CAVITATION PHENOMENON

Fig. **4 25.** Frames from a high showing cavitation (opposite page)
Source: Letterman Army Institute of Research, Department of Audio-visual Resources

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25–*a*. A 5.45-mm bullet fired from an AK74 has just struck the left side of a 7-inch-thick block of 10% gelatin (note that the ruler is calibrated in centimeters). The striking velocity is about 2,900 fps. **A** small amount of the gelatin—the tail splash—is being extruded from the site of impact.

25–b. The bullet has exited from the right face of the block and is followed by a small amount of expelled gelatin. Although not visible on the motion picture, it is likely that the bullet tumbled before it exited from

25–c. The earliest stage in the development of the temporary cavity. At this stage, the cavity lacks perfect axial symmetry.

25–d. The cavity's explosive expansion is apparent.

25-e. Note the extensive amount of gelatin displaced—the head cone—at the wound of exit as the cavity continues to expand.

25–*f*. The cavity has reached its maximum size.

25–g. The cavity begins to collapse.

25–*h*. The negative pressure within the cavity has aspirated the previously expelled gelatin.

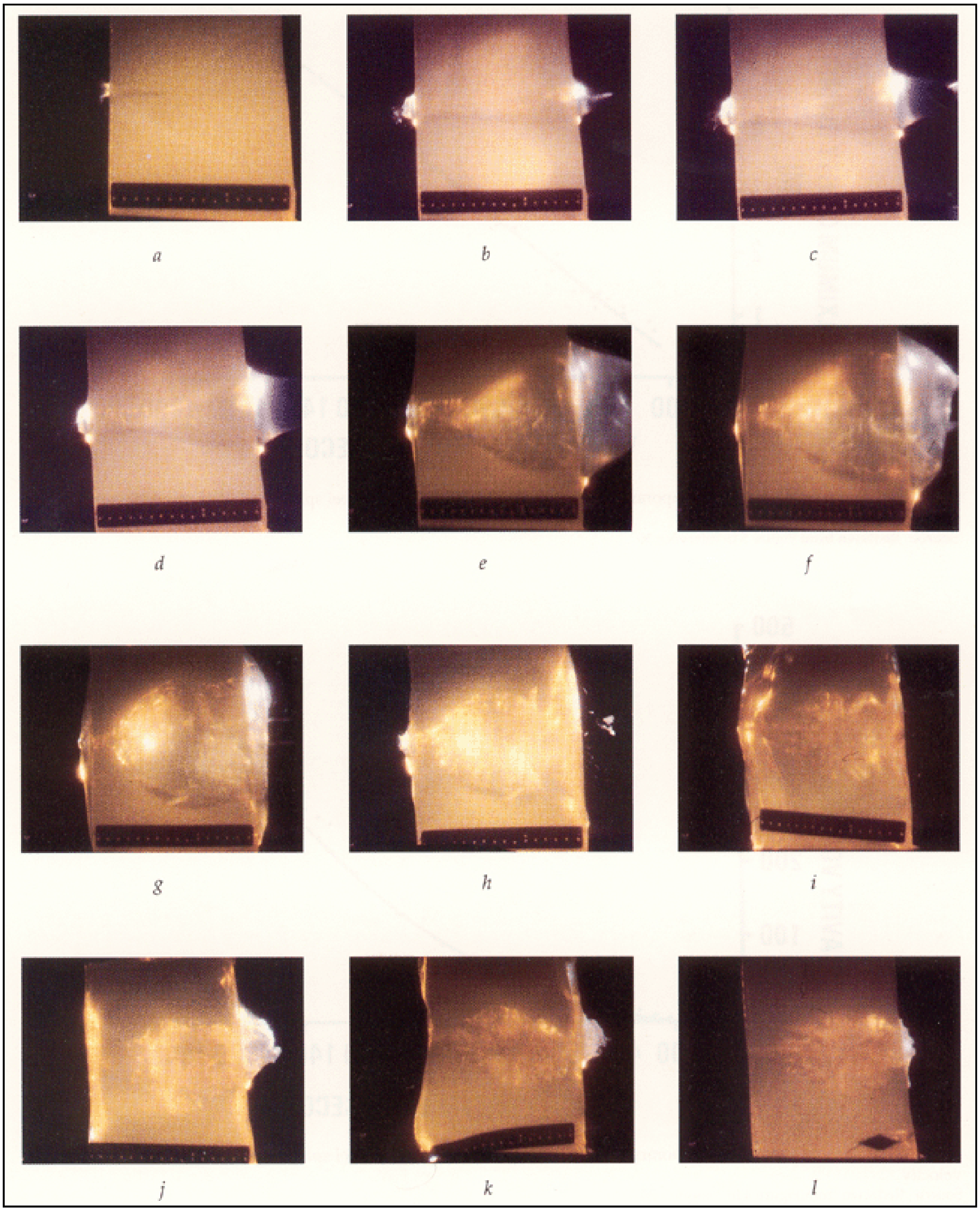
25–*i*. The cavity has completely collapsed. The total elapsed time (Figures 4-25–*a* through 4-25–*i*) is about 4 msec.

25–*j*. The peak cavity size of the second oscillation

25–k. The peak cavity size of the fifth oscillation. Note the distortion of the block as a whole and the displacement of the

25–*l*. Cavitation is complete. The gelatin block has a permanent deformity at the site of the bullet's exit, and the gelatin that was displaced by the cavity shows multiple air-filled fissure fractures. Note that in this example, the radial fissures underestimate the maximum size of the temporary cavity

Figure 4-25



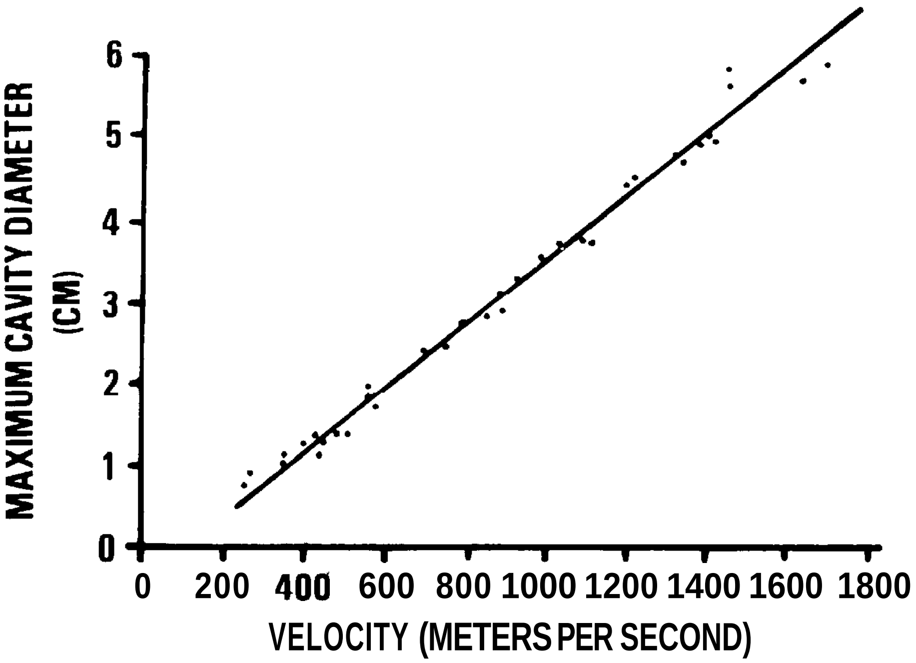


Fig. 4-26. Maximum diameter of temporary cavities in soap blocks struck by steel spheres, plotted as a function of impact velocity

Source: Redrawn from Figure 5 in reference 30

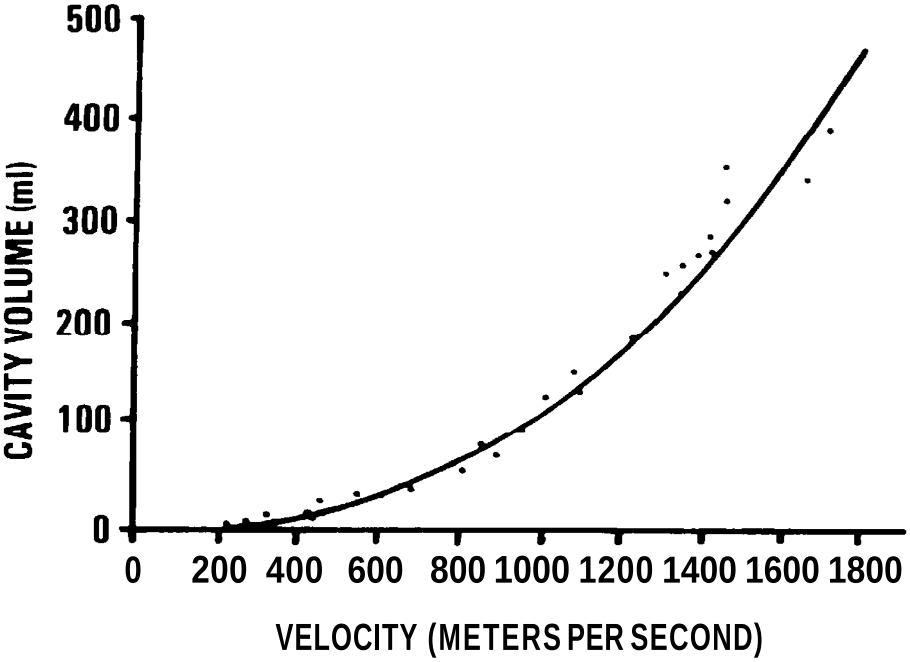


Fig. 4-27. Maximum volume of temporary cavities in soap blocks struck by steel spheres, plotted as a function of impact **velocity**

Source: Redrawn from Figure 4 in reference 30 over 40 msec in Figure 4-25), although one cycle is the rule in body parts such as the abdomen. The speed at which maximal expansion of the cavity occurs is much lower than of the missile it (that is, several hundred feet per second, or about 10% of the projectile's impact velocity.)

The permanent cavity often contains foreign material.[29] Part of the target that had been expelled as the projectile perforated (Figure 4-25, frames *b* and *c*) was sucked back into the cavity along For this to occur, pressure within the fully developed cavity must be subatmospheric, and the cavity must communicate with the outside through either the wound of entrance or exit.

Determinants of Cavity Dimensions. Cavity size can be impressive: The maximum cavity diameter shown in Figure 4-13 is 20-fold larger than the diameter of the bullet that made it, and the cavity's cross-sectional area is more than 400-fold larger. The quantitative relationship between cavity dimensions and projectile parameters—such as velocity and energy transfer—is best determined in homogeneous solids using spherical projectiles, so that extraneous factors like projectile stability and deformation are unlikely to interfere. Figure 4-26, showing cavity diameter, and Figure 4-27, showing cavity volume, both as functions of impact velocity, are from experiments that studied steel sphere projectiles being shot into soap blocks.[30]

The linear relationship between the cavity's diameter and the projectile's velocity is unexpected. The curvilinear relationship between cavity volume and projectile velocity seems intuitively more reasonable, since one does not expect a simple linear relationship to exist in so complicated a process as projectile penetration. Since none of the projectiles in either experiment perforated their targets, the abscissas in both figures are directly proportional to the kinetic energy and energy that was transferred. The researchers found no threshold velocity beyond which cavitation appeared. Nor was there any evidence that projectiles striking at velocities above the speed of sound in the target transferred their energy by a different process than did the subsonic projectiles.

The exact relationship of cavity volume and energy transfer in tissue is not known, but, contrary to Harvey's opinion:" it is unlikely to be linear. No doubt boundary effects are prominent. Target size is one determinant of maximum cavity volume (that is, for a given energy transfer, the smaller the target, the larger the cavity). This is known as a *scaling effect* and is an important methodological consideration influencing the design of wound ballistics experiments.[31]

In general, the more energy that is transferred, the larger the temporary cavity will be. A large cavity requires substantial energy transfer. In practice, however, cavitation is not usually significant when the striking velocity is less than 1,000 fps unless *(a)* the projectile is massive, with great striking kinetic energy, or *(b)* the projectile's tumbling, fragmenting, or deforming maximizes its energy transfer.

Pressure Transients Around the Temporary Cavity

In a series of ingenious experiments, Harvey's group investigated pressure transients in target material lying outside the temporary cavity. They shot spheres into water tanks containing many tiny air-filled balloons, and correlated changes in the balloons' dimensions with the phases of the temporary cavity. The balloons expanded and contracted with the cavity, indicating that pressure around the cavity fell as the cavity expanded, and increased as the cavity retracted. In some experiments, the air bubbles expanded so greatly that the balloons ruptured. In subsequent experiments, the researchers observed air bubbles expanding in intestinal segments. Harvey suggested that intestinal rupture might occur when gas within the bowel expands in response to subatmospheric pressure around an expanding temporary cavity.

"[T]his decreased pressure . . . in part [is] due to Bernoulli lowering of pressure as a result of the high radial velocity of water around the expanding cavity."[32] If this is why pressure falls around an expanding temporary cavity, the explanation must apply only to cavitation occurring in a nonrigid structure like the abdomen, because bulk movement of the target's material must occur. The rigid skull does not meet this condition. Since an intact skull would prevent the radial thrust of brain tissue that temporary cavitation requires, positive-pressure transients should be prominent in of a penetrating head wound. This aspect of the projectile-target interaction is poorly understood. Harvey's mid–1940s experimentation needs to be reinvestigated with modern technology.

Stress Waves

Stress waves are elusive and poorly understood phenomena that occur when a projectile hits its target tissue. They probably cause less tissue damage than the other methods of energy transfer (except heating) do. Stress waves propagate through tissue from the point of impact with that tissue's characteristic speed of sound (usually about 1,500 m/s). Therefore, stress waves precede the projectile and appear as a pressure transient much earlier than the pressure transients associated with the expansion and contraction of the temporary cavity. Do not confuse the two pressure transients. Overpressures as high as 100 atmospheres have in water and homogeneous solids such as gelatin, but the duration of an individual wave is very short (20–30 ysec is typical). Bursts of stress waves of much longer duration (about 1 msec) have been recorded in tissue. This exceptional duration, which approaches that of stress waves associated with blast overpressure in air, probably results from the reflection and diffusion of stress waves by heterogeneous body parts.[33]

Harvey and his group demonstrated (somewhat artificially—they suspended still-beating frog hearts in water and injected air into some of them) that stress waves probably do not cause any tissue damage.[28] However, this conclusion obscures the fact that the air-filled frog hearts *were* damaged. Since blast overpressure waves (which are known to damage air-containing organs such as the lungs) are also stress waves, the possibility that stress waves from a penetrating projectile might also cause tissue damage cannot be completely ruled out. Interpreting these results leaves room for doubt, because Harvey's experimental design did not totally suppress temporary-cavity formation; thus damage from the explosive expansion of air in the region of subatmospheric pressure around the temporary cavity cannot be excluded. Furthermore, even given the existence of stress waves of considerable amplitude and duration, bulk movements of tissue—caused by the temporary cavity and not pressure transients alone—are likely to be the major source of indirect tissue injury.

Heating

Heating is the energy-transfer method least likely to kill or damage tissue. For example, assume than an M193 ball with an energy transfer of 400 J makes a soft-tissue wound containing 60 g of damaged tissue. The specific heat of an adult human male is 0.8 (that is, 0.8 calorie will raise the temperature of 1 g of tissue by 1° C). Let us assume that the specific heat of skeletal muscle is also 0.8. If all the transferred energy were instantaneously absorbed as heat, the temperature of the 60-g core of tissue around the bullet's path would increase by only 2.0° C (400 J equals 95 cal).

The friction that occurs as a bullet passes through a gun barrel does produce heat, but not enough to increase tissue damage.

THE PERMANENT CAVITY

The mechanisms of energy transfer are usually discussed only in the contexts of *(a)* the visible hole—the permanent cavity—which is the most impressive aspect of the wound and *(b)* the transient hole caused by shear waves—the temporary cavity—which can be seen only when special techniques are used to make it visible. Many believe that the projectile's cutting through the target tissue is the only determinant of the permanent cavity; therefore, the diameter of the permanent cavity should approximate the diameter of the projectile. This view oversimplifies the wounding process and ignores the actual determinants of the permanent-cavity's dimensions:

- The permanent cavity is completely defined only after temporary cavitation has occurred. In organs such as liver, the temporary cavity itself is an important determinant of the size of the permanent cavity.
- The presenting area of the projectile may change due to yaw, deformation, or fragmentation as it cuts through tissue,
- The elastic recoil of the severed tissues and the weight of the overlying surrounding tissues may alter the dimensions of the permanent cavity.

A permanent cavity has an entrance wound and, if the projectile perforates the tissue, an exit wound. A wound made by a nonperforating fragment is said to be blind.

Much of our understanding of permanent cavities comes from experimental studies rather than from battlefield observations. Many experimental studies contain quantitative data on the dimensions of the wounds of entrance and exit and on the volumes of permanent cavities; few studies, however, report the simultaneous measurement of the maximum volume of the temporary cavity. In a study performed on excised goat skeletal muscle and liver (Table 4-4), researchers fired 30-caliber (7.62-mm) armor-piercing bullets at well-defined velocities.[34] They filled the permanent cavities with plastic and determined their volumes from the weights, and they measured the temporary cavities using X rays. This study has several significant limitations: *(a)* the skin had been excised, *(b)* the tissues were not only dead but were studied *ex situ*, and *(c)* the wound tracts were extremely short (average 4 cm). Nevertheless, two concepts emerge:

- As velocity increased, the dimensions of both

TABLE 4-4

WOUND DIMENSIONS IN SKELETAL MUSCLE AND LIVER*

	Permanent Cavity (midtrack)		Temporary Cavity	
Velocity (m/s)	Diameter (cm)	Volume (cm^3)	Diameter (cm)	Volume (cm^3)
Skeletal Muscle N = 10 (for each velocity group)				
419.0	0.6 ± 0.07	0.7 ± 0.23	3.0 ± 13.0	30.0 ± 13.0
857.0	1.0 ± 0.13	2.7 ± 0.65	4.9 ± 0.32	116.0 ± 34.0
1,291.0	2.2 ± 0.44	14.0 ± 4.8	6.8 ± 0.75	320.0 ± 54.0
Liver N = 5 (for each velocity group)				
419.0	1.0 ± 0.35	3.4 ± 0.98	4.0 ± 0.68	52.0 ± 9.9
857.0	2.6 ± 0.63	30.0 ± 9.0	6.1 ± 0.63	198.0 ± 69.0
1,291.0	4.8 ± 0.43	65.0 ± 16.0	9.6 ± 0.48	708.0 ± 106.0

*Mean ± 1.0 standard deviation

Source: Reference **34**

the temporary and the permanent cavities also increased, and were (in all groups but one) substantially larger than the diameter of the bullet. Since the researchers did not detect yaw in the roentgenograms and since they used nondeforming-nonfragmenting bullets, it is hard to escape the conclusion that temporary cavitation associated with high velocity increased the size of the permanent cavity.

- Liver is more sensitive than muscle is to cavitation. The permanent cavity in skeletal muscle was about 3% of the maximum volume of the temporary cavity; in liver, it was about 10%.

In another study from the same laboratory, researchers measured wound dimensions at autopsy 4 days after wounding. They found that average permanent-cavity dimensions in goat thighs were slightly smaller along the entire wound tract than they had expected from the bullet dimensions alone. There was one exception: "[T]he permanent wound tract was larger in the wounds from higher velocity missiles and in areas where bullets had tumbled."[12]

Studies in which measurements are made in living animal tissue give especially useful information concerning the morphology of the permanent cavity. Researchers shot dogs with two commonly used military assault-rifle bullets (Table 4-5). To obtain a wide spectrum of data, they *(a)* varied the amount of propellent to adjust bullet velocity and *(b)* measured impact and exit velocities. The dogs were positioned so the bullets traversed only the soft-tissue of both thighs, yielding wound lengths of 11–12 cm. They measured the wound dimensions 6 hours after wounding.[10]

In this study, the wounds of entrance were little different than the size of the bullets that made them. The wounds of exit, however, were larger than the bullets, and were dramatically larger when, as happened with the M193 fired by the M16, the bullet fragmented before it exited. Fragmenting bullets also created the largest permanent cavities. Thus, the volume of the permanent cavity can be much larger than the projectile that created it.

Another laboratory obtained similar results (Table 4-6). In this study? 30-kg anesthetized swine were shot at 30 or 100 m through the soft tissue of one thigh with bullets from either the M16 or the AK47. Researchers examined the wounds **6** hours later. The wounds of entrance were the same size as the projectile, while the wounds of exit made by the M193 were very large, no doubt reflecting the propensity of the M193 ball to fragment in soft tissue. The wounds of exit made by the M43 ball fired by the AK47, however, were little different from the wounds of entrance. Longer experimental wound tracts (about 15 cm, the average length of wounds through human extremities) would have allowed the bullets time to develop sufficient yaw before they exited, perhaps producing bigger exit wounds.

Several studies have investigated the permanent cavities of experimental fragment wounds (Table 4-7). Researchers fired square steel fragments weighing 0.35 g into the thighs of anesthetized dogs.[35] This study

TABLE 4-5

MEASUREMENTS OF PERMANENT CAVITIES IN BULLET WOUNDS IN DOGS*

Bullet	Impact Velocity (m/s)	Energy Transfer (J)	Wound Dimensions (maximum diameter in cm)		Volume of Permanent Cavity (cm^3)	Number of Animals
			Entrance	Exit		
7.62	956 ± 4	42.6 ± 10.3	0.7 ± 0.1	3.6 ± 2.7	21	10
7.62	514 ± 12	20.2 ± 9.3	0.3 ± 0.1	1.1 ± 1.0	11	8
5.56	929 ± 8					
Intact		25.1 ± 5.8	0.2 ± 0.1	4.4 ± 3.8	13	12
Broken		51.3 ± 18.9	0.3 ± 0.03	19.7 ± 13.9	42	5

***Mean** ±1.0 standard deviation

Source: Reference 10

TABLE 4-6

MEASUREMENTS OF PERMANENT CAVITIES IN BULLET WOUNDS IN SWINE*

Weapon	Impact Velocity (m/s)	Wound Areas (mm^2)		Length (mm)
		Entrance	Exit	
AK47-M43 ball:				
30 m	693 ± 2	41 ± 13	20 f 12	87 ± 20
100 m	641 ± 12	25 ± 8	30 f 13	86 ± 24
M16-M193 ball:				
30 m	926 ± 9	27 ± 12	2152 ± 2841	91 ± 15
100 m	846 ± 19	26 ± 5	345 ± 533	100 ± 25

***Mean** + 1 0 standard **deviation**

Source: Reference 9

TABLE 4-7

THE PERMANENT CAVITY IN EXPERIMENTAL FRAGMENT WOUNDS IN DOGS*

Impact Velocity (m/s)	Area of Entrance (cm^2)	Description
716 ± 119	1.52 ± 0.71	Blind, square and regular, cylindrical
1015 ± 159	2.43 ± 1.29	Blind, elliptical and irregular, cone-shaped
1506 ± 99	6.85 ± 4.35	Blind, tissue blown out, funnel-shaped

*All fragments have diameters of approximately 4 mm; data expressed as mean ± 1.0 standard deviation.
Source: Reference 35

demonstrates that permanent-cavity formation frequently involves more than the projectile's direct cutting action. Clearly, temporary cavitation contributed to the size of the wounds of entrance seen in these experiments. The unfavorable aerodynamic shape of the projectile caused maximum energy transfer and temporary cavitation at the wound of entrance. The gigantic wound of entrance shown in Figure 4-14 was made by a bullet striking blunt-end forward. The dimensions of the wound vastly exceed the dimensions of the projectile, and can only be understood as a consequence of temporary cavitation's having ripped the tissue apart.

SOFT-TISSUE BALLISTIC WOUNDS

Damage to soft tissue (that is, skin, fat, and skeletal muscle) and to specific organs (that is, the viscera, bones, and so forth) are of course not separate, since an injury to a viscus will necessarily have a soft-tissue component. But because *(a)* experimental wound ballistics has focused upon soft-tissue injury, *(b)* ballistic injuries involving skin, fat, and skeletal muscle form the bulk of the combat surgeon's practice, and *(c)* the major controversies in wound ballistics arise from managing soft-tissue injuries, these two groups can logically be separated.

The concepts of kinetic energy and energy transfer that have been useful in understanding the physical aspects of wound ballistics are much less useful in understanding the medical aspects. There certainly can be no tissue damage if there is no energy transfer, but rigorously defining tissue damage is difficult. Can tissue damage be measured quantitatively? If it cannot, then correlating tissue damage with a measured quantity of energy transfer is futile. Furthermore, the main threat to many casualties arises not from the mechanical disruption sustained by the soft tissue but from sepsis in the contaminated wound tract, which is poorly understood in relation to energy transfer. Thus, medical officers will find that concepts such as energy transfer may be less relevant to the purely medical aspects of wound ballistics than they are to the study of wound ballistics as a branch of physics.

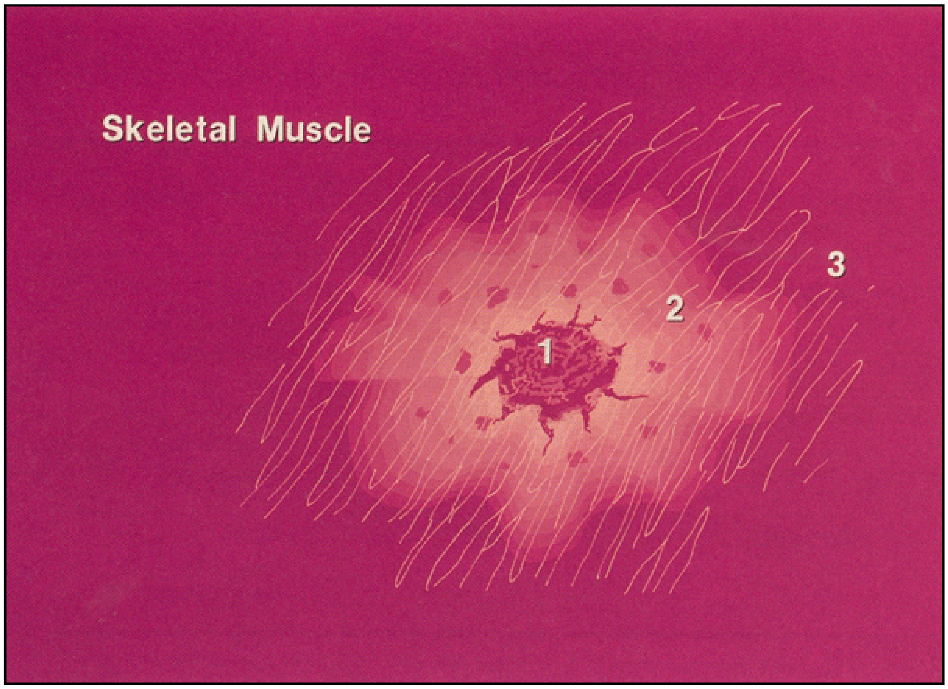


Fig. 4-28. Idealized pathomorphology of a soft-tissue wound involving skeletal muscle. The wound consists of three components: (1) the permanent cavity, (2) the zone of extravasation, and (3) the zone of concussion.

Pathomorphology of Soft-Tissue Wounds

Unfortunately, little data have been published on wound-tract morphology in humans. The Wound Data and Munitions Effectiveness Team (WDMET) database found that the median wound tract was only 60 mm long, and the largest single group of casualties had wound tracts measuring 20 mm or less. About 10% of the WDMET population had wound tracts 250 mm or longer. About 75% of casualties in whom wound-tract shape was assessed had elliptical or circular wounds. About 80% of the wound tracts were blind. Wound-tract volume was measured in about 10,000 wounds; 97% had a volume less than 99 cc. The WDMET data are consistent with the clinical observation that a 15-cm wound tract will usually either perforate an extremity or strike an internal viscus.[36]

Recent data from the Chinese conflict with Vietnam extend these observations. Of those casualties who were hit by bullets, 87% had perforating wounds, almost all of which were made by 7.62-mm bullets. The exit wounds (4.25 cm^2) were larger than the entrance wounds (1.0 cm^2). In some instances, surgeons observed very large permanent cavities (with diameters of 7.5 cm) with even larger wounds of exit. Wounds made by fragments (85%) were usually blind. The probability that a fragment would cause a perforating wound depended upon the casualty's proximity to the detonation site: Of the wounds sustained within 1 m of the explosion, *60%*

while beyond 6 m, nonperforating wounds were common.[37] This finding is not unexpected; fragment velocity rapidly degrades in air (Figure 4-2).

The gross pathomorphological components of a typical wound (Figure 4-28) involving skeletal muscle are, from inside out, *(a)* the permanent cavity, which is a hole containing blood clots, detached chunks of tissue, and foreign material that may have been aspirated or carried into the wound; *(b)* the zone of extravasation, which is the grossly hemorrhagic, shredded, pulped muscle around the permanent cavity; and *(c)* the zone of concussion, which is grossly normal muscle, but with histological evidence of damage such as interstitial hemorrhage, vascular congestion, and abnormal myocytes.

The Permanent Cavity. Except in "explosive" wounds, little tissue is actually expelled from the target in forming the permanent cavity. The unopposed elastic recoil of the partly detached surrounding tissue keeps the hole open.

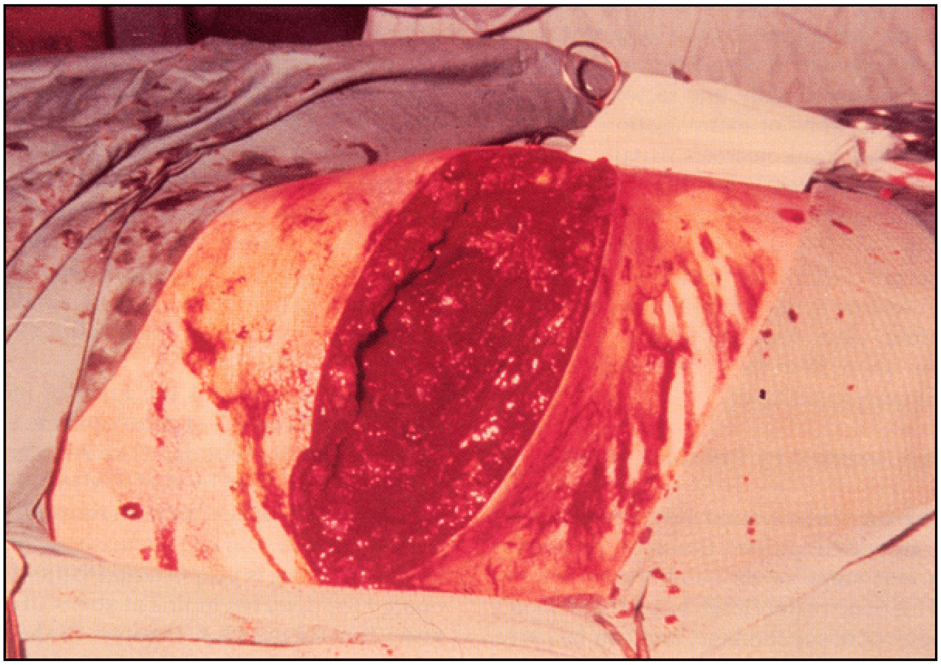


Fig. 4-29. **A** thigh wounded **by** an **M43** ball at close range. The permanent cavity **has** been opened, exposing the hemorrhagic zone of extravasation.

Source: Wound Data and Munitions Effectiveness Team

The Zones** of **Extravasation and Concussion. Damage to the soft tissue surrounding the permanent cavity is probably caused by stretching during temporary cavitation, and extravasation probably results from small blood vessels being stretched until they rupture. The pulling apart of the Z bands of individual myocytes supports this contention.[38]

A representative skeletal-muscle wound made by a high-velocity bullet (Figure 4-29) shows the open permanent cavity and the typical hemorrhagic zone of extravasation. Typical animal studies show that the zone of extravasation usually extends for 5–10 mm beyond the permanent tract.[38] The zone of concussion extends another 20–30 mm beyond the zone of extravasation. The boundary between the two zones may be discrete; however, localized areas showing the typical histopathology of the zone of extravasation (that is, necrotic myocytes) are commonly found within the concussion zone. Similarly, the vascular congestion and hemorrhage within the zone of extravasation frequently extend into the zone of concussion. Bones and fascial planes control the expansion of the temporary cavity; therefore, the zones of extravasation and concussion may not be symmetrical around the permanent cavity.

The histopathology of the zones of extravasation and concussion in skeletal muscle changes with time after wounding.[38] Within ***6*** hours, the zone of extravasation is characterized by *(a)* necrotic myocytes with fragmentation, hyalinization, and loss of transverse bands; *(b)* dilated and ruptured capillaries and venules, with extravasation of red blood cells and plasma; and *(c)* beginning infiltration by leukocytes. In the zone of concussion, the most prominent changes after 6 hours are edema and interstitial hemorrhage in myocytes; after 12 hours, progressive dissolution of myocytes and increasing infiltration by leukocytes; after 24 hours in the zone of extravasation, the collection of large numbers of leukocytes around necrotic myocytes; and after 72 hours in both zones, inflammation, frequently with outright cellulitis, and the permanent cavity may now contain purulent exudate.

Blood flow in the tissue surrounding the permanent cavity also changes over time. In the zone of concussion, the initial generalized vasoconstriction is followed within **6** hours by vasodilation. Vasodilation persists for many hours and indicates both the ongoing inflammatory reaction and the ultimate healing of the wound. Various markers of perfusion such as radiomicrospheres, supravital dyes, and so forth, fail to label the zone of extravasation and indicate that blood flow in the tissue immediately adjacent to the permanent cavity is impaired for some time.[12,13,39] The resulting ischemia is probably one factor leading to cellular death in the zone of extravasation. Various studies indicate that frank necrosis usually involves less than 1 cm (and frequently less than 5 mm) of the zone of extravasation.[13] This dead tissue constitutes the slough that John Hunter had described in the eighteenth century. Ultimate healing of the wound and of tissue in the zone of extravasation are not incompatible. Any dead tissue not sloughed is absorbed when tissue from the zone of extravasation grows into the permanent cavity.

Tissue Damage Assessed by Debrided Muscle

Traditional soft-tissue wound surgery excises the hemorrhagic, shredded, pulped tissue of the zone of extravasation and some of its neighboring zone of concussion. This mass of debrided tissue is commonly used as an index of tissue damage, and can be correlated with measured energy transfer. Methodological considerations (specifically recognizing the tissue around the permanent cavity that needs to be surgically removed) are very important in these experiments. The criteria for making these judgements usually employ the four Cs: Skeletal muscle is surgically excised if its color is abnormal, if it fails to *contract* when pinched, if its *circulation* is impaired (that is, it does not bleed when cut), and if it has abnormal *consistency*. Skeletal muscle subject to excision should be considered damaged but not necessarily dead or devitalized.

The results of a typical experiment show the mass of debrided skeletal muscle from swine thigh plotted against energy transfer (Figure 4-30). Although it looks like a scattergram, the graph shows a definite tendency for the mass of debrided tissue to increase with greater energy transfer.[14]

Although the data can be fitted by a linear regression model, no biophysical process, especially one as complicated as a projectile's penetration through tissue, is likely to be described by a simple linear relationship. Nevertheless, Swedish ballistic researchers, on the basis of their extensive experience, estimate that each J of energy transferred damages 0.3 g of muscle.[31]

Stratifying the outcome by the behavior of the bullet might be expected to provide insight into the relationship between tissue damage and energy (Figure 4-31). Breakup or severe deformation of a bullet was usually associated with greater energy transfer, but there was a disproportionately small increase in the amount of excised muscle, indicating that some of the energy that appears to have been transferred from the bullet was actually used to alter the projectile's structure rather than to damage muscle.[14]

Total energy transfer, however, gives only part of the available information about the projectile-target interaction. Energy transfer plotted as a function of depth of penetration gives a much clearer picture. The concept is further illuminated when the magnitude of debrided tissue is seen as a function of energy transfer and both are plotted along the wound tract. Figures 4-32 and 4-33 show the results of especially elegant experiments that were designed to relate tissue damage in skeletal muscle to energy transfer along the wound tract.[2]

Figure 4-32 shows the force of retardation as a function of the depth of penetration in soap blocks for two assault-rifle rounds. (The Ak 5 is similar to the 5.56-mm M855 fired by the US M16A2, and the Ak 4 is similar to the NATO 7.62-mm round.) Note that both bullets have a marked increase in retardation (the increase in drag is proportional to a similar increase in energy transfer) beginning at about 10 cm for the Ak 5 and 12 cm for the Ak 4. Figure 4-33 shows the amount of tissue debrided from the wound tract in the thighs of anesthetized swine The marked increase in tissue damage corresponds to the site of the bullet's maximal energy transfer in the soap blocks. The conclusion is inescapable: Tissue damage and energy transfer are closely linked. Almost all of the Ak 5 bullets disintegrated after penetrating about 10 cm. None of the Ak 4 bullets broke up or deformed, but all began to yaw and tumble after penetrating about 12 cm. These experiments are difficult to perform, but they are essential to provide comprehensive information on the biophysical aspects of ballistic tissue damage and to strengthen the field's scientific validity.

How much of this tissue damage can be attributed to the temporary cavity's stretch? Encasing a target thigh in an unyielding plaster-of-Paris cast partially suppressed the temporary cavity's formation and decreased by 40% the amount of gross skeletal-muscle damage.'" Because the plaster cast did not completely suppress it, cavitation may have caused some of the damage observed in this experimental wound. Additional damage must have been due to direct cutting by the projectile, but the researchers suggest that stress waves may have caused most of the residual damage. This suggestion, and the estimate of damage that the cavity's forceful implosion might cause (in addition to that caused by the stretch that occurred during the cavity's initial explosive expansion), are controversial. Fragmentation and cavitation may increase tissue damage synergistically: The fragments lacerate the tissue around the trajectory and the ensuing cavitation tears the weakened tissue apart.[20]

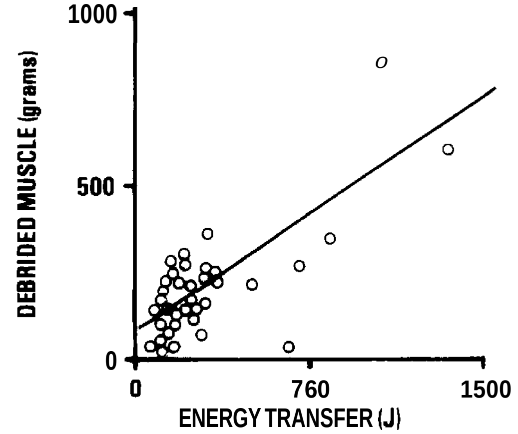


Fig. 4-30. The mass of surgically excised swine-thigh muscle is plotted against measured total energy transfer. Each symbol represents data from a single swine. A variety of different rounds were used to make the wounds: 7.62 x 51 mm; 5.56 x 45 mm; and 7.62 x 39 mm. The data are fitted by Y = 0.24x + 71.4, r = 0.74.

Source: Redrawn from Figure 4-25 in reference 14

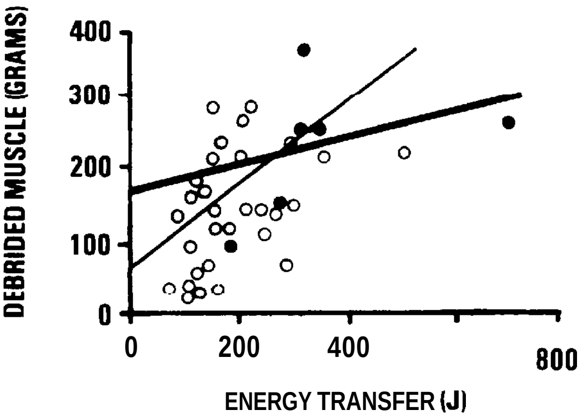


Fig. 4-31. The mass of surgically excised swine thigh muscle is plotted against measured total energy transfer. **These data** are from different experiments than those shown in Figure 4-30. The same rounds were used in Figure 4-30, but the data have been stratified according to whether or not the 5.56-mm bullet deformed or fragmented (solid circles). The open circles (thin line) are fitted by y = 0.44x + 65, r = 0.48. Data for damaged 5.56-mm bullets (thick line) are fitted by y = 0.18x + 168, r = 0.39. The smaller x coefficient for the latter equation compared to the former suggests that some of the energy transferred by the damaged bullets does not go into injuring muscle.

Source. Redrawn from Figure 24 in reference 14

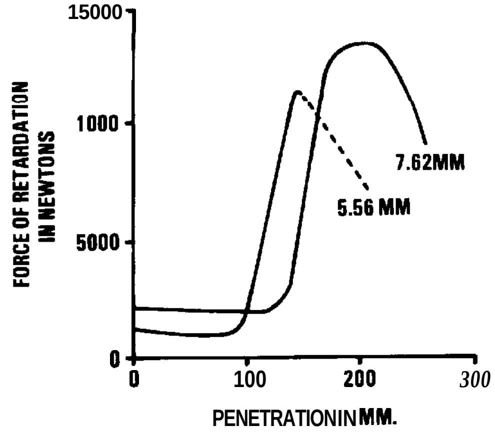


Fig. 4-32. The force of retardation measured by an X-ray methodology for 5.56-mm bullets (similar to the M855) and 7.62-mm bullets (equivalent to the NATO 7.62 x 51-mm round) as they penetrate into soap blocks. Because it is smaller, the 5.56-mm bullet experiences less retardation in the initial part of its trajectory than does the larger 7.62-mm bullet. After penetrating about 10 cm, retardation of the 5.56-mm bullet greatly increases due to yaw, tumbling, and finally fragmentation. The dashed curve is an estimate of the retardation of the fragments. The 7.62-mm bullet characteristically yaws and tumbles after penetrating 12 cm.

Source: Redrawn from Figure 4 in reference 2

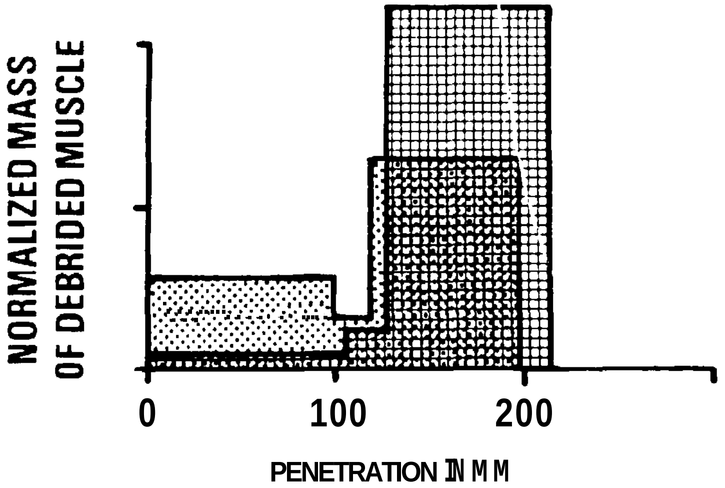


Fig. 4-33. Debrided swine skeletal muscle as a function of the depth of penetration (the abscissa, in mm) for 5.56-mm (cross-hatched) and 7.62-mm bullets (stippled). Data from one each bullet is shown. Tissue damage as assessed by debrided muscle was markedly increased at the site at which bullet instability occurred.
Source: Redrawn from Figure **4 in** reference 2

ORGAN-SPECIFIC WOUNDS

Body parts other than soft tissue have unique wound-ballistics characteristics that influence the relative importance of direct (cutting) and indirect (shear and stress waves) effects as sources of injury. Controversy exists regarding the relative importance of these effects, but it is probably safe to say that in most casualties who are candidates for surgical care, injury results from the direct effects of the projectiles. That is not to say that indirect effects are inconsequential. They are important in the overall context of wound ballistics, but less so as a source of surgical treatment problems. Casualties with wounds of the head, chest, and abdomen, in whom indirect effects (especially cavitation) are prominent, are frequently not candidates for surgery: Such casualties are usually killed outright.

The Skull and Brain

Ballistic wounds of the skull and brain are often grossly destructive, and in the past have been ascribed to explosive bullets. The explosive wound of the skull shown in Figure 4-34 is typical; as Horsley and Woodruff suggested at the end of the nineteenth century, this phenomenon results when temporary cavitation occurs in a fluid-like viscus (in this instance, the brain surrounded by its subarachnoid space) enclosed in a rigid container (the bony skull).[41] Kocher and other late-nineteenth-century ballisticians observed the identical phenomenon (that is, the hydraulic or hydrodynamic effects) when they shot high-velocity projectiles into water-filled lead containers (Figure 4-35).

Harvey and his group, working at Princeton University in the 1940s, demonstrated the necessity for a fluid medium (the brain) to be present for the explosive effects associated with the temporary cavity in the skull (and other organs) to develop. They emptied cat skulls of brain and shot them with 1/8-inch steel spheres at 3,800 fps. The only damage to the empty skulls were "rather neat entrance and exit holes." But an intact cranium sustained quite different damage:

> The cavity formed by a missile in the brain of an intact cranium is of finite size, partly because brain tissue is forced through regions of less resistance (such as the frontal sinuses and the various foramina of the skull) and partly because of the stretching of the cranium itself. When the energy delivered is very great, skull bones are actually torn apart along suture lines.[28]

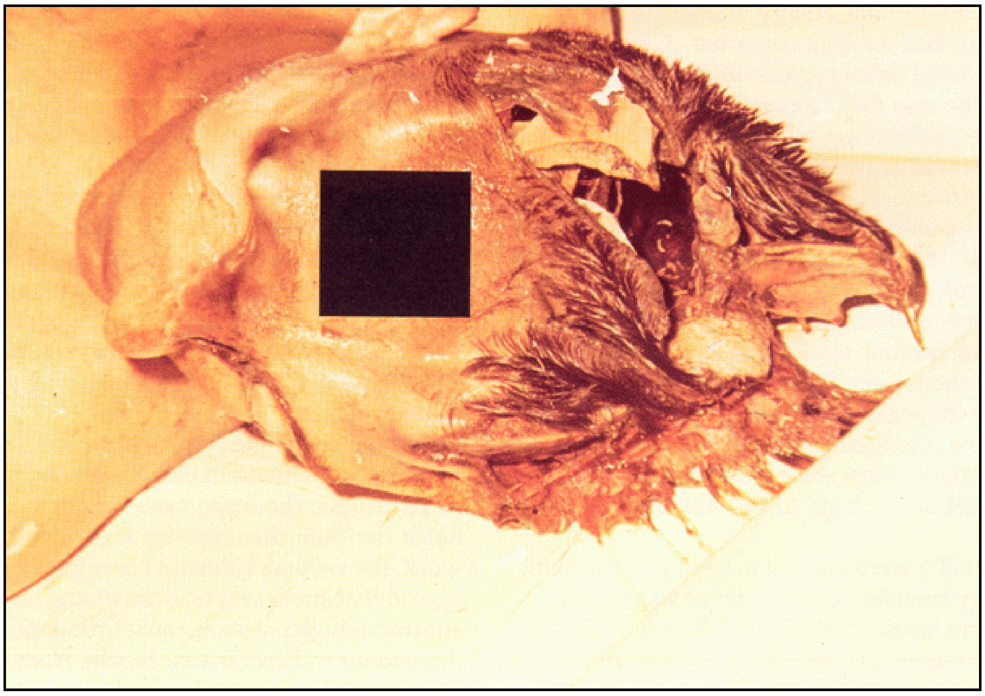


Fig. 4-34. This casualty was killed when an **M43** ball **fired** by an AK47 blew his skull apart.
Source: Wound Data and Munitions Effectiveness Team

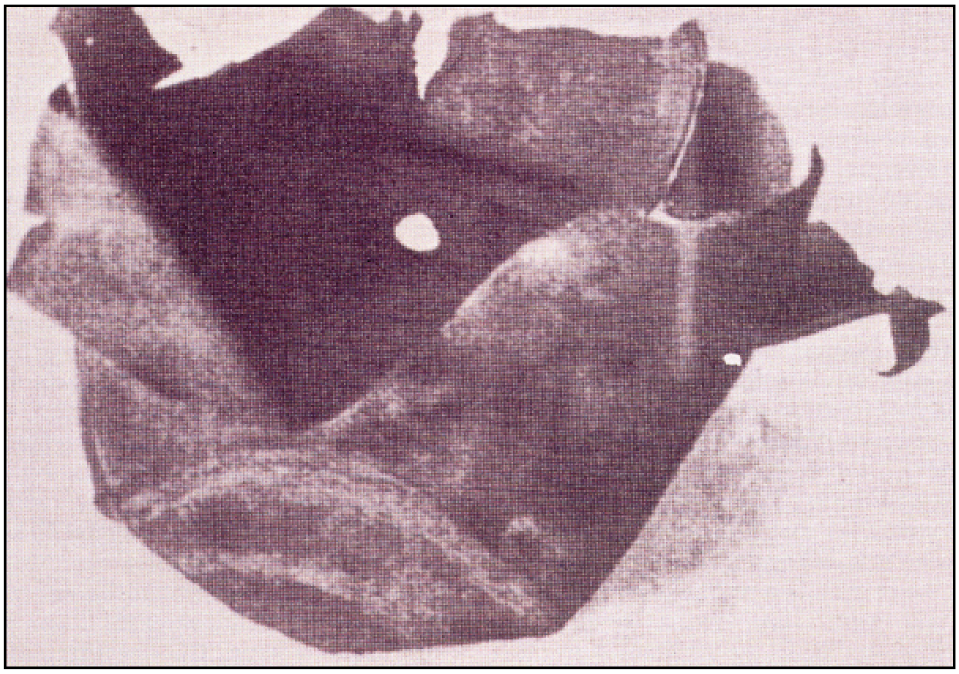


Fig. 4-35. The appearance of a water-filled lead container after it had been shot with a military rifle bullet. The bullet made the small hole at the back upon entering. The similarity between the damage shown here and that shown in Figure 4-34 should **be noted.**
Source: Reproduced courtesy of the Royal Army Medical College Museum

Clearly, enormous energy transfer occurred in both the skull and the lead container. Callender and French calculated that a typical rifle bullet—probably the one that caused the injury shown in Figure 4-34—undergoing maximum retardation (that is, maximum energy transfer) corresponded to 4,000–5,000 horsepower.[7]

Recently-published elegant pathophysiological studies go beyond gross observations of pathomorphology.[42] These researchers fired steel spheres with 3- or 6-mm diameters into gelatin-filled, instrumented human skulls and correlated impact velocities in the range of 376–1,015 m/s with energy transfer and intracranial pressures. In some studies, they made cine-roentgenograms as the projectile passed through the skull. Most shots traversed the skull, but some were set at an angle to hit tangentially. They found that:

- About 70 J were needed to perforate the skull
- Energy transfer on the order of 400 J caused severe breakup of the skull bones
- Shock (stress) waves with durations of less than 100 psec and with overpressures exceeding 5,000 kiloPascals (kPa)—that is, greater than 35,000 mm Hg, perhaps equivalent to 700 psi—occasionally occurred
- *Quasi-static overpressures* (that is, the average pressure during the temporary cavity's cyclic dimensional changes) with durations of 2–3 msec and pressures of about 200 kPa commonly occurred
- A linear relationship exists between the energy of impact and the quasi-static overpressure
- Energy transfer for a tangential hit (that is, the projectile did not enter the gelatin and had no direct contact with "brain") was about one-seventh that observed for a penetrating hit

In one of the experiments, a 6-mm steel ball with an impact-velocity of only 205 m/s perforated one parietal bone and penetrated 18 mm into the gelatin. The energy transferred was about 19J, some of which went into defeating the bone, and the quasi-static overpressure was 75 kPa. To put this in perspective, others have estimated that a penetrating projectile delivering as little as 20 J into the cerebral cortex can cause death,[43] and even less energy delivered to the brain stem will cause a fatal injury. Is there any wonder why ballistic injury to the brain is so often fatal?

Figures 4-36 and 4-37 illustrate the experimentally observed pressure transients that occurred when a 6-mm sphere with a striking velocity of 838 m/s passed tangentially across a model skull. The effect of the impact was to depress a section of skull 25-mm in diameter to a depth of 10 mm. Figure 4-36 shows the high-frequency vibrations that indicate the passage of the stress wave. The waves had a duration of about 30 µsec and an overpressure of 800–1,000 kPa (110–140 psi). The negative phases occurred when the skull reflected the wave. Within 1 msec of impact, a quasi-static overpressure of about 200 kPa developed from the initial expansion of the temporary cavity. Figure 4-37 shows the subsequent pressure perturbations that occurred over at least 50 msec, resulting from the rhythmic expansion and contraction of the temporary cavitation.

These two figures provide considerable insight into the mechanisms of ballistic injury in general, and, in particular, the importance of pressure transients. Since the time that Harvey and his group did their work, the wound-ballistics community has generally agreed that stress waves, even though associated with enormous high pressure, cause little damage. Pressure-dependent indirect injury results from shear waves. This hydrodynamic process physically displaces and injures tissue; the motion of the medium itself (in this case, the gelatin, representing brain), which the projectile is passing through, causes injury.[42]

The Chest

The two major intrathoracic viscera (the lungs and the heart and its great vessels) tolerate ballistic injury differently.

The Lungs. Lung tissue has very low density compared to other organs in the body (that is, 0.2 g/cm^3; other organs' density is about 1.0 g/cm^3, and the density of bone is about 2.0 g/cm^3). According to the drag equation, resistance offered to the passage of a projectile will be low if the target's density is low; thus, energy transfer and tissue damage may be correspondingly small. Lung is also easily stretched compared to other organs. As a result of these physical properties, lung has considerable tolerance to the stretch and shear of temporary cavitation. Figure 4-38 shows the lung of a casualty killed in the Vietnam War—not by the wound tract in the lung but by a wound to his head. The lack of ecchymosis around the probe through the wound tract may indicate that either *(a)* temporary cavitation was minimal, or *(b)* it was tolerated with little tissue damage. This does not mean that temporary cavitation cannot be a destructive process in lung, however. The post-traumatic pneumatoceles that occurred in a few combat casualties in the Vietnam War show that projectiles with high energy transfer are

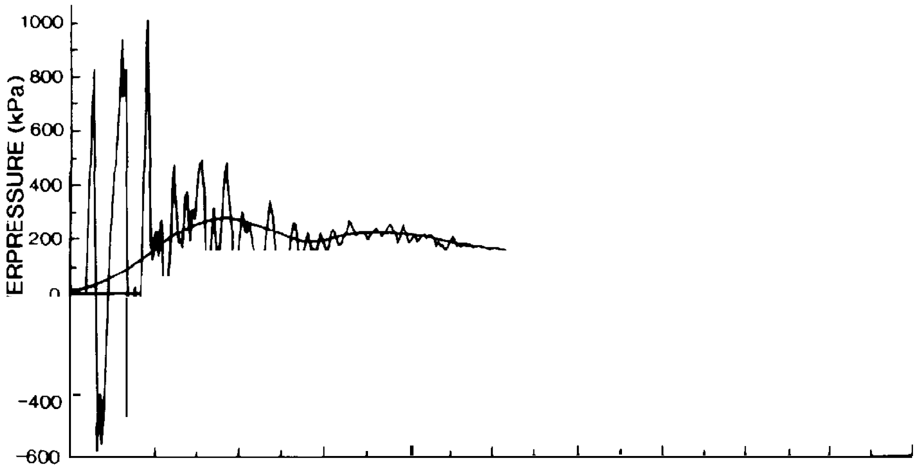


Fig. 4-36. High-frequency pressure transients observed during the first 2 msec after tangential impact of a 6-mm sphere with a striking velocity of 838 m/s on a gelatin-filled human skull. The initial vibrations are due to stress waves. The thick line indicates the development of quasi-static overpressure associated with the first expansion of the temporary cavity.
Source: Redrawn from Figure **3** in reference 42

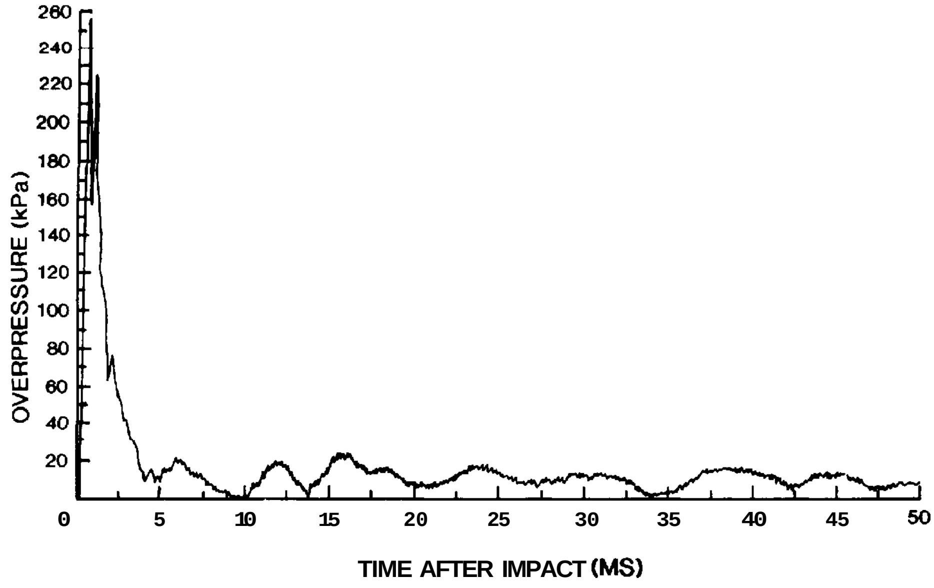


Fig. 4-37. Low-frequency pressure transients observed during the first 50 msec of the experiment discussed in Figure 4-36. The damped frequency response characteristics of the pressure transducer results in a fusion of **the** pressure transients associated with the stress wave and the first expansion of the temporary cavity. Subsequent expansions and contractions of the temporary cavity are apparent as the cyclic change in pressure.
Source: Redrawn from Figure **3** in reference 42

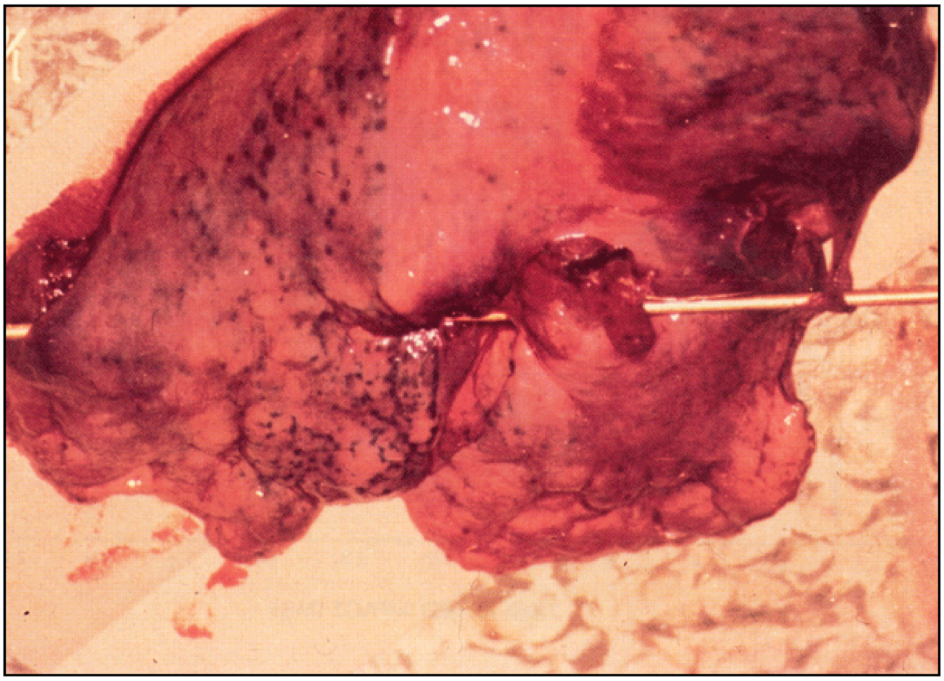


Fig. **4-38.** This casualty was killed by an AK47 wound of the skull, but he **also** sustained the **lung** wound shown in this photo. There is little evidence of hemorrhage or ecchymosis around the probe, which delineates the permanent cavity.
Source: Wound Data **and** Munitions Effectiveness Team

Fig. 4-39. This casualty sustained a through-and-through AK47 wound of the soft tissue of the left shoulder. The benign appearance of the wound makes it unlikely that massive temporary cavitation occurred.
Source: **Wound** Data Effectiveness Team

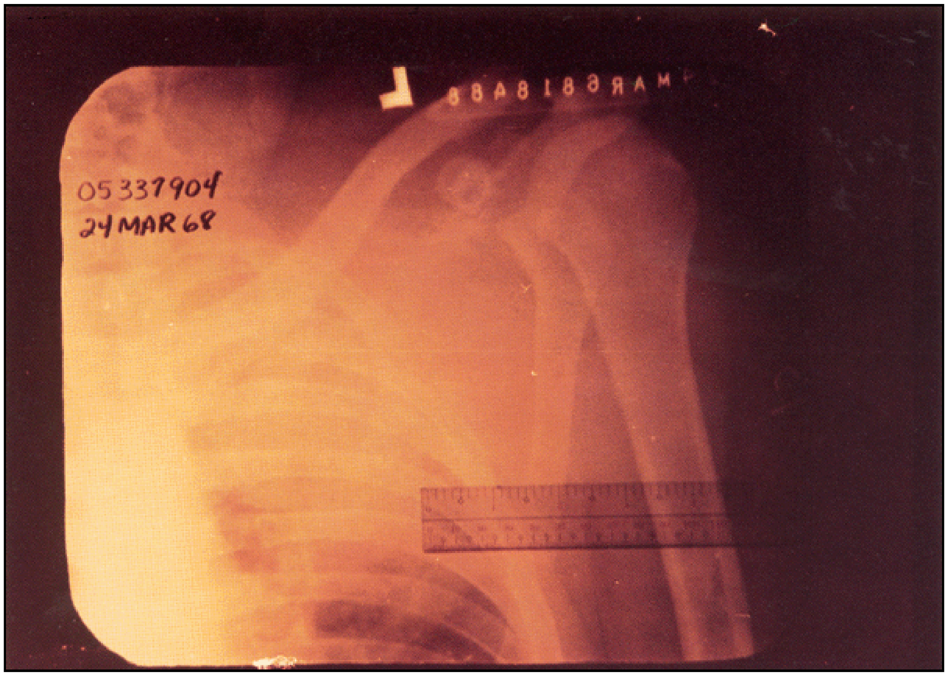


Fig. 4-40. This roentgenogram shows the chest of the casualty pictured in Figure 4-39. It was taken about 1 hour **after wounding** and shows a massive pulmonary contusion of the upper lobe of the left lung. The pulmonary injury may be the result of a stress **(shock)** wave.
Source: Wound Data **and Munitions Effectiveness Team**

capable of causing indirect damage to lungs.

The mechanism by which a penetrating projectile causes pulmonary injury is sometimes difficult to understand. The following example from the WDMET database may be an example of just such an injury: **A** soldier sustained a through-and-thruugh wound of the shoulder made by an **AK47** bullet fired from about 50 m away (Figure **4-39). A** roentgenogram made about **1** hour after wounding (Figure **4-40)** shows that the lung nearest the wound has an extensive pulmonary contusion. The cause of this injury is not clear. If temporary cavitation were the cause, some evidence of chest-wall damage or even a fracture of the humerus might be found. Certainly, the soft-tissue injury shows no evidence (such as ecchymosis) of the effects of massive temporary cavitation that would be necessary to have caused this distant lung injury. Could this observed injury be a manifestation of stress waves?

Lung has another distinctive biophysical property; it is perhaps the only organ in the body in which the speed of sound (50 m/s) is likely to be less than the velocity of a penetrating projectile. Thus, the potential exists for a projectile penetrating through lung to be associated with a true shock wave,[44] but whether or not this has biophysical **or** medical ramifications is unclear.

The *Heart.* Wounds of the heart, especially when made by bullets fired from military small arms, are frequently as destructive as wounds of the skull. The heart shown in Figure **4-41** was hit by an **M43** ball. The bullet's trajectory, shown by the wooden rod, traverses the base of the heart (that is, the atrioventricular valves). But the most impressive feature of this injury is that the left ventricular free wall is missing; the left ventricle cavity has been blown open. This catastrophic injury is likely to have been caused by the mechanism that Woodruff described: temporary cavitation occurring in a fluid-filled viscus.[41]

The large vessels like the aorta and the pulmonary artery are susceptible to the same catastrophic damage as the heart.

The Abdomen

Intraabdominal viscera can be divided into two classes: solid organs such as the liver, and hollow organs such as the urinary bladder, which contains liquid, and the gastrointestinal tract, which can contain gas, liquids, and solids. Both types of viscera can respond similarly when penetrated by a high–energy-transfer projectile.

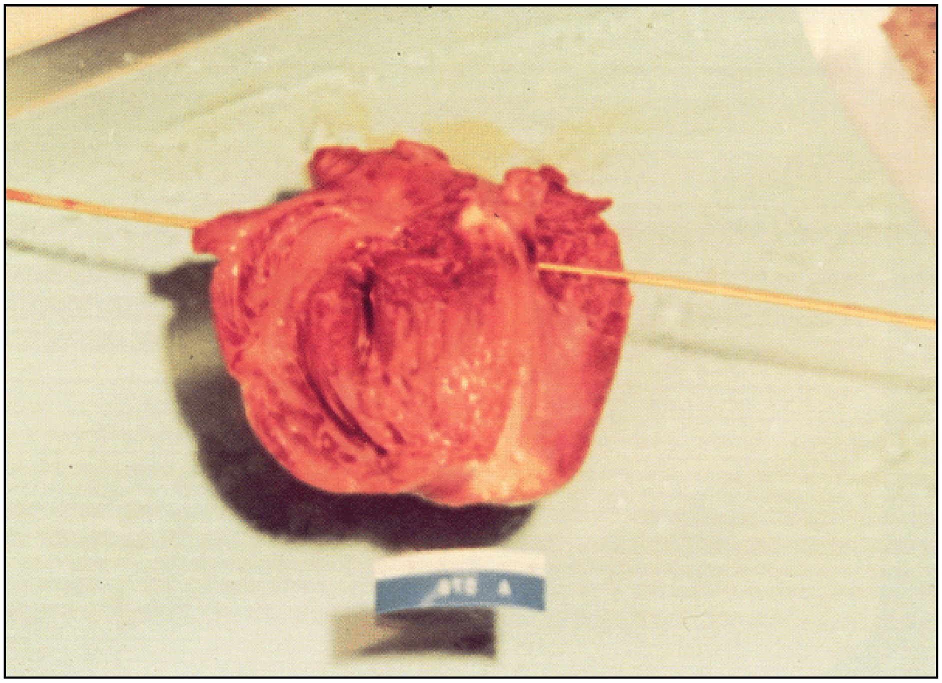


Fig 4-41 **The probe shows the line** of **flight of a bullet fired by an AK47 through a casualty's heart. The free** wall of **the left** ventricle has been blown open by what must have been explosive cavitation. Since the bullet, passing as it did through the atrioventricular valves, could not have made physical contact with the left ventricular free wall, this injury must be an example of an indirect effect. The mechanism is very similar to the hydrodynamic effect that destroyed the lead container shown in Figure **4-35.**

Source: Wound **Data and Munitions Effectiveness Team**

Liver, spleen, and kidney are highly vascular, friable organs (that is, the tissues lack elasticity; they tear when they are stretched). Temporary cavitation causes severe tissue disruption (Figure 4-42). The very large permanent nearly matches the size of the temporary cavity. Such injuries are rapidly fatal.

The gastrointestinal tract is capable of a dichotomous response when a high-energy transfer projectile penetrates it. If the gastrointestinal tract is empty, the wound's permanent cavity will probably be the same size as the projectile. If the system is fluid-filled, however, the potential exists for severe disruption caused by the hydrodynamic forces arising from temporary cavitation that Woodruff described. Severe damage can also result from the explosive expansion of a gas pocket during the negative-pressure phase of cavitation, a mechanism that Harvey described. Figure **4-43** shows a small bowel shredded by an M43 ball fired by an AK47. The gut probably was filled with succus entericus or gas at the moment of wounding, and was ruptured in several places by temporary cavitation.

The abdomen is one body region in which damage from indirect ballistic effects may be common. The injury shown in Figure **4-42** and possibly the injury shown in Figure 4-43 are examples of indirect effects. The damage shown in these examples extends far beyond the tissue that is likely to have come into direct contact with the in this interpretation is the concept that the temporary cavity developed within the target organ after the projectile penetrated it.)

Rigorous proof of this contention requires that there be no possibility that the projectile could have come into contact with the injured organ. If the damage was caused by an indirect effect, it cannot have been caused by the projectile's cutting. **A** gunshot wound of the extraperitoneal abdominal wall that caused a perforation of the underlying small bowel might be an example. There seems to be little doubt that such indirect injuries do occur,[45] but their frequency is probably quite small. The WDMET database contains only five documented examples of such rigorously defined indirect injuries out of 299 surviving casualties with intraabdominal trauma:

- **A** bullet passed across the first casualty's anterior abdominal wall, lacerating an **although the**

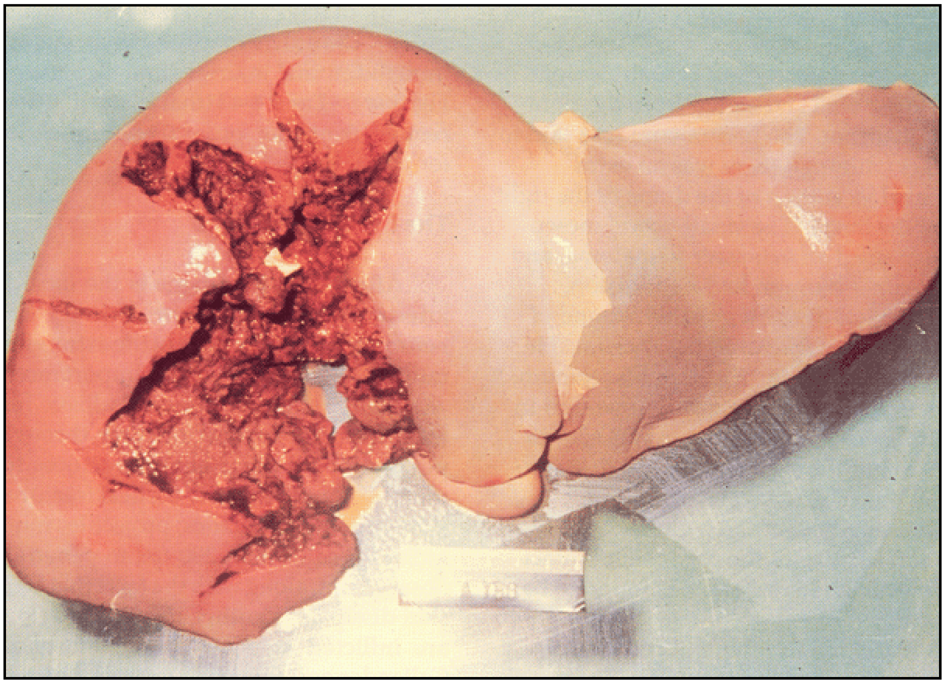


Fig. **4-42.** An M43 ball **fired by** an **AK47** caused **injury. The permanent cavity is probably the same size as the** temporary cavity that made it.
Source: Wound Data and Munitions Effectiveness Team

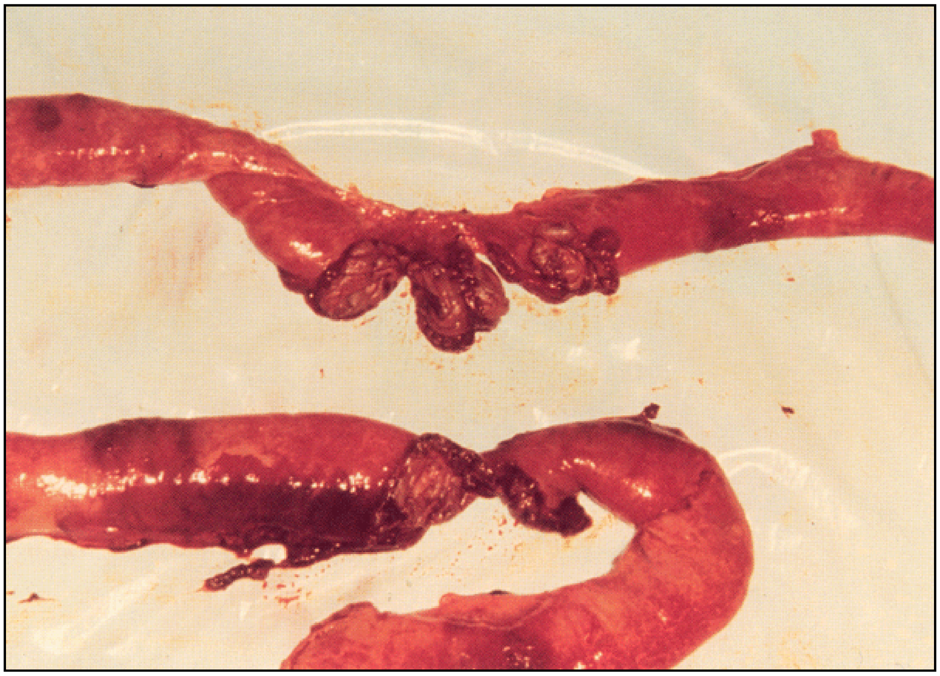


Fig. 4-43. The casualty whose injured small intestine is pictured sustained **a** perforating wound of the abdomen made by an AK47. The bowel looks as if it had been shredded. Although absolute proof is lacking, it is likely that at least some of this massive injury was due to cavitation in a fluid-filled bowel, rather than to direct cutting by the bullet.
Source: Wound Data **and** Munitions **Effectiveness** Team

peritoneum was intact, the cecum contained a 2-mm hole.

- **A** bullet entered the second casualty's right lower chest wall and exited from the right lower quadrant. The peritoneum was said to be intact (although there was an extraperitoneal laceration of the dome of the right lobe of the liver). The small-bowel mesentery contained an extensive hematoma, and the proximal jejunum had a contusion.
- **The** [illegible] **d** [illegible] **of** the buttock that fractured his sacrum. He also had a hole from "blast" in his jejunum.
- **The fourth casualty had a gunshot wound in** his left flank. The peritoneum was said to be intact, but the sigmoid and the descending sections of colon were "ruptured."
- The fifth casualty also had a gunshot wound in his left flank with the peritoneum intact. At laparotomy, his spleen was found to be lacerated.

A very strict definition of an indirect injury was applied to these five abdominal wounds: The projec**tile cannot have entered the abdominal cavity. Many** more casualties probably sustain indirect intraabdominal injuries similar to the ones shown in Figures **4-42** and **4-43** (that is, the injuries occur at sites remote from the projectiles' intraabdominal trajectories).

The Extremities

After soft tissue, bone is the most frequently injured **tissue of the extremities.** Wounds **of** the neurovascular structures of the extremities are of lesser numerical (but not clinical) importance.

Bone. The spectrum of ballistic bone injury extends from tiny cortical fractures, through drillholelike perforations, through simple fractures, to grossly comminuted fractures. Tiny cortical fractures are made by slow-moving projectiles; projectiles must travel at velocities greater than **200** fps to penetrate bone. This observation, along with the facts that *(a)* penetration of skin dissipates another **150** fps, and *(b)* most wounds are inflicted at other than point-blank range, led Callender and French to criticize heavy, slow bullets:

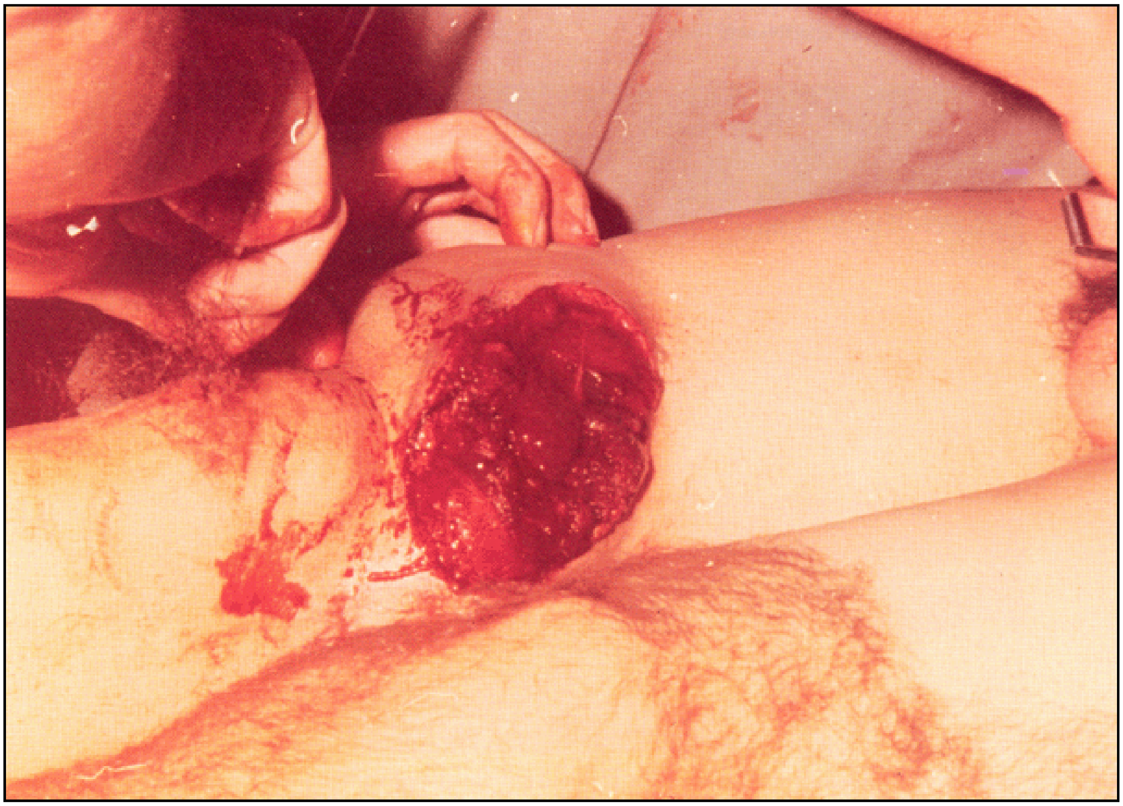


Fig. 4-44. The wound of exit in a casualty's distal thigh, made by an M193 ball fired by an M16 at close range

Source: Wound Data and Munitions Effectiveness Team

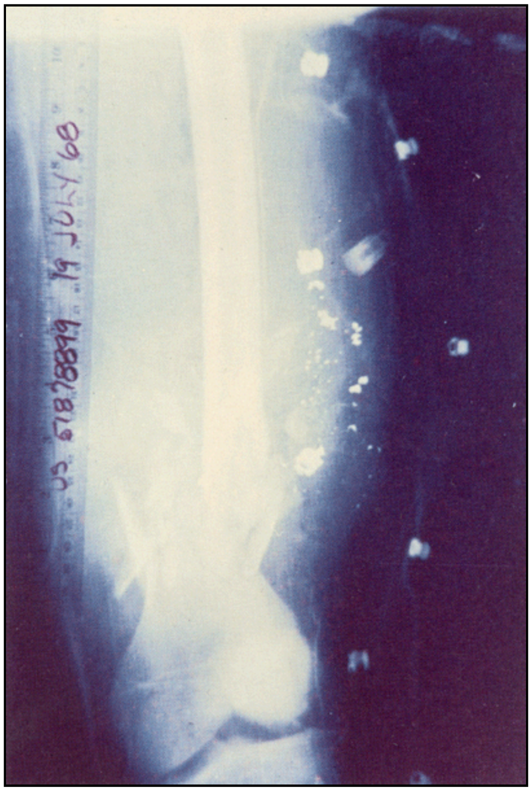


Fig. 4-45. The roentgenogram of the injury shown in Figure 4-44. Secondary missiles of bone and lead in conjunction with temporary cavitation caused the huge wound of exit. This injury is an example of an "explosive wound" such as those first described in the nineteenth century when conoidal bullets were introduced.
Source: Wound Data and Munitions Effectiveness Team

> [I]t can be readily appreciated that the .45 caliber bullet is of little value as a wound-producing agent except in the softer tissue and at near range. The bullet often fails either to penetrate or to fracture bone and practically never shatters bone in the manner common to the rifle bullet or fragment.[7]

The more serious fractures that Callender and French refer to are usually characterized by extensive soft-tissue damage that arises from secondary missiles of shattered bone. These injuries' gaping wounds of exit frequently seem to have exploded (Figures 4-44 and 4-45). A projectile that strikes bone will experience maximum drag (that is, the projectile is stopped and frequently is also deformed or broken up); thus the potential for massive energy-transfer exists. A projectile-target interaction visualized by high-speed cinematography demonstrated that the temporary cavitation may, by itself, contribute to the medical treatment problem by causing osseous sequestrations. In experiments with bones embedded in gelatin, researchers found that the tissue simulant was stripped from the embedded bone in a process that, if it were to occur in living tissue, might be expected to disrupt periosteal blood vessels.[46]

Indirect fractures (that is, those that occur in penetrating wounds in which the projectile appears not to have had physical contact with the bone) are possible in extremity wounds. These fractures, which are caused when bone is displaced by the expanding temporary cavity, have been demonstrated in laboratory experiments since Harvey's pioneering work in the 1940s[28]

Chinese investigators have provided important data that illuminates the indirect-fracture mechanism.'" The researchers shot the muscular portion of canine thighs with 440-mg triangular fragments at impact velocities of 460–1,500 m/s. Indirect fractures first occurred when the velocity reached 1,250 m/s (that is, impact–kinetic energy of about 340 J). When impact velocities reached 1,250–1,450 m/s,

> thigh bones 5 to 10 mm from the wound channel may suffer from indirect fracture with an occurrence rate of about 15%. When impact velocity reaches 1,450 m/s (about 460 J), the thigh bone 15 to 20 mm from the wound channel may have an indirect fracture incidence of about 29%.[47]

In a companion study, Chinese investigators measured the pressures at various distances from steel spheres as they passed through soap blocks and swine torso.[48] The pressure transients they found were similar in shape to those shown in Figure 4-36. Peak overpressures of 3,0004,000 psi were found within 5 cm of the trajectory. The formula

$$P = k\ d^{-3.8}$$

approximates the decrement in pressure P with distance d.

They found that pressure falls very rapidly. The quasi-static overpressure was tenfold less than the peak pressure, but, within a few centimeters of the trajectory, it probably exceeded the 155 kg/cm² (2,200 psi) that the investigators estimated was sufficient to fracture a bone.[48]

Bearing in mind differences in bone strength and size between humans and experimental animals, these data suggest that an assault-rifle round passing within a centimeter of a long bone might very well be capable of causing an indirect fracture. Indirect fractures, in

Fig. 4-46. This casualty, who was shot through his calf with an M193 ball fired by an M16, has a large wound of exit. The wound of entrance is barely visible at the medial edge of the calf.
Source: Wound Data and Munitions Effectiveness Team

Fig. 4-47. This roentgenogram of the wound shown in Figure 4-46 shows a hairline linear fracture in the tibia about 2 inches proximal to the ankle. Pieces of lead are visible near the wound of exit. It *is* likely that *(a)* the bullet fragmented as it exited the calf and *(b)* the associated temporary cavitation caused an indirect fracture.
Source: Wound Data and Munitions Effectiveness Team

contrast to fractures caused by direct contact with the projectile, might be simple linear fractures. About 10% of the fractures in the WDMET database are listed as ”transverse (no displacement)” and “linear”.[49] These may be indirect fractures (Figures 4-46 and 4-47).

Blood Vessels. Compared to bones, large arteries and veins are much more flexible and thus better able to tolerate the stretch and shear caused by nearby cavitation. Figure 4-48 reproduces Harvey’s famous roentgenogram showing the impressive distortion of a cat femoral artery caused by temporary cavitation and occurring over a few milliseconds.’” Stretch and shear to this extent cause microscopic loss of endothelial cells, rupture of the internal elastic membrane, and focal bleeding as far as 6 cm away from the permanent cavity in experimental wounds.[50] Chinese researchers fired M193 bullets into swine thighs and found thrombi attached to the injured endothelium in about one-half of the animals 72 hours after wounding. However, the current opinion is that the only significant wounding mechanism is the cutting and crushing of direct projectile contact and “there is no evidence that resection of normal-appearing artery on either side of an injured segment is necessary.”[16]

Ballisticians have speculated for years that pressure transients arising from the stress wave or from temporary cavitation (that is, the hydrodynamic effects) might propagate along major vessels and cause distant indirect injuries.[4] For example, pressure transients arising from an abdominal gunshot wound might propagate through the vena cavae and jugular venous system into the cranial cavity and cause a precipitous rise in intracranial pressure there, with attendant transient neurological dysfunction. Clinical and experimental data need to be gathered before such indirect injuries can be confirmed.

Nerves. From the standpoint of preserving their anatomical integrity, nerves resist the stretch and shear

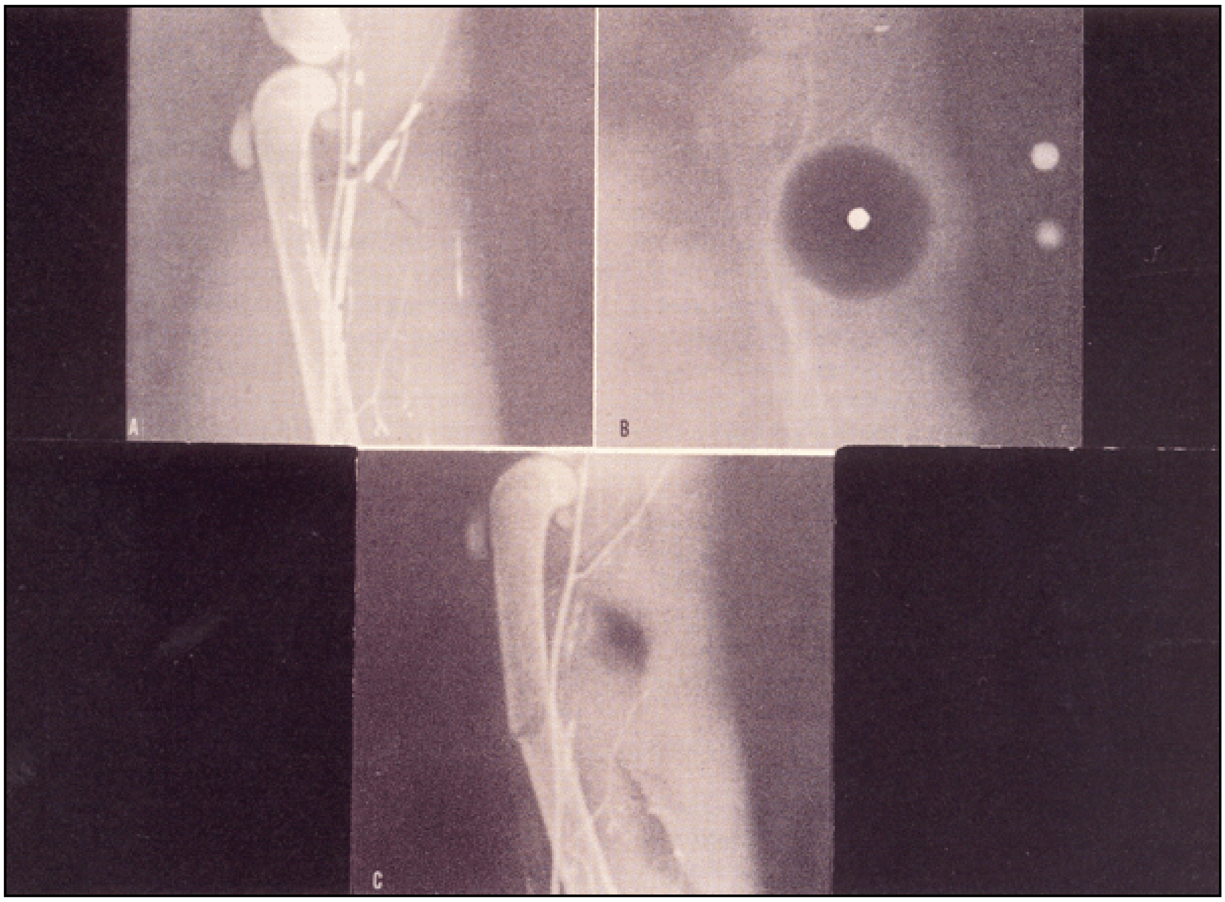


Fig. 4-48. Harvey's roentgenogram used a spark X ray to show the distortion of a feline femoral artery (containing radiopaque dye) caused by an expanding temporary cavity. The animal's thigh was shot with a 6-mm sphere fired at 980 m/s. Frame **A** shows the cat's thigh before it was wounded (the sciatic nerve was impregnated with barium sulfate to show its location). Frame B shows the projectile's passage and the early cavitation. Frame C was taken after cavitation had occurred, and shows an indirect fracture of the cat's femur

Source: Reproduced from Figure 27 in reference **28**

of temporary cavitation rather well. However, studies dating back to Harvey demonstrate histological abnormalities in peripheral nerves that have been subjected to stretch by a nearby temporary cavity.[28]

Experimental data, also dating back to Harvey, suggest that electromechanical effects—perhaps produced when nerves are deformed by nearby cavitation—may cause depolarization and consequent neurodysfunction.[51] The WDMET database contains at least one possible example of this phenomenon. **A** soldier sustained a perforating gunshot wound of the trapezius muscle in his neck. He stated that for **5** minutes after he was wounded, his body felt numb and he was unable to move any of his extremities. The subsequent physical examination revealed only soft-tissue damage to the muscle. Despite its anecdotal nature and the possibility that this was actually a combat-stress reaction, one is tempted to believe that the stress wave passing through the soft tissue of the soldier's neck indirectly caused a transient cervical-cord dysfunction.

The frequency of peripheral nerve defects caused by the stretch of a temporary cavity is unknown. However, many experienced military surgeons can recall casualties who had neurological defects in the distribution of nerves that were found to be grossly intact during surgical exploration. In fact, a training movie made during the Vietnam War shows just such an occurrence: a soldier who was wounded in the thigh by multiple grenade fragments and had a neurological defect in the distribution of the sciatic nerve. Surgeons found no gross nerve injury at surgical exploration, but the casualty's sciatic nerve lay next to a large permanent cavity.[52]