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14. ABSTRACT

This report describes progress toward scientific and technical objectives of the Military Operational Medicine Research Program. The further development of the Toxic Gas Assessment Software (TGAS) includes models for respiratory, circulatory, and metabolic systems and the control of breathing. The first year's work on developing a biomechanically-based assessment of behind body armor blunt trauma is described, including measurements of actual loads and estimated response.

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Contents

1. Introduction

1.1 Critical Issues

The US Army Medical Research and Material Command (USAMRMC) faces ever-increasing pressure to answer more mission questions with less resources and time. The Catch-22 aspect is that problems cannot be satisfactorily solved at the moment they arise unless the supporting research basis has already been laid. Consequently, it is imperative to be proactive: anticipate need and put in place the broadest infrastructure of applied research that can be practically accomplished.

In addition to basic research programs, the USAMRMC has formulated a number of Scientific and Technical Objectives (STO) to achieve certain specific technical results over a period of 3-5 years. By their nature and firm objectives, these programs are applications of the basic findings. Their goals, by and large, are to transition scientific findings into devices, treatments, procedures, or standards that can be used or applied in a military environment. In these programs, scientific breakthroughs are not planned, but high probability of a useful product is.

As of FY99, the Military Operational Medicine Research Program (MOMRP) has 13 STO programs proposed or active. These programs are designed to develop useful products in a wide range of military medicine areas from A (Laser Bioeffects and Treatment) to Z (Mass Properties of Head-Support Devices and Soldier Health). In each case the proposed product is based on promising results obtained in more basic research, which must be refined and validated in the less controlled environment of military operations.

To make the transition from the laboratory to the field, it is critical to take full advantage of the findings from the laboratory. Those findings are primarily in the form of experimental data, often collected under idealized conditions and perhaps in animal or surrogate models. Those data must be extrapolated to man in a military scenario in order to guide the device, treatment, procedure, or standard being developed by the STO.

Rapid, comprehensive data retrieval and analysis, coupled with mathematical modeling putting the results in the context of physiological and physical processes, are highly effective and often indispensable tools for achieving these goals. In some STOs (K, U, and Y), mathematical models are the product. In others (H and W), mathematical models and data analysis are specific components that will be used to achieve the desired product. In every STO data analysis and extrapolation play a critical role.

1.2 What is Needed

In each MOMRP STO, but particularly STOs H, K, U, W, and Y, there is a need for mathematical models that capture the scientific findings of the underlying basic research and provide a product that can be used to meet the objectives of each respective STO. The models should be as complete and sophisticated as possible, yet be reliable enough to ensure that the final goals are met. These requirements suggest a program of incremental improvement, based on laboratory testing and more research-oriented mathematical modeling, and of practical design that expresses input and output in the framework of the particular application.

1.3 Technical Objective

The research program sponsored under contract DAMD17-00-C-0031 will provide the USAMRMC with data organization, mining, and knowledge management tools and with practical mathematical models that guide the effort in the MOMRP STOs. The approach is to define a "base" model that can be incrementally improved over the life of the STO. The successive model improvements are designed to meet the evolving requirements of each STO. A review and assessment of the literature and collection and organization of relevant data will proceed in step with the model development.

1.4 Second Year's Accomplishments

In 2000, the first modeling STO was approved, STO-Y: Inhalation Injury and Toxicology Models. A multiyear effort will deliver a comprehensive assessment tool, the Toxic Gas Assessment Software (TGAS), for acute exposure to toxic gases, particles, and aerosols generated in fires. During Year One, the first version of the model, implemented in an Excel spreadsheet was delivered to WRAIR for evaluation. In May 2001, the plan and first year's work was peer-reviewed by the American Institute of Biological Sciences.

During Year Two, a number of enhancements to the TGAS model were made. First, the model was recast in a state-of-the-art simulation language, SIMULINK. This formulation will allow the model to grow in complexity in a systematic manner without having to expend effort developing numerical solution algorithms. The recast model was revalidated against immediate incapacitation data to verify that the formulation was done correctly. Next, a procedure was developed to generate a stand-alone version of the software, eliminating the need for the user to purchase the SIMULINK development language. A graphical user interface was created that guides the setting up of exposure conditions and the automatic generation of documentation on input and output. This first production version of TGAS, Version 1.2, was delivered to WRAIR for evaluation and use in

on-going toxic gas assessment projects. A journal article describing the TGAS methodology and data comparison was prepared for and accepted by *Inhalation Toxicology*. A source book on control of breathing was finalized and a master plan for adding breathing control into the model was developed. The model was expanded to include respiratory, circulatory, and metabolic systems and ventilation and cardiac controls. Data collected in small animals by WRAIR was analyzed to determine ventilation pattern changes due to exposure to toxic gases. The data was qualified, organized, and analyzed in a form that allows direct comparison with model prediction. Preliminary validation of the model against data is encouraging.

In 2001, the second modeling STO was approved, STO-K: Behind Armor Trauma Modeling. A multiyear effort will develop a methodology for estimating the potential for blunt trauma injury behind nonpenetrated personal body armor. The current standard, based on the depth of depression in clay, is controversial and without scientific basis. It is conjectured that the standard may be too stringent, thereby forcing body armor to be too inflexible and uncomfortable and therefore reducing the use of this protective gear. This STO will provide a biomechanically-based criterion that should improve both the assessment of current armor and assist developers in creating better armor in the future.

During the current reporting period, a review of previous behind armor research was conducted to determine the magnitude of loads delivered to the body and the nature of injuries observed. The primary injury observed is lung contusion, an injury previously seen in blast overpressure exposure and one for which good biomechanical models exist. Next, a prototype load-measuring device was constructed for determining reliably the nature of behind armor loading. The device incorporates force and pressure distribution instrumentation and, when combined with high-speed cinematography, provides a complete dynamic description of the loading process. Field tests were then conducted with both hard and soft body armor (HBA, SBA) to test the feasibility of the measuring equipment and to collect actual behind armor data. The loading observed is consistent with simulations of bullet-armor interaction. Based on these measurements, a laboratory impactor is being constructed to deliver equivalent loading to animal test subjects. The first version of the impactor has been built and tested and a second-generation impactor is in design. The animal tests will be conducted at UCSD. Preliminary approval of an animal protocol has been obtained. Work has begun on constructing detailed, anatomical finite element models of both the test animal species, pig, and of man. The work will use high resolution CT imaging to be collected by UCSD as part of the animal testing program.

The body of this report summarizes work accomplished and products produced. Some of the products listed have been provided to other researchers to assist their own projects and are not to be distributed until those researchers have a chance to publish their work. Those products are listed as [in review] or [internal use].

2. STO Y—Toxic Gas Incapacitation and Injury

2.1 TGAS 1 in SIMULINK

The first version of the Toxic Gas Assessment Software, TGAS, uses an internal dose to predict toxic effects. The internal dose is the total mass absorbed by the body divided by the body mass. This normalized internal dose is expected to be valid across species, thereby allowing small animal data to be used to predict effects in man.

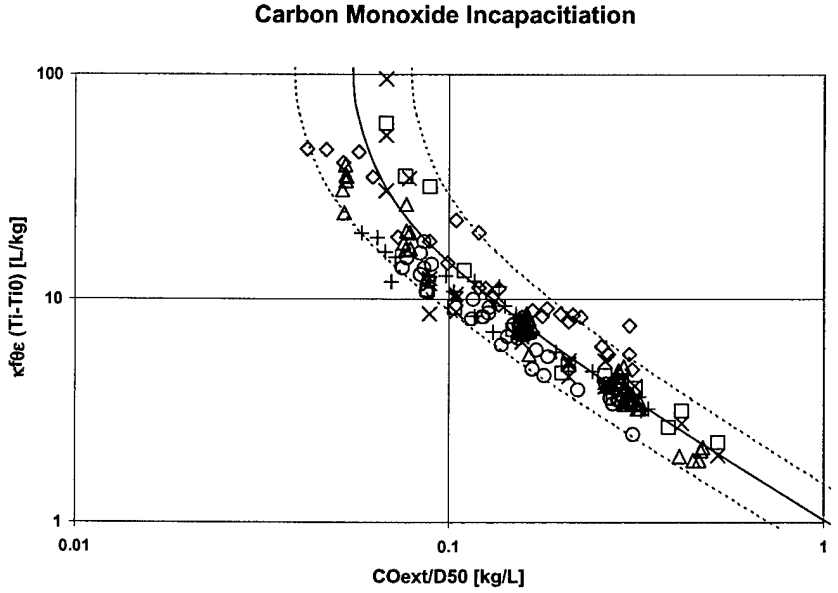


Figure 1. Example of correlation of normalized internal dose as calculated by TGAS with the observed time to incapacitation.

The probability of immediate incapacitation, the end point effect predicted by TGAS 1.0, is correlated to the normalized internal dose. The effects of gas mixtures are found by combining the probability of effects from individual gases.

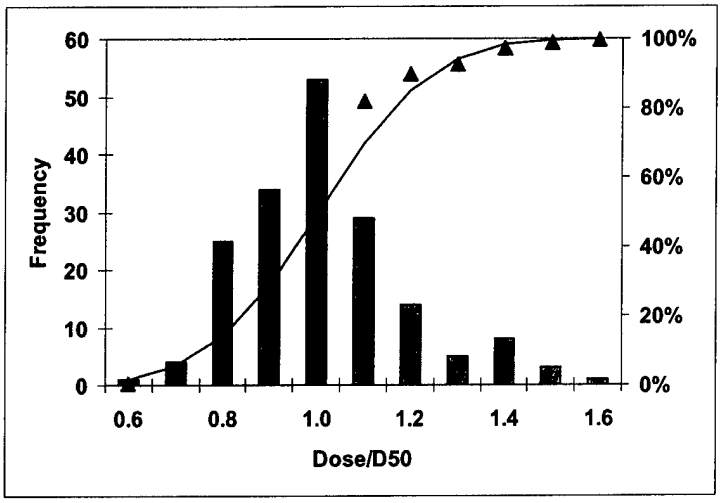


Figure 2. Probabilistic dose-response curve determine for carbon monoxide.

The models used in TGAS 1.0 to determine the total mass absorbed are relatively simple and were solved in an Excel spreadsheet during Year One. As the model becomes more physiologically correct, however, the model equations will become too complex for a spreadsheet, so the model equations were recast into the simulation language, SIMULINK, manufactured by MathWorks, Inc. After the model was reformulated, all of the previous data validation tests were repeated to demonstrate that the model was correctly implemented.

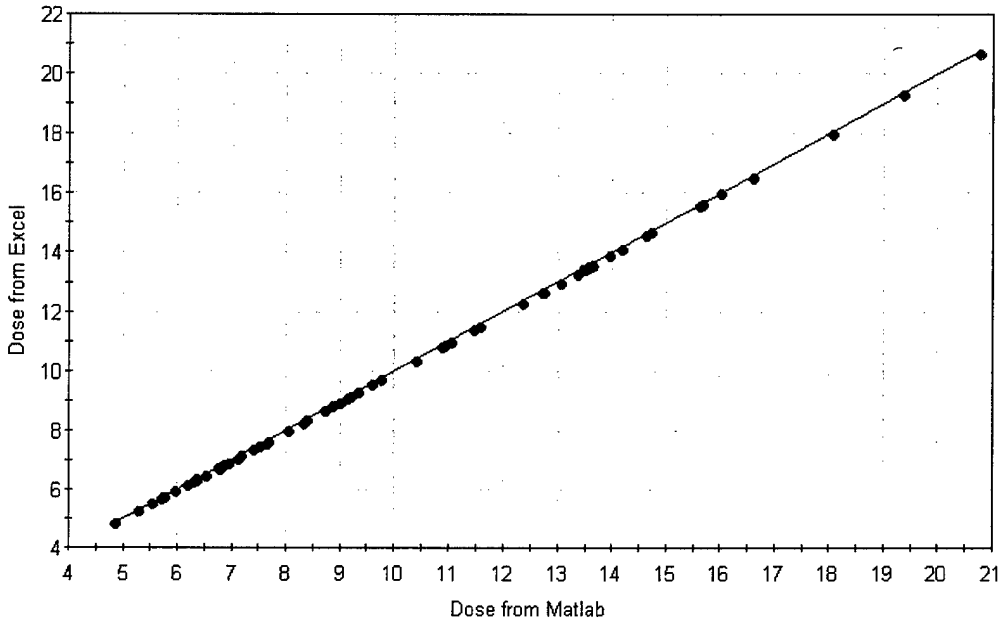


Figure 3. Dose comparison for HCL.

Since SIMULINK is an extremely expensive software development package, it is not feasible to distribute TGAS in the development format. Consequently, Jaycor worked with MathWorks to develop a procedure for producing a stand-alone executable form of the model that can be distributed without purchasing any other software product. The executable version uses the same input format as the development version so that all validation tests can be conducted to verify the correct operation of the distributed software.

To facilitate the use of the software, a graphical user interface was developed in Visual Basic. The user can select or enter all of the parameters of the exposure from a single screen and make calculations that determine the time at which 50% incapacitation will occur in a time-varying, toxic gas mixture or determine the time at which a user-requested probability of incapacitation will occur in a time-constant, toxic gas mixture. In each case a summary report is generated which shows the input conditions and the predicted results.

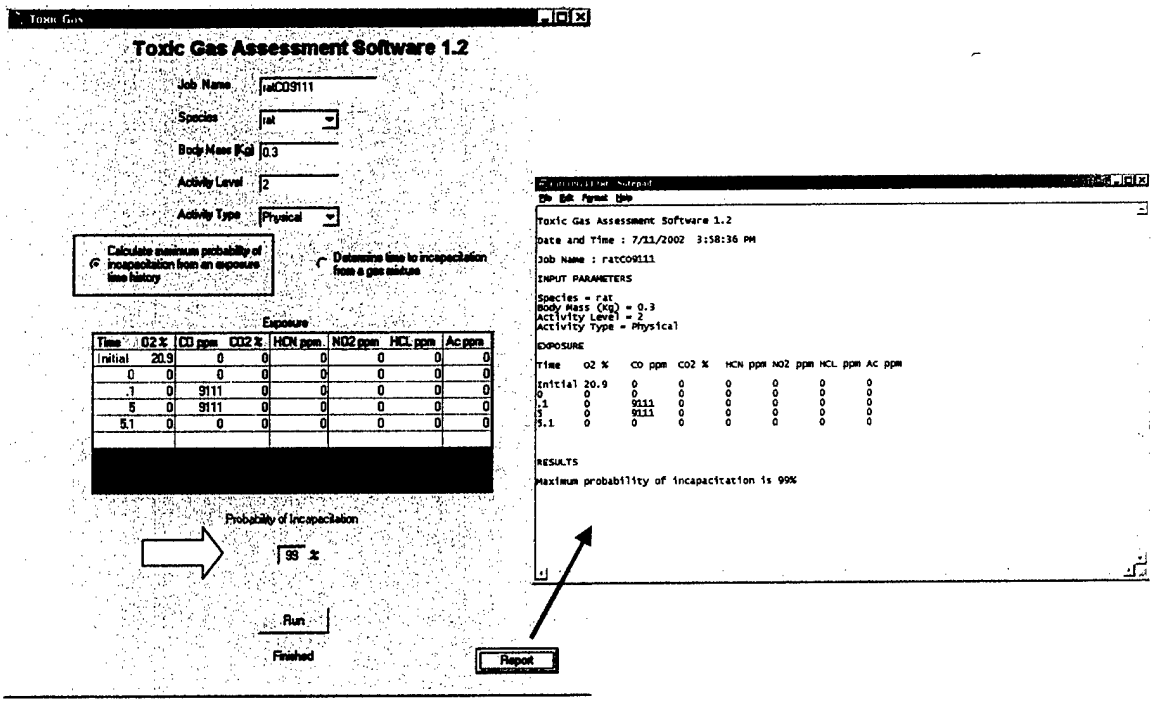


Figure 4. TGAS 1.2 Input screens and output report for the option of a time varying, toxic gas mixture.

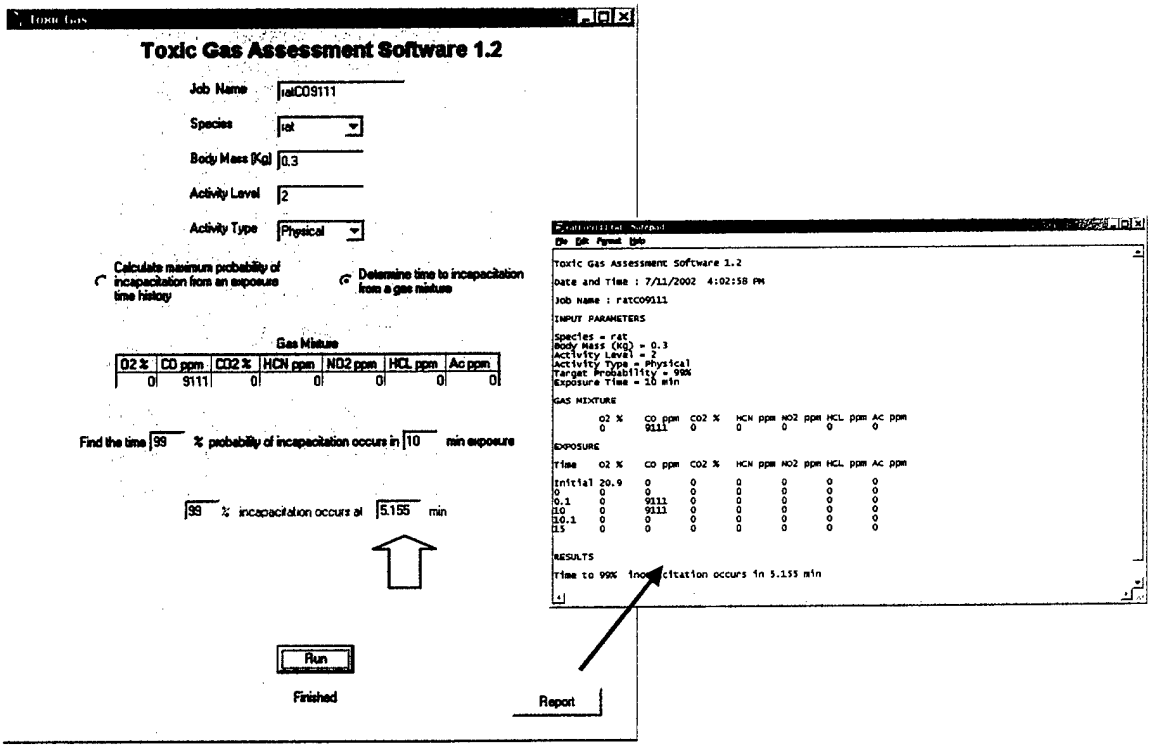


Figure 5. TGAS 1.2 input screens and output report for the option of determining the time to a particular percentage incapacitation for a toxic gas mixture.

TGAS 1.2 has been delivered to the Walter Reed Army Institute of Research for testing and evaluation and for use in the on-going Live Fire Test Program hazard assessments.

Product 1. TGAS 1.2 Software.

2.2 Incapacitation Paper for Inhalation Toxicology

The theoretical development of the TGAS 1.0 model and the extensive validation of the model against animal data have been accepted for publication in the journal *Inhalation Toxicology*.

Product 2. Stuhmiller, J.H. and Stuhmiller, L.M. (2002). "An Internal Dose Model for Inter-species Extrapolation of Immediate Incapacitation Risk from Inhalation of Fire Gases," Inhal. Toxicol., 14:101-129, 2002 (accepted for publication).

2.3 Control of Respiration Source Book

One of the principal conclusions of the TGAS 1 studies was that ventilation changes caused by gas exposure is a dominant effect in determining internal dose and, consequently, incapacitation and injury. Adding a physiologically based model of ventilation to TGAS became the primary goal of the second year's work. A comprehensive review, analysis, and synthesis of existing breathing control models was begun during Year One and completed at the beginning of Year Two. That review, captured in "The Control of Respiration Source Book," provides a detailed specification for the models that must be incorporated in TGAS to correctly define these processes.

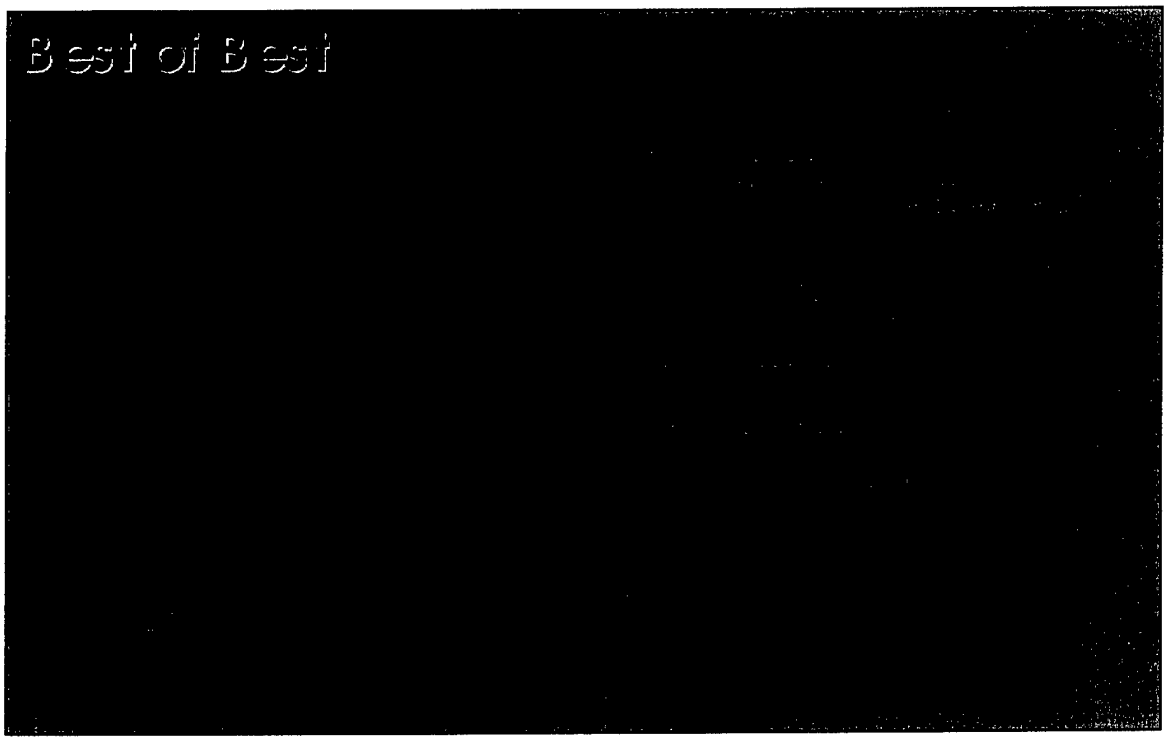


Figure 6. Summary slide presented at AIBS review identifying the modeling components required to produce a comprehensive description of the control of breathing.

Product 3. Stuhmiller L.M. (2001). "Control of Respiration Source Book," Jaycor Report J3150.12-01-141.

2.4 Analysis of WRAIR data

During Year One, WRAIR conducted small animal (rat) tests to determine the changes in ventilation that accompany exposure to toxic gas. Previously, we reported the development of software, ViewCODAS, to automatically analyze each test record and produce standardized ventilation parameters and time-history records of a minute volume, tidal volume, and breathing frequency. During Year Two, the compilation of all test data taken by WRAIR was further analyzed to produce statistically significant trends.

A new suite of software programs was written to manipulate, analyze, and visualize the data. First, all of the data sets were reviewed to ensure that the data could be reliably used in the analyses. Some of the data was rejected because exposure conditions were not maintained or because pretest baselines were not stable. In other cases, examination of the raw data revealed that the tests had been mislabeled; this was corrected and the same exposures were analyzed together. A tabulation of all useful tests is shown below.

Test	Experiments	Duration	O2	CO2	CO	NO2	# Subjects
38	e1	7 min	20.9%		1000 ppm		5
40	e1	5 min	20.9%		3250 ppm		5
42	e1	5 min	20.9%		6000 ppm		5
44	e1	5 min	20.9%		12000 ppm		4
47	e1	5 min	20.9%	5%	3200 ppm		5
48	e1	5 min	20.9%	5%	1200 ppm		5
49	e1	5 min	20.9%	5%	500 ppm		5
50	e1	5 min	20.9%	5%	6250 ppm		4
51	e1	5 min	20.9%	5%	12000 ppm		4
52	e1	5 min	20.9%	5%	12000 ppm		3
53	e1	5 min	20.9%	5%	12000 ppm		2
66	e1, e2, e3	5 min	20.9%	5%			6
67	e1, e2, e3	5min	20.9%		6000 ppm		6
68	e1, e2, e3	5 min	20.9%			475 ppm	6
69	e1, e2, e3	10 min	20.9%				6
70	e1, e2, e3	20 min	20.9%				6
71	e1, e2, e3	20 min	20.9%				6
72	e1, e2, e3, e4	5 min	20.9%	10%			8
73	e1, e2, e3	10 min	20.9%		3000 ppm		6
74	e1, e2, e3	10 min	15.0%				6
76	e1, e2, e3, e4	10 min	12.0%				8
77	e1, e2, e3, e4	5 min	15.0%	5%			8
78	e1, e2, e3, e4	5 min	12.0%	5%			8
79	e1, e2, e3	5 min	12.0%				6
80	e1, e2, e3	10 min	50.0%				6
81	e1, e2, e3	10 min	97.0%				6
82	e1, e2, e3	10 min	97.0%				6
83	e1, e2, e3	5 min	20.9%		12000 ppm		6
84	e1, e2, e3	5 min	20.9%			1000 ppm	6
103	e1, e2, e3	5 min	20.9%		12000 ppm		6
104	e1, e2, e3	5 min	20.9%	5%	12000 ppm		6
105	e1, e2, e3	5 min	20.9%		23000 ppm		6
106	e1, e2	5 min	20.9%		12000 ppm		3
106	e3, e4	5 min	20.9%	5%	12000 ppm		3
107	e1	15 min	20.9%		12000 ppm		2
107	e2	10 min	20.9%		12000 ppm		1
107	e3, e4	10 min	20.9%	5%	12000 ppm		3
108	e2	30 min	20.9%		3000 ppm		2
109	e2	5 min	20.9%		10000 ppm		2
109	e3, e4	5 min	20.9%		12000 ppm		4
110	e2, e3, e4	5 min	20.9%		23000 ppm		6
112	e1, e2, e3	5 min	20.9%			1900 ppm	6

Software was then written to align the time axis of each experiment so that exposure began at t = 0. Data from each experiment with the same exposure conditions was extracted from each data set. For each animal, the pretest quantities were averaged over a five-minute period and then the quantity normalized by that pretest average. This normalization removes the differences of individual animals. The normalized data was then averaged and standard deviations across data sets computed, and then written to General Data Interchange Format (GDIF) files for storage. The PLOXY data analysis software was modified to allow predefined plots to be constructed that produced figures showing the processed data.

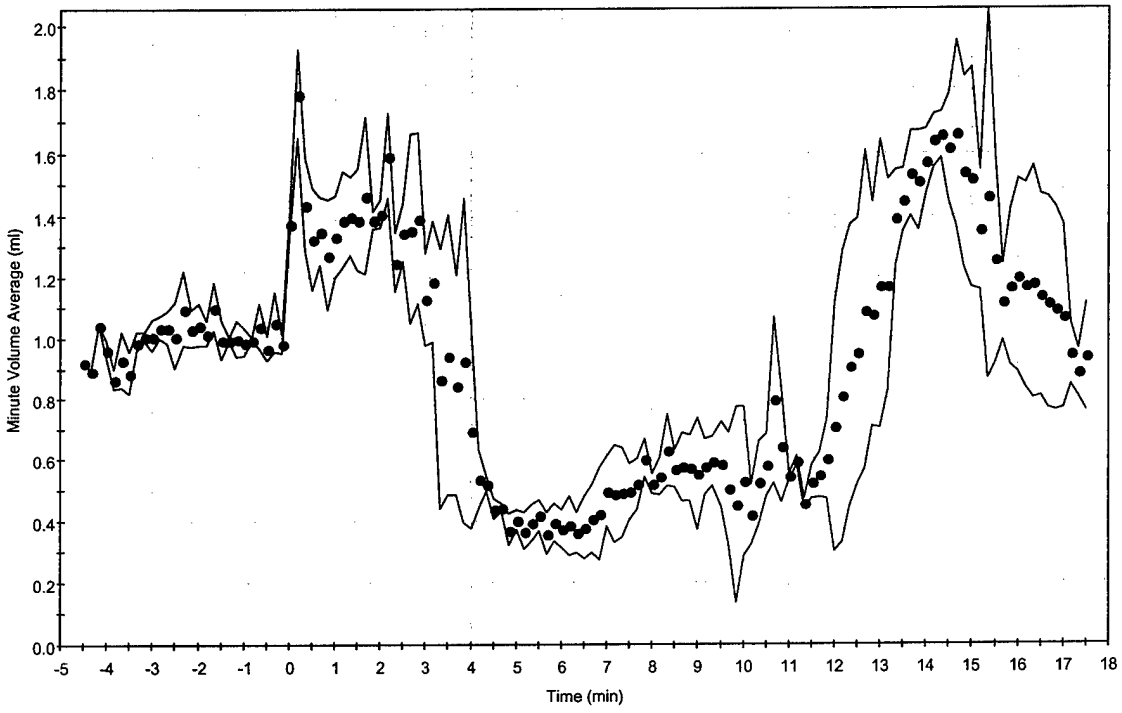


Figure 7. Composite data from all exposures using 12,000-ppm carbon monoxide and 5% carbon dioxide. The averaged value of normalized minute ventilation is shown by the red symbols, while the range of data express by the standard deviation is shown by the blue lines.

Product 4. Long, D.L. (2002). "Small Animal Ventilation Analysis - Qualified Data," Jaycor Technical Report J3150.11-02-182.

Product 5. Long, D.L. (2002). "Small Animal Ventilation Data Qualification and Reduction (Based on Experimental Data of Dr. Z. Gu)," Jaycor Technical Report J3150.11-02-183.

2.5 Circulatory and Blood Chemistry Models

Implementation of the control of breathing models identified in the Control of Respiration Source Book requires extending the TGAS model to include models of the respiratory, circulatory, and metabolic systems and to include interacting control models for the ventilatory and cardiac systems. Working from previous studies, SIMULINK models of these systems were developed.

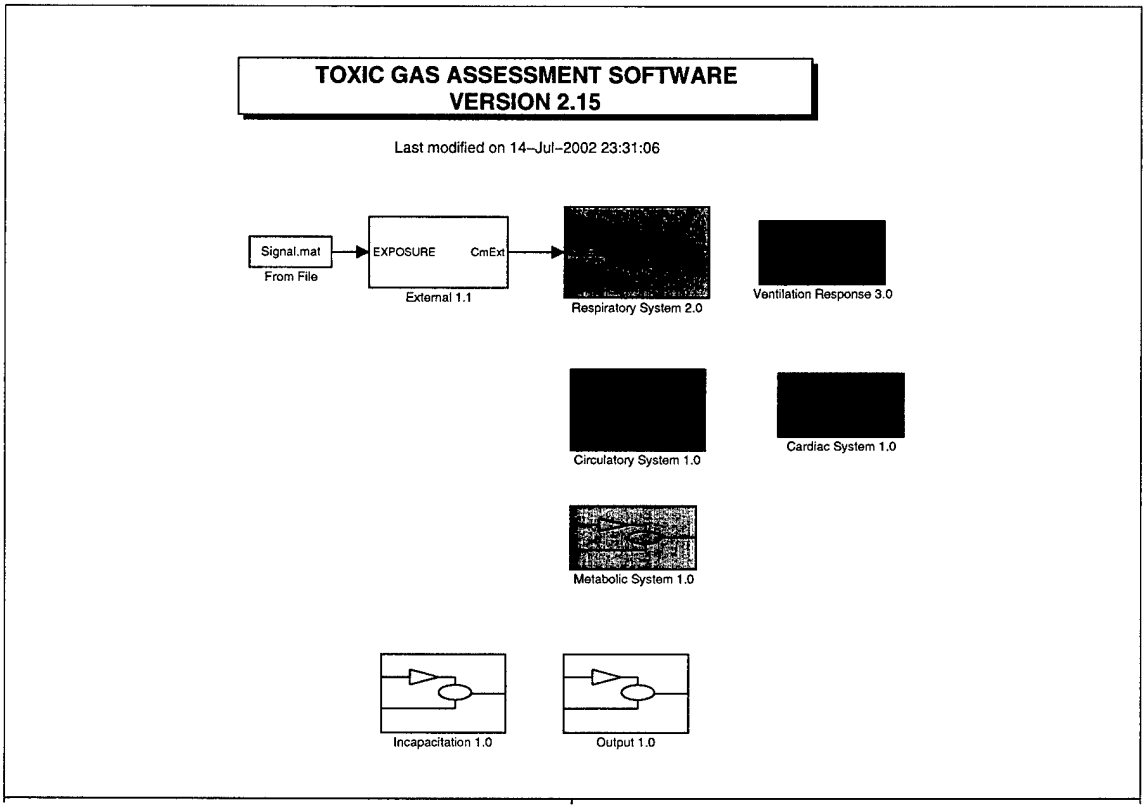


Figure 8. Schematic overview of TGAS 2 model structure. Model systems for the respiration, circulation, and metabolism of the body have been added, along with control system control ventilation and cardiac output.

Each of these systems is composed of subsystems. For example the circulatory system is further divided into the arterial, venous, and target organs. The flexibility of SIMULINK allows this description to grow in complexity, almost without limit.

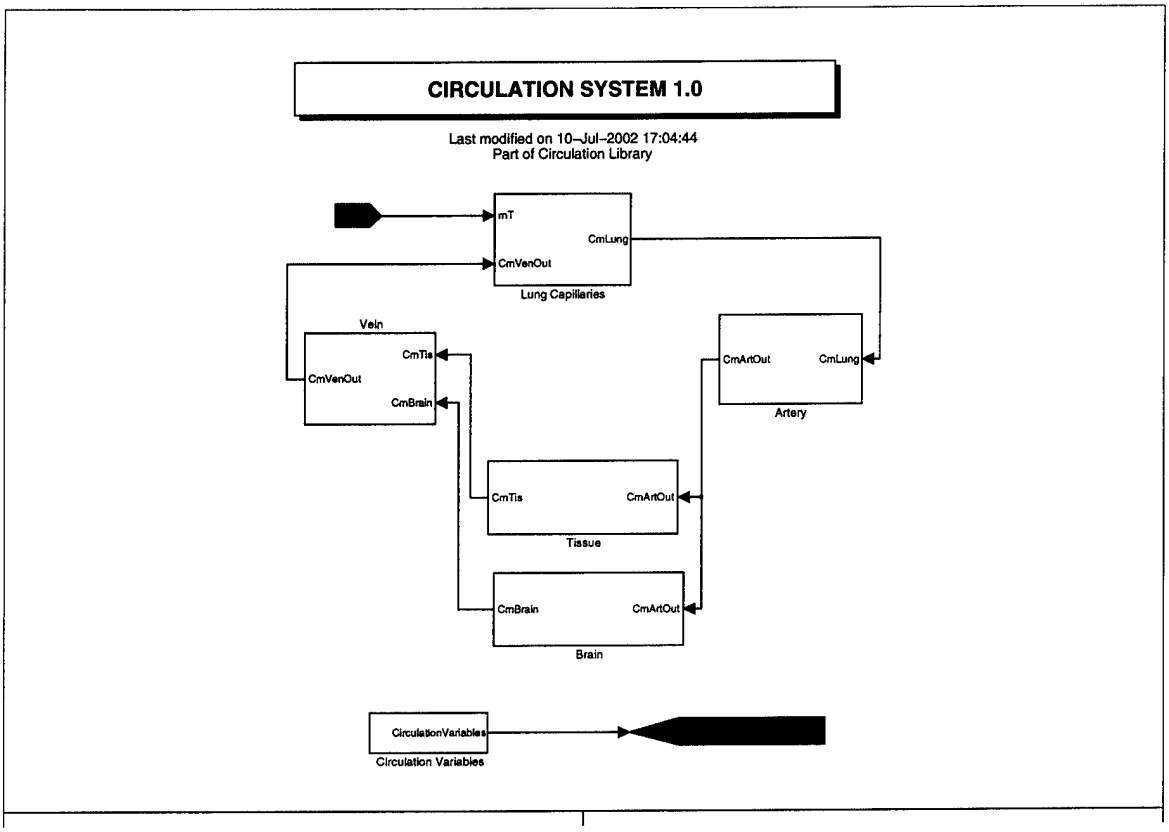


Figure 9. TGAS 2 describes the circulatory system by five blood volumes: the lung capillaries, the arterial and venous blood systems, the blood capillaries in the brain and those in the rest of the body's tissues.

2.6 Control of Breathing Models

The ventilation response is composed of subsystems that describe the response to peripheral and central chemoreceptors, metabolic effects associated with exertion, and neurologic effects associated with brain hypoxia.

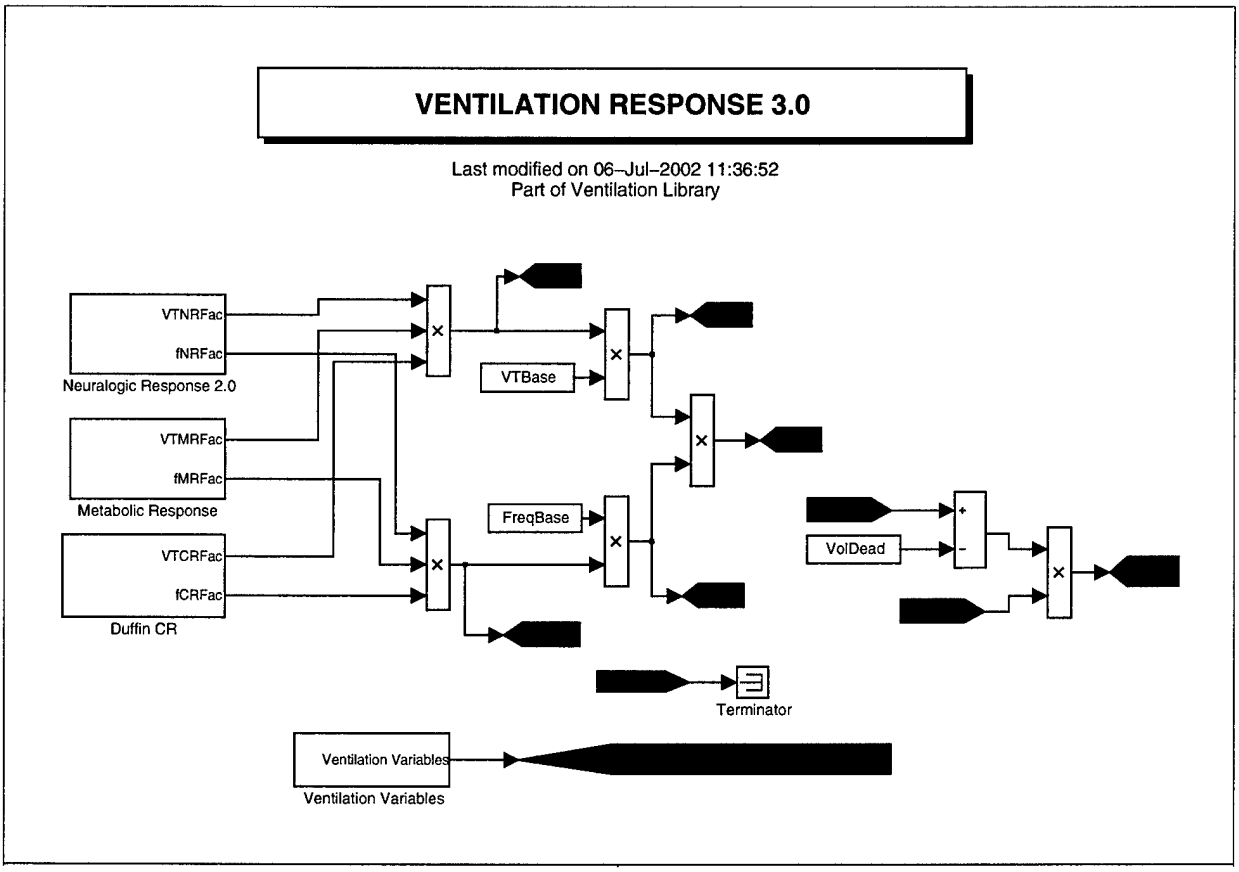
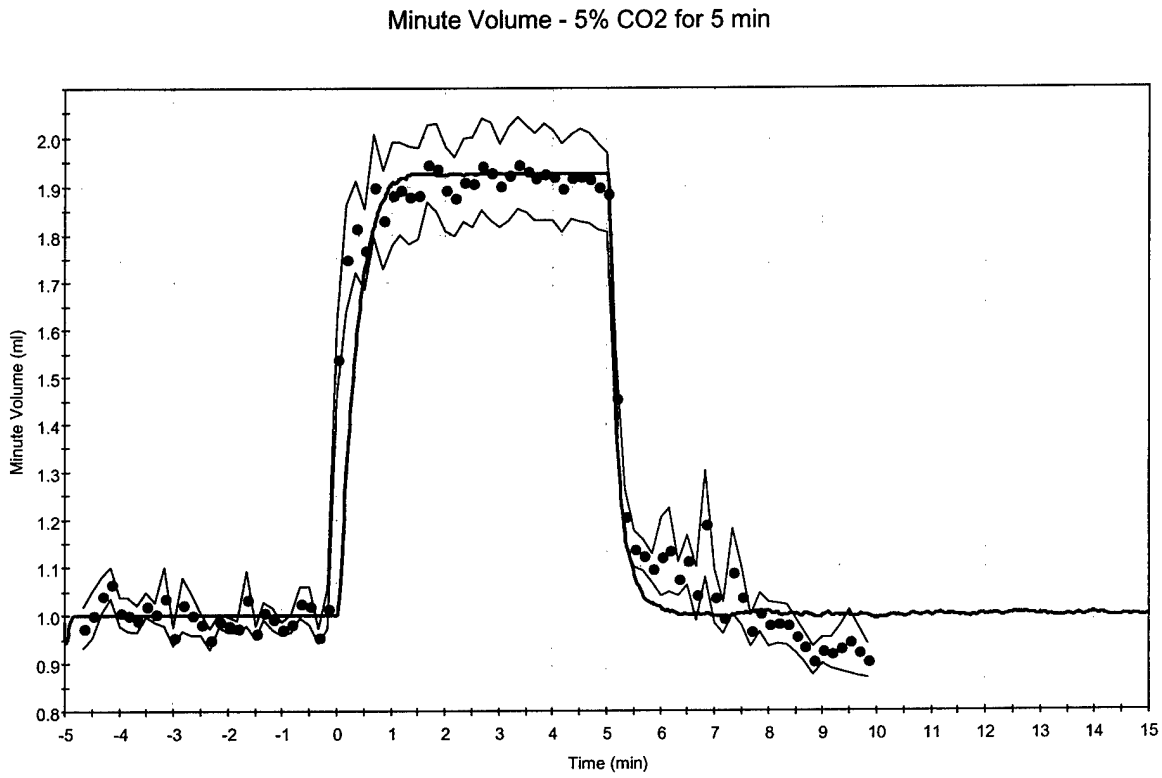


Figure 10. SIMULINK model schematic for ventilation response.

2.7 Validation of TGAS 2.0 Model Calculations with Data

A preliminary validation of the TGAS 2 model has been made against the WRAIR animal test data. A number of parameters in the control of breathing model, which have only been determined for man, had to be estimated for rodents. The results are encouraging and show that these mathematical models can capture the principal timing and magnitude of the response.



Minute Volume - 5% CO2 for 5 min

Figure 11. Increased ventilation due to inhalation of carbon dioxide on the external atmosphere is reproduced with the TGAS 2 model.

3. STO K—Behind Armor Injury

3.1 Review of Previous Behind Armor Research

A review of previous behind armor researches was conducted. Most previous efforts to evaluate blunt trauma behind body armor have involved firing a projectile at body armor fitted to either animals (e.g., goats or pigs) or cadavers. This approach has many limitations. Accurate measurement of the magnitude, time-history, and spatial distribution of forces behind body armor, a key element in solving this problem, has not been particularly successful in previous research. A close examination of data from the 2000 Nato Osborn test, where pigs mounted with accelerometers and pressure gauges wearing hard armors were shot by a rifle reveals that the measurements are unreliable. Also, firing a projectile at body armor will not deliver the same forces to the surrogate target due to small variations in projectile mass, velocity, armor-projectile interaction, and armor-surrogate interaction. It is difficult to scale the force delivery to accurately determine injury and lethality thresholds using this approach. Cadavers provide anatomic similarity but produce no injury to vital organs, do not incorporate muscular response, and provide no physiologic information. Animal models provide physiologic data but are not accurate from an anatomic standpoint. Converting the information gained by either method to a model valid for living humans is key to this effort.

3.2 Prototype Load Measuring Device

In lieu of using a projectile fired at armor applied to an animal or cadaver surrogate, this project will simulate the loading received by the body under the armor. To determine the characteristics of that loading, we will fire projectiles at armor placed against an impact-measuring device. The prototype load-measuring device was developed. The device consists of a fixture holding a soft and/or hard body armor backed by layers of surrogate material (neoprene rubbers) and various sensors including a force gauge, a high frequency Tekscan pressure sensor, and Pressurax thin pressure films.

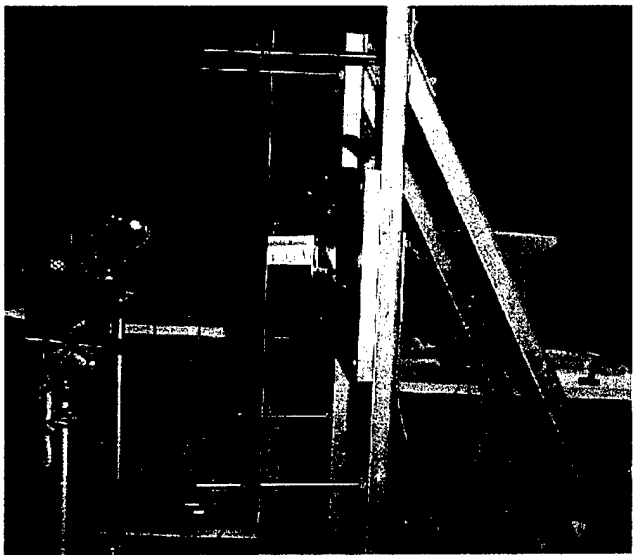


Figure 12. Prototype load measuring device.

3.3 Field Tests with Actual Armor

Live fire tests using the impact-measuring device were conducted for different levels of body armors. Temporal and spatial pressure distribution behind armor and force gauge, high-speed thin film pressure array sensors, and pressure films measured surrogate materials. Wave motion of the soft body armors were recorded by high-speed digital movie camera. Several important mechanisms were revealed. In order to further interpret the test results, Jaycor developed a three-dimensional finite element model (FEM) to simulate the interaction among the bullet, armor, and backing materials. The bullet was modeled as an elastic-plastic metal material; the armor as an elastic-plastic composite material; and the backing as rubbers. Jaycor compared the numerical simulations from the FEM with the sensor measurements and high-speed movies from the live fire tests. Major findings from the testing and simulation are summarized as follow:

- The magnitude and duration of impacts matched well with the measurements. The duration of impacts between bullet and armor was usually within one or two milliseconds, while the duration of impacts between the armor and backing materials was much longer, usually on the order of ten milliseconds, although the actual value depended on the velocity of the bullet and the configuration of the armor and the backing material.
- Simulated behind armor pressure distribution and wave propagation also matched very well with the sensor measurements and high-speed movie records.
- The main damage mechanism for bullet is plastic deformation. For soft armor there are two distinct loading modes: shearing and tension. At certain bullet velocity, shearing mode dominates and penetration occurs. For hard armor, smeared cracking is the main mechanism.
- A soft armor prevents injury by spreading the momentum and energy of the impacting bullet to a larger area over the armor. Thus more mass is involved and the impacting velocity is decreased. Although the longitudinal wave speed of composite armor material is very fast, usually above 5000 meters per second, the speed at which the momentum and energy are distributed over the armor is much slower, usually much less than 1000 meters per second. This speed is predominantly affected by the stress-strain relationship of armor material.
- A ceramic hard armor prevents injury by blunting the high-speed rifle bullet and creating a smashed cracking zone. The bullet is usually fragmented during the process and energy is dissipated. This smashed zone, which has a much higher mass and lower velocity than the original bullet, then hits the soft armor on the back and further distributes the energy over a larger area.

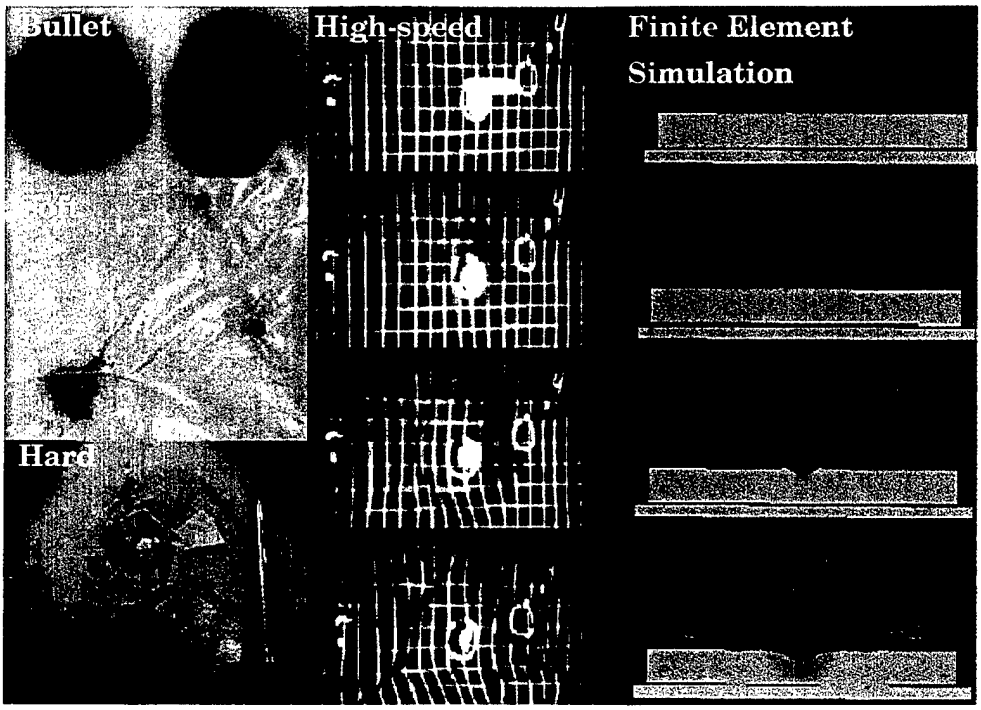


Figure 13. Wave propagation during bullet-armor interaction is the physical process by loading is redistributed by the armor. The figure shows the final effects on the bullets and the armor; frames from high-speed movies of the impacts; and results of mathematic simulation.

3.4 Impactor Development

The force characterization data from the impact-measuring device is used to develop impact simulators for both SBA and HBA. These impactors will be capable of reproducing the impact characteristics over the range of conditions driven by the expected military threat. The impactors will be mounted onto an impactor launch and driven by high pressure helium gas. A preliminary design was finished for the soft armor impactor and impact launcher. Mathematical relationship between the impactor velocity and the gas pressure has been developed.

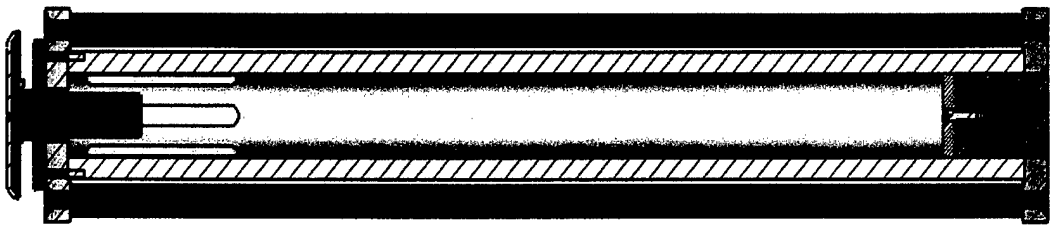


Figure 14. Impactor design.

3.5 Animal Testing

A protocol has been developed jointly by Jaycor and UCSD to apply the impactors directly to animal surrogates (pigs) and obtain physiologic, biomechanical, and injury data. The object is to develop correlations between animal deformation characteristics and the injuries it leads to by obtaining medical images of actual anatomy and animal response data, and develop and calibrate swine finite element model with real anatomy. The protocol is under the review of the animal committee at UCSD.

3.6 Finite Element Modeling and Medical Imaging of Pig

Data derived from animal studies will be converted to a human model of behind armor blunt trauma through finite element models. Jaycor is currently developing an anatomically detailed human thoracic FEM to simulate the human response and injury potential due to high-speed impact. This model includes body muscles, ribs, sternum, cartilage, and major organs such as the lungs and heart (Figure 15). It will be able to capture the temporal and spatial stress distribution inside the human body, which is the cause of lung contusion from high-speed impact. An effort of developing a similar model for pig is also undergoing. We have looked into the feasibility of constructing a finite element model from medical imaging and have conducted a full body CT imaging of a pig.

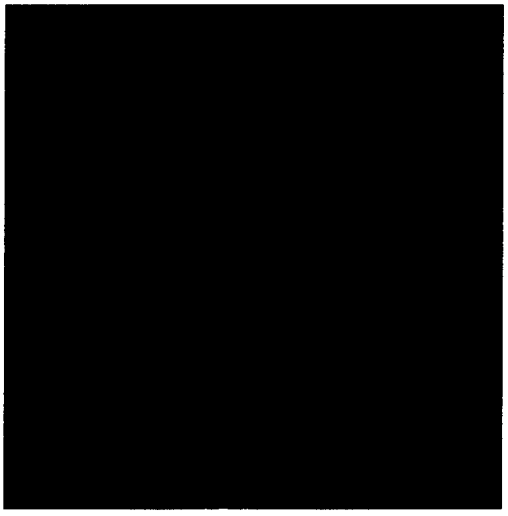


Figure 15. Three-dimensional finite element model of the human thorax.

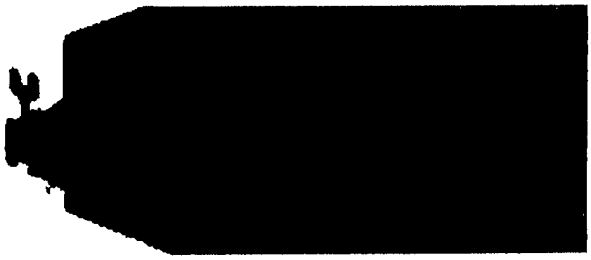


Figure 16. Computed Tomographic (CT) image of swine to be used to develop a finite element model.

4. Metabolic Cost of Locomotion

Metabolic cost, measured by the amount of oxygen consumed, is often used as a method of quantifying energy expenditure during exercise. There are many benefits to being able to anticipate the metabolic cost from various human activities, including the ability to monitor performance, to make direct comparisons between different exercise protocols, to assess individual variability, and to design better equipment for load carriage. Even though important inroads in this subject have been made, knowledge of metabolic cost has not reached a level where we can accurately anticipate the effects of activity, equipment, and individual differences.

4.1 The Metabolic Cost of Force Generation

The purpose of this study was to provide support for a general relationship between metabolic cost and force by reviewing existing data, providing a more fundamental basis for predicting metabolic cost of locomotion. We revisited the various equations that have been proposed to relate metabolic rate with mass, velocity and step contact time during running and found that metabolic rate is proportional to the external force generated and the number of steps per unit time. We showed that these equations are in agreement with a previously proposed hypothesis that the metabolic cost to generate a single application of a unit external force is a constant. Thus, we found that metabolic rate can be expressed as

$$\dot{E} = c \cdot \overline{F} \cdot \dot{N},$$

where $\dot{E}$ ($J \cdot s^{-1}$) is the increase in metabolic rate above resting, $\overline{F}$ (N) is the average force generated, $\dot{N}$ ($appl \cdot s^{-1}$) is the rate of force application, and c ($J \cdot N^{-1} \cdot appl^{-1}$) is a proportionality constant that may vary with activity.

Data from the literature was collected for a number of different activities and species to support the hypothesis. We found that running quadrupedal and bipedal species as well as human cycling, cross-country skiing, running (forwards, backwards, on an incline, and against a horizontal force), and arm activities (running, cycling, and ski poling) all have a constant metabolic cost per unit external force per application. See ***Figure 17***. The constant varies with activity, possibly reflecting differences in the mechanical relation between the external force created and the muscular force required. See ***Figure 18***. It is speculated that the general relation, coupled with biomechanical analyses, will allow metabolic cost estimates to be made for activities where a combination of movements are made.

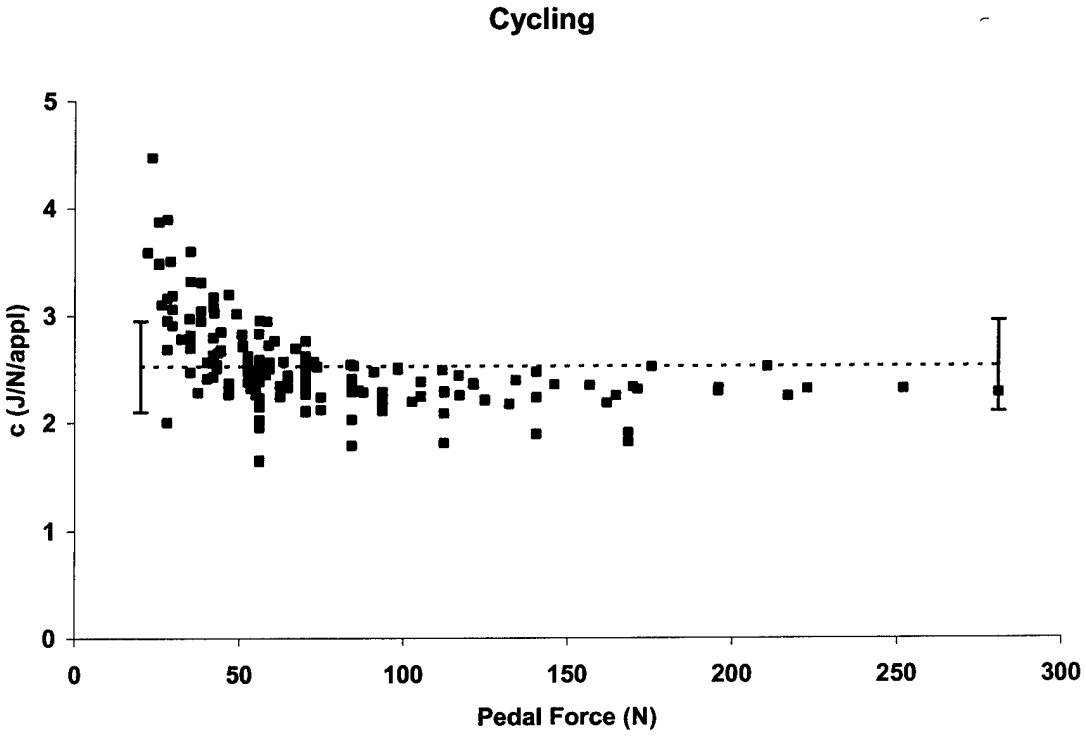


Figure 17. The metabolic cost coefficient for cycling at various pedal forces with cadences ranging from 30 to 120 rpm. Ignoring low pedal forces (<20 N) where the metabolic cost of overcoming limb inertia may have been influencing the results, the dashed line with error bars at the end points represent the total average value of 2.52±0.42 J·N-1·appl-1 over the range specified. Despite the almost 14-fold increase in pedal force and four-fold increase in pedal rate, the cost coefficient remained nearly constant.

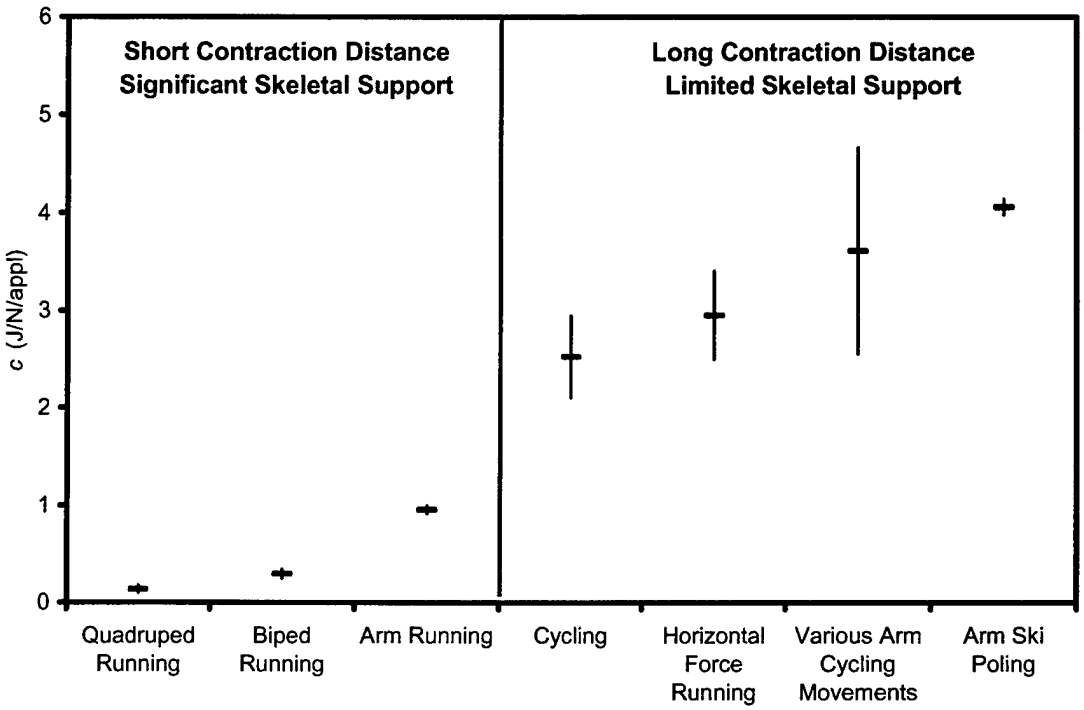


Figure 18. The mean value for the metabolic cost coefficient is remarkably constant for each of the seven different movements presented. However, movements where skeletal support is large (bones aligned with external force) and muscle contraction distance is short is approximately 5× smaller than with limited skeletal support and increased contraction distance. Error bars represent one standard deviation. Sixty-eight species are represented, which were gathered from 26 published studies.

Product 6. Sih, B. L. and J. H. Stuhmiller. (2002). "The metabolic cost of force generation." Med Sci Sports Exerc. *Submitted for publication*

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5. List of Products