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MODELING OF THE NON-AUDITORY RESPONSE
TO BLAST OVERPRESSURE

ANNUAL REPORT

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FOREWORD

In conducting the research described in this report, the investigator(s) adhered to the "Guide for the Care and Use of Laboratory Animals," prepared by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Animal Resources, National Research Council (DHEW Publication No. (NIH) 86-23, Revised 1985).



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The goal of this project is to develop mathematical models of the physical processes that cause blast injury so that the results of tests using animals in simple blast environments can be safely translated to estimating hazard to man exposed to blast both in the free field and within enclosures. The present project builds upon earlier work to develop models of the mechanics of the thorax and lung exposed to simple blast waves. The scope of activity has been expanded to include the lung, the gastro-intestinal tract, the upper respiratory tract, and the tympanic organs. In addition, the work now addresses occupational and combat level exposures. This report covers the second year of the contract. A considerable amount of progress has been made in understanding the basic mechanisms of injury and in providing practical tools for the measurement and prediction of blast effects.					
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Summary

The goal of this project is to develop mathematical models of the physical processes that cause blast injury so that the results of tests using animals in simple blast environments can be safely translated to estimating hazard to man exposed to blast both in the free field and within enclosures.

The present project builds upon earlier work to develop models of the mechanics of the thorax and lung exposed to simple blast waves. The scope of activity has been expanded to include the lung, the gastro-intestinal tract, the upper respiratory tract, and the tympanic organs. In addition, the work now addresses occupational and combat level exposures.

This report covers the second year of the contract. A considerable amount of progress has been made in understanding the basic mechanisms of injury and in providing practical tools for the measurement and prediction of blast effects.

(1) Models have been developed for the prediction of injury to the tympanic membrane and the lung. These models are built upon the findings of more detailed structural models of the organ systems and of laboratory tests with surrogate materials. Their ability to correlate a wide range of field data is encouraging.

(2) A computer program has been developed for the prediction of the blast field within an enclosure. The code describes a great detail of geometric complexity, including the effects of doors and windows, and has been coupled with the injury models developed earlier. It is now possible, working on a microcomputer, to describe the geometric conditions of the problem (from the free-field to the inside of a combat vehicle), to describe the location and strength of the explosion, and to obtain estimates for injury to the lung, URT, and TM.

(3) The methodology described above has been applied to explosions within an Armored Personnel Carrier (APC) and the injury predictions agree well with animal tests in the field. This accomplishment represents the first working version of a generalized damage risk criterion for point charge explosions in all geometries.

(4) Three blast measuring devices have been either conceived, developed, or tested during the past year. The Lambdroid unit, which provides direct measurement of load distribution, has been refined and is now in use in the field. The Probe-In -Balloon device for intestinal pressure measurement in regions of likely injury, has been designed and tested in the laboratory. The Portable Lambdroid unit, for self-contained blast measurements inside combat vehicles, has been designed and is awaiting administrative approval before fabricating.

(5) A dynamic surrogate for the thorax has been constructed and tested. Dynamics of the motion of the chest wall and the pressure waves within the lung have been reproduced. This apparatus has been central in the development of the lung response model. In addition, the surrogate has revealed that pressures measured with air-containing tubes, such as the esophagus or the larger airways, is fundamentally different from that actually in the lung parenchyma. In particular, at larger blast loading, a sharply rising pressure

wave, not unlike the blast wave itself, passes through the parenchyma. This finding brings into question all of the previous conclusions about the relation between ITP and injury.

(6) In the course of testing the predictions of the generalized models of injury, a discrepancy was uncovered between the Bowen criteria for injury (based on data taken in nuclear-level exposures) and that constructed by WRAIR (based on weapon-level blasts). The inconsistency has been traced to difference in injury mechanisms, the long duration blasts produce a crushing effect, while the short duration blasts produce parenchymal shocks.

Research Area 1: Load Determination

The goal of this area of research is to develop models necessary to convert environmental parameters of blast into the load distributions used in the body response models.

Model for blast within an enclosure

A method of calculating the blast field inside an enclosure was formulated. The solution is based on the method of images, which assumes geometric reflections of the blast wave from the boundaries.

A computer code, COMPLX, was written based on the mathematical model. The code runs on a personal computer and uses self-explanatory screen input to enter data. The output can be directed to the screen for plotting, to a variety of printers, or to disk storage.

The basic model has been expanded in several respects. A full implementation of Baker's parameterization of blast wave propagation and a wide choice of explosive composition is available. Provisions have been made to allow windows and doors within any boundary. Effects of enclosure pressurization due to the liberation of explosive gasses and the venting through external openings is allowed. The sensor or body receiving the blast can be described by its position, orientation, pressure loading characteristics. A matrix of sensor positions can be made within a single run.

The Generalizable models for the Upper Respiratory Tract, the Lung, and the Tympanic Membrane have been incorporated into the calculation. Calculations not only give the pressure-time histories of the blast field, but an estimate of the body response and hazard potential to biological systems.

The code has been compared to the pressure data measured in the APC and bunkers at the Albuquerque test site. Agreement is qualitatively good, but not all parameters of the instrumentation placement have been specified. Comparison with the occurrence and severity of injury observed during these tests is very encouraging.

Device for measuring pressure within an enclosure

The Lambdroid test fixture, developed by JAYCOR to directly obtain body loading data in a blast field, was refined. To eliminate spurious vibration in the unit that interfered with the pressure signal, the structure was internally stiffened and the transducer mounts redesigned. Together with changes

made in the field during testing, the problems were eliminated and the unit is now an integral part of the field program.

A portable version of the unit was designed that will allow easy placement within combat vehicles. The unit is totally self-contained, requiring no data communication lines. The fabrication and testing have been delayed by administrative considerations at Ft. Detrick.

Blast Data Base

Blast Data Bases have been set up for Thoracic Response, Simple Waves, and Complex Waves. Data taken in the APC and in the underground bunker have been reduced to standard format, evaluated, and placed in the Complex Wave Data Base.

Data reduction software for Albuquerque Test Site

At the request of the COTR, JAYCOR developed the VU data manipulation program for accessing, viewing, plotting, and manipulating the data collected by the Gould DAAS at Albuquerque. This software has reduced to first look analysis time for data collected at the site from a matter of weeks to a few minutes.

Research Area 2: Application to the Upper Respiratory Tract

The goal of this research area is to produce a mathematical model that predict the risk of injury to the URT in wide variety of blast environments.

A literature search was conducted to determine the mechanical properties of the upper respiratory tract and to estimate the material strengths of the tissues injured during blast. From that data critical stress values were determined for the Generalizable Model for URT. The values agreed very closely with those used earlier to predict URT injury.

Research Area 3: Application to the Lung

The goal of this research area is to produce a mathematical model that can predict the risk of injury to the lung in a wide variety of blast environments.

Thorax Response Data Base

A separate data base was established for data collected on the thoracic response of animals to blast. The data stored includes free field conditions, surface loading (animal and Lambdroid), chest wall accelerations, and multiple intrathoracic pressures. Data from the 1986 summer and 1987 winter field studies at Albuquerque were translated to physical units, placed in the data base format, entered, analyzed for consistency, and then plotted in hardcopy. The results were used to plan the 1987 summer field study.

One-dimensional model

The 1D model of the chest-lung was validated against two data sets. In the first, the results of an earlier double peak study was used. Very good prediction of the variation of lung injury with blast separation time was achieved by correlating peak parenchymal pressure with incremental lung weights.

In the second effort, the model was compared against the composite thoracic response data from the 1985 and 1986 field studies. The findings have been reported in a paper to be presented at the MABS-10 meeting this Fall.

Generalizable model for Lung

A Generalizable Model for the Lung has been developed. The key discovery that makes the model possible came from the 1D model studies and showed that there is a predictable relationship (at least at low blast pressures) between the chest wall velocity and the parenchymal pressure at the pleural surface.

The GM was implemented in the COMPLX code and compared with injury data taken in the APC. The peak parenchymal pressure, which had correlated well with injury as measured by lung weight in the double peak study, did not correlate with injury in this complex wave situation. Work done on the lung tissue itself did, however, predict injury quite well and is now considered to be the mechanical correlate of choice.

Hazard distribution with the APC as predicted by the GM and as observed in the field were compared. The results were very encouraging. The model, for example, was able to clearly distinguish between free-field exposures and those within the vehicle, even when conventional criteria would have been incorrect.

This work uncovered a discrepancy between the injury criteria developed by Bowen, for long duration blast waves, and those developed by WRAIR, for weapon-like blasts. The difference can be understood from the modeling work as being due to a difference in injury mechanisms. The long duration blasts produce injury by crushing the chest into the lung and consequently require much greater impulse for a given peak pressure. The short duration blasts, on the other hand, set up parenchymal waves that require only a small (but rapid) motion of the chest, thus can be caused by a smaller impulse.

This difference explains why the injury in the complex wave field of the APC correlates better with the WRAIR criteria than with Bowen, because the environment is actually a composite of many short duration wave reflections. The interpretation of the envelope of the signal as being equivalent to a long duration blast is incorrect.

Surrogate lung

In order to reduce animal testing and to better understand test results, a surrogate lung material was sought. A fine, air-water foam was found to have almost the same physical characteristics (density and compressibility) as lung parenchyma.

A test fixture was constructed in which propagation properties could be measured and in which the local motion and distortions could be photographed. The local compression wave is clearly seen in high speed movies. The dissipation rate was measured and agrees qualitatively with that seen in sheep lungs in the field.

Measurements made in the foam and in a neighboring, long balloon showed significant differences. The pressure signal in the balloon has a gradual rise and fall, similar to the ITP measurements seen in field tests. The signal in the foam has the rapid initial rise and exponential decay, similar to that seen in air shocks. This finding brings into question the interpretation of previous ITP measurements made in large airways.

Next, a moveable end plate was added to the test fixture with the same mass per area as the sheep chest wall. The plate is instrumented with pressure transducers on the forward and rearward face and with an accelerometer. In this configuration, the chest wall velocity-parenchymal pressure relationship was tested. The results, at low blast levels, confirm the linear relation predicted by the 1D model.

At large blast levels, the parenchymal pressure appears to exceed that predicted by the velocity alone and has the character of a shock. Later, during the 1987 summer field tests similar pressure traces were observed in sheep when the pressure probes were forced well into the small airways.

Small animal protocol

A quantitative measure of injury has been established based on a count of petechia and ecchymoses on the excised lung surface.

A series of quasi-static, in vivo, lung pressurization tests were conducted with rabbit. Petechia began to appear for lung pressures of 6 kPa above ambient, increasing in number until 9 kPa when lung rupture occurred. Direct measurement showed that approximately 120 cc of air was injected to reach the threshold point of injury. Based on a normal lung volume of 60 cc for the rabbit, this result indicates that injury occurs when the volumetric strain reaches a value of 3.

Next, static decompression tests were conducted with rabbit. A similar pattern of petechial injury was observed to begin at conditions when the external pressure was lowered to 35 kPa, with injury increasing as the pressure was lowered further. The intrathoracic pressure was about the same as the external value. Assuming that the rabbit's vascular system maintains the air in the lung at constant temperature, then the volumetric strain is again about 3. We believe this may provide a direct correlation of injury with the disturbed mechanical state of the tissue and therefore can be used in the mathematical models.

Research Area 4: Application to the Gastro-Intestinal Tract

The goal of this research area is to produce a mathematical model that can predict the risk of injury to the gastro-intestinal tract in a wide variety of blast environments.

Refinement of the surrogate tests

Previously, a hemispherical membrane shape had been tested and the internal pressure magnitudes and frequencies of oscillation agreed well with the BUBBLE mathematical model. The test fixture was modified to allow other membrane shapes and other surrounding flow constrictions. The results indicate that the flow pattern of the water to the bubble is a major factor in determining the bubble response characteristics.

A series of tests were formulated to isolate the geometric influences. The original test configuration gave the flow a 3D character. Placing the surrogate near the chamber lid caused the liquid motion to be confined in a plane (2D), while surrounding the surrogate with a cylindrical tube restricted the flow to a unidirectional up and down motion (1D). The findings show that the frequency of bubble oscillation increases with dimension, but the magnitude of the oscillation decreases.

To better compare the experimental data with the predictions of the BUBBLE code, a computer program was written to transfer and manipulate the data taken on the Nicolet oscilloscope. The data was then transferred to a microcomputer where a GI Surrogate Data Base was established.

The geometry model within the BUBBLE code was then modified to reflect the change in dimensionality between the different test configurations. The code gave results which are in quantitative agreement with data if the proper choice of flow patterns is made. A predictive approach to obtaining the flow pattern from the test chamber geometry was formulated, but was not implemented.

Next, experiments were conducted to determine the influence of a tubular geometry on the results. Data was collected on the effects of bubble volume, bubble length, internal fluid viscosity, initial membrane stress, and neighboring gut sections. The results seem to agree with early data taken in isolated perfused rabbit intestines, but a complete analysis of the effects of each parameter has not been made, nor has the BUBBLE code been correspondingly modified.

Material strength tests conducted

Tests were conducted to see if the material elastic properties of the surrogate material being used corresponds to that of the animal model. A series of static pressure tests showed that the pressure-volume curve was linear in all cases, but that the commercially prepared lamb caecum material had properties most closely matching that of rabbit.

Tests were conducted in which load was applied until the surrogate material ruptured. The time to reach the rupture point was varied from a few milliseconds to tens of seconds. These results showed that the pressure at the moment of rupture depends on the rate of pressurization. Further tests are being formulated to determine if this difference if the *strain* at the moment of rupture differs. This result will shed light on whether the material has a rate-dependent strength.

Field data

Data on intra-abdominal pressure collected during the 1986 summer field study was reduced and placed in a computer data base. That data was analyzed to determine the characteristics of the pressure field in the neighborhood of the injured gut sections. It was concluded that a more systematic and well-defined experimental procedure is required to make these determinations.

Probe-In-Balloon

The attempts to measure intra-abdominal pressures in the field revealed how difficult it is to control the placement of the pressure probe relative to intestinal air bubbles. The pressure signals can vary so widely that without such control the data is virtually impossible to interpret. To meet this need, a device was conceived and tested for surrounding the probe with a balloon containing a precisely controlled amount of air. The device has been tested in the surrogate test chamber and will be further tested and refined in the small animal protocol and in field tests.

Research Area 5: Application to the Tympanic Membrane

The goal of this research area is to produce a mathematical model of injury to the tympanic membrane and related organs that can be applied in a wide variety of blast environments.

Generalizable Model for Tympanic Membrane Rupture

Based on an extensive literature search, mechanical properties of the tympanic membrane were identified and used to create a Generalizable Model for tympanic membrane response. The data reported by James, et al., on the observed rupture of cadaver ear drums exposed to blast, was used to calibrate the critical stress of the membrane. Finite element analysis of the membrane itself produced stress concentration patterns at the critical stress that are similar to the rupture patterns seen in animals exposed to blast as reported by Hamernik. The data of James could be reproduced over the entire pressure-impulse range and for injury levels from threshold to severe.

A second literature search was performed to determine directly the strength of the tympanic membrane. No direct measurements were found, however, histological observations of the composite structure of the membrane combined with separate measurements of the strength of the individual tissues produced a range of failure stresses that agrees well with those chosen empirically.

A paper was prepared for Annuals of Otology, Rhinology, and Laryngology based on that presented at the symposium on Blast Injuries to the Ear.

Project Review Meetings

1. September 25, 1986 (Washington). Work on tympanic membrane injury prediction reviewed.
2. October 13-16, 1986 (San Diego). Complete project review meeting.
3. October 29, 1986 (Albuquerque). Planning of field tests with input from modeling findings.
4. November 14, 1986 (Washington). Review of plans for coming quarter.
5. April 20, 1987 (Ft. Detrick). Briefing of entire model program to Medical Command.
6. April 21-22, 1987 (Tysons Pond). Complete project review meeting and identification of areas of concentration for the next quarter.
7. June 22, 1987 (Vicksburg). Briefing to Waterways Experiment Station on WRAIR program and evaluation of WES support of program.
8. July 24, 1987 (Albuquerque). Review of parenchymal wave findings.

Reports and Publications

1. J.H. Stuhmiller, "Use of Modeling in Predicting Tympanic Membrane Rupture", Seminar on Blast Injuries to the Ear, Walter Reed Army Institute of Research, 26-27 September, 1986.
2. M.J. Vander Vorst and J.H. Stuhmiller, "Calculation of Parenchymal Pressure Due to Double Peak Loading".
3. M.J. Vander Vorst, K.T. Dodd, J.H. Stuhmiller, Y.Y Phillips, "Calculation of the Internal Mechanical Response of Sheep to Blast Loading", paper for presentation at MABS 10.

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