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Computer Modeling of Thoracic Response to Blast

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Primary blast injury affects the gas-containing structures of the body. Damage to the lungs with resultant respiratory insufficiency and arterial embolization of air from alveolar pulmonary venous fistulae is the predominant cause of morbidity and mortality following high-level blast exposure. In an effort to generate a widely applicable damage-risk criterion for thoracic injury from blast we are developing a complex computer finite element model (FEM) of the thorax. Taking an engineering approach, a horizontal cross-section of the thorax is divided into small discrete units (finite elements) of homogeneous structure. The necessary physical properties (density, bulk modulus, etc.) are then determined for each element. Specifying the material constants and geometry of the elements, the computer can load the surface of the structure with some force-time function (blast pressure-time history) and calculate the resultant physical events such as displacement, compression, stress, strain, etc. Computer predictions of pressure wave phenomena in the lung parenchyma are compared with trans-bronchially measured pressures in blast-exposed animals. The model should prove useful in assessing the risk of blast injury in diverse overpressure environments and may give insight into pathophysiologic mechanisms and strategies for protection.

Interest in the lethality of the blast following a nuclear explosion prompted several animal studies in the 1960's that identified the circumstances in which death would occur (1, 2). Although there was no need to define the conditions of incipient or chronic injury, the results clearly showed that the soft, air-filled organs (lungs, gastrointestinal tract, larynx, and tympanic cavities) are damaged. Research into the mechanisms of injury have continued since then at several laboratories around the world (3–5).

In the past decade there has been interest by the U.S. Army in blast injury at occupational exposure levels. Several weapon systems, notably self-propelled howitzers and shoulder-fired antitank rounds, are of such power that the crews and troops using them are exposed to pressure fields of unprecedented magnitude. Although it is certain that such exposures are not associated with acute injury, they do approach the exposure limits set by military standards. The limits are based on experience with safe conditions, rather than on known injury thresholds. To extend these boundaries for training purposes, it is necessary to establish the conditions under which subtle or chronic injury will not occur.

A common procedure for determining human risk is to make comparison with similar animal exposure. The uncertainty of this procedure arises from the extrapolation of results between species. Body weight, size, orientation, internal organ arrangement, and other anatomic factors must be considered in interpreting test results. Furthermore, large numbers of animals must be used to produce statistically significant averages and to overcome variations in individual animals. As the number of blast conditions to be studied increases, the total number of animals, the cost, and the duration of the testing, grow dramatically.

One way of reducing the amount of animal testing required is to use mathematical models. In the simplest applications, mathematics is used to fit a smooth curve through some test conditions in order to extend the results to other conditions. This approach may not correctly predict results outside of the range already tested and cannot address extrapolation to other species.

A more satisfactory model results from incorporating the mechanics of the process and physiology of the animal. Such a model was proposed as an adjunct to the animal testing at the Lovelace Inhalation Toxicology Research Institute (ITRI) (6). The lung was represented by a gas-filled volume, the chest wall by a piston, and the rigidity of the skeletal system by an opposing spring. When the pressure history of the blast wave is applied to the external surface by the piston, the piston accelerates inward, compressing the gas until it is finally brought to rest by the combined action of the gas pressure and the force of the spring. The various parameters of

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the model were calibrated to reproduce the peak internal pressures seen in the test animals. It was also proposed that the parameters would scale with total body mass of the animal according to certain geometric rules.

This model is able to correlate, and to some extent explain, a limited range of internal pressure data for simple waves. Still, it is not capable of answering the hazard questions discussed earlier. First of all, the parameters of the model are not directly related to measurable physiologic properties; instead, they have been chosen to give the best agreement with internal pressure data. Therefore, although one may speculate as to their origin, one cannot confidently judge how they would change between species. Second, there is no connection made with the mechanism of injury. While larger internal pressures undoubtedly indicate a more hazardous environment, the location and severity of injury cannot be inferred from such a model.

There is another kind of model of the thorax that has taken the physiologic details into account. Borrowing from the techniques of structural engineers, detailed models of the skeletal system of the chest have been produced that use measurable mechanical properties of the bone and incorporate all of the connections and linkages. These models have been quite successful in studying the blunt trauma of automobile crashes, where the body is thrown into a solid object. The injury of interest in a crash is bone fracture, so that no modeling of the soft tissue is included. In blast exposure, however, skeletal deformation is relatively small and serves only to transmit motion to the compliant organs inside where the damage processes take place. Therefore, although the ambiguity of the description is removed, the models do not address the problem of interest.

The work summarized in this paper has expanded upon these ideas to construct a model of the thorax that contains a structural description of the hard and soft tissues. Supplemented with field measurements of load distribution and laboratory measurements of tissue properties, the model predicts the detailed motion of the thorax and indicates the magnitude and distribution of stresses that may be linked to damage. The detailed work and results have been documented in References 12 and 13.

BIOENGINEERING APPROACH

The same approach that would be used to determine the safety of a structure can be applied to a biologic system exposed to blast. A series of causal links can be established that translate the blast conditions into load, motion, and tissue stress. The material strength of the various organs determines their susceptibility and mode of injury. Verification can be based on animal tests and then confidently extended to man and to other environments that have not been tested.

The causal connection between blast and injury can be described as follows. The blast wave, created by the weapon, reflects and evolves as it propagates to the location of interest. There it strikes the body and produces a load distribution that depends on body shape, orientation, and perhaps clothing. This external loading sets the body in motion, which produces rapidly changing internal stresses. These internal stresses are concentrated by geometric features and at the boundaries between dissimilar materials. When the local stresses exceed a certain threshold value, failure of the tissue and blood vessels results in observable injury.

For each step in the chain of events, there is a quantity that can measure the result of the process and provides a separate test of each component model. It is this separate verification that gives confidence to the overall model when it is applied to a new situation. Conversely, the nature of the linkage suggests measurements that will specifically test the underlying concepts.

The steps leading to the determination of local tissue stress have a one-to-one correlation with conventional engineering analysis and therefore the same approach is likely to be successful. To have confidence that stress can be related to injury, we must know that there is an equally strong analogy between the failure of ordinary materials and the characteristics of injury we want to capture. Several such examples exist.

The observation that injury increases with blast strength and that there is a threshold level for injury (7) is certainly described by the concept of a material failure stress level observed in all materials. Another pattern is that the threshold for injury is less for repeated exposures (8). This behavior parallels *fatigue* failure in which the material is damaged a little on each stressing until the cumulative damage leads to failure (for example, bending a paper clip repeatedly). Direct evidence of this explanation would be revealed in material property changes to the organ. Finally, there is some evidence that blast waves in rapid succession can produce injury that is different from the same number of repeated exposures. Again, there is analogous behavior in other materials in which their properties change momentarily under large stress and require a certain characteristic time to recover to their nominal values. If they are subjected to additional stress before they can recover, they may be more or less susceptible to damage.

These analogies between engineering situations that have been successfully described by mechanistic concepts and the aspects of blast injury that must be quantified to develop occupational level safety criteria are the source of guidance in the modeling program.

Based on these concepts, a project was initiated by the U.S Army Medical R&D Command to develop analytical methods of determining the body's response to blast wave loading. The primary emphasis was placed on occupational level exposure and on the lung as the threatened organ. The goal was to identify the aspects of the blast field that can be correlated with injury observed in ani-

mals. Secondary emphasis was placed on identification of the specific injury mechanisms in the lung, determination of stress distribution in viscera such as the trachea, and extension of the results to complex wave environments.

During the course of the work, the gastrointestinal tract took on more importance as a target organ and a separate experimental effort was initiated. Recently, complex waves within vehicles have become a concern, but data describing the phenomena have not yet been released. In addition, field studies (9) showed increased intrathoracic pressure responses for subjects wearing ballistic jackets, so an additional study task was added to quantify the change in body loading. The details of the work are contained in project reports.

SUMMARY OF RESULTS

In order to determine the load distribution on a subject in a blast field, model tests were conducted at ITRI and calculations were made with JAYCOR's EITACC computer code. From this work we found that load impulse can be a multiple of the free-field impulse, depending on the wave intensity, and that the spatial and temporal distribution of the load can be reasonably predicted by computational models for the occupational level exposures.

Structural and Material Description. The animal chosen for field test exposures was the sheep. The sheep has a thorax size and construction that is similar to man and has been the test animal in previous blast investigations so that a body of data already exists. The first step in the structural determination was to review the available anatomic literature and select typical dimensions and orientations of organs. The primary difference is that sheep have large, multiple stomachs that have a considerable air content. It was important to establish early in the investigation what effect this difference might have on the cross-species inferences.

Next, the structural analysis method called finite element modeling was applied (10). The object to be studied is divided into contiguous blocks, called elements, with shapes that fit natural boundaries. The continuous differential laws of mechanics are transformed into algebraic equations for the position, velocity, and stress at points within each element. More accuracy (and complexity) results from using more points per element. The properties of the material enter as parameters that are determined by conducting particular experiments. The more complete the description of the material, the more parameters that must be determined. Finally, to advance the model one time step requires solving thousands of equations for thousands of unknowns. There are a variety of numerical algorithms available and a trade-off between cost and accuracy of the solution must be made.

There are four types of choices to make in performing a finite element analysis: size of the element, number of points within the element, complexity of the material description, and the numerical solution technique. For this project we used the FEAP computer code which employs the Newmark method of solution. Each element contained four nodal points with a bilinear interpolation scheme. The material was assumed to be of a linear viscoelastic type, requiring that seven parameters must be determined for each substance. Finally, the size of elements was chosen to be small enough to resolve the phenomena of interest, yet resulting in a mathematical problem that can be solved at reasonable cost.

In order to determine if the gas content of the sheep stomach would significantly influence measurements taken within the thorax, a finite element model was constructed of the entire sheep torso. Three-dimensional blocks were used of a size sufficient to capture the major organs (Fig. 1b). In this model, the inertia of the rib cage, skeletal muscle, and diaphragm were incorporated at the appropriate nodal points, thus reducing the number of elements required.

A blast loading, corresponding to cases in which field data were available, was applied to the model surface and the subsequent intrathoracic pressure (ITP) time histories were compared with data. Two extreme cases had the rumen filled with all water and with all air. The difference in the predictions of ITP was judged to be slight and no greater than that due to uncertainty in the data or material constants. Other calculations using this model, however, showed that the element size was too large to capture the behavior of more rapid events. Based on these results, it was decided to develop a separate thorax model with sufficient resolution to follow the phenomena of interest.

From the earlier collection of anatomic data, a sheep cross-section was selected that corresponds to the approximate location where intrathoracic pressure measurements are made. Based on that view, a two-dimensional finite element model was constructed that captured the geometric arrangement of four distinct parts: skeletal muscle, rib, lung, and a water-filled organ such as the heart (Fig. 1c and 1d).

There are several approximations that must be taken into account when using and interpreting a two-dimensional representation of a three-dimensional body. First, the motion should be primarily in that plane. Since the thorax of a sheep or man is somewhat cylindrical and since it was previously shown that the motion of the diaphragm has only a small influence on the thorax, this assumption is reasonable. Second, the internal arrangement of the organs varies with the cross-section location and with individual so that the results are only typical, rather than specific. It is likely that intrathoracic pressures, which are taken in a region removed from the lung boundaries, will be less affected by the choice of cross-section. Third, the cross-section view at some locations cuts across the diaphragm, showing thoracic and abdominal organs in the same plane. Since we know these two

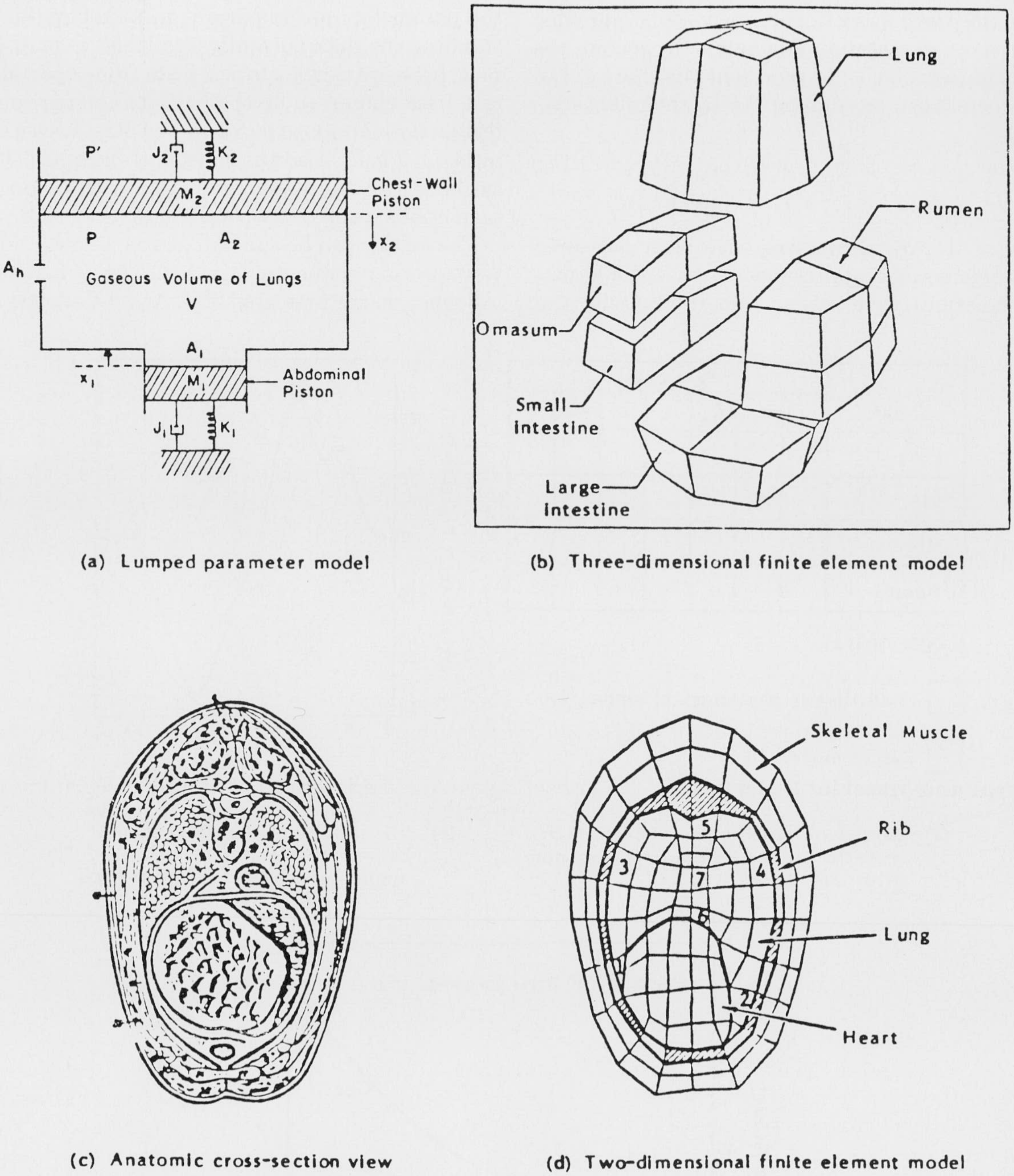


FIG. 1. Various models of a sheep thorax.

regions are not strongly connected dynamically, the region has been modeled as an equivalent water-filled (hard to move) organ. Finally, the rib cage adds stiffness to the chest wall through forces that do not originate in the plane being analyzed. Studies were made to determine the best way to include this effect and it was concluded that modifying the rigidity of the muscle/bone region to a value intermediate between muscle and bone produced the most satisfactory result. This point is discussed in more detail below in the section on thoracic response.

Material Properties Determination. The properties of the lung parenchyma have the greatest influence on the thorax response, the evolution of intrathoracic pressure, and the nature of damage to the tissue itself. Because of its central role, a special effort was made to determine its properties precisely. The experiments were conducted in the Bioengineering Laboratory at the University of California, San Diego, under the direction of Professor Y. C. Fung. There, special instrumentation was used to determine the viscoelastic properties of the lung tissue and of the whole lung, and to conduct dynamic experiments on wave propagation through the parenchyma.

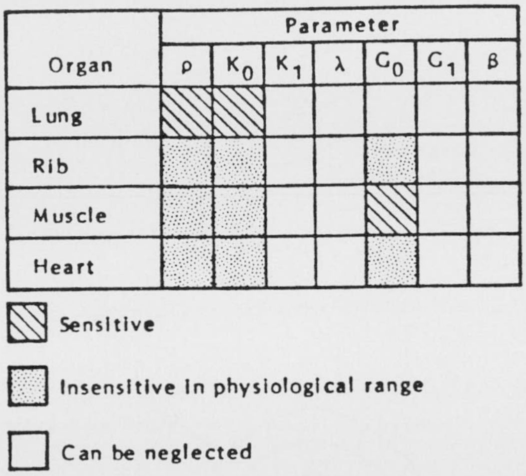
Thoracic Response. To use the finite element model

described in the previous section it is necessary to provide values for the seven material parameters for each of the four body materials chosen to represent the thorax (11). Those parameters can be summarized by the relations

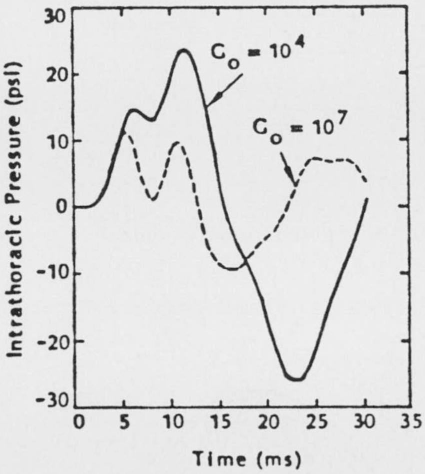
$$\text{Mass density} = \rho$$
$$\text{Bulk modulus} = K_0 + K_1 * \exp(-t/\lambda)$$
$$\text{Shear modulus} = G_0 + G_1 * \exp(-t/\beta).$$

Only a few of the 28 parameters have been measured directly, so before elaborate tests were devised and performed, calculations were made to determine which of the parameters are important to predicting and understanding the data currently available, that is, intrathoracic pressure time histories. Data from a particular field test were chosen to be the basis of comparison. In this test an animal was exposed to two blast waves separated by about 7 msec. Each parameter of the model was varied systematically and in combination with others, and the predictions compared with the measured data.

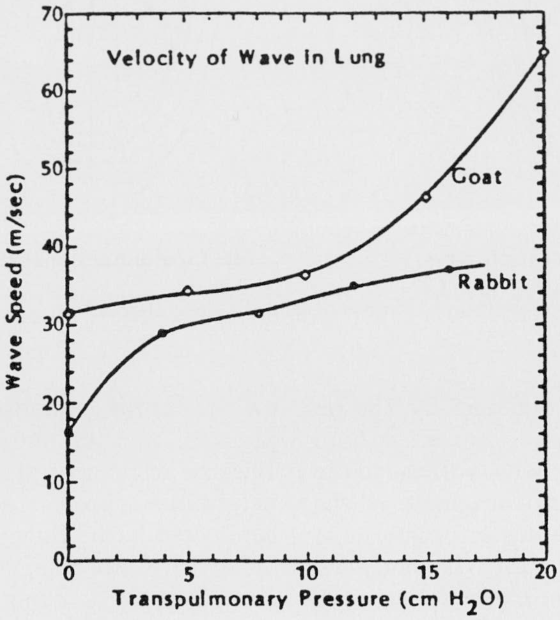
The results can be summarized as follows. None of the viscoelastic parameters (K_1, λ, G_1, or β) had significant influence on the predicted ITP. Any differences observed



(a) Sensitivity studies have shown which material properties are important for gross motion and ITP.

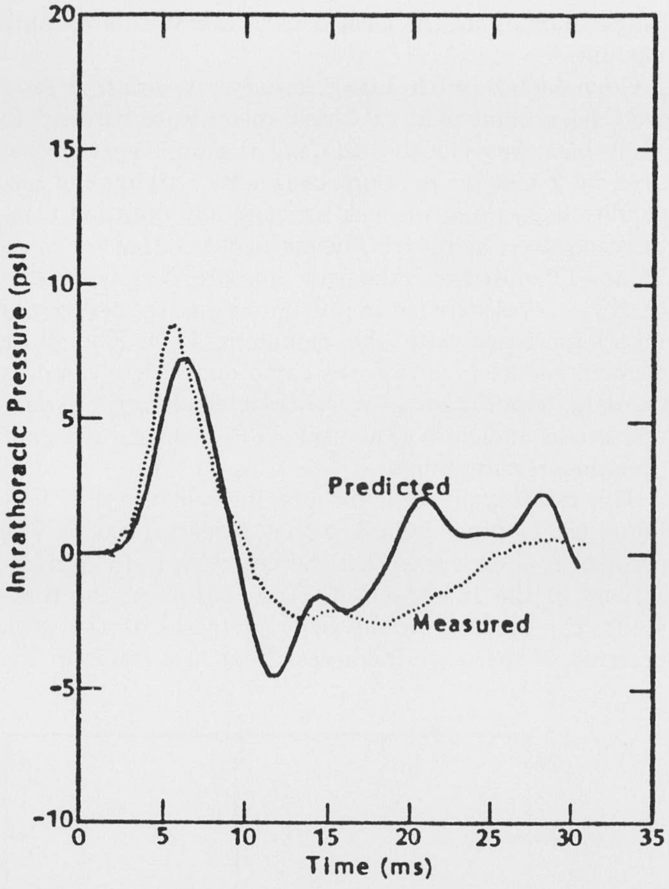


(b) The rigidity of the rib cage must be incorporated into the shear modulus of the thoracic material.



(c) Measured values of wave speed in the lung are consistent with the separately determined elastic moduli and mass density.

FIG. 2. Material properties of the finite element model.



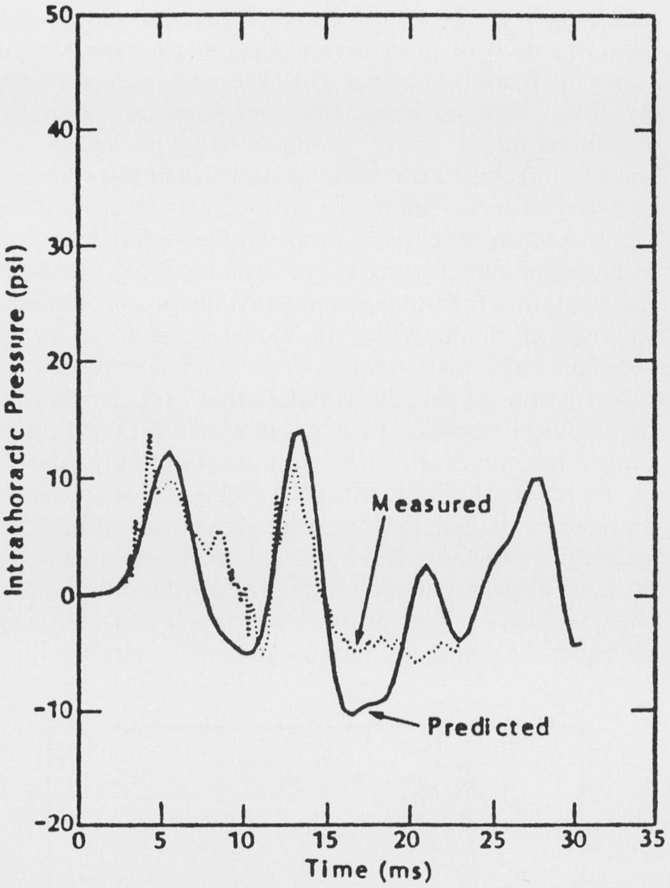


FIG. 3. Comparison of predicted intrathoracic pressure and measured esophageal pressure in sheep.

were small compared with the deviation of the prediction from measurement and were small compared with the effects of varying other parameters. Next, it was found that the elastic properties of the rib and heart elements had little effect on the predictions provided they were chosen reasonably close (within a few orders of magnitude) to the known physiologic values. The mass density of the rib, muscle, and heart are well known and reasonable variations (tens of per cent) were not significant. The only truly sensitive parameters were the mass density and bulk modulus of the lung, which have been well measured in the experiments described earlier, and the effective shear modulus of the muscle layer. (See Figure 2a for a summary.)

It was mentioned earlier that one approximation introduced by a two-dimensional representation is that out-of-plane forces, such as those due to the rib cage, cannot be mechanistically modeled. If the shear modulus of muscle, $G_0 = 10^4$, were used in the model, the model would predict unnaturally large distortions and produce ITP results completely unlike measurements. (See Figure 2b.) If, on the other hand, the muscle layer is assigned a shear modulus that will give the two-dimensional chest the kind of stiffness actually observed, then the ITP predictions are much more reasonable. This parameter can be independently determined through experiments measuring the displacement of the chest wall under loading.

With the material parameters determined, comparison was made with field test data for sheep exposure to blast. For each case, the measured free-field blast wave was translated into a loading distribution based on the findings of the torso tests and calculations. When multiple blasts were involved, the loading was simply repeated at the appropriate time interval.

Figure 3a compares prediction and measurement for a 16-lb TNT charge that produced a single peak blast wave with a peak pressure of about 12 psi. The agreement is considered to be within the uncertainty of the blast conditions, instrument response, and particular animal anatomy. Similar results were obtained for other single-blast conditions. After the initial peak, the predictions show continuing reverberation that arises from not including damping processes in the material description.

Figure 3b compares the results for an exposure to two blast waves with peak pressure of 40 psi separated in time by 7.6 msec—this was the case used in the sensitivity study. The agreement is also good, although the reverberation is more pronounced. The peaks are rounded off due to the finite spatial size of the elements and the negative phase is significantly overpredicted because *constant* material properties are being used.

The dominant feature of the calculated lung pressure distribution is the propagation and reflection of relatively slow waves, predicted by the model to be about 30 m/sec. This phenomenon arises in the model because of the combination of highly compressible, yet moderately dense lung material. In a parallel effort in Professor Fung's laboratory at UCSD, the propagation of parenchyma waves due to direct blast exposure was observed and measured. The results varied somewhat with species and transpulmonary pressure, but fell in a range about 30 m/sec. (See Figure 2c.) These results not only support the qualitative nature of the model predictions, but confirm that the dominant material properties for describing lung dynamics are the mass density and the elastic bulk modulus.

Correlation with Lung Injury. A series of tests have been conducted in which sheep were exposed to single blast waves of constant, positive impulse, as measured by a side-on pressure gauge. By varying the test conditions, a range of peak pressure and duration combinations were achieved. The tests showed that the maximum ITP varied with the peak pressure, despite the fact that the waves were iso-impulse, and that the severity of injury increased with the maximum ITP. The finite element model produced the same qualitative trend as the data. (See Figure 4.) In contrast, the lumped parameter model indicates that peak ITP is nearly constant over the pressure range.

This result is the most encouraging evidence that blast injury can be predicted using an engineering model. The prediction is dependent on the entire causal chain described in the Introduction. First, based on the torso study, the loading on the body increases as the peak pressure of the wave increases. Next, the stress in the

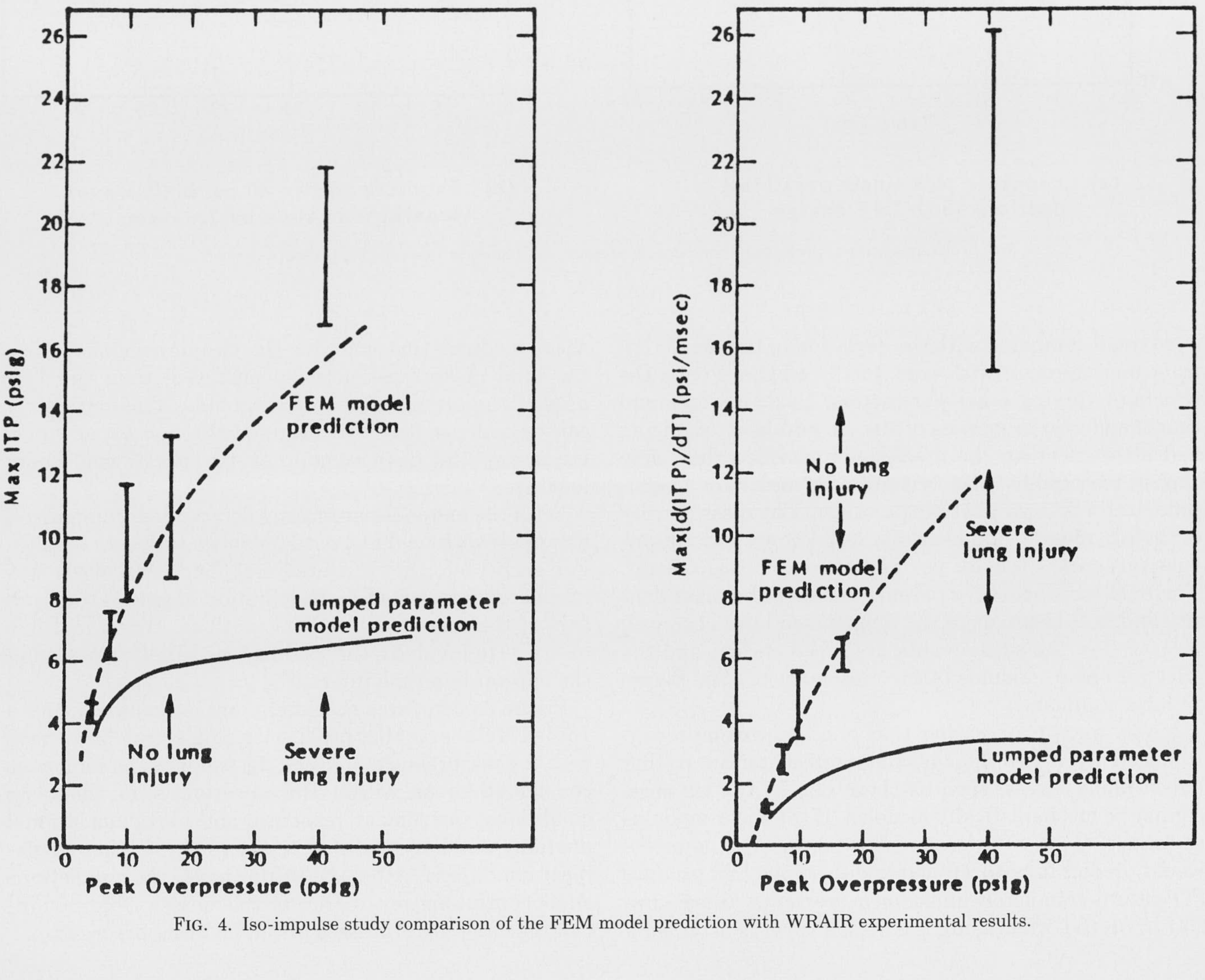


FIG. 4. Iso-impulse study comparison of the FEM model prediction with WRAIR experimental results.

lung is amplified by the slow wave speed of the parenchyma. Finally, the location of the esophageal measurement corresponds to a geometric focussing point of the compression waves.

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Comparison of Low- and High-Velocity Ballistic Trauma to Genitourinary Organs

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Serious interest in wound ballistics started in the 1850's and continued through various conflicts, with a number of investigations being performed just after the Second World War (11, 13). Since that time, for a variety of political and economic reasons, research activity has declined.

Generally, gunshot wounds may be divided into low-, medium-, and high-velocity wounds. These divisions are arbitrary but generally accepted as low velocity being less than 1,200 feet per second; medium velocity 1,200–2,500 feet per second, and high velocity greater than 2,500 feet per second (22, 23). The incapacitating ability of a given wound is dependent upon the structure of involved organs as well as the mass, velocity, and shape of the missile. The severity of wound is also dependent upon the angle of the bullet at impact (yaw), density of tissue struck, organs in the wound tract, and diversion of the bullet path by fascial planes or bone.

The amount of tissue damage is dependent upon the mass and velocity of the missile. There are three general theories used to explain the relationship of wounding to missile characteristics (1). The Momentum Theory considers wounding effect to be proportional to (mass × velocity). Second, the Kinetic Energy Theory where the wounding effect is considered proportional to mass × $(\text{velocity})^2$, and last, the Power Theory where the wounding effect is proportional to mass × $(\text{velocity})^3$. Presently, the Kinetic Energy Theory is the most widely accepted. That is to say, the wounding effect of a projectile is proportional to the kinetic energy inparted to the body by the missile. Some theories hypothesize that the wounding effect of high-velocity missiles is proportional to the power mass × $(\text{velocity})^3$ needed to create the temporary cavity (22).

The missile wound itself may be divided into three areas. First is the permanent cavity, which is produced by the missile cutting and tearing along its tract—in its simplest form, a sword thrust. There are some theories that suggest that this is the most important aspect of the wound because all of the tissue within it is destroyed. In the view of clinicians, this area is not reparable and surgical attention is directed to areas away from the permanent cavity where prompt and correct treatment will preserve life and function. The second area is that of extravasation, around the permanent cavity in the

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