <li>• Material properties.</li> </ul> <p>5.2 Lung Injury Prediction Model for Blast Overpressure</p> <ul style="list-style-type: none"> <li>• In use by US Army for 20 years for health issues of artillery/weapons systems.</li> <li>• Contusion and injury from blast over pressure.</li> </ul> <p>5.3 Integrated Biomechanical Modeling of Lower Body Exercises on the Advanced Restrictive Exercise Device (ARED) using LifeMOD</p> <ul style="list-style-type: none"> <li>• Only tested under earth gravity.</li> <li>• Not relevant to this TG effort as not pertinent to blast effects.</li> </ul> <p><b>MS</b></p> <p>5.4 Human Head-Neck Computational Model for Assessing Blast Injury</p> <ul style="list-style-type: none"> <li>• Develop surrogate head based on FEA model.</li> <li>• Used 6" Shock tube.</li> <li>• It was noted that the model was 25% out on ICP and motion 30 – 540 % out.</li> <li>• ICPs of 70 – 120 kPa (500 – 900 mm Mercury).</li> <li>• Blast wave modeled separately in CFD and the FE model of the head. Uses coupling of some sort.</li> <li>• One is with HIII, and one is with human neck.</li> <li>• Limitations such as one brain material and stuck to inside of the skull.</li> <li>• It is an application of a model not development of the model. There are two models in the paper.</li> <li>• Added to framework.</li> </ul> <p>5.5 Finite Element Model of Fracture Stability in Tibia Fractures.</p> <ul style="list-style-type: none"> <li>• Tibia fractures.</li> <li>• Virtual Stress Test (VST).</li> <li>• CT Scan of soldiers.</li> <li>• Use image analysis.</li> </ul> <p>5.6 Finite Element Model of L4 – L5 Motion due to Blast Loading</p> <ul style="list-style-type: none"> <li>• Vertebral impact loading for UBB scenarios.</li> <li>• Seems to be for whole spine motion with disk in between.</li> </ul> |        |

|  | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Action |
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|  | <ul style="list-style-type: none"> <li>• Have four layers in annulus fibrosis even though there are probably 10, in reality, it is still a good model. Only model compression not really bending which could be a real loading where it compresses say posterior while relaxing anterior portions of the disk.</li> <li>• Load based on Demotrapolous.</li> <li>• Dropped 5 kg mass from 40 cm, thus impact loading.</li> </ul> <p><b>MP</b></p> <p>5.7 Development and Validation of a Predictive Bone Fracture Risk Model for Astronauts</p> <ul style="list-style-type: none"> <li>• Risk model not applicable as risks not useable.</li> <li>• Method however is applicable as sustained loading etc., can be accommodated. The biomechanical model could be applicable to the framework.</li> <li>• Force loading (hip/wrist).</li> <li>• It is a risk on fracture thus seen a Pathology / Pathological outcome.</li> <li>• Seems to use population distributions to get injury risks.</li> <li>• Added to framework.</li> </ul> <p>5.8 The Impact of Ocular Hemodynamics and Intercranial Pressure on Intraocular Pressure During Acute Gravitational Changes</p> <ul style="list-style-type: none"> <li>• Only micro gravitational with slow changes thus not relevant i.e., 0.5 to 1.25 G.</li> </ul> <p>5.9 A Three-Dimensional Computational Human Head Model That Captures Live Human Brain Dynamics</p> <ul style="list-style-type: none"> <li>• Uses a Material Point Method (MPM).</li> <li>• Validated against human tests. <ul style="list-style-type: none"> <li>• 3 – 5 rad/s.</li> <li>• Uses published material models.</li> </ul> </li> <li>• Input is MRI images and model is built for each individual. They tune to a 3.5 ms and can then use this calibration to get higher loading effects.</li> <li>• Calculate shear force and related to diffuse axonal injury.</li> <li>• Use live specimens thus not injurious loading. <ul style="list-style-type: none"> <li>• The loads are low but are relevant for a human tripping and hitting head. Validated against NFL load cases.</li> </ul> </li> <li>• Added to framework.</li> </ul> |        |

|  | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Action |
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|  | <p><b>AF</b></p> <p>5.10 Development of a Geometrical and Adaptable Head Model for Impact Simulation Naval Research laboratories</p> <ul style="list-style-type: none"> <li>• Adapt the mesh for the FE simulation according to MRI slices.</li> <li>• Well established model and is being used.</li> <li>• Limitations is that it is not validated to the real tissue properties.</li> <li>• It is a modification of an MRI picture methodology.</li> <li>• Fluid content and viscosities not included.</li> <li>• Blast impact determined for 45° and frontal impact for 430 kPa.</li> <li>• Seems worried T1 does not include fatty and fluid content which is visible in T2 images.</li> <li>• Uses visco elastic elements for model.</li> <li>• Added to framework.</li> </ul> <p>5.11 Conductive hearing loss in acute otitis media model of guinea</p> <ul style="list-style-type: none"> <li>• Built model with cadaver ear mounted to a head block.</li> <li>• Model able to predict tension and pressure at surface of ear drum as well as ear drum rupture due to blast exposure.</li> <li>• It is well validated model.</li> <li>• The kinetics are related to their connection and upper respiratory tract (the ear tube).</li> <li>• Added to the framework <ul style="list-style-type: none"> <li>• Pathology: Bleeding (not included in the model) thus excluded.</li> <li>• Pathophysiological Finding: Risk of Rupture or hearing loss.</li> <li>• Biomechanical: Motion of the ear drum (output).</li> <li>• Module X should be the medical interpretation of the results. <ul style="list-style-type: none"> <li>• For this its eardrum motion is an input in Module X.</li> </ul> </li> <li>• The actual risk / injury is not modeled, this one has no module X.</li> </ul> </li> <li>• It is again an adaption of an existing model.</li> </ul> <p>Seems it is based on the tension of the ear drum and this is linked to other injury work to determine injury.</p> <p><b>RG</b></p> <p>5.12 A Computational Model for Articulated Body Dynamics</p> <ul style="list-style-type: none"> <li>• Multi-body dynamics with coupling of fluid-structure interaction.</li> <li>• Main feature is human shape and area contact with surrounding structure.</li> <li>• The exact linearization of the weak form of both the rigid body dynamics and the joint constraints was obtained in closed form.</li> <li>• Validation is in progress.</li> </ul> |        |

|  | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Action |
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|  | <p>5.13 A Fast Robust Whole Body Control Algorithm for Running</p> <ul style="list-style-type: none"> <li>• An algorithm for whole body external loads simulation of human running in real time.</li> <li>• AB asked if there are stress contours, etc. Does give skeletal forces and loads.</li> </ul> <p>5.14 A Fast Running Model for Skeletal Impact Biomechanics Analysis</p> <ul style="list-style-type: none"> <li>• Simulating the rib cage and the lower extremity under the impact loadings.</li> <li>• Appears to be MBD using non-linear beam elements and considered novel.</li> <li>• The beam element appears to accommodate variable cross section.</li> <li>• Has skeletal and only inter costal cartilage.</li> <li>• Seems to only be rib cage and tibia.</li> <li>• They state that they have tested data for high strain rate (8 kN over 1 ms for tibia and 2 kN over 200 microseconds).</li> <li>• Model not able to predict when failure will occur.</li> </ul> <p><b>TS</b></p> <p>5.15 The Influence of Neck Kinematics on Brain Pressures and Strains under Blast Loading</p> <ul style="list-style-type: none"> <li>• Use Human Head Finite Element Model (HHFEM) and another that are compared to each other</li> <li>• The neck model is detailed with ligaments and note that brain loading is from shearing</li> <li>• Added to framework</li> </ul> <p>5.16 Spatial Modeling for Cell Biology</p> <ul style="list-style-type: none"> <li>• CFD Research Corporation commercial companies contracted.</li> <li>• Notes combining biomechanical and biophysics difficult and not in the paper.</li> <li>• Uses COBi MS noted that there are mechanisms on cellular level. Seems that they are trying to model cell functions.</li> </ul> <p>5.17 Bone Fracture Risk Module for Impact</p> <ul style="list-style-type: none"> <li>• It is a computational model, have a load, a target and a response based on low gravity and space flight parameters.</li> <li>• Not a validated model.</li> <li>• Different to MP as applied to zero gravity situation.</li> </ul> |        |

|  | Day 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Action |
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|  | <p><b>TJ</b></p> <p>5.18 BOP HHA v2.0 Health Assessment from Airblast</p> <ul style="list-style-type: none"> <li>• Probability and severity of lung injury from contusion due to blast loading.</li> <li>• The model uses the L-3/Jaycor normalized work approach to predict injury and uses the results to present the operator with an Allowable Number of Rounds (ANR) which can be fired during a single day or training.</li> <li>• This uses additional factors based on the core model presented by ML due to health hazard assessment. ML noted that all US systems have to undergo this assessment.</li> <li>• Severity goes from negligible to catastrophic and probability of occurrence.</li> <li>• The pathology is lung injury.</li> <li>• Added to framework.</li> </ul> <p>5.19 Injury 8.3 A Model for Predicting Primary Blast Lung Injury</p> <ul style="list-style-type: none"> <li>• Calculates normalized work and correlates to injury.</li> <li>• Does not consider repeated blast effects (i.e., no cumulative effects).</li> <li>• Does not include multidimensional dynamics of stress wave reflections in the lung or adjacent organs.</li> <li>• No mechanism of lethality, only a correlation (phenomenological).</li> <li>• Utilizes BTD pressures to predict chest wall velocities.</li> <li>• Lethality correlation is based on 1-hour.</li> <li>• Pressure loading from four pressure gauges on a BTD is the key input.</li> <li>• Sheep lung tissue response similar to that of human lung tissue.</li> <li>• Limited sample size for slight or greater injury.</li> <li>• Model is claimed to be validated against lung contusion data collected from sheep subjects exposed to a range of blast levels in free field tests and in confined conditions.</li> </ul> |        |
|  | <p>5.20 Comparing Blast Effect on Human Torso Finite Element Model Against Existing Lethality Curves</p> <ul style="list-style-type: none"> <li>• This uses Human Torso Finite Element Model (HTFEM).</li> <li>• Funded with Darpa similar to GHBM (Global Human Body Model).</li> <li>• Says to model effect of over pressure on heart, liver, lungs, stomach, intestinal mass, kidneys, and skeletal structure.</li> <li>• NB Module X is when the model predicts injury or lethality.</li> <li>• Used LS-DYNA blast load.</li> <li>• Added framework.</li> </ul> <p>The TT reallocated non-reviewed papers to the people attending the meeting to be presented on day 4.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |        |

## ANNEX G – MINUTES FROM THE HFM-270 PANEL MEETING DECEMBER 2018

|   | Day 3                                                                                                                                                                                                                | Actions |
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| 6 | <b>Cultural day</b><br>Dr. Reinecke, Mr. Pandelani and Ms. R. Ahmed organized a cultural day out for the TT members attending the meeting. TG members availed the remainder of the day to catch up on paper reviews. |         |

|   | Day 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Action |
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| 7 | <b>Welcome</b><br>ML welcomed everyone to the day 4 of the meeting. ML outlined the goals remaining for the meeting:<br>7.1 Complete the paper review summaries.<br>7.2 Presentation of Subject Matter Experts (SME).<br>7.3 Work Group (TAP, Dictionary and Publications) feedback/update.<br>7.4 Additional 200 papers being done by DB, perhaps share load among the TT members. There are an additional 150 papers from ML paper review. These need to be reviewed (Action 7-6 and 7-7)<br>7.5 Final report and strategy for section allocation.<br>7.6 Scenarios (threats/loading).<br>7.7 MR to provide Stockholm Meeting details.<br>7.8 Recap action items.<br>7.9 Discuss available current models that could be used now.                                                                                                                                      |        |
|   | <b>Review of papers</b><br>Reallocated non-reviewed papers to the people attending the meeting are summarized below.<br><b>DB</b><br>8.1 Development of a Zealand White Rabbit Deposition Model to Study Inhalation Anthrax <ul style="list-style-type: none"> <li>Model lung structure bi-furcation and tri-frication thus describes distribution (1 micron).</li> <li>Own mathematical model.</li> <li>The model was added to the alternative list.</li> </ul> <b>MS</b><br>8.2 Effective Eye Armor During Blast Loading <ul style="list-style-type: none"> <li>Eye armor goggles / sport glasses model.</li> <li>Goggles has lower back pressure.</li> <li>Have Fluid Structure Interaction (FSI) model in another paper, head form from another computer model developed before (FOCUS Humanetics and Virginia Tech for Army Medical Research lab model).</li> </ul> |        |

|   | Day 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Action |
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| 8 | <ul style="list-style-type: none"> <li>• FOCUS head form has injury risk curves associated with it. There is eye rupture (annulus) and fracture of facial bones, gives injury curve that was developed elsewhere. Model gives pressure and uses other injury probability.</li> <li>• Only facial loading, developed for airbag and frontal loading (face-eye).</li> </ul> <p>Validation not clear; appears to have used cow eye. <b>PN</b></p> <p>8.3 A Computational Model of Belts Loading on the Human Eye</p> <ul style="list-style-type: none"> <li>• 2 kg TNT about 2.5 m away free-in-air and reflected off the ground, seemed to use Kingery Bulmash and Swisdak loading at 1.8 from detonation point.</li> <li>• Investigated the features of the skull on the eye loading. <ul style="list-style-type: none"> <li>• Focus areas formed by nose and ocular brow for face on. Off ground 40% lower and no gas trap by nose and ocular ridge.</li> <li>• Highest pressure at posterior of eye.</li> </ul> </li> <li>• Model deformation as well as stresses, time history of the Inter Ocular eye Pressure (IOP).</li> <li>• Noted code called FSI used.</li> </ul> <p><b>AK</b></p> <p>8.4 An Enhanced Articulated Human Body Model Under Blast Load</p> <ul style="list-style-type: none"> <li>• Apply pressure loading on human form and see its biomechanics response.</li> <li>• It has a biofidelic surface.</li> <li>• Use a separate blast generator.</li> <li>• Get software for response to load and then separate software for injury.</li> <li>• Loading based on rigid body not compliant. No muscle loading / load paths / response; also assume homogenous density to simply head model.</li> <li>• Validated with PMHS at Laboratory of Accidentology.</li> </ul> <p>8.5 Modeling of Articulated Human Body Dynamics Under a Representative Blast Load</p> <ul style="list-style-type: none"> <li>• Using PMHS data to generate improved model data that is used in the model above.</li> <li>• Previous assumption if it has both dynamic and static pressures.</li> </ul> <p><b>MR</b></p> <p>8.6 Experimental Characterization of Anatomical Structures of the Lumbar Spine under Dynamic Saggital Bending (2 papers)</p> <ul style="list-style-type: none"> <li>• Separated spine specimens.</li> <li>• 2015 paper looked at flexion bending of spine and removed parts such as ligaments and joint capsules and then tested again; thus, deflexion increased as these are removed thus are important for stability.</li> </ul> |        |

|  | Day 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Action |
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|  | <ul style="list-style-type: none"> <li>• 2016 paper used drop weight impact and rapid compression supposed to simulate under body blast.</li> <li>• Used special electrodes as employed in other studies.</li> <li>• Don't fit into the framework as these are biomechanical studies on the spin, they are limited in how they were performed as musculature effects are not included.</li> </ul> <p><b>DR</b></p> <p>8.7 Integrated Experimental and Computational Framework for the Development and Validation of Blast Wave Brain Biomechanics and Helmet Protection (HFM-207 Paper)</p> <ul style="list-style-type: none"> <li>• Use of computational modeling (CoBi) to evaluate head protection of helmets.</li> <li>• CoBi software developed by United States Army Aeromedical Research Laboratory (USAARL) and CFD Research Corporation (CFDRC).</li> <li>• Model set up description partial (appears incomplete, some data such as mesh joining, cell types, etc. noted but coupling / loading not discussed in detail).</li> <li>• Notes use of CT scans to get anatomically correct model data and then reverts to standard CoBi "Young Soldier".</li> </ul> <p><b>ML</b></p> <p>8.8 CFRD Fatigable Head-Neck loading of aviators</p> <ul style="list-style-type: none"> <li>• Not blast, modeling stresses of aviators in high-g maneuvers.</li> <li>• May have modeling info / techniques of interest.</li> </ul> <p>8.9 Challenges in Measuring and Modeling Whole Body Blast Effects</p> <ul style="list-style-type: none"> <li>• Difficulty to characterize blast environment with techniques and methods to measure blast.</li> <li>• Refers to SHAMREC developed by ARA, the Computational tool which can compute blast load at any point in time and space. Thus, they sue SHAMREC to disprove assumptions and understanding of blast load.</li> <li>• It is in the framework.</li> </ul> <p><b>ZS</b></p> <p>8.10 Response of Thoracolumbar Vertebral Bodies to High-Rate Compressive Loading</p> <ul style="list-style-type: none"> <li>• Experimental material characterization of the thoracolumbar vertebral bodies' response due to loading rates associated with Under Body Blast (UBB) events.</li> <li>• Does provide good vertebrae material properties for use of high strain rates.</li> </ul> <p><b>AB</b></p> <p>8.11 FEM of Factors Influencing the Optic Nerve Head Deformation due to Intercranial Pressure</p> <ul style="list-style-type: none"> <li>• Seems to confirm concern with posterior pressure reflection in the eye.</li> <li>• Used Monte Carlo Simulation but rather Latin Hypercube for DOE.</li> </ul> |        |

|  | Day 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Action |
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|  | <ul style="list-style-type: none"> <li>Looked at effect of Microgravity.</li> <li>Material properties and models of some use but loading not applicable to our regime.</li> <li>Move to additional information on Framework.</li> </ul> <p><b>AF</b></p> <p>8.12 FE Model of Head by Fanigen</p> <ul style="list-style-type: none"> <li>Seems summarized before as adjusted anatomical model using MRI techniques, this is similar but only hypothetical anatomical structures.</li> <li>Model is in the framework.</li> <li>Calculated blast over pressure with CFD software and then used LS Dyna for bone structures FE to adjust the findings on the facial region movement.</li> <li>Initially only calculated strain and second paper added ICP local pressure in several areas of FEM.</li> <li>Not validated.</li> <li>Pressures 800 kPa for 5 ms.</li> </ul> <p><b>RA</b></p> <p>8.13 Characterizing Brain Mechanics during a Two-Phase Response to Dynamic Overpressure Loading</p> <ul style="list-style-type: none"> <li>Developed methodology.</li> <li>Note two-phase loading from blast initial high speed and then much slower biomechanical response.</li> <li>Data for verification and validation.</li> <li>MP notes relate to a head in-front of a shock tube not inside, this according to MP is not a blast load.</li> </ul> <p>8.14 Improvements and Additions to Multiple Part Particle Dosimetry Model</p> <ul style="list-style-type: none"> <li>Same as DB's paper and it is for workplace health and dose of medicine.</li> </ul> <p><b>MP</b></p> <p>8.15 Challenges in Measuring and Modeling Whole Body Blast Effects</p> <ul style="list-style-type: none"> <li>The publication gives an overview of challenges when assessing the human body response to blast.</li> <li>This is a summary of software available and the body region.</li> <li>Review this paper against the Framework to ensure all models are captured.</li> </ul> |        |

|   | Day 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Action |
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|   | <p>8.18 Computational Models for Blast Injury Prevention (CoMBIP)</p> <ul style="list-style-type: none"> <li>• FEM of spine to assess injury mechanisms in vertical loading to see effect of torso mass and posture.</li> <li>• Model T12/L1 to L5/S1-Disc.</li> <li>• Used SHPB material properties and shear tests.</li> <li>• Used CT scan to develop model using 54.1 kg torso mass simulant (inertia effects).</li> <li>• Ligaments non-linear springs.</li> <li>• Also have seated and supine.</li> <li>• Seem to validate against HIII STD and used this for input for the FEM.</li> <li>• Assume pelvis does not fracture before the lumbar spine fails.</li> <li>• Validation is tenuous.</li> <li>• Model predicts compression and shear forces within the disc and spine.</li> <li>• Fits in the Framework and is already listed therein.</li> <li>• Decision made to change the naming of all reviews using the Primary Author and year of publication, DB will do this, thus modify the paper and the summary files (Action 7-4).</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |        |
| 9 | <p><b>Subject Matter Experts (SME) presentation</b></p> <p><b>Injury Biomechanics of Pelvis Under Blast Conditions – TP</b></p> <p>Presentation covered PhD research on pelvic fracture injury due to severity of this injury type. Injury patterns seen in combat replicated with section PMHS using Imperial College London ANUBIS test rig with sacral fractures, rami (superior and inferior) fractures. For modeling calibration additional accelerated drop test executed. A 2D computational pelvic model being developed using MSC MARC® software based on PMHS scans for skeletal structure and live volunteer for soft tissues. The model uses eroding cell failure on the model to determine failure. The model to facilitate high strain rate testing of soft tissues. Material tests conducted strain rates of 1 up to 125 s<sup>-1</sup>. Questions:</p> <ul style="list-style-type: none"> <li>• AB asked how they matched the registration points for scaling. Points from PMHS MRI were matched to human volunteer and scale from there.</li> <li>• During MRI of the volunteer, the buttocks were not loaded. Axel noted that to get a realistic perspective, it would be good to see live tissue performance changes when loaded. During the drop tests, the buttocks were loaded by the body mass of the PHMS.</li> <li>• AF wanted to know if the occupant can respond to blast load, MP noted there is not time to respond, the event is too quick; it is not possible. With car accidents whiplash the body can respond as it is so slow and that leads to the injury.</li> </ul> <p><i>As the model is not yet published, it was added to Framework as a personal communication to the RTG.</i></p> |        |

|    | Day 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Action |
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| 10 | <p><b>Determining the Load Paths from Seat to Occupant During Under Body Blasts – ZS</b></p> <p>Published research indicates that introduction of EA seats tends to change the injury location up the spinal column from the base bones. This PhD study is focusing on assessing alternative Injury Assessment Reference Values for application in the assessment of energy absorbing blast protection seats. The work is planning on using published PMHS data as well as coupled commotional modeling for injury prediction (LS-DYNA and MADYMO).</p> <p><b>Blast Overpressure Effects Using the Blast Test Device – TP</b></p> <p>This presentation summarized blast overpressure work that the CSIR is currently involved in assessing free-filed, single reflected and complex blast loading with BTB, AEP55 and soldier borne blast sensors. The research is applying available injury assessment and criteria (Axlesson, Blast 8.3, Bowen) for evaluation.</p>                                                                                                                            |        |
|    | <p><b>Meeting 8 Preparation update – MR</b></p> <p>10.0 Sweden, Karolinska Institute will host the next meeting from 3 – 5 April 2019.</p> <p>10.1 The meeting details will be finalized during the teleconference in February. (Action ML)</p> <p>10.2 ML suggested the 2nd as an additional day. TBC (Action All)</p> <p>10.3 Final meeting will be in Paris in October 2019. (Action All)</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |        |
|    | <p><b>Working group update</b></p> <p><b>TAP – AB</b></p> <p>11.1.1 TAP Committee consisted of AB, SW, RA, MS and DB. Uses a standard format from NATO.</p> <p>11.1.2 AB presented the slides to recap the scope of the TAP on verification and validation of the computational models. (Slides are attached)</p> <p>11.1.3 AB, RG, and SW to draft initial TAP draft proposal and send out for input. (Action AB/RG/SW)</p> <p>11.1.4 AB wanted to make a working meeting in SA but SW not available. (Action AB)</p> <p><b>Publication – DB</b></p> <p>11.2.1 RTG-234 has 3 publications in British Army Medical Corps Journal (Systematic research).</p> <p>11.2.2 DB wants to publish in medical and engineering journal (systemic research). (Action DB)</p> <p>11.2.3 ML asked what about publication of the Framework. TT agreed can possibly be published. DB Suggested the TT first sort it and then discuss how to use this output.</p> <p>11.2.4 DB suggest the dictionary be published at Wikipedia.</p> <p>11.2.5 AF noted that the TT divides up the model into CFD, FEM, etc.</p> |        |

## ANNEX G – MINUTES FROM THE HFM-270 PANEL MEETING DECEMBER 2018

|  | Day 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Action |
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|  | <p>11.2.6 ML wants to know if the methodology the TT used is publishable. TT agrees that we must first prove that the framework works. TT will have to pose a question to the Framework to see if it works. Then, both can be published. AF noted that the TT must build a road map on how to proceed with the framework.</p> <p>11.2.7 TT needs to clear up the framework first on what is a computational model, and which is not.</p> <ul style="list-style-type: none"> <li>• Each person to pose a question for the framework (Done in day 5).</li> <li>• Review the framework to identify computational model and what is a risk prediction (Done in day 5).</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                          |        |
|  | <p><b>Dictionary – AK</b></p> <p>11.3.1 IC no longer sponsored by ML thus no longer participating in the RTG.</p> <p>11.3.2 MS as part of committee has reviewed the dictionary partially but not seen any major changes.</p> <p>11.3.3 MS recommends computational modeling terms to be added. (Action AK)</p> <p>11.3.4 Strategy required as IC who was key contributor is no longer participating. TP volunteered to assist. ML to contact AK/RG to confirm status and discuss at February teleconference. (Action ML)</p> <p>11.3.5 Draft dictionary sent by SW to TP uploaded it on the share point.</p> <p><b>Systematic Literature Review</b></p> <p>11.4.1 DB will do this and write a summary paper. (Action DB).</p> <p>11.4.2 All TT members to give Dan copies of the paper reviews (Action all).</p> <p>11.4.3 Ensure ML add 2 and MP add 3 of their reviews. (Action ML/MP).</p> <p>11.4.4 There are 200 papers that TT to volunteer to do a summary and submit to DB. (Action TT).</p> <p>11.4.5 ML to assign equal number of papers from DB to each remaining member of these papers. (Action ML).</p> |        |

|    | Day 5                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Action |
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| 12 | <p><b>Discuss/review framework</b></p> <p>5.17 TT reviewed the framework to confirm all the papers listed belong in the framework.</p> <ul style="list-style-type: none"> <li>• There was some discussion on what a computational model is. AF noted that this definition must be added to the dictionary and that there are injury and there are health prediction models. (Action AK).</li> <li>• AF noted that, there are static models e.g., calculating an injury risk and then there are dynamic models which determine the outcome or loading.</li> </ul> |        |

|           | Day 5                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Action |
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|           | <ul style="list-style-type: none"> <li>• <b>Question:</b> How does literature describe computational models and differentiates between prediction and injury models? Progress to be reported February Teleconference and defined by Stockholm at the latest (Action 7-18).</li> <li>• TT to identify all computational models and color code them with yellow identifying computational model and purple identifying that model has been reviewed by TT. ML to send out to TT members. TT Must confirm information in spreadsheet are correct based on the papers reviewed by the individuals (Action 7-13).</li> </ul> <p>5.18 MP presented three papers published at MABS 26 of model of threat, vehicle, and occupant.</p> <ul style="list-style-type: none"> <li>• The papers had three elements: Blast (threat), Vehicle and Occupant (Human Body (Biomechanical)).</li> <li>• AB noted that vehicle is a transfer function or intermediary that can attenuate or exacerbate, it was also noted that buildings/walls also part of the “system”.</li> <li>• AB asked if the intermediary (vehicle, PPE, etc.) falls in module 1 or 2? It was agreed by TT that in falls in module 1.</li> </ul>                                                                 |        |
| <b>13</b> | <p><b>Assessing the capability of the current framework to answer questions</b></p> <p>13.1 The framework should be able to answer questions such as: Given mission specific threat scenario what is the probability of injury (primary, secondary, and quaternary) and then lethality and impairment, thus three questions:</p> <ul style="list-style-type: none"> <li>• Threats.</li> <li>• Occupant.</li> <li>• Intermediaries.</li> </ul> <p>13.2 TT asked the following questions to test the framework robustness in answering the questions:</p> <ul style="list-style-type: none"> <li>• What is the probability of injury and long-term prognosis (6 months) from a hand grenade blast in a room with the soldier wearing PPE standing, kneeling and supine?</li> <li>• What is the probability of injury of a supine person in a protected vehicle subjected to a UBB?</li> <li>• What is the probability of injury/lethality when exposed to 10 kg TNT underbody blast inside the vehicle?</li> <li>• How likely is the injury of the spine?</li> <li>• For what kind of injuries are computational models available?</li> <li>• What are the different computational models to simulate an explosive related to a distinct explosive device?</li> </ul> |        |

|  | Day 5                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Action |
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|  | <ul style="list-style-type: none"> <li>• Which models provide injury risk with respect to collateral damage due to ERA (Explosive Reactive Armor)?</li> <li>• Can the framework predict acute and chronic health risks to service members who fore heavy weapons?</li> <li>• As above but for immediate and/or delayed performance decrements?</li> <li>• How adequately accurately and comprehensively does the framework or computational model predict injury or the probability thereof?</li> <li>• Will a soldier survive 10 kg TNT blast standing against a wall 20 m away?</li> <li>• Will the soldier above lose his hearing when subjected to the blast?</li> <li>• What are the simulation methods to model the load propagation for mounted and dismounted soldiers and the associated mitigation strategies?</li> <li>• How accurately can the framework model the effect of different blast scenarios on different parts of the human body?</li> </ul> |        |
|  | 13.3 The framework will be a map to provide a key to find what the user needs in the black box.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |        |
|  | 13.4 It was noted that module X and Y of the framework have research gaps thus rely on statistics.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |        |
|  | 13.5 Module 1 and 2 there are models, but most are not validated or validated against blast type loading.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |        |
|  | 13.6 AF noted that The TT's questions show the categories that we need to identify within the framework. This should be done individually based on the categories.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |        |
|  | 13.7 MP and AF are proposing a structured database that provides a list of software programs that can model injury prediction.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |        |
|  | 13.8 ML noted that the framework should demonstrate that one can take a series of models and model an event from threat to outcome. MP noted that there are models out there, but one cannot randomly match these as they require custom interfaces.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |        |
|  | 13.9 There are defined methods for model/test/load interfaces between the various models i.e., threat, intermediary and occupant models. TT must test this and see how it affects how we model.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |        |
|  | 13.10 ML is satisfied that the structured database will provide this information.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |        |
|  | 13.11 There was a question to the TT members on what the follow-up group will address. Some of the suggestions were: <ul style="list-style-type: none"> <li>• DB feels that we cannot do a STANREC but can state what is the standard for verification and validation;</li> <li>• DR suggested verification and validation of the models; <ul style="list-style-type: none"> <li>• MP noted that there are already publications dealing with Verification and Validation. DR disagrees as this is a unique set of models and as such requires unique verification and validation and having a standard set of data to verify and validate against would be great.</li> </ul> </li> </ul>                                                                                                                                                                                                                                                                            |        |

|    | Day 5                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Action |
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|    | <ul style="list-style-type: none"> <li>AB noted that the TT must review the models to find how many are validated and verifiable. Thus explore the state of validation of the identified models and add to the database.</li> <li>ML noted that TT will also as HFM 270 identify gaps in the research (this will come from validation but will also come from interface investigation between software models). This will be given to the funders of research to show them where to invest in research. Thus, shape and focus future research.</li> <li>AF to draw and explain his structure and method (what the database summary represents in terms of modules and links), what the black box output of HFM 270 represents and how it progressed to new TG (Action 7-23). AB notes it as a flow and connectivity diagram to go from threat to injury prediction and prognosis.</li> </ul> |        |
| 14 | <b>Final report</b> <ul style="list-style-type: none"> <li>RG has sent the draft report outline in July. Only got feedback from TP.</li> <li>ML to send final outline to the RTG members and request volunteers for each section of the report. (Action ML)</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |        |
| 15 | <b>Closing remarks</b><br>ML thanked the group for their contributions and the host for organizing the meeting.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |        |
| 16 | <b>Date of 8<sup>th</sup> meeting</b><br>3 – 5 April 2019 – Stockholm, Sweden                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |        |

| Action                                                  | Description                                                                                                                                                                          | Person | Date      |
|---------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|-----------|
| <b>Meeting 7, 3 – 7 December 2018, Stellenbosch, SA</b> |                                                                                                                                                                                      |        |           |
| 7-1                                                     | AB to prepare summaries of the Sandia and SWRI computational modeling papers and then email the summaries to DB who will upload them onto the Science Connect site.                  | AB/DB  |           |
| 7-2                                                     | TS still need to provide summary on subject matter expert presentations in Suffield.                                                                                                 | TS     | 28/2/19   |
| 7-3                                                     | Develop a draft TAP for a follow-on RTG and send it to all RTG members before meeting 8 in Stockholm. A review and discussion of the draft TAP will be an agenda item for meeting 8. | AB/RG  |           |
| 7-4                                                     | Establish a file naming convention for the summaries of the modeling papers and upload the files to the Science Connect site.                                                        | DB     | Completed |
| 7-5                                                     | Develop a process and information flow scheme for the Framework and present it to the RTG members for consideration and discussion at meeting 8 in Stockholm.                        | DB/AF  | 28/2/19   |

## ANNEX G – MINUTES FROM THE HFM-270 PANEL MEETING DECEMBER 2018

| Action | Description                                                                                                                                                                                                                                                                                                                                                         | Person   | Date      |
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| 7-6    | Review 150 references cited in a paper identified by MP to determine which ones provide relevant information about computational models that should be considered for incorporation into the Framework.                                                                                                                                                             | DB       | 31/03/19  |
| 7-7    | Prepare a spreadsheet with assignments for all RTG members to review and summarize the 200+ papers from the systematic literature review plus the relevant papers from the 150 references identified by MP, and then send the assignment spreadsheet to ML who will email it to all RTG members requesting that they complete their review and summary assignments. | DB       |           |
| 7-8    | Develop a strategy for completing the dictionary of terms and be prepared to discuss it during the February 2019 RTG teleconference.                                                                                                                                                                                                                                | EK/DB/TP | 15/02/19  |
| 7-9    | Ask Pierre Praz at the French-German Research Institute of Saint Louis (ISL) in France if he can provide information on available French models that may be appropriate for the Framework.                                                                                                                                                                          | MP       |           |
| 7-10   | Ask the NATO STO CSO if they can create a searchable database of reference papers identified in the framework.                                                                                                                                                                                                                                                      | MP       |           |
| 7-11   | Incorporate TNO models into the Framework spreadsheet.                                                                                                                                                                                                                                                                                                              | MP/TP    | 7/12/18   |
| 7-12   | Email final report outline to all RTG members with a request for volunteers to write portions of it.                                                                                                                                                                                                                                                                | ML/RTG   | 24/12/18  |
| 7-13   | ML to send out to TT members the updated computational models' spreadsheet.                                                                                                                                                                                                                                                                                         | ML       | Completed |
| 7-14   | Send an email to all RTG members who prepared summaries of the modeling papers asking that they review the latest version of the Framework spreadsheet on the Science Connect site to confirm the accuracy of the information pertaining to the models they summarized.                                                                                             | ML/RTG   | 24/12/18  |
| 7-15   | Send an email to all RTG members asking that they consider the terms, “ <b>computational model</b> ,” “ <b>mathematical model</b> ,” “ <b>risk calculator</b> ,” “ <b>simulation tool</b> ,” and “ <b>statistical model</b> ,” and come to meeting 8 in Stockholm prepared to discuss and finalize definitions for these terms.                                     | ML/RTG   | 24/12/18  |
| 7-16   | Email DB's modeling paper summary assignment spreadsheet (i.e., 200+ papers from systematic literature review and relevant papers from 150 references identified by Mat) to all RTG members requesting that they complete their assigned summaries and email the summary files to Dan Bieler who will upload them to the Science Connect site.                      | ML       |           |

| Action      | Description                                                                                                                                                                                                                                                                               | Person       | Date             |
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| <b>7-17</b> | Prepare summaries for two papers (“A Fatigable Musculoskeletal Model for Prediction of Neck Maneuvering Loadings on Aviators,” and “Challenges in Measuring and Modeling Whole Body Blast Effects,” and email the summary files to DB who will upload them onto the Science Connect site. | <b>ML</b>    | <b>24/12/18</b>  |
| <b>7-18</b> | Notify the NATO STO CSO that Phillipe May is no longer available to serve on the RTG and enquire as to the advisability and practicality of adding a representative from France at this late stage of the RTG’s activities.                                                               | <b>RG</b>    |                  |
| <b>7-19</b> | How does literature describe computational models and differentiates between prediction and injury models?                                                                                                                                                                                | <b>ALL</b>   | <b>24/2/19</b>   |
| <b>7-20</b> | Draw and explain his structure and method with explanation (what the database summary represents in terms of modules and links) what the black box output of 270 and how it progresses to new TG.                                                                                         | <b>AF/DB</b> |                  |
| <b>7-21</b> | Follow up with Thomas Sawyer about providing a summary of the SME presentations from the Suffield meeting.                                                                                                                                                                                | <b>RG</b>    |                  |
| <b>7-22</b> | Upload meeting 7 SME presentation onto the Science Connect site.                                                                                                                                                                                                                          | <b>TP</b>    | <b>Completed</b> |
| <b>7-23</b> | Confirm location and dates for the final RTG meeting in Paris                                                                                                                                                                                                                             | <b>RG</b>    |                  |
| <b>7-24</b> | Prepare meeting 7 minutes using the same format as that used for the previous meeting minutes and email the draft minutes to Raj Gupta.                                                                                                                                                   | <b>DR</b>    | <b>10/1/19</b>   |



## **Annex H – MINUTES FROM THE HFM-270 PANEL MEETING APRIL 2019**

### **H.1 MEETING #8, 2 – 5 APRIL 2019, KAROLINSKA INSTITUTET**

HFM-270 (RTG) “Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats”.

| <b>PRESENT</b>              |                           |
|-----------------------------|---------------------------|
| <b>Members</b>              |                           |
| Mr. Thanyani Pandelani (TP) | Dr. Anette Fransson (AFr) |
| Dr. Mat Philippens (MP)     | Dr. Emrys Kirkman (EK)    |
| Dr. Axel Franke (AF)        | Mr. Tyson Josey (TJ)      |
| Dr. Amit Bagchi (AB)        | Dr. Sarah Watts (SW)      |
| Dr. Raj Gupta (RG)          | Mr. Mike Leggieri (ML)    |
| Dr. Mattias Sköld (MS)      | Dr. Mårten Risling (MR)   |
| <b>Apologies</b>            |                           |
| Dr. Dan Bieler (DB)         | <b>Skype:</b>             |
| Dr. Ibolja Cernak (IC)      | Dr. David Reinecke (DR)   |

#### **H.1.1 Day 1**

##### **H.1.1.1 Introduction – (MR)**

The Karolinska Institutet (KI) was founded by King Karl XIII after losses suffered by the Swedish army during 1808 – 1809. The university was founded in 1810. It moved to the current location, the KI campus in Solna, in 1945. At the most KI was composed of 140 departments, which later were merged to 20 larger departments.

MR, MS and AFr work in the experimental Traumatology Unit (XT) at the neuroscience department. The XT unit was a part of the Defence Research Agency (FOI) until 2008, when it was decided to transfer the defence research in traumatology to KI. The Karolinska hospital in Solna is one of the teaching hospitals that are associated to KI. This hospital is located nearby the KI campus and the regional trauma center is located at this hospital. One other teaching hospital, the south general hospital (Södersjukhuset) from 1940, has a large shelter area that was constructed as a war hospital. The XT group has labs for blast experiments in this shelter area.

### **H.1.1.2 Chairman Briefing (ML)**

ML thanked the host nation and the members. This is the second last meeting.

WEBex meetings have not been so successful, so the remaining meeting is the meeting in Paris in September.

ML presented the framework for modeling and simulation of human lethality, injury, and impairment from blast-related threats, just to remind everyone about the objectives of the TG.

The approach is to develop a black box of computational modeling capability which can predict lethality, injury and impairment and help with weapon system health risks, rapidly design protection concepts, and cost reduction. This approach will enable the development and testing for individual and vehicle occupant blast protection concepts in virtual environment. The black box to cover blast injuries from primary to quinary.

### **H.1.1.3 Objectives for the Meeting**

- Evaluate concept of the framework.
- Identify gaps where no suitable models exist.

### **H.1.1.4 Action Items from SA Meeting (RG)**

- Minutes from SA – AB had comments, that will be sent to TP to finalize.
- Strategy to complete dictionary term – Identify what is missing in the terms. EK pointed out that it is important to have a member with experience in modeling in the dictionary group. RG to send out the current version to the dictionary team – EK, AB, RJ, TP, DR, TJ. AB was concerned that the group might not have enough time at the next meeting to complete the task. The meeting needs to be structured in a such that all items must be covered. It was suggested that the work to include new terms should be finished during May.
- MP – had been assigned to check the possibility to have a new member from France. Contact was made and it was not possible to recruit a new member and this needs to be pointed out in the final report.
- ML had indicated that he would send out a request for volunteers to take the lead for the production of each chapter in the final report. ML had received a number of positive responses.
- DB had been assigned to distribute papers for the systemic review. AF will check the timeline for this.
- MP – to check if it was possible to use the TNO example of coupled models. Still open.
- MP – NATO CSO for the searchable database – NATO needs more details, and the group must come up with the list of requirements – to be done at this meeting.
- Mat to submit a new summary sheet from TNO models – MP.
- Paris meeting will be expanded to four days. 3 – 6 September. Send security info in time for the Paris meeting – All.

**H.1.1.5 Process and Information Flow Scheme for the Framework**

How to connect the models?

Use the TNO models to test the framework. MP to write up for the report and explain the gearbox in detail.

Discussion of the idea of a living document, so modules can be updated. NATO has probably no possibility to maintain that, but ML indicated that the DoD Blast Injury Research Program Coordinating Office possibly could take the lead for that. A DoD workgroup could maybe be transformed into an international.

**H.1.1.6 TAP Discussion – AB****Topic**

Validation of modeling and simulation methodologies for human lethality, injury, and impairment from blast related threats.

**Objectives**

Develop over-arching architecture to integrate computational models of human responses to blast-related threats to predict human lethality, injury impairment and long-term health effects.

Evaluate the framework hypothesis (concept) to integrate computational models that were not designed to work together to provide end to end modeling capability from threat to outcomes.

Characterize the limitations and the statistical confidence of the output of the over-arching architecture.

**List of topics were presented – See TAP document**

Overall approach for validation and development of a validation methodology for integrated framework that is broad and flexible enough to validate different computational models which address different needs, organs, threats, and desired outcome.

**Deliverables**

Description of specifications for evaluations of over-arching architecture.

Updated dictionary of terms.

Representative examples that will be analyzed to establish the limitations of the architecture.

**Technical Lead**

Lead nation: USA

Chair: AB

**Timeline for TAP**

Draft in middle of 15 May 2019.

Deadline: 22 June – Final version.

**H.1.2 Day 2**

| <b>PRESENT</b>              |                           |
|-----------------------------|---------------------------|
| <b>Members</b>              |                           |
| Mr. Thanyani Pandelani (TP) | Dr. Anette Fransson (AFr) |
| Dr. Mat Philippens (MP)     | Dr. Emrys Kirkman (EK)    |
| Dr. Axel Franke (AF)        | Mr. Tyson Josey (TJ)      |
| Dr. Amit Bagchi (AB)        | Dr. Sarah Watts (SW)      |
| Dr. Raj Gupta (RG)          | Mr. Mike Leggieri (ML)    |
| Dr. Mattias Sköld (MS)      | Dr. Mårten Risling (MR)   |
| <b>Visitors</b>             | <b>Skype:</b>             |
| Dr. Ulf Arborelius (UPA)    | Dr. David Reinecke (DR)   |
| SMEs                        |                           |

**H.1.2.1 Discussion on the Outline of the Final Report of HFM-270**

RG did suggest the following sections/chapters. ML and RG had sent out a request for volunteers could take the lead for each chapter. It was decided to distribute the work as below.

**H.1.2.2 Report Sections**

Chapter 1 – Introduction/Background – ML.

Chapter 2 – IED explosion, Blast physics, human body blast loading and injury, Mounted and dismounted – TJ (Lead) and MP, MR, TP, and Simon Ouellet.

Chapter 3 – Computational Modeling/Framework – MP (Lead) EK, RG, DB, AF, MS.

Chapter 4 – Design of Framework – RG (Lead) DR, AB, AF, MS.

Chapter 5 – Scope of existing Computational Models – DB (Lead), AF, AB.

- SW mentioned that some of the reviews were done by non-experts. A statement should be added that the reviews are personal opinions of the authors.
- ML said we need to stress the value of having multi-disciplinary review.

Chapter 6 – maybe delete for now.

Chapter 7 – MP (Lead) DR and AB.

Discuss TNO models that were designed to work together and identify models from the matrix that were not designed to work together but could be used to show how different models may work together.

The country that gets the models from the home into the framework will be required to Complex a section as well.

Chapter 8 – Findings-Gaps. – AB Lead.

Chapter 9 – Recommendations.

Chapter 10 – Annexes.

### **H.1.2.3 Publication Group**

- The work with the systemic review is ongoing.
- EK to contact the publisher of the Journal of the Royal Army Medical Corps and find out how much can be published. A deadline for finishing by the end of 2019 is suggested.
- A summary paper with the matrix can also be presented.
- AB asked if it's possible to get a computational paper in a computational journal. The connection between X and module Y. DR/TP to assist with identifying the journal.

### **H.1.2.4 Presentations by Subject Matter Experts**

**SME 1 Johan Davidsson** Chalmers Technical University, Gothenburg

- Development an experimental model for rotational TBI and validation of FE model of experimental TBI. The experimental model has been developed for rats. There is no head impact that can result in skull fracture. Head attachment glued to the head of rats and the head can be rotated without direct impact. Rotation can be graded and can generate injuries from mild to severe. The typical pathology is diffuse axonal injuries in white matter areas, such as the corpus callosum. Axonal injuries can occur without any vascular damage.
- Scaling is critical for translation of the rat experiment to a clinical setting. Rat brain proportions different from human, without the folded shape that is typical for the human brain. Tissue properties may be different, but the shape and function of the cells are similar. PPT file included as annex (PDF).

**SME2 Niclas Wisén** (Capt) Psychologist in Swedish Army and PhD student at KI

Low Level Blast (LLB) exposure Breaching studies in Special Forces. During breaching training operators had used Blast Gauge Sensors (BGS) which did occasionally signal red. A study was initiated to evaluate the physiological response during breaching training. The operators were equipped with BGS, Equivital sensors for respiratory and cardiac functions. Biomarkers were sampled before, during and after exercise, cortisol was analyzed from saliva and Tau, NSE, NFL and S100b was studied in blood samples. Cognitive performance was measured using Defense Automated Neuro Assessment (DANA) a tablet-based test battery of cognitive functions, such as reaction time, working memory, stimuli discrimination, impulse control, etc. There was no evidence of brain injury. The biomarkers related to brain injury showed some reactivity but returned to baseline after only one day. The return to baseline in a short timeframe indicates that it's not too severe at least not in the short run, suggesting that training as it is performed today is to be considered safe. Stress sensitive measures did

not indicate any confounding stress/strain, indicating that participants were both mentally and physiological prepared for the task. Neither did the training show any effects on cognitive measures and values from the blast gauge indicated that LLB was comparatively low. PPT file included as annex (PDF).

**SME 3 Svein Kleiven** KTH (Royal Institute of Technology), Stockholm

### **Computational Modeling of Human Head Injuries**

Described the need for age-specific models of the body. The outcome of injuries is different in small children and old age. The group at KTH has studied the mechanical properties of the brain during rotational injury and produced a number of models, that include directional properties of the white matter fiber tracts and also models for subcellular response in axons during injury. The models have indicated a mechanical load in the depth of the sulci of the brain during impact. The group has also been involved in the development of the MIPS helmets. The MIPS BPS System can reduce the rotational motion and thereby reduce the risk of brain damage. PPT-files are included as annex (PDF-format).

### **H.1.3 Day 3**

| <b>PRESENT</b>              |                                       |
|-----------------------------|---------------------------------------|
| <b>Members</b>              |                                       |
| Mr. Thanyani Pandelani (TP) | Dr. Anette Fransson (AFr)             |
| Dr. Mat Philippens (MP)     | Dr. Emrys Kirkman (EK)                |
| Dr. Axel Franke (AF)        | Mr. Tyson Josey (TJ)                  |
| Dr. Amit Bagchi (AB)        | Mr. Mike Leggieri (ML)                |
| Dr. Raj Gupta (RG)          | Dr. Mårten Risling (MR)               |
| Dr. Mattias Sköld (MS)      |                                       |
| <b>Skype:</b>               | <b>Absent</b>                         |
| Dr. David Reinecke (DR)     | Dr. Sarah Watts (SW) (returned to UK) |

#### **H.1.3.1 Outline for Each Chapter of the Report. Discussion Lead by ML**

##### **CH1 – Introduction/Background – ML**

Concepts to be highlighted:

- Need to be written in a way that it will be understood by everyone.
- ML to draft the entire background and send to everyone.
- To help them understand the impact of the work.
- Describe the over-arching value of having computational modeling capability that can model the human outcome from threat to outcome.

- Illustrate the value of the modeling capability/framework.
- Rapidly response and anticipate future threat.

**CH2 – IED Explosion, Blast Physics, Human Body Blast Loading, and Injury – TJ Lead**

- Should address the entire spectrum of blast – Primary to Quinary.
- Focused on decision makers, not modelers in their technical contents.
- Add the basics equations, but not the details. Example, with photos of experiments.
- Explain according to experiment what kind of injuries can be caused.
- Difficulties in sharing the experiments and standardizing the experiments.
- MR suggest we should use the perspective that old studies have been developed and add new work, such as repeated exposure.
- Describe the needs of computational model from the basics.
- Add high level what is a computation model in CH2.
  - Key terminology – Modeling, threat.
  - RG will assist with describing the terminology.
- Background information to make sure the reader understands what the framework is about.

**CH3 – Computational Modeling/Framework – MP (Lead), EK, MS, TJ**

- Describe the chain and different models.
- Describe how the framework was developed and how it fits together.
- Use the overview done in NL as the basis for the report.
- Look at other platform/publications how the computational models are defined.
- Introduce the modules.
- Definition of threat and blast, loading, injuries, etc.
- Include the example of old work, such as Bowen curves. Which covers 2 – 3 modules.
- Change name of Ch3: Chain from blast scenario to human effects.

**CH4 – Design of the Framework – RG (Lead) DR, AB, AF, MS**

- Cover the three elements and the four modules.
- Explanation for the numbering convention for the modules.
- Modules 1 and 2 are extra-corporeal – Outside the body.
- Module X and Module Y are in-corporeal – biomedical response.
- Description of matrix in likes of module X and Y.
- Give an example of computation model for each module.

**CH5 – Scope and Breadth of Existing Computational Models – (DB) Lead**

- Details of what a computational model is.
- Add details of the review paper.
- Future application of the framework.
- Structure in a way to give a short overview to categories the models.
- Systematic inventory of the models by questionnaire and reviews.
- Explain exactly how the review was conducted.
- Include actual questionnaire in the appendix.

**CH6 – Deleted. This will be incorporated in Chapter 5.****CH7 – Illustrations of Models that Can Work Together – MP – Lead, DR, and AB**

- Discuss TNO models that were designed to work together and identify models from the matrix that were not designed to work together but could be used to show how different models may work together.
- Explain in the chapter what it takes to get the models to work together.

**CH8 – Findings-Gaps – AB – Lead**

- No models that can start from threat to outcome.
- Identify models that are missing based on the matrix.
- Research gaps.
- More models in one part of the framework and less in the other parts of the framework.
- More models for some part of the body and less on some part of the body.
- There is no organization/coordinated effort/entity that is coordinating the development of end to end (threat to outcome modeling).
- Models are using different codes/languages.
- Lack of validation/verification of the models.
- Define validation/verification in the documents.
- A process or procedure for model validation/verification in this field.
- Input data into the models, often very unsatisfying.

**CH9 – Recommendations – AB**

- Knowledge gaps should be indicated and lead to recommendations for a follow-on group, these gaps can be divided into short-term and long-term gaps.
- Suggest a platform for a maintained database. CSO or DoD Blast Injury Research Program Coordinating Office. Suggestion for a State of the Science Meeting with focus on linked models.

**CH10 – Annexes**

- Technical team members will add the annexes (meeting notes, presentations).

**H.1.3.2 Notes**

AB suggested that we could have two telecon meetings. ML said it is difficult to have more people participate at the telecon, but the emails should work well.

Due date for the chapters before Paris meeting – end of July 31.

Send your chapters to RG.

Coordinate within your team about writing deadlines.

RG to send the report template to the TG members.

**H.1.3.3 Planning for the 9th Meeting**

Meeting date: 3 – 6<sup>th</sup> September 2019 in Paris.

Planned as writing meeting. The draft report should be finalized at the meeting.

### Appendix H.1: Report Writing and Compilation Dates

| Task/Step                                                                                              | Target Date (Internal) | Responsibility                                     |
|--------------------------------------------------------------------------------------------------------|------------------------|----------------------------------------------------|
| Chapter leads to send their chapters to Chapter Team members for a final acceptance                    | 30 September 2019      | Chapter Leads/Chapter Team Members                 |
| Chapter leads to submit all final chapters to Raj                                                      | 20 October 2019        | Chapter Leads                                      |
| Raj to submit all chapters to Emrys                                                                    | 25 October 2019        | Raj                                                |
| Emrys to send consolidated draft HFM-270 report in the CSO template to all RTG members for information | 10 November 2019       | Emrys                                              |
| Consolidated draft HFM-270 report review by Raj and editorial team (Raj, Emrys, Amit, Mattias)         | 30 November 2019       | Editorial team                                     |
| Raj to send out NATO STO Form 13-1                                                                     | 30 November 2019       | Raj                                                |
| Raj to send out final report to RTG members                                                            | 30 December 2019       | Raj                                                |
| RTG members to completed NATO STO form 13-1 to Raj (i.e., country approval)                            | 31 January 2020        | RTG members                                        |
| Submit final report to US DOD STO with NATO STO forms 13-1                                             | 28 February 2020       | Raj                                                |
| US DOD sends final report and documentation to STO                                                     | 15 April 2020/ TBD     | US                                                 |
| <b>Chapter</b>                                                                                         | <b>Lead</b>            | <b>Team Members</b>                                |
| 1: Introduction                                                                                        | Mike                   |                                                    |
| 2: Blast Physics                                                                                       | Tyson                  | Mat, Maarten, Thanyani, Raj, Emrys, Mattias        |
| 3: Concept of Computational Modeling Framework                                                         | Mat                    | Emrys, Dan, Axel, Mattias, Tyson, David, Amit, Raj |
| 4: Design of Framework                                                                                 | Raj                    | David, Amit, Axel, Mattias                         |
| 5: Scope and Breadth of Existing Computational Models                                                  | Dan                    | Axel, Amit                                         |
| 6: Findings                                                                                            | Amit                   | All                                                |
| 7: Conclusions and Recommendations                                                                     | Amit                   | All                                                |

## Annex I – TWO EXAMPLES OF REPORTS EVALUATED BY THE PANEL

### I.1 EXAMPLE 1

Armiger, R.S., Otake, Y., Iwaskiw, A.S., Wickwire, A.C., Ott, K.A., Voo, L.M., Armand, M., Merkle, A.C. Biomechanical Response of Blast Loading to the Head Using 2D-3D Cineradiographic Registration. In Mechanics of Biological Systems and Materials – Proceedings of the 2013 Annual Conference on Experimental and Applied Mechanics. Conference Proceedings of the Society for Experimental Mechanics Series; 4, pp. 127-134.

#### Objective

Blast Overpressure – Health Hazard Assessment Software

#### Overview of Model

This model analyzes skull and brain deformation in Post-Mortem Human Subjects (PMHS) using 2D cineradiographic images during a high loading event.

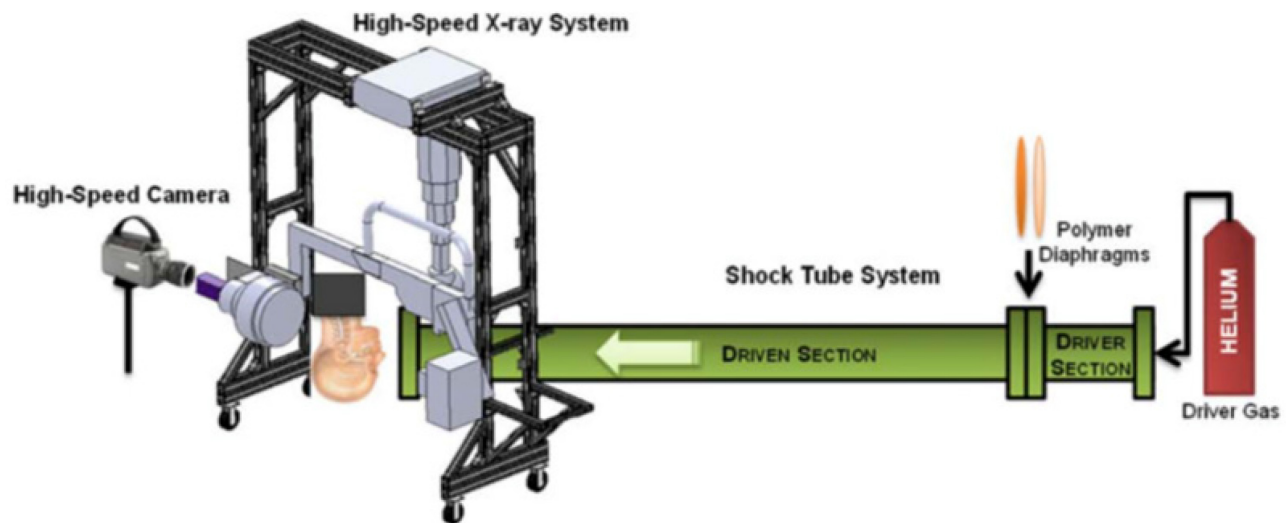


Figure H-1: Experimental Setup Showing Specimen Position with Respect to the Shock Tube and Orthogonally Aligned to HSXR.

#### Computational Modeling Technique

Biomechanical injury model

## **ANNEX I – TWO EXAMPLES OF REPORTS EVALUATED BY THE PANEL**

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### **Assumptions/Limitations**

- Calculates skull and brain injury due to shock tube loading (1000 kPa).
- Uses anatomic cadaver, which were frozen before.

### **Data Input Needed/Used**

- Pressure and time data from a shock tube.

### **Validation**

None

### **Modules Assessment**

A biomechanical model that utilizes loading as input to characterize biomechanical parameters scoring that can be utilized for product (e.g., protective equipment) assessment.

### **References**

- [1] Barthelat, F. et al., Mechanics of Biological Systems and Materials, Volume 4, DOI 10.1007.

## **I.2 EXAMPLE 2**

Shoge, R.O., Hsu, Y. Lung Injury Prediction Model for Blast Overpressure.

### **Objective**

Blast Overpressure – Health Hazard Assessment Software

### **Overview of Model**

This model analyzes pressure-time data recorded from blasts to compute the extent of lung injury. The extent of observed lung surface contusion is correlated to the irreversible work done to the lungs caused by blast impact to the thorax. The model outputs are:

- a) Normalized irreversible work done on the lung by the pressure wave;
- b) Lung surface injury severity into four injury severity levels utilizing a Walter Reed Army Institute of Research;
- c) Injury probability derived from a pool of 1,300 specimens; and
- d) Allowable number of small arms fire rounds to which a person may be exposed for each level of injury severity.

### **Computational Modeling Technique**

The biomechanical injury model developed by L-3 Applied Technologies (formerly Jaycor) is based on the JAYCOR INJURY model; solving software is BOP-HHA.

**Assumptions/Limitations**

- Calculates physical lung injury only (24 hours post blast only).
- Does not consider repeated blast effects (i.e., no cumulative effects).
- Does not anticipate changes in intersegmental distances that may occur in different postures that could affect blast pressure.
- Pressure loading to thorax is the key input to the model.
- Sheep lung tissue response similar to that of human lung tissue.

**Data Input Needed/Used**

- Pressure vs time data from a blast event.
- Blast test device with specified transducers.
- Lethality data developed by Walter Reed Army Institute of Research (US).

**Validation**

Model is claimed to be validated against lung contusion data collected from 1300 sheep subjects exposed to a range of blast levels in free field tests and in confined conditions. Injury is characterized based on work done to the lungs and correlated to four levels of lung injury.

**Modules Assessment**

A biomechanical model that utilizes loading as input to characterize biomechanical parameters and injury scoring that can be utilized for product (e.g., protective equipment) assessment.



## **Annex J – LITERATURE RESEARCH USED TO CREATE FLOWCHART**

Table J-1 gives an overview of the included articles sorted by effect organ.

**Table J-1: Full Text Articles Sorted by Affected Organ.**

| Full Text Articles Sorted by Affected Organ |    |
|---------------------------------------------|----|
| Brain                                       | 83 |
| Head and face                               | 17 |
| Ear and cochlea                             | 5  |
| Eye                                         | 18 |
| Cervical spine and neck                     | 5  |
| Lung                                        | 22 |
| Chest and abdomen                           | 9  |
| Thoracal and lumbar spine                   | 8  |
| Leg and lower limb                          | 8  |
| Musculoskeletal                             | 8  |
| Soft tissue                                 | 1  |
| Whole body                                  | 7  |
| Not applicable to a body region             | 72 |

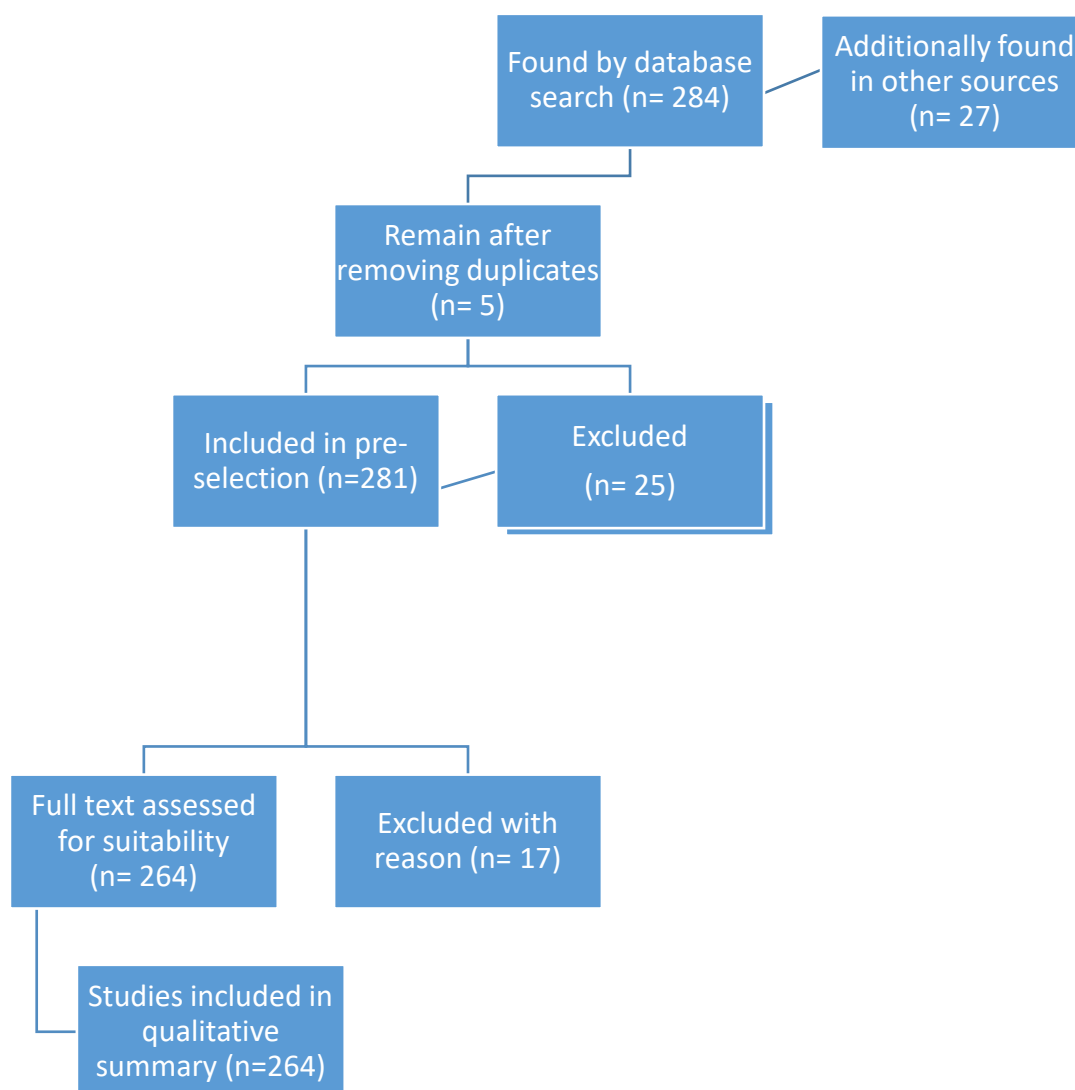


**Figure J-1: Flowchart for Literature Research.**

## J.1 BRAIN

- [1] Akula P, Hua Y, Gu L. Blast-induced mild traumatic brain injury through ear canal: A finite element study. *Biomedical Engineering Letters*. 2015; 5(4): 281-288. doi:10.1007/s13534-015-0204-0.
- [2] Baalman KL, Cotton RJ, Rasband SN, Rasband MN. Blast wave exposure impairs memory and decreases axon initial segment length. *J Neurotrauma*. 2013; 30(9) :741-751. doi:10.1089/neu.2012.2478.
- [3] Brady RD, Shultz SR, Sun M, Romano T, van der Poel C, Wright DK et al. Experimental traumatic brain injury induces bone loss in rats. *J Neurotrauma*. 2016; 33(23): 2154-2160. doi:10.1089/neu.2014.3836.

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- [12] Goeller J, Wardlaw A, Treichler D, O’Bruba J, Weiss G. Investigation of cavitation as a possible damage mechanism in blast-induced traumatic brain injury. *J Neurotrauma*. 2012; 29(10): 1970-1981. doi:10.1089/neu.2011.2224.
- [13] Golman AJ, Wickwire, Alexis C., Harrigan, Timothy Patrick, Iwaskiw, Alexander S., Armiger, Robert S., Merkle, Andrew C. Hierarchical model validation of the falx cerebri and tentorium cerebelli. *Injury Biomechanics Research Conference Proceedings*. 2014.
- [14] Gullotti DM, Beamer M, Panzer MB, Chen YC, Patel TP, Yu A et al. Significant head accelerations can influence immediate neurological impairments in a murine model of blast-induced traumatic brain injury. *J Biomech Eng*. 2014; 136(9): 091004. doi:10.1115/1.40.
- [15] Gupta R. Multiscale modeling of blast induced traumatic brain injury: from whole body responses to brain microdamage. 2014. *Proceedings of 11th World Congress on Computational Mechanics*, 991-999.
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## ANNEX J – FLOWCHART FOR LITERATURE RESEARCH

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| <b>6. Title</b>                      | Framework for Modeling and Simulation of Human Lethality, Injury, and Impairment from Blast-Related Threats                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                             |                                               |
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| <b>13. Keywords/Descriptors</b>      | Biomechanics; Blast exposures; Blast injury; Blast model coupling; Blast simulation; Clinical prediction; Computational; Dismounted; Explosion; Health effects; Health outcome; Impairment; Injury criteria; Lethality; Mounted; Multi-physics; Multiresolution; Multiscale; Pathophysiology; Predict; Prevent                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                             |                                               |
| <b>14. Abstract</b>                  | <p>Explosive Weapons (EW) are a continuing and significant source of casualties in NATO operations. The spectrum of operational scenarios involving these blast threats is broad and includes both mounted and dismounted operations. As EW technology and deployment methods becomes more complex, the same trend is seen for injuries, requiring increasingly sophisticated protective countermeasures and medical interventions. The HFM-270 (RTG) explored a novel conceptual multiscale, multiresolution computational framework that integrates existing and planned models of human responses to blast-related threats. The conceptual framework created a methodology to predict human lethality, injury, impairment, and long-term health effects with the potential to reduce the time required to develop and field effective strategies to prevent, mitigate and treat blast injuries. The three major deficiencies in implementing the new conceptual framework were: a) Lack of end-to-end connection and continuity in current simulation models to address combat injuries utilizing the techniques; b) Insufficient and incomplete material models essential for such simulations; and c) Limited validation of the models based on experimental and clinical data. It is the intention of the HFM-270 (RTG) that each NATO nation should consider the gaps identified by this RTG when planning future investments in computational modeling and prediction efforts.</p> |                             |                                               |





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