PENETRATION

The factors in the drag equation (that is, the coefficient of drag, the density of the medium, and the cross-sectional area and velocity of the projectile) also determine *(a)* the depth that a projectile will penetrate its target and *(b)* the velocity of the projectile at a given depth of penetration. Ideally (that is, if a stable, nondeforming projectile passes through a homogeneous, infinite solid), the depth of penetration X will be:

$$X = \frac{M}{(CD)\,(d)\,(A)} \ln \frac{V_i}{V_x}$$

and the residual velocity Vx at X will be:

$$V_x = V_i \frac{1}{e^{(X)\,(CD)\,(d)\,(A/M)}}$$

where *Vi* is the initial velocity, *CD* is the coefficient of drag for a projectile of mass *M* and cross-sectional area ***A*** passing through a medium of density *d*. In these equations, penetration is a logarithmic function of initial velocity, and decrement in velocity is an exponential function of penetration. The equations demonstrate that, all other factors being equal,

- the greater a projectile's mass, the greater will be its depth of penetration
- the greater a projectile's residual velocity, the greater will be its depth of penetration
- the greater a projectile's sectional density, the greater will be its depth of penetration

Conversely, a lightweight projectile with a large presenting surface, such as a chunky aluminum fragment, will penetrate shallowly. These formulae also demonstrate that, given equal initial kinetic energies, a light, fast projectile will slow more rapidly and penetrate less deeply than will a heavy, slow projectile.*

These penetration equations apply to a hypothetical target of infinite length. In the practical situation when the target has finite thickness, knowing the projectile's residual velocity is more useful, but the mathematical treatment is also more complicated. To perforate, a projectile must have a striking velocity above a characteristic minimum, which is determined by the target's material properties. The curve relating the striking and residual velocities of stable, nondeforming projectiles is exponential:

$$\frac{V_r}{V_s} = 1 - e^{-a\,[V_s - MIN]^b}$$

where *Vr* and *Vs* are the projectile's residual and striking velocities, *MIN* is the minimum striking velocity compatible with perforating the target, and a and *b* are experimentally derived constants related to the material properties of the target and the ballistic characteristics of the projectile.

Figure 4-8 illustrates the mechanics of penetration. **A** perforating projectile loses little velocity unless its striking velocity approaches the minimum velocity required for perforation. This explains the frequent all-or-nothing performance of protective equipment such as helmets and armored vests: The projectile is either completely stopped and does no damage, or else it perforates and loses little of its damaging potential.

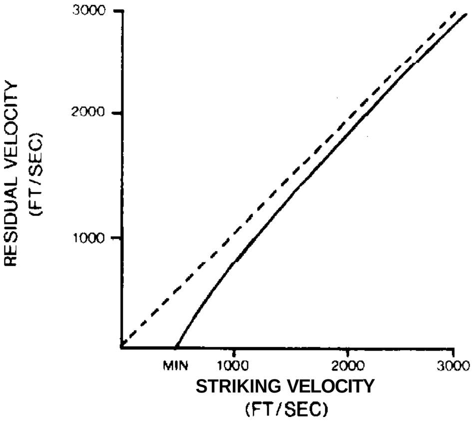

Fig. 4-8. The curved line shows the relationship between striking velocity and residual velocity after penetrating a target for an idealized, nondeforming, stable projectile. MIN is the minimal velocity that the projectile must have to perforate the target. The separation between the curved and broken lines represents the loss of velocity that the perforating projectile incurred. The residual velocity is only slightly degraded, except when the striking velocity is near the minimal velocity required for perforation.

ENERGY TRANSFER IN THE PROJECTILE-TARGET INTERACTION IN TISSUE

Drag slows a projectile as it passes through a medium. The medium also exerts an equal but opposite force on the projectile, and the medium is physically disrupted as a result. If the medium is tissue, the physical disruption is a wound. The projectile's kinetic energy *works* on the tissue (that is, the energy of the projectile's motion is transferred from the projectile to the tissue) and causes the tissue's disruption.

Kinetic energy and drag are independent descriptors of a projectile's behavior in tissue. Neither high nor low values of drag necessarily accompany high or low values of kinetic energy. But kinetic energy and drag together do determine the amount of the projectile's kinetic energy that will be transferred to the target as the projectile slows. A projectile with high kinetic energy and high drag will be associated with *high energy transfer,* and a projectile with low kinetic energy and low drag will be associated with *low energy transfer*. The concept of energy transfer clarifies the physical and biophysical aspects of the projectile-target interaction.

Total Energy Transfer

Theoretically, measuring the energy transferred from a projectile to a target tissue is easy. If a projectile perforates without either losing its substance or deforming, the formula for calculating the energy transferred is:

$$1/2 \text{ MASS } [(V_{et})^2 - (V_{ex})^2]$$

where V_{et} and V_{ex} are the velocities of the projectile as it enters and exits the target, respectively. If the projectile does not perforate but comes to rest within the target tissue, the formula for calculating the energy transferred is:

$$1/2 \text{ MASS } (V_{et})^2$$

Extensive data describe energy transfer for a variety of different bullets and fragments measured in tissue simulants such as gelatin and soap, and in living animal tissues.[2, 9, 10, 11] Among the conclusions are the following:

- Perforating, nondeforming rifle bullets transfer a small fraction (8%–19%) of their kinetic energy in traversing soft tissue. (Dr. Charles Woodruff strongly suspected this fact in the late nineteenth century.)
- Stable, perforating, nondeforming rifle bullets transfer less of their kinetic energy than do similar bullets that became unstable (11% versus 16%).
- Bullets that break up while traversing tissue transfer more of their kinetic energy than do bullets that remain intact (40% versus 23%).
- Fragments, because they usually do not perforate the target, are much more likely than bullets are to transfer their total kinetic energy.
- Projectiles with lower absolute kinetic energy sometimes transfer more kinetic energy to the target than do more energetic projectiles. In these instances, energy transfer by the less energetic projectile is more complete. For example, the M193 bullet of the M16 assault rifle frequently transferred more kinetic energy than the 7.62-mm bullet of the AK47 assault rifle did (424 J versus 153 J) even though the latter fired a much more energetic bullet (1,919 J versus 1,543 J).
- The target medium (that is, soap, gelatin, pig thigh, and so forth) affected energy transfer less than was anticipated.

The available kinetic energy of the projectiles in these 1,000 and 3,000 J. Both the absolute magnitude of the energy transfer and the fraction of the total kinetic energy transferred depend upon the length of the projectile's trajectory in the target, which, in turn, depends upon the size of the target. In most of these experiments, the trajectory lengths were similar to those found in wounds of human extremities.

Nonuniform Energy Transfer. Energy transfer that is calculated for the projectile's entire trajectory through tissue (that is, the *wound tract* or *permanent cavity*) may be misleading. Energy transfer usually does not occur uniformly along the trajectory because *(a)* the projectile may behave unpredictably (that is, it may yaw, deform, and so forth) and *(b)* the target substance will be nonhomogeneous (that is, it is composed of skin, fat, muscle, and bone). For these reasons, tissue damage also may not be uniform along the wound tract.

Experiments performed at the army's ballistics laboratory at Edgewood, Maryland, demonstrate nonuniform energy transfer occurring along a wound tract.[12] An ultrahigh-speed motion picture photographed a 30-caliber Ball M1 bullet as it passed through a gelatin block (Figure 4-9). Measuring frame-by-frame the distance the bullet travelled, the researchers could calculate the bullet's velocity, kinetic energy, and energy transfer. They showed that the sudden increase in energy transfer after the bullet had penetrated 14 cm was due to marked yaw. They elaborated upon these data by performing a series of experiments with the same type of bullets penetrating goat thighs. By measuring multiple cross sections of the wound tract and plotting these measurements against energy-transfer data from the gelatin blocks, they demonstrated that the wound tracts through the goats' thighs increased in size at the same point that significant yaw occurred in the gelatin blocks. The wound tracts, narrow at the wounds of entrance, broadened considerably at the wounds of exit, where bullet yaw became prominent in the goats' thighs.

A second example from the same laboratory[13] shows energy transfer both as suggested by the gross tissue disruption in sheep and as a function of depth of penetration in gelatin (Figure 4-10). The researchers shot a sphere through the hind legs of a sheep. After sacrificing the animal, they made multiple transverse cuts across the wound tract. They measured the cross-sectional area of the wound tract as they had done with the goat thighs. They also shot identical spheres into 20% gelatin blocks and recorded the spheres' passage on ultrahigh-speed motion pictures. Measuring frame-by-frame, the researchers used the changes in velocity to calculate energy transfer.

Figure 4-10 illustrates two facts that emerged. First, energy transfer (as calculated from the retardation of the sphere) was maximal at the sphere's point of impact, and the huge wound of entrance shows that tissue damage there was correspondingly massive. And second, the cross-sectional area of the wound tract was not uniform. The marked diminution in the size of the hole in the muscle of the downrange thigh signifies that the sphere's velocity falls as it penetrates the tissue. The differences in morphology along the wound tract (and the implied differences in energy transfer) may also be due to the different viscoelastic properties of skin, fat, and skeletal muscle that the sphere passed through. Such differences in energy transfer would not be apparent in the homogeneous gelatin block.

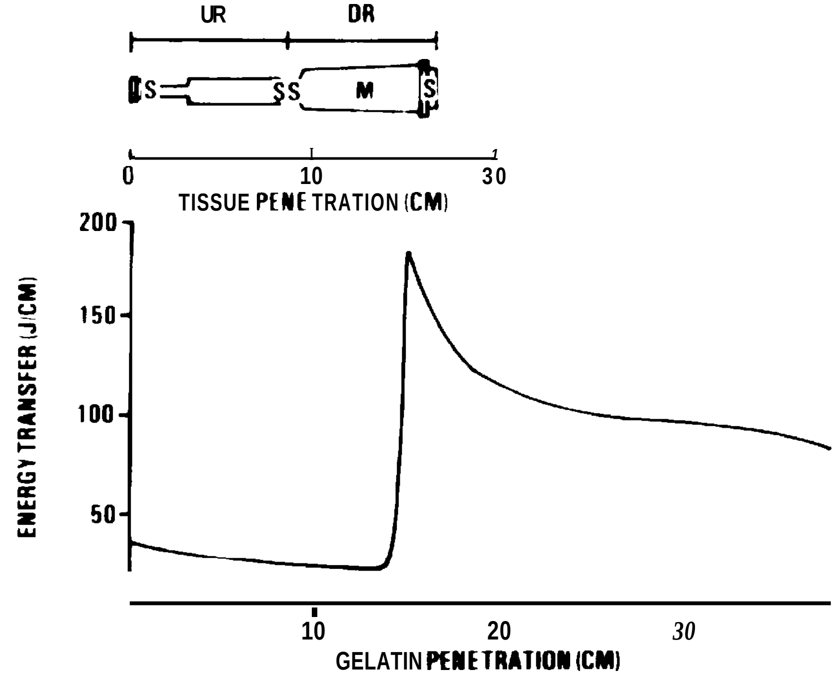

Fig. 4-9. Data pertaining to the penetration of a .30-caliber Ball military bullet: *(a)* energy transfer as a function of the depth of penetration in a block of 20% gelatin (lower diagram), and *(b)* a qualitative assessment of the width of the permanent cavity observed in the combined thighs of a goat (upper diagram). The width of the permanent cavity was larger in the downrange thigh (DR) and the wound of exit in the downrange thigh was larger than the wound of entrance in the uprange (UR) thigh. By comparing the two types of data, it can be seen that there is a rough correspondence between gelatin-block energy transfer and wound morphology. Skin: (S); muscle: (M).
Source: Redrawn from **Figure** 3c in reference 12

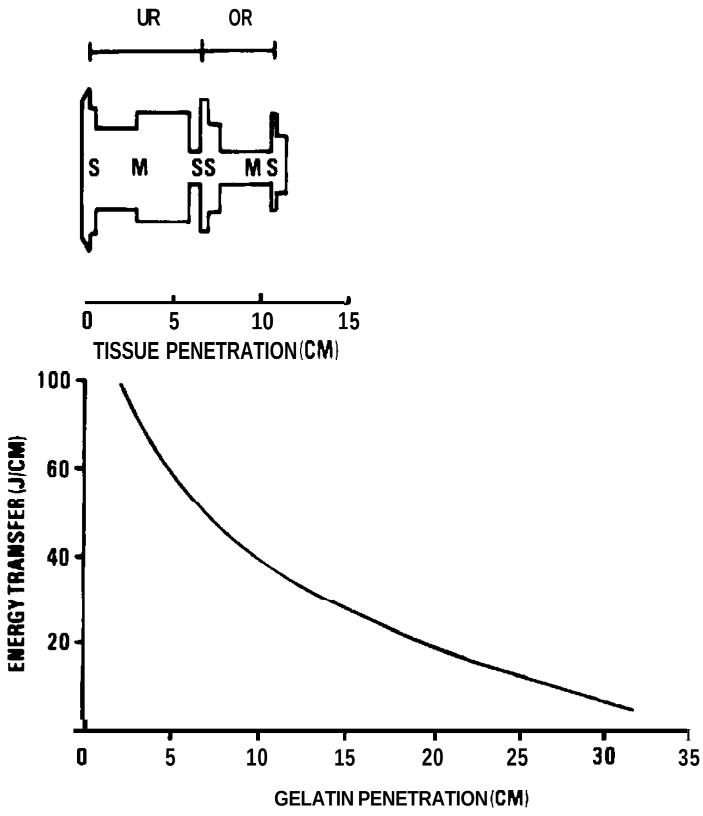

Fig. 4-10. The methodology used to obtain these data is similar to that used in Figure **4-9,** except that the projectile shown here is **a 2.6-g** sphere and the wound morphology is the reverse: The permanent cavity is smaller in the downrange thigh and the wound of entrance is larger than the wound of exit. Energy transfer as measured in the gelatin block falls as a function of the missile's depth of penetration. The greater energy transfer in the uprange thigh appears to be associated with greater tissue disruption.

Source: Redrawn from Figure 11 in reference 13

Newer methodologies using multiple-flash roentgenography to measure velocity in tissue and tissue simulants have confirmed these **findings.**[14] Figure 4-11 shows energy transfer (as assessed by the force of retardation) as a function of depth of penetration for 5.56-mm bullets into both pig thighs and soap blocks. The initial trajectories (8–12 cm) of the bullets are stable and associated with little energy transfer. Then, in what can only be described as an explosion, the bullets transfer much of their kinetic energy. This methodology clearly shows that yaw, tumbling, and breakup caused the nonuniform energy transfer along the wound tract.

The Wound Profile. Idealized projectile-target interactions called ***wound profiles***[15] depict hypothetical energy transfer occurring in a homogeneous target (Figures 4-12 and **4-13). A** wound profile is a drawing made after a projectile has been shot through a block of 10% gelatin. This concept assumes that the radial fissures or cracks around the projectile's path through the gelatin block indicate the size **of** the temporary cavity created by the passage of the projectile. The size of the temporary cavity is an important factor in determining the magnitude of the energy transferred from a projectile to its target, and the length of the radial fissures, indicating the imaginary diameter of the void

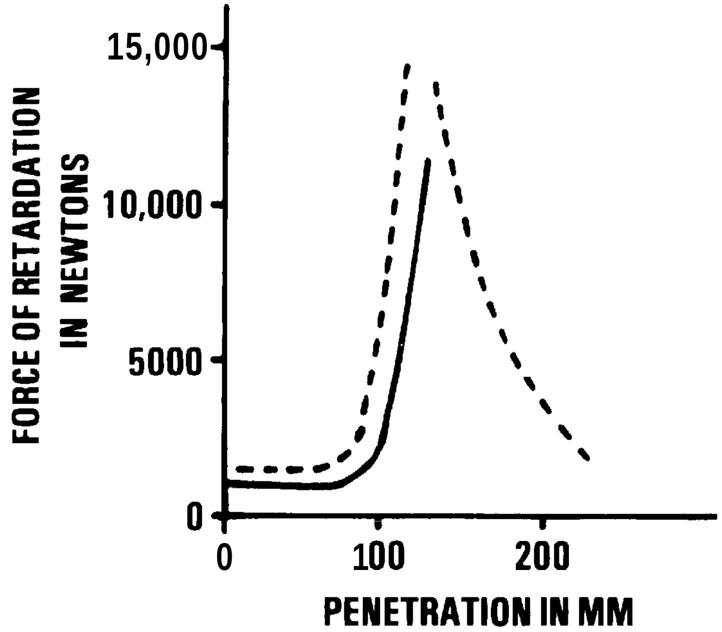

Fig. 4-11. The force of retardation calculated from the deceleration of 5.56-mm bullets as a function of the depth of penetration in a swine thigh (solid lines) and soap (broken line). In both cases, the sudden increase in retardation was associated with tumbling, which was clearly visible in high-speed roentgenograms.
Source: Redrawn from Figure 36 in reference 14

shown in the wound profile, may be taken as a qualitative index of energy transfer.

Figure 4-12 shows the presumed behavior of a stable, nondeforming bullet, with a channel of fairly uniform width extending along the entire trajectory. Energy transfer (and, by implication, tissue disruption) is fairly uniform along the line of flight.[16]

Figure 4-13 shows the more complex, as well as the more common, situation: nonuniform energy transfer.[16] Once again, the width of the disturbance created by the bullet indicates the magnitude of energy transfer. The first third of the trajectory is uneventful and consists of a narrow uniform channel. The middle third of the trajectory is very different: The actual gelatin block from which the drawing of the wound profile was made showed both a huge cavity and long fissures running perpendicular to the trajectory in this region. The final third of the trajectory resembles the first third. The vastly greater width of the trajectory in its middle third indicates that energy transfer markedly increased. For there to have been such a marked increase in energy transfer, there must have been a marked increase in projectile drag. Although the wound-profile methodology does not allow direct visualization of projectile yaw, the site of maximum disruption in the gelatin was probably also the site of the projectile's maximum yaw.

Projectile Characteristics That Determine Energy Transfer Within Tissue

Just as the characteristics of the target determine the energy that is transferred (that is, a bullet's striking a bone ensures high-energy transfer), so the physical characteristics of the projectile, which may change as it penetrates the target tissue, also must be considered separately. If a bullet (or all or most of its fragments) comes to rest within the target tissue, all (or most) of the bullet's kinetic energy will transfer to the tissue and will have the potential to produce greater wounds.

Shape at Impact. Blunt or irregular projectiles make larger wounds of entrance than smooth or pointed projectiles of the same relative size. Researchers at Letterman Army Institute of Research (LAIR) convincingly demonstrated this fact (Figure 4-14).[17] Holding all other variables constant (such as velocity, distance from the target, and projectile size and construction) and varying only the orientation of the bullets, they shot a pig in each buttock: on the left with a rifle bullet loaded point-forward, and on the right with an identi-

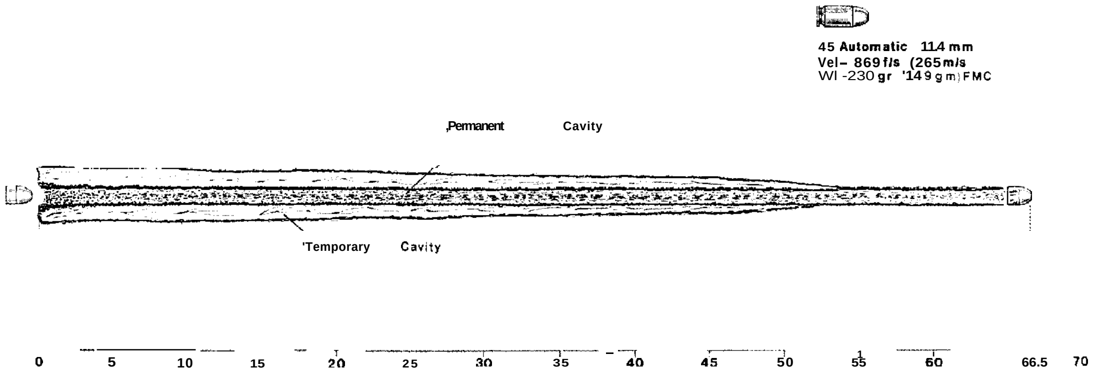

Fig. 4-12. A wound profile for an ACP M1911 .45-caliber bullet. Energy transfer, shown by the width of the idealized permanent and temporary cavities, is fairly uniform along the line of flight.
Source: Reproduced from Figure 4 in reference 16

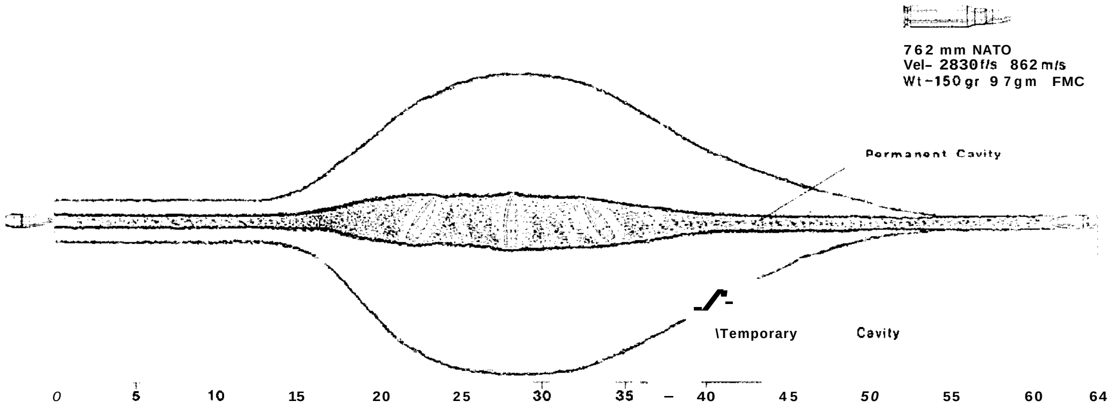

Fig. **4-13.** A wound profile for a NATO 7.62-mm bullet. Energy transfer, shown by the width of the idealized permanent and temporary cavities, was greatly increased at the presumed site of the bullet's tumbling in mid-trajectory.
Source: Reproduced from Figure 7 in reference 16

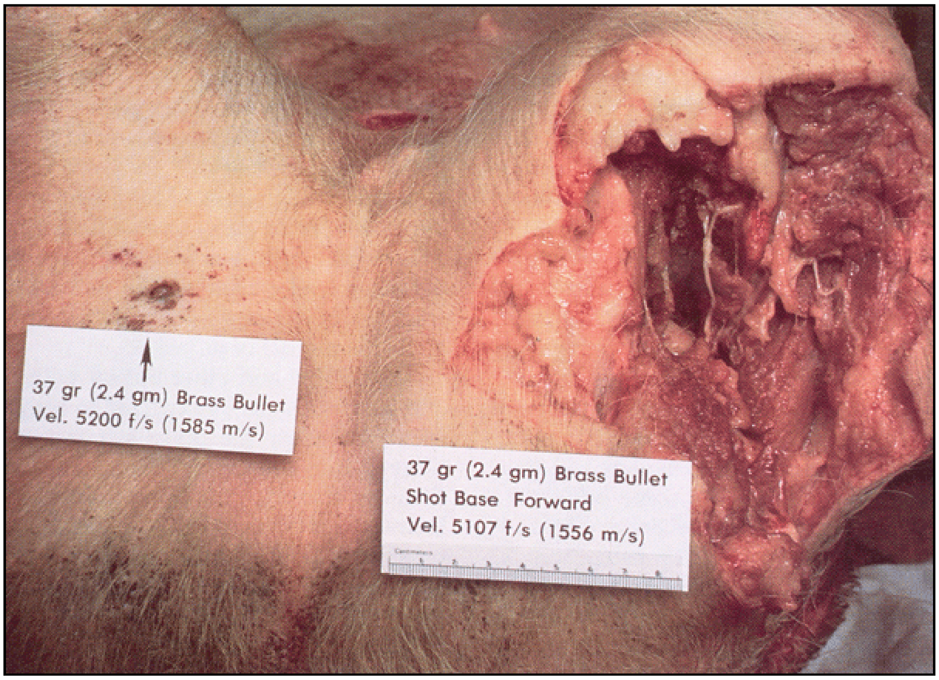

Fig. 4-14. This photograph shows the importance of the projectile's shape to a wound's morphology. The buttocks of a 100-kg swine (that had been sacrificed earlier) were struck by two solid brass 5.56-mm bullets with striking velocities greater than 5,000 fps. The wound on the left was made by a bullet traveling point-forward; the wound on the right by a bullet traveling with its flat base forward.
Source: Letterman Army Institute of Research

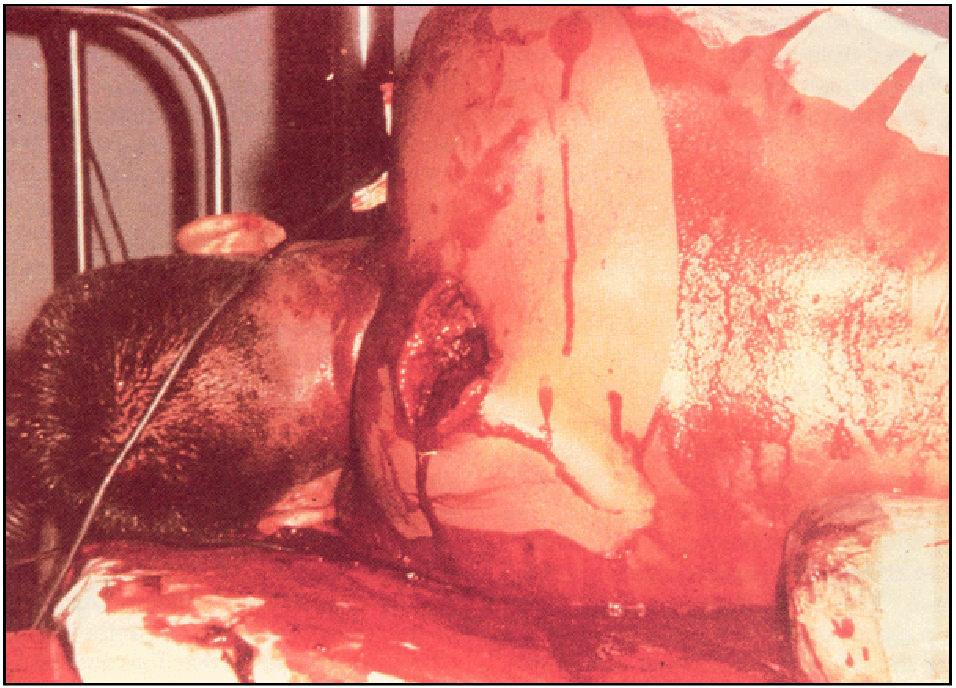

Fig. 4-15. This casualty's wound of entrance was made by a large, blunt, irregular fragment from a 105-mm shell. The permanent cavity involved the second thoracic vertebra, the left lung, and the subclavian artery. The casualty died about 3 hours after being wounded.
Source: Wound Data and Munitions Effectiveness Team

cal bullet loaded base-forward. The dramatic difference in the two wounds is due entirely to the different shapes of the two bullets at the moment of impact. Because blunt or irregular projectiles present relatively large areas of contact with the target tissue, their energy transfer is accelerated compared to that of more streamlined projectiles. Nonuniform energy transfer due to projectile shape may be further complicated by the fact that projectile velocity is not constant throughout the tissue trajectory but is greatest at the instant of penetration. Large fragments from older, explosive, random-fragmentation munitions characteristically caused huge wounds of entrance (Figure 4-15).

Fragmentation. The fact that bullets break up in tissue is an important but frequently ignored factor in projectile-target interaction.[18] Most bullets will fragment if they hit a large bone, but some bullets are notorious for breaking up even in soft tissue. Figure 4-16 shows the two basic types of bullet construction: *(a)* the NATO 7.62-mm bullet, which has a copper jacket and a lead core, and *(b)* the M43 bullet (fired by the Soviet AK47 rifle), which has a thick steel jacket, a large soft-steel core, and a small amount of lead. Because of its construction, the M43 bullet is quite strong and usually breaks up only when it strikes bone or a hard external object. Figure 4-17 shows a casualty whose skull was penetrated by a bullet fired from an AK47. The bullet broke up after hitting and fracturing the opposite occipital bone. Figure 4-18 shows the bullet after it was removed from the dead casualty's brain.

Figure 4-19 is a roentgenogram of an M43 ball fired from an AK47 that broke up within a casualty's abdomen. The bullet probably started to break up when it struck a hard object on the casualty's web gear just before it penetrated the soldier's body. The large size of the wound of entry suggests that the bullet either yawed significantly or deformed before it struck the soldier (Figure 4-20).

Although it is unusual for an AK47 bullet to break up when not associated with hitting a hard object first, such breakup commonly occurs with bullets fired by the M16. Figure 4-21 is a roentgenogram showing a fragmented bullet within the wound of entrance in a casualty's chest. Even though there is no evidence of a fractured rib, the collection of lead within the casualty's lung indicates that the bullet fragmented. Figure 4-22 is an abdominal roentgenogram showing the bullet's nose. This large fragment (the bullet's nose, a breakup characteristic of the M16 bullet) was extracted from the casualty's abdomen at autopsy (Figure 4-23).

A bullet's construction may increase its tendency to break up, Some copper-jacketed bullets with lead cores (such as the M193 fired by the M16A1) cannot stand the by angular velocity during yaw. The radial stress created when the bullet tumbles around its center of mass (as measured with multiple-flash roentgenograms) has been estimated to exceed by a factor of four the force required to fracture a bullet-sized cylinder of lead.[19] Furthermore, as the bullet slows, very high retardation forces crush the jacket, expell lead from the core, and flatten the bullet. The M16 bullet (and others with lead cores) begins to break up when lead extrudes from its base and the bullet fractures at its *cannelures* (that is, the grooves that circle the middle of its jacket).

The M193 and other bullets with copper jackets and lead cores can be expected to break up and fragment whenever the bullet's trajectory through the target is long enough for significant yaw to develop. Breakup also depends upon the bullet's strilung velocity. An M193 might break up at about 600 m/s, and breakup is assured at speeds faster than 700 m/s.

Externally similar bullets may have very different tissue effects because they have been constructed differently. Breakup of the Soviet M43 bullet fired by the AK47 starts at the nose, where the jacket usually peels back and exposes the steel core (Figure 4-18), but design and construction of ammunition for the Kalashnikov assault rifle is not uniform worldwide. For instance, unlike the bullets designed and made by the Soviets, bullets that are produced by Chinese and Egyptian manufacturers of AK47 ammunition have a copper jacket and a soft, lead core. This bullet is far more likely to break up than is the M43. Unfortunately, examples of similar differences in construction are commonplace. For instance, the NATO standard 7.62-mm bullet manufactured in West Germany has a copper jacket only one-half as thick as the same bullet made in the United States (Figure 4-16). Not surprisingly, bullet breakup is much more common with the former than with the latter.[20]

Deformation. All other factors being the same, a projectile that deforms will transfer more of its kinetic energy than will a projectile that does not deform (Figure 4-24).[21] Bullets that are designed to deform, such as hollow- and soft-point bullets (forbidden for use by the military) will do so only if they strike with a velocity above a characteristic minimum. Since the bullet's velocity will be greater early in its trajectory through tissue, deformation, if it occurs, will occur shortly after the projectile strikes. Thus, maximal energy transfer will occur near the wound of entrance. Of course, a projectile that does not normally deform in soft tissue may do so if it hits bone, and maximal energy transfer will occur there.

Stability. Energy transfer will greatly increase when a projectile's angle of yaw increases from a few

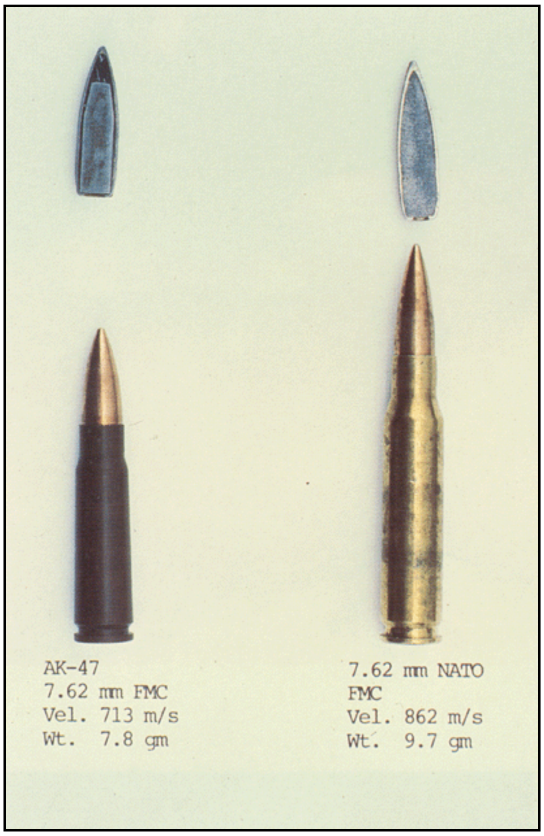

Fig. 4-16. Examples of the two most common forms of bullet construction: (left) the **M43** round of the AK47 with its steel jacket and steel core penetrator and (right) the NATO 7.62 round with its copper jacket and lead core.
Source: Letterman Army Institute of Research

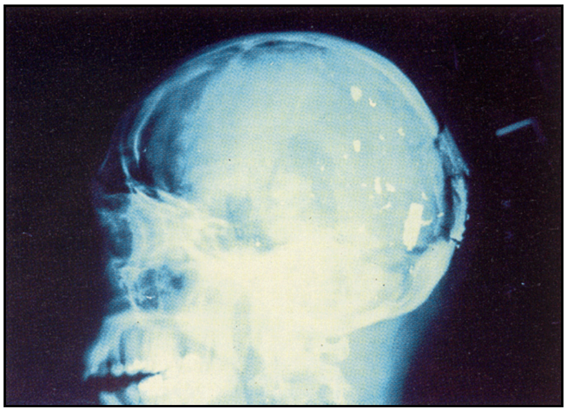

Fig. 4-17. The casualty whose skull is shown in this roentgenogram was killed by an **M43** ball fired from an AK47. The bullet broke up as it perforated the temporal bone and ricochetted after fracturing the opposite occipital bone. Note that a segment of the occipital bone has been detached from its surrounding tissue.
Source: Wound Data and Munitions Effectiveness Team

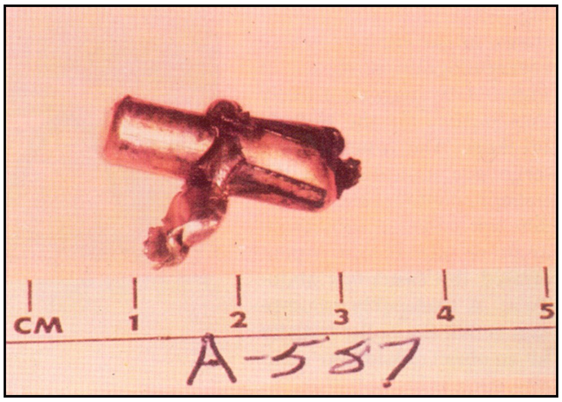

Fig. 4-18. The bullet after it had been extracted from the brain of the casualty shown in Figure 4-17. The steel jacket has peeled back, exposing the penetrator that constitutes the bullet's core. This behavior is characteristic of the breakup of the **M43** bullet.
Source: Wound Data and Munitions Effectiveness Team

Fig. 4-19. An abdominal roentgenogram of a casualty who was wounded by an M43 ball fired from an AK47 rifle. The M43's steel core lies in the left lower quadrant of the casualty's abdomen. There was extensive damage to the small intestine and the sigmoid colon.
Source: Wound Data and Munitions Effectiveness Team

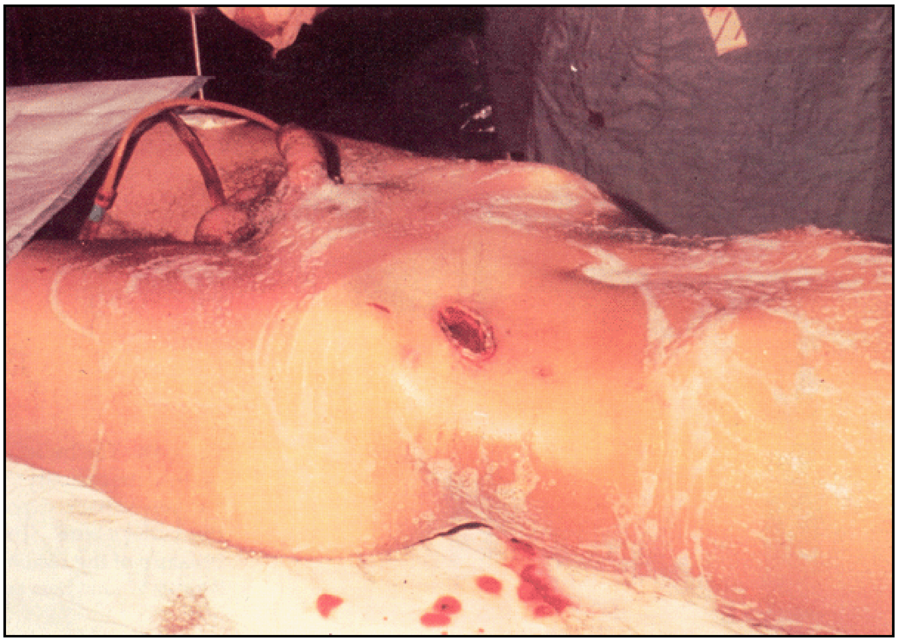

Fig. 4-20. **The wound** of entrance of the casualty whose roentgenogram is shown in Figure 4-19 suggests a likely explanation for the bullet's breakup. The wound's very large size indicates that the bullet had either already broken **up** or had a substantial angle of yaw before it penetrated the casualty's abdomen. A reasonable assumption is that the bullet initially hit an object outside **the** casualty, such as his web gear.
Source, Wound Data **and** Munitions Effectiveness Team

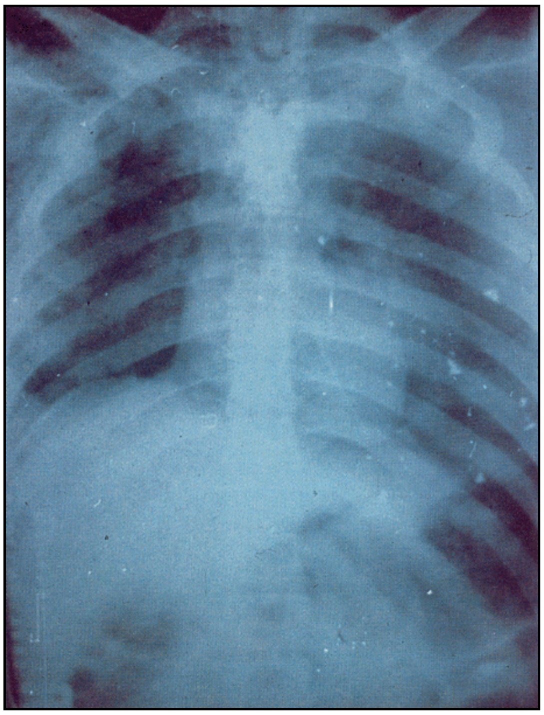

Fig. **4-21.** This chest roentgenogram was taken of a casualty who was killed by an M193 ball fired by an M16. The bullet entered his chest, where the lead that constituted the bullet's core broke up into multiple metal fragments.
Source: Wound Data and Munitions Effectiveness Team

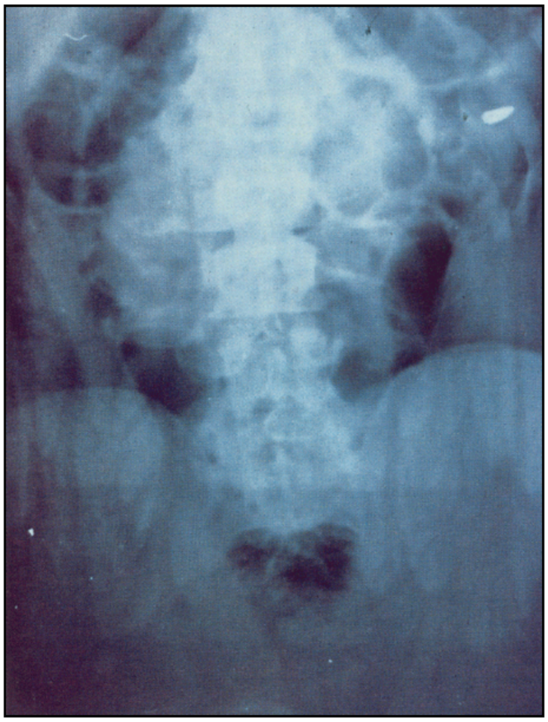

Fig. 4-22. This abdominal roentgenogram of the casualty whose chest roentgenogram was shown in Figure 4-**21** shows a major fragment of the bullet.
Source: Wound Data and Munitions Effectiveness Team

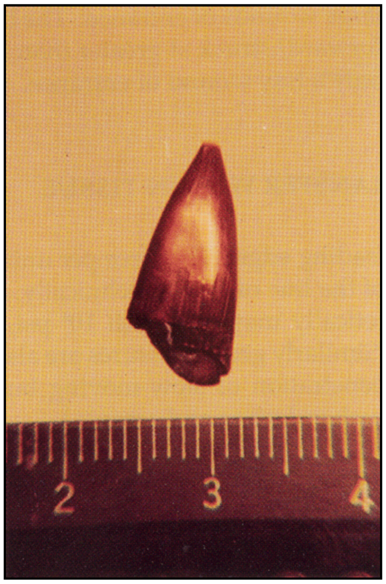

Fig. **4-23.** The bullet fragment shown in Figure **4-22** after it had been extracted at autopsy. The characteristic fragment is the nose of the M193.
Source: Wound **Data and Munitions Effectiveness Team**

degrees to actual tumbling. In fact, projectile instability is probably the single most important cause of a bullet's nonlinear energy transfer. Yaw and tumbling may occur and increase anywhere along a trajectory, but most bullets require a characteristic minimum trajectory length within the target before they become unstable. For example, the M193 fired by the M16 requires a 6–7-cm trajectory through the target, and a bullet from the AK47 a 15–20-cm trajectory.[22] If the target trajectory is less than this critical distance, significant yaw will not occur, and energy transfer will be not only lower but also more uniform. External disturbances, such as striking foliage or pieces of the soldier's gear, may cause a bullet to yaw significantly before it hits its target. A bullet striking with a large angle of yaw ensures that accentuated yawing will also occur within the target, with correspondingly greater and earlier energy transfer and tissue damage.

The phenomenon of yaw helps to explain subtle problems in wound ballistics, such as the report that the exit wounds made by M193 bullets fired from the M16 were sixfold larger at target distances of 30 m than at 100 m. Perhaps at a distance of only 30 m from the muzzle, gyroscopic stability had not yet decreased the yaw that was present shortly after the bullet left the rifle barrel. Thus the angle of yaw—and the potential for accelerated increase in yaw on penetration—were greater at 30 m than at 100 m.[9]

Bullet design also influences stability. The apparent increased tendency of the Soviet 5.45-mm bullet to yaw very early in its trajectory through tissue may be due to its design. This bullet deforms internally on impact: Lead at the front of the bullet's steel core shifts forward, replacing a small pocket of air in the tip, thus shifting the center of mass.[23] However, if this explanation is correct, the shift must be asymmetric, because a symmetrical forward shift of the center of mass will increase stability

Velocity. The drag equation shows that the force of retardation is greater when the projectile's velocity is greater. A projectile will slow more rapidly in the early part of its target trajectory and therefore, all other factors being the same, it will transfer more of its energy at the beginning of its penetration than at the end. Even a symmetrical, nondeforming, non-yawing projectile such as a sphere normally has a nonlinear energy transfer. Energy transfer is maximal at the point of impact because projectile velocity is maximal then. The biophysical consequence of early energy transfer is greater tissue disruption near the wound of entrance (Figure 4-10).

The coefficient of drag is known to increase when the projectile's velocity exceeds the speed of sound in the medium. Since the speed of sound in soft tissue is about 1,500 m/s, much greater than the velocity of most projectiles on the battlefield, nonuniform energy transfer in tissue due to a supersonic coefficient of drag is not likely to be common. Nevertheless, some have suggested that very fast fragments cause explosive wounds of entrance for that reason.[24] A more recent study, however, found no indication that energy transfer accelerated (as measured by the size of the temporary cavity in gelatin) as striking velocity increased from subsonic to supersonic Mach numbers.[25] The

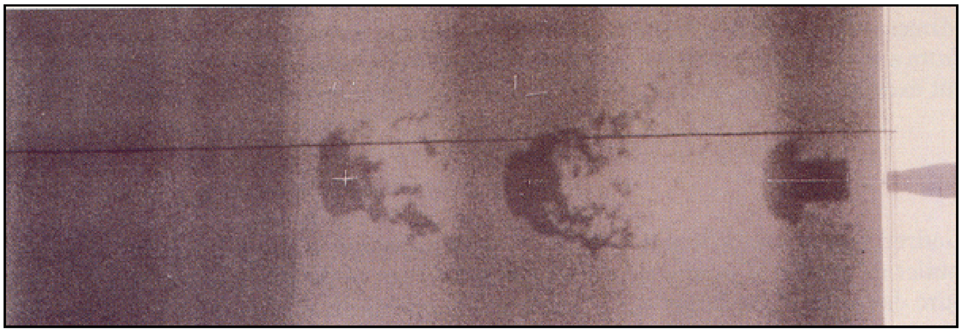

Fig. **4-24.** A roentgenogram made with flash X rays of a .308 soft-point bullet as it deforms within a gelatin block, demonstrating massive increase in cross-sectional area and, by implication, drag.
Source: Reproduced from reference 21

appearance of the wound shown in Figure 4-14 provides no support for the suggestion that projectiles with very high velocities will necessarily make very large wounds of entrance. The bullet (traveling nose-forward) struck at greater than 5,000 *fps*, but created only a tiny wound of entrance.

MECHANISMS OF ENERGY TRANSFER WITHIN TISSUE

The energy that a projectile transfers as it penetrates tissue is associated with several direct and indirect phenomena:

- Cutting—the tissue that comes in direct contact with the projectile is cut.
- Stretch and shear—the transfer of kinetic energy from the projectile to the tissue causes low-frequency, high-displacement transverse waves (known as shear waves), which cause the tissues surrounding the bullet's trajectory to be thrust aside creating a temporary void. (Since the time of Woodruff, this process has been called *cavitation* in ballistics literature.)
- Compression—transferring kinetic energy from the projectile to the tissue also causes high-frequency, low-displacement longitudinal waves known as stress waves. (This mechanism is usually called the shock wave in ballistics literature.)
- Heating—some energy that is transferred from the projectile to the target is in the form of heat.

Cutting and heating are direct effects of the projectile's passage through tissue. Damage resulting from shear and stress waves is indirect, since these injuries do not depend on direct contact between the injured tissue and the projectile.

Both shear and stress waves generate pressure transients that, in theory, can propagate throughout the body and cause damage. Pressure transients arising from shear waves have been measured in the abdomen of swine that were shot in the thigh, and systemic effects due to propagation of stress waves through major blood vessels are possible.[26] A controversy exists regarding the relative importance of direct and indirect effects, but indirect effects occurring more than several centimeters from a wound tract are probably clinically insignificant except in organs such as brain, heart, and liver.

Cutting

During the several hundred microseconds that it takes for a typical rifle bullet to penetrate tissue, a region of very high pressure develops at the bullet's leading edge. The force per unit area in the direction of the line of flight (technically, a stress), which theoretically may approach 10^6 psi, ruptures the tissue. (Similarly great pressures are also associated with the penetration of slow-moving but very sharp objects such as knives and arrows.)

The rupture modulus is a biophysical parameter that can be used to quantitate the ease of cutting through a viscoelastic medium such as tissue. A modulus relates stress to *strain* (that is, it relates a fractional change in an object's dimension to the applied force). The rupture modulus describes the stress required to strain a tissue to the point of disruption. Unfortunately, data on rupture moduli in tissue, which would greatly advance our understanding of wound ballistics, are not available.[27]

However, certain conclusions can be drawn from the facts known about moduli in other areas of physics. Since moduli usually depend upon the rate at which the stress is applied (that is, the shorter the time over which a given force is applied, the stiffer the tissue will be), it is likely that the rupture modulus, when such data do become available in wound ballistics, will be found to depend upon the velocity of the penetrating projectile. That is to say, the faster the projectile, the greater the force required to cause a given degree of tissue disruption. This is another reason why a relatively slow but very sharp object like an arrow expends far less energy than a rifle bullet does in cutting through tissue.

Stretch and Shear

Energy transfer associated with shear waves is almost always discussed in the context of cavitation in ballistics literature. Cavitation is a poorly understood process; its essence is its dynamic nature—the duration is measured in milliseconds—and the process and its result are usually called temporary cavitation and the temporary cavity. (The observed wound is called the permanent cavity.)

Temporary Cavitation. Ordinary experience provides no clue to the mechanism of temporary cavitation; it is not apparent in everyday life that the viscoelastic properties of tissue depend upon the time-course of an applied force. The more rapidly a force acts upon viscoelastic tissue, the tissue becomes. Tissues that might behave like marshmallows when a force is gradually applied over seconds behave more like marbles when the same force is applied over milliseconds. In fact, the process of temporary cavitation can be compared with striking a heap of marbles with a hammer. **A** void is created as the marbles in the middle move outward and strike peripheral marbles that, in turn, move outward and strike even more-peripheral marbles. The important difference is that the marbles fly off unrestrained, while **tissues** moving away from a projectile snap back to their original location. The elasticity and weight of the surrounding tissues not only arrest the cavity's expansion but also cause its ultimate collapse.

Energetics of Cavity Formation. Forming a temporary cavity requires considerable kinetic energy. Calculations based on data that Harvey and his group gathered in the mid-1940s (Callender and French published equations derived from Harvey's data in *Wound Ballistics)* demonstrate that, in this instance, forming a temporary cavity required approximately **83%** of the kinetic energy transferred during projectile-target interaction (Table 4-3).[28] Harvey's original data are no longer available, but assuming that they are approximately correct, these calculations show that the size of the temporary cavity increases by 0.7 ml for each joule of kinetic energy transferred. Most of the kinetic energy transferred from a high-velocity projectile is probably expended on cavitation.

Temporary cavitation and its consequent tissue damage have important organ-specific aspects: The physical properties of the target tissue determine the dimensions of the temporary cavity. For example, the cavity may be small in lung but large in liver. In lung, the cavity's expansion as tissue is flung aside is presumably arrested **as** air is compressed in the alveolar spaces, but no such containment occurs in liver once the capsule has been ruptured.

Gross Characteristics. The low-frequency, high-displacement transverse wave that follows a rifle bullet through a tissue simulant and generates the temporary cavity has been visualized (Figure 4-25). Formation of the temporary cavity follows the passage of the projectile by about 1 msec; thus, the projectile has already left the target before the cavity begins to form. The shape of the cavity in this instance is that of an axially symmetrical ellipse, but it is not unusual to find a more irregular cavity, reflecting both the heterogeneity of most body parts and the irregular shape and trajectory of the projectile. Cyclic expansion and collapse of the cavity may occur in gelatin (nine times

TABLE 4-3

ENERGY REQUIREMENTS IN WOUND CAVITATION

Components of the Wound	Transferred Energy* (x 10^{-3} ft-lb)	Volumes Found in a Typical Wound** (in^3)	Total Energy † (ft-lb)
Temporary cavity	66.247	132.49	8.8
Zone of Extravasation	30.105	60.21	1.8
Permanent Cavity	2.547	5.09	0.013

*Transferred energy required **to** form a 1.0 in3 cavity in **tissue**

Measured cavitation volumes from a projectile with a striking energy ***of* 2,000 **ft-lbs.** These are volumes of a wound that Callender and French considered "typical."
Source: Reference 7

‘Source: Authors' calculations from data in columns 2 and 3