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THE MODELING AND APPLICATION OF SMALL ARMS WOUND BALLISTICS

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U.S. ARMY LABORATORY COMMAND

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Due to renewed interest in flechette projectiles as antipersonnel devices, attention has once again been focused on Army methods for evaluating projectile effectiveness. This report describes some of the early wound ballistic work and presents the rationale and theory behind the current methodology for assessing small arms wound effects. A bibliography of technical reports on the subject is included.

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PREFACE

The writing of this memorandum was prompted by the need to redress undue criticisms of certain Army methods involving the estimation of antipersonnel weapon effects. These criticisms, which have appeared in recent magazine and technical journal articles, have challenged results of some Army small-arms effectiveness studies on the basis of alleged deficiencies in the underlying assessment methodology. In particular, the appropriateness of using kinetic energy as an indicator of bullet wounding potential, the importance of temporary wound cavities, and the size and formulation of tissue simulant targets were questioned and other related issues raised. All of this has resulted in an Army Materiel Command (AMC) peer review of its current position on each of these issues. It is not the intent of this memorandum to rebut individual criticisms but rather to provide a summary of correct information to inform those who are interested in an account of the rationale and experimental details behind the present wound ballistics methodology.

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Dr. Wayne Copes	Consultant

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1. INTRODUCTION

Within the military community, the uses for projectile wound data can be grouped into two related, but different categories:

[1] Operational - quantitative and functional in nature; domain of the weapons analyst.

[2] Medical - somewhat more qualitative in nature and treatment oriented

Although both areas depend on an understanding of the physiological and mechanical phenomena behind the body's response to penetrating wounds, the needs and applications of the analyst and physician are quite different.

While there is common ground in the two uses of wound information, the nature and measure of what is important are different. Therefore, the respective wound ballistics methodologies used by the two communities need not be and are not the same.

2. APPLICATIONS OF WOUND BALLISTICS DATA

At many points in the Army Research, Development, and Acquisition (RDA) cycle, the requirement arises for quantitative comparisons of weapon performance among competing candidates. Development of these quantitative comparisons is the business of the various agencies in the Army assessment, evaluation, and analysis communities; the comparisons are used to support major milestone decisions throughout the RDA process. For weapons which are primarily designed for an antipersonnel role, one quantitative comparison of interest is the ability of the weapon to degrade a soldier's effectiveness in performing military tasks.

In any armed conflict, the objective is to neutralize the opposing force. While killing an enemy soldier certainly accomplishes this, incapacitating him (i.e., destroying or degrading his ability to complete his tactical mission) achieves the same goal and places an additional burden on the opponent's medical and logistical resources. It is actually the weapon's ability to incapacitate, not wound severity nor killing potential, that is of interest to weapon designers. Moreover, as the examples that follow show, incapacitation data are often required in a relative, rather than an absolute sense.

In 1974, the Army, using estimates of incapacitation as a measure of effectiveness, performed a comparative analysis of incapacitation as a function of fragment size for antipersonnel grenades.[1] For several grenades producing various sizes of preformed fragments, incapacitation levels as a function of distance from the target were computed. The results of this study were used to determine the optimum fragment size needed to defeat protective clothing and incapacitate soldiers. These results have influenced the design of subsequently developed weapons.

Another example requiring quantitative wound data involves the weapon system analyst's need to compare the effectiveness of competing systems. By establishing a numerical ranking of candidate systems on the basis of expected incapacitation, the analyst can select the best overall system. Again, in this context, a complete characterization of the wounds produced by weapons A and B is *not* necessary, but rather a comparison of their potential for inflicting wounds which will incapacitate is preferred.

The same philosophy is applied in the development of protective equipment designed to improve the survivability of U.S. soldiers. The efficacy of new body armor materials or designs, for example, is gauged by comparing expected casualty levels associated with current and candidate personnel armor systems given certain threat munition scenarios. Here, as in the previous example, this is accomplished by evaluating the overall average effect that can be expected to result from projectiles impacting each item. To determine that effect, it is sufficient to know how a particular wound will biomechanically impair limb function.

On the other hand, the wound ballistic data requirements of the medical community are geared to the objective of providing the most efficacious medical and surgical treatment of traumatic injuries. The military surgeon needs to know the extent of a missile injury to determine what procedures and resources will be required for treatment.

3. REQUIREMENTS FOR WOUND BALLISTICS DATA

Up to a point, the needs of the weapons developers and the medical users of wound information are the same. That is, both require knowledge of a projectile's ability to penetrate and cause damage as a function of shape, mass, velocity, etc. Similarly, both require information such as size, shape and location of the permanent wound cavity, and any projectile fragments in order to characterize and quantify the amount of tissue damage. The surgeon's requirements focus on actual tissue damage and are generally related to quantifying the amount of contused and nonviable tissue surrounding the wound in order to repair the damage and prevent complications.

There is, however, a third need for the weapon developer: a technique for mapping the projectile performance and tissue response information into an effectiveness model. The current technique, which has evolved over several decades of testing and research, is known as expected kinetic energy (EKE) deposit. EKE is a measure of ballistic dose which provides the link from the set of independent variables such as projectile parameters and initial conditions to incapacitation, the measure of effect.

4. MEASURES OF EFFECT

As previously noted, the weapons effectiveness community uses incapacitation as a measure of weapon system performance. Since a wound is a structural derangement which *may* cause incapacitation, incapacitation is a functional rather than a structural concept, dependent upon a predefined tactical role/time relationship. Different tactical roles involve different tasks, so it follows that wounds are not always incapacitating. Similarly, the same wound received by two individuals performing different tasks may be incapacitating to one but not the other. Within the framework of the present operational assessment methodology (described in section 5), incapacitation is directly related to an individual's ability to use his arms and legs. In order to calculate incapacitation one must consider both the biomechanical degradation caused by the wound and the biomechanical requirement that goes with the soldier's military role.

For medical purposes, lethality is probably the most widely used measure of effect for projectile wounds. In the case of sublethal injury, the surgeon needs some method to quantify the amount of damaged, necrotic tissue which surrounds, and which can extend considerable distances away from, the wound channel. The Wound Profile method of Fackler et al.,[2] is an example of an approach designed to provide the surgeon with the information to satisfy this requirement.

5. CURRENT WEAPONS ASSESSMENT APPROACH

The general form of the incapacitation model described in this section is shown in Figure 1.

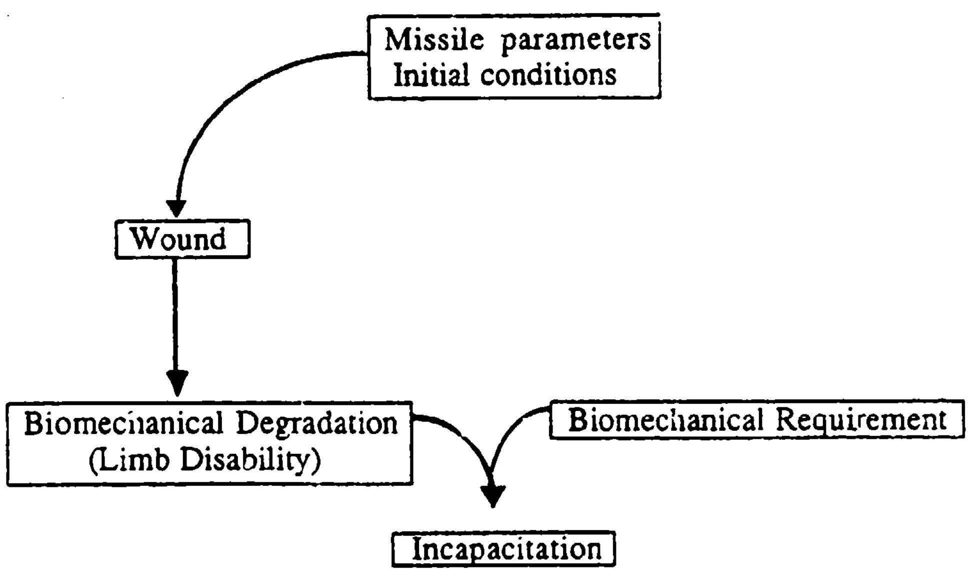

Figure 1. The General Incapacitation Model.
(Incapacitation implies some specific biomechanical requirement dictated by tactical role and some injury-induced disability which degrades the biomechanical function.)

There are two ways, discretely or generically, in which one can arrive at an estimate of incapacitation for a given projectile. It is important to make a distinction between the discrete or specific effect that results from a single projectile/tissue encounter and the generic or predicted overall effect averaged over the entire body or body part. Specific incapacitation values are obtained either experimentally or from the ComputerMan simulation model,[3] which simulates the wounding process and mimics the manual analysis that was carried out in the early fragment evaluations. Generic incapacitation values are the product of combining discrete values associated with the outcome of a number of individual events (e.g., 4-g projectiles impacting with 1000 m/s striking velocity at random locations on the abdomen of a soldier in the assault role).

To generalize over a range of mass and velocity values, regression curves are fit to these data points to allow incapacitation predictions for untested combinations (see Figure 2). The result from these curves is a number which reflects the average incapacitation level to be expected from a random hit to a particular part of the body (i.e., head and neck, thorax, abdomen, pelvis, arms, and legs). It is this generalized type of estimate that is used to evaluate weapon system effectiveness since it provides a convenient way to assess the weapon's overall antipersonnel effect. Direct comparisons between discrete and generic incapacitation values are not particularly meaningful. One would not expect close agreement between the outcome of a specific wound tract and the average outcome taken over a large number of wound tracts distributed over the same body part.

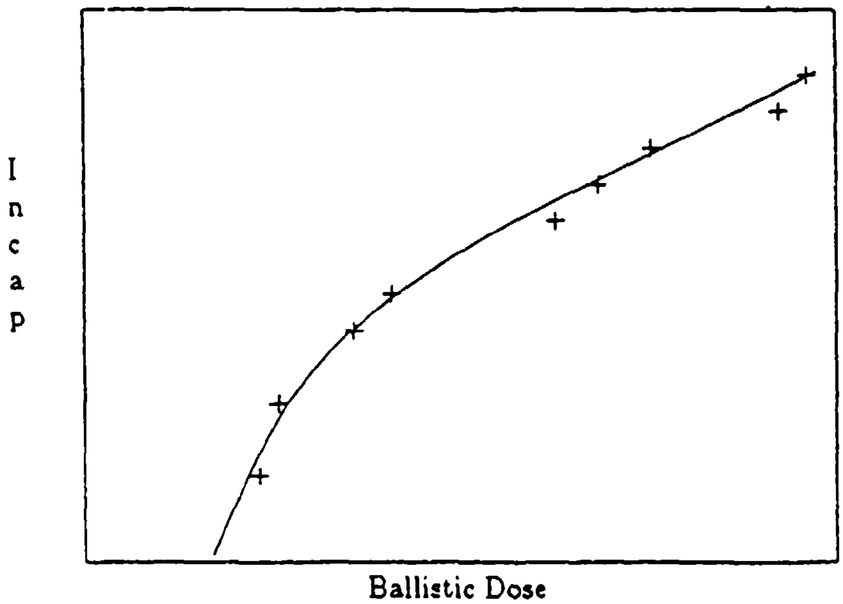

Figure 2. Incapacitation As A Function of Ballistic Dose.
(Families of curves are available for a variety of military stress situations and postwounding time periods.)

5.1 Incapacitation Database. The wound ballistics database developed over the last 30 years with the assistance of the Surgeon General's Office has established permanent wound tract information for a variety of projectiles including fragments, fragment simulators, bullets, and flechettes. The original process for determining the incapacitation potential of a particular fragment at a given striking velocity involved the generation of actual wounds in laboratory animals and a projection of the magnitude and effect of those wounds to the human body.

5.2 Biomechanical Degradation. In the projectile evaluation process, each observed wound was assigned, as a function of time after wounding, a functional group which described the expected effect that such a wound would have on a soldier's ability to use his arms and legs. Six postwounding times were considered (i.e., 0-30 seconds, 5 minutes, 30 minutes, 12 hours, 24 hours, and 5 days). These assessments were made by a team of analysts and experienced combat physicians. Each limb was predicted to suffer either no effect, an intermediate effect (weakness or loss of fine muscular coordination), or total loss of function. In assessing the wounds (assigning limb disability), the medical assessors considered size of the damaged area as well as the gross animal response exhibited during the wound ballistics experiments. Medical intervention was not considered nor were any psychological effects such as pain or fear.

5.3 Biomechanical Requirement. Independent of how physical damage to the body occurs, there is an established relationship between the resulting disability (described by functional group) and the level of incapacitation associated with that disability. For several tactical roles (Assault, Defense, Reserve, and Supply), each functional group was assigned an incapacitation value of either 0, 25, 50, 75, or 100% (corresponding to no, mild, moderate, severe, and total incapacitation, respectively) by tacticians familiar with the tasks required in each role. These values represented the percent loss of function (with respect to predefined tasks) an individual would be expected to suffer given the occurrence of that functional group.

5.3.1 Wound Analysis. The calculation of an average incapacitation for a projectile of interest was accomplished by overlaying the wound information on full-scale charts of the human anatomy and cross-referencing the projectile performance data and tactical effect estimates. By considering literally thousands of possible wounds to all parts of the anatomy, an average incapacitation value was determined for a particular projectile/striking velocity combination. The collection of these incapacitation values, commonly known as probabilities of incapacitation given a hit, or P(I/H), constitute the current fragment incapacitation database. This database is common to virtually all Army, Air Force, and Navy antipersonnel weapon effectiveness estimates involving fragmenting munitions; these data are also widely used by North Atlantic Treaty Organization (NATO) countries and other U.S. allies. Although the incapacitation criteria are used to predict both U.S. and enemy casualties, they were originally developed as a means to evaluate the effectiveness of U.S. weapons. The primary purpose of these data was to allow discrimination between weapon systems effects and not to predict absolute injury levels or their medical consequences.

5.4 Incapacitation Correlations. Prior to about 1960, various simple rules for predicting casualties existed. Probably the best known and most widely misused casualty criterion is the so-called 58 ft-lb rule. This rule of thumb, established around the turn of the century, states that missiles having at least 58 ft-lbs of kinetic energy will produce a casualty. In the years since about 1960, correlations have been established between P(I/H) for a standard set of fragments and various ballistic parameters (mass, velocity, etc.). Due to the complex behavior exhibited by bullets, estimates of bullet incapacitation have been obtained by firing the bullet of interest into a gelatin tissue simulant and then relating the kinetic energy deposited to some previously determined empirical relationship between energy deposit in gelatin and P(I/H). The methods for recording the energy deposit in gelatin blocks have improved and, with advances in computer technology, the empirical relationships between P(I/H) and energy have undergone varying changes in sophistication and complexity.

Also, since about 1960,[4,5] incapacitation potential from random impacts by chunky steel fragments and flechettes have been calculated using an MV^{α} correlation which relates mass and striking speed of the projectile to P(I/H). The functional form of the P(I/H) relationship is the following:

$$P(I/H) = 1 - e^{-a(MV^{3/2} - b)^n} .$$

In 1960, Dziemian[6] showed that the conditional probability that a random hit by a sphere, disc, cube, bullet, or flechette would incapacitate an infantry soldier could be related to the amount of energy (ΔE_{1-15}) lost by the missile during its passage between 1 and 15 cm of penetration into a 20% gelatin block tissue model at 10 degrees C. The mathematical function he used for this relationship was the following:

$$P(I/H) = \frac{1}{1+e^{a+b\,(\log_{10}(\Delta E_{1-15}))}} .$$

Dziemian also developed empirical rules for calculating ΔE_{1-15} for spheres, cubes, and stable flechettes, but could find no simple relationship to estimate ΔE_{1-15} for unstable flechettes in gelatin or for bullets. To assess these projectiles, high-speed motion pictures taken as the projectile penetrated a 38-cm long block of gelatin were analyzed frame by frame to obtain remaining velocities of the missile at any distance of penetration. Remaining kinetic energies were then calculated from the projectile's known weight. The Dziemian ΔE_{1-15} gelatin criteria were used by the Army and other services to estimate bullet and flechette effectiveness through 1968.

In an attempt to reduce test costs and eliminate some of the technical difficulties associated with inferring precise projectile position in a gelatin target using a light photographic method, a ballistic pendulum method was adopted in 1969.[37] This required a new relationship which was obtained by correlating the 15-cm energies and corresponding P(I/H) values for a modified projectile set which included both fragments and flechettes. The function chosen to relate P(I/H) and energy deposited in a 15-cm cube of gelatin as measured by the BRL pendulum was the following:

$$P(I/H) = 1 - e^{-a(\Delta KE)^n} .$$

The ballistic pendulum and the BRL ΔKE casualty criteria were the principle methodologies used by the small arms community to estimate incapacitation for bullets between 1969 and 1975.

In 1975, an alternate methodology for estimating bullet or flechette effectiveness was proposed by the now designated Research Directorate of the U.S. Army Chemical Research, Development, and Engineering Center located at the Edgewood Area of Aberdeen Proving Ground, MD.[8] In 1977, an expert panel endorsed this new EKE model as the U.S. recommended method for the NATO small arms trials and also established it as the official Army model.[35,36] This new EKE correlation[7,8,9] correlates P(I/H) with the experimentally determined, incremental expected kinetic energy deposit in a 20% gelatin target. Experimental projectile paths in gelatin are obtained out to 38 cm and extrapolated, if necessary, to 45 cm (the theoretical maximum horizontal trajectory through the human anatomy in a standing position). The weighted EKE deposit is then calculated from the following:

$$EKE \approx \frac{m}{2} \cdot \sum_{i=1}^{45} P_i \left(v_{(i-1)}^2 - v_i^2\right),$$

where EKE is the expected energy deposit (joules); P_i is the probability of the projectile being in body tissue at depth i given a random impact on the body; v_i is the projectile velocity at depth i; and m is the mass of the projectile.

EKE can be determined experimentally or analytically [8] for stable projectiles. Probability of incapacitation is then estimated from the following logistic function:

$$P\,(I/H) = \frac{\lambda}{1+e^{-\alpha-\beta \ln (EKE-\gamma)}},$$

where α, β, γ, and λ are constants based upon stress situation and time.

6. COMPARISON OF PREDICTED P(I/H) TO COMBAT EXPERIENCE

Data extracted from those collected by the Wound Data and Munitions Effectiveness Team (WDMET) in Vietnam provided a basis upon which to compare predicted incapacitation levels for specific munitions with those experienced in actual combat, a useful check on the validity of the P(I/H) methodology. There have been two analyses[9,10] made of the effects of the M26 grenade and one analysis comparing predicted and observed incapacitation due to rifle bullets.[11] The predicted P(I/H) estimates were directly compared with the P(I/H) estimates observed in combat.

In the M26 grenade comparisons, the combat data exhibit lower incapacitation than expected. This was due to the fact that the theoretical curve is derived for an unprotected soldier, whereas the majority of c[illegible]bat incidents involved soldiers wearing various kinds of protective clothing. [illegible]he rifle analysis, the observed number of incapacitations for the 30-second assault criterion is in close agreement with the corresponding predicted value. A similar comparison based upon the 30-second defense criterion shows an observed value about one-third less than the predicted value. Given the limited sample size available for this study (25), a change in decision of several of the subjective parameters could noticeably alter the observed estimates. These studies conclude that the observed incapacitation values are not inconsistent with predicted values.

6.1 Gelatin as a Tissue Simulant. Gelatin is used throughout most of the wound ballistics community as a muscle tissue simulant. It has the advantages of consistency (as compared to live tissue), reproducibility over time and between laboratories, and economy. Typically, 20% (by weight) gelatin targets at 10° C have been used to simulate skeletal muscle tissue. This is the NATO standard target for evaluating small arms projectile lethality.

Numerous wound ballistic studies[12-17] have been performed which demonstrate for a variety of projectiles the correlation between the velocity/penetration curves in various soft tissues and those in 20% gelatin targets at 10° C. Flechettes, fragments, and bullets retard at the same rate in animal tissue and 20% gelatin and form temporary cavities in each of the same shape and approximate volume. Although missile tracts in gelatin blocks are not direct indicators of the amount of tissue damaged by penetrating projectiles, 20% gelatin does simulate the average human tissue response in terms of projectile penetration depth and retardation.

An analysis of gelatin properties and performance data by Peters,[18] a professor of mechanical and aerospace engineering at the University of Tennessee Space Institute, concluded that typical 20% gelatin at 10° C caused "projectile retardation that is close to the retardation in typical living pig thighs."

6.2 Kinetic Energy Deposit as an Indicator of Projectile Effectiveness. The role of kinetic energy in the wounding process has been the subject of much research and discussion. While there may not be a unique relationship between the amount of kinetic energy transfer to a target and the resulting amount of tissue damage, kinetic energy deposit does provide a convenient, physically consistent means of explaining damage which occurs both locally and at distances away from the projectile path and well outside of the permanent wound cavity. There are many examples in the literature[19,20] of such damage in the form of nerve damage and bone fractures which have occurred outside of the penetrating missile's path. In these cases and others involving human gunshot victims, it is clear that besides damage to the tissue which comes in contact with the projectile, there can be additional damage which cannot be explained by the mechanisms of crush and tear. The composite damage model of Peters[21] provides further theoretical support that projectile wounding is caused by a combination of permanent and temporary cavity damage.

In the wound studies described in section 5.1, kinetic energy deposit was not an *a priori* consideration in the assessment of individual wounds. Rather, the expected kinetic energy deposit, weighted by a hit distribution, is used in the present methodology to relate projectile characteristics to the average expected level of incapacitation, P(I/H). Again, the P(I/H) database was derived from experimentally determined permanent wound tract information. As described previously, statistical evidence of a correlation between these two variables has been established.

7. FLECHETTES

Flechettes, from the French word for "little arrows," have long been of interest to military weapons designers. Modern steel flechettes have length-to-diameter ratios (L/D) on the order of 13-25 and weights of 0.1-4.5 grams. Because of their slenderness, flechettes exhibit extremely low air drag and can maintain high striking velocities at long ranges - hence their attractiveness as candidate projectiles to weapons designers. A major drawback to fielding an individual weapon system incorporating flechette projectiles has been weapon accuracy. Recent advances in sabot technology show promise in reaching the accuracy levels required for modern individual weapon systems.

The wounding potential of flechettes has been well established through wound ballistics studies dating back to 1959.[22-30] Depending upon construction and striking velocity, flechettes exhibit basically two types of behavior in tissue and tissue simulants. At striking velocities below approximately 900 m/s, homogeneous steel flechettes tend to penetrate soft tissue target media in a stable mode (i.e., without tumbling or buckling), causing wounds that are relatively constant in diameter from entrance to exit. Such wounds are typical for artillery launched (BEEHIVE) and shotgun launched flechettes, projectiles which were used in Vietnam. At striking velocities higher than 900 m/s these flechettes begin to deform and buckle (i.e., the flechette nose becomes blunted and the shaft bends), causing wounds which initially are constant in diameter but which become larger as buckling progresses and the projectile presents a larger surface area to the target. This behavior has been demonstrated experimentally[22-30] and theoretically.[31,32,33] A recent series of firings[34] with flechettes into both standard 20% gelatin and 10% gelatin at velocities above 900 m/s have reconfirmed this deformation behavior.

The general conclusions of the Special Purpose Infantry Weapon (SPIW) study[30] and others cited previously support the inclusion of the flechette as a candidate projectile for the next generation individual combat weapon system. These conclusions can be summarized as follows:

[1] High velocity flechettes compare favorably at normal engagement ranges with modern rifle bullets in terms of incapacitation and tissue destruction.

[2] Flechettes can fracture bone at velocities obtained at normal engagement ranges.

[3] Flechette weapons, designed to be fired in multiple round bursts, can provide a wound synergism to enhance incapacitation.

8. CONCLUSIONS

Wound ballistic studies with fragments, bullets, and flechettes with substantial medical input provide a consistent database upon which the current incapacitation assessment methodology is based. Considerable effort has gone into development of a methodology which, although constantly undergoing refinement, is based on sound research. Although certain elements of the methodology have not been well documented or publicized, a clear audit trail exists for the majority of this research. All aspects of the methodology, in particular, those involving medical expertise, are subject to being updated whenever the need for improvement is identified and medical input is available.

The purpose of this methodology is to provide a technique for quantifying the difference in antipersonnel effect between competing weapon systems and to provide a means for evaluating improvements in weapons, ammunition, and items of protective clothing and equipment. The interactions which take place between wounding agents and the human tissues they encounter are complex and depend on a large number of variables. While some of the relationships are not fully understood, the present suite of models based on kinetic energy transfer theory accomplish their intended purpose and provide reasonable, useful, and scientifically sound results.

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