CHAPTER 36
OPEN FRACTURES AND GUNSHOT INJURIES

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SECTION ONE
MANAGEMENT OF THE OPEN FRACTURE

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- Physical Examination
- Radiographic Examination
- Surgical Debridement
- Fixation
- Postsurgical Management

An open fracture can be defined as a broken bone that is in communication through the skin with the environment. The amount of communication can vary from a small puncture wound in the skin to a large avulsion of soft tissue that leaves bone exposed. In contrast, a closed fracture is one that is contained within the extremity without a break in the integument. The old nomenclature of simple for closed fracture and compound for open fracture has largely been discontinued. Open fractures are much like pregnancy: they either are or they are not. Closed fractures, on the other hand, can contain devitalized skin that can be easily penetrated by bacteria resulting in the same problems that occur with open fractures. Closed fractures should, therefore, be evaluated very carefully in regard to the intactness of the integument and its viability. Closed fractures can usually be considered clean if the skin is not devitalized. All open fractures, on the contrary, are considered contaminated. Deceivingly small, seemingly insignificant puncture wounds associated with a fracture may, in fact, have severe consequences brought about by penetration of foreign matter into the extremity combined with neglect through nondiagnosis or improper treatment of the open fracture (Fig. 36-1).

Open fractures are classified according to their severity.(33,42) In a first-degree open fracture, the bone fractures and then penetrates the skin from within. Firstdegree open fractures have very small wounds and following surgical debridement can be treated in the same manner as a closed fracture. Second-degree open fractures are more extensive than first-degree open fractures, and there is usually a larger wound that communicates with the fracture. Soft tissue may be injured to greater extent, and these fractures represent a middle ground between first-degree and third-degree fractures. Third-degree open fractures represent the most severe form of open fracture with comminution of the fracture and massive soft tissue damage. Soft tissue and bony avulsion may be part of the fracture, and often these injuries are caused by forces from without. Most commonly third-degree open fractures in the dog are the result of high-velocity bullet wounds. Some open fractures caused by vehicular trauma can also fall into this category. With the loss of soft tissue, these fractures represent the most demanding type of problem seen by the veterinarian.

Any open fracture represents a contaminated wound. Contamination can occur at the time of the injury and anytime thereafter while the wound is exposed to the environment. Therefore, it is important to provide first aid measures whenever dealing with open fractures. The two major problems that must be overcome with open fractures are hemorrhage and protection of the wound. Many times, application of a pressure bandage with a clean dressing can solve both problems simultaneously. If hemorrhage is not a severe problem, the wound should still be covered and protected by a clean dressing. Most animals will be able to support themselves, but some animals following open fracture and severe bleeding may be in a state of shock and must be transported on a board or stretcher. The importance of covering the wound initially cannot be overemphasized.(42) Most of the organisms that are recovered from the wound following development of an infection can be traced to a hospital serotype and do not represent organisms that were present at the accident site.(33,42) Protection of the wound during transport and entrance into the hospital may significantly reduce this form of contamination.

PHYSICAL EXAMINATION
When an animal presents with an open fracture, diagnosis of the fracture has already been made and hopefully the wound covered with a dressing. The purpose of the physical examination is to determine the status of the patient, to stabilize the patient, and to assess all injuries. If external bleeding is a problem at the time of injury, usually a pressure dressing applied to the area can control hemorrhage while the physical examination is performed. Occasionally, spurting blood may require the use of a hemostat to directly control the source of bleeding. Rarely, if ever, should a tourniquet be applied to control bleeding in a hospital environment. Physical examination should include all of the body systems, usually leaving the fracture until last. If, in fact, the fracture is not covered on presentation, it should be covered immediately and bandaged with a sterile dressing. If a dressing has already been applied, it should not be disturbed at this time. If the dressing is inadequate, additional dressing can be applied over the existing dressing to completely cover and isolate the wound from the environment. Initial physical examination should try

to assess neural and vascular supply to the limb below the area of the fracture. Blanching of the capillary bed or a pulse felt below the injury is indicative of adequate vascular flow. The warmth of the extremity is also a helpful sign, but the extremity may be cool if the animal is in shock, and the capillary bed may also be affected by this situation. Clipping a toenail short is another way to assess peripheral vascularity beyond the fracture site. If capillary bleeding exists, it is a positive sign for ah intact vascular supply for the foot. If the status of the limb's vascularity remains in doubt, arteriography should be performed.

FIG. 36-1 (A) An undiagnosed open fracture of the proximal femur was referred for internal fixation. Clipping of the leg prior to surgery showed a punched-out skin lesion on the lateral thigh. (B) Surgical exploration revealed the missing skin attached to the end of the distal fragment. Frank infection was present. Approximately 1 liter of purulent fluid was removed and the internal fixation applied using a suction drain. (c) A poor clinical result correlated well with this radiograph picture of a degenerative arthrosis of the hip at 3 months.

The history surrounding the injury is of great importance when dealing with open fractures. It is important to know, for instance, whether the automobile struck the animal or ran over it. The soft tissue damage that is always a part of this injury can in great measure be a part of the prognosis regarding it. Very often, the amount of soft tissue injury can be assumed only by looking at the radiographs; a comminuted fracture would indicate a high-energy type injury and/or massive soft tissue swelling, which in turn would indicate a large amount of soft tissue damage and/or hemorrhage. Kinetic energy involved in the wounding of the animal ($KE = 1/2 \, mv^2$) is just as important in vehicular injury as it is in wounds created by missiles. Complications such as tetanus or clostridial myonecrosis (gas gangrene) are more likely in open fractures associated with high kinetic energies. The devitalization of muscle mass and loss of vascularity, hence oxygenation of the tissues, are all important for these obligate anaerobes. Since the incubation period of the clostridial organism is usually less than 24 hours, it is important to recognize quickly the conditions that may lead to its presence. During the physical examination it is important not to manipulate the injured extremity to any great extent. More severe soft tissue injuries may occur through manipulation, and any lacerated vessels that have been temporarily occluded may start to hemorrhage again. The dressing that was placed over the limb should not be removed until the animal is taken to the operating room for debridement. The unnecessary examination and probing of an open wound by one or several clinicians in a hospital environment is conducive to further contamination with pathogenic organisms of a hospital serotype.

RADIOGRAPHIC EXAMINATION

Following evaluation of the patient, including blood work and any stabilization necessary, radiographic examination of the injured extremity should be undertaken. It is necessary to examine the entire involved limb segment radiographically. This should include the joint above and below the actual fracture. Biplane radiographs are necessary to determine the extent of injury to the bone. Arteriography may be used if indicated. Radiographs will reveal the extent of the bony injury and suggest the soft tissue involvement. The radiographic picture will allow for a plan of action to be undertaken when the animal is taken to the operating room for complete wound debridement and definitive fracture treatment. This plan may be modified or changed as surgical debridement of the wound is undertaken and the extent of the soft tissue injury is realized; therefore, it is important to have all the necessary instruments prepared to undertake the definitive treatment of this fracture.

SURGICAL DEBRIDEMENT

Surgical debridement is accomplished in the operating room under aseptic conditions. Surgical preparation of the limb is carried out through clipping and scrubbing of the area around the wound before removal of the bandage. Following general preparation of the leg and donning of a cap, mask, and gloves by the surgeon, the rest of the wound may be clipped and surgically scrubbed. A sterile lubrication jelly can be placed in the wound to avoid contamination of the wound with the hair while clipping. This lubrication jelly is miscible with water and is rinsed away during surgical debridement. The wound itself is cleansed in the same manner as the leg. Copious amounts of fluid are used to rinse the wound clear of hair and debris. A complete surgical scrub is carried out and the wound is draped; the surgeon, who is regowned and regloved after inspection of the wound during surgical preparation, begins the surgical debridement. Since copious amounts of fluid will be used in washing the wound, it is important to provide a plastic sheet or other impenetrable barrier for fluids between the extremity and the rest of the body or table. In general, during debridement the wound should be flushed with liters of fluid. The literature shows a decreased infection rate when 10 liters or more of fluid are used for wound flushing during debridement.(23) This flushing can be accomplished with the use of a bulb syringe or, as has been more recently recommended, the use of a pulsetile water jet such as a Water Pik.(22) Just forceful cleansing of the surface of tissues will rid them of bacterial contamination as well as debris, which would have the potential for bacterial colonization. A significant difference seems to exist in bacterial infection in experiments associated with the use of a bulb syringe versus Water Pik-type cleansing.(22) These studies have shown the beneficial effect of the Water Pik-type device in contaminated crush wounds.

The use of antibiotics in the irrigation solution has been shown experimentally to reduce the incidence of infection in contaminated wounds. However, the use of antibiotics is no substitute for good surgical debridement. The rapid penetration of the wound by pathogenic organisms was demonstrated by Petty to prevent complete sterilization by antibacterial solutions.(44) However, antibiotics are useful in decreasing the bacterial population and may reduce the surface contamination to zero. Commonly, the agents used are those that are not used systemically because of toxicity. In the past the most common combination was a neomycin-polymyxin-bacitracin solution containing 1 g neomycin, 500,000 units polymyxin, and 50,000 units of bacitracin per liter of saline or Ringer's solution. Kanamycin at a concentration of 2 g/liter solution is also a popular choice. All combinations of the above drugs have been used as well as many others. The kanamycin solution seems to work well if Pseudomonas is not a problem. Polymyxin added to this will control the Pseudomonas. When using any local antibiotic, systemic absorption may represent a problem; therefore, it is very important not to overdose the patient by this route. The effects of local antibacterial agents are local not systemic, but the ototoxic, neurotoxic, and nephrotoxic effects can be achieved through local lavage. Recently, we have gone to flushing the wound during operative procedures using the antibiotic solution in a spray bottle, to allow a gentle mist to be sprayed over the entire wound once every 5 minutes. The spray bottle limits the amount of solution used, so that adequate concentrations are achieved with minimal volumes. The antibiotic solution is not used during initial debridement and

irrigation, since the fluid volumes required at this stage are so large (> 10 liters). Surgical exposure should be adequate for debridement but should not devitalize more tissue. The skin incision should be through a skin surface that does not appear to have vascular compromise. Sometimes the incision can be an extension of the wound, whereas a separate incision away from the wound may be necessary in other cases. The use of a surgical implant may also modify the approach that is taken. It is important to remember that wound healing can take place only where the skin has adequate vascularity. The surgical debridement should be thorough, with removal of all devitalized tissue. Sometimes it is difficult to determine if some tissues may be viable. The dependable features for predicting viability of muscle are listed in order of decreasing significance: ability to bleed, consistency, contractility, color. Color, an often used criterion, is really one of least reliable and depends on the light source being used to examine it or tissue perfusion. If adequate tissue perfusion is present, active bleeding will be present during resection. All nonviable tissue is excised. There must be no exceptions if wound healing is to proceed. Once the wound is clean, the fracture is reduced and stabilized. The techniques used to stabilize open fractures are those that can be used in the open treatment of closed fractures as well as in the closed treatment of closed fractures.

FIXATION

The use of a cast or splint in the treatment of an open fracture depends on the stability of the fracture after reduction (it must be inherently stable) and on the amount of soft tissue damage. Casts and splints make wound care difficult and usually allow excessive movement of the fracture during the frequent cast changes that are necessary to deal with open wounds. The compromised skin vascularity may also prohibit the use of a cast or splint.

Intramedullary devices can be used with first- and second-degree open fractures, but the introduction of an intramedullary device in a contaminated or infected fracture may spread the contamination to the entire medullary cavity, where it is difficult to treat. Therefore, intramedullary rods are used in first-degree open fractures in the dog with results similar to those that would be expected with open treatment of closed fractures by the same methods. Intramedullary devices are not used in third-degree open fractures. Their effective use in seconddegree open fractures is related to the stability they confer to the fracture and to the severity of the soft tissue injury.

Plates and screws for fixation in open fractures of the first-and second-degree type have found widespread use in veterinary orthopaedics (Fig. 36-2). This stable internal fixation has allowed the surgeon to reduce and stabilize the fracture, permitting the soft tissues to heal without motion at the fracture site. When dealing with severe, third-degree open fractures in the dog, the acceptance of internal fixation with plates and screws is not universal. It has been shown that certain severe fractures can be stabilized and heal with the use of plates and screws, but severe unrelenting infection can also be a possibility. My choice for severe, third-degree open fractures depends on the type fracture, vascularity of the skin, and the nature of the incision that would be necessary to place the plate.

The implant should be placed away from the open wound, although sometimes it must encompass it. External skeletal fixation is my first choice for treating severe third-degree open fractures (Fig. 36-3). The placement of the pins away from the fracture site and soft tissue injury preserves tenuous vascularity and allows for adequate wound care. The combination of interfragmentary screw fixation with a full-frame external skeletal fixation often represents the optimal method of stabilizing the fracture without stripping away vascularity that plating may demand. Simple interfragmentary lag screws can be inserted without increased wound exposure following good surgical debridement.
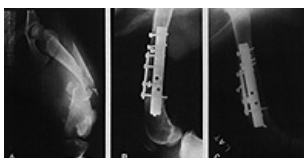

FIG. 36-2 (A) This comminuted second-degree open fracture of the femur occurred in a Great Dane that was hit by a garbage truck. (a) Two plates and a massive bone graft were used to stabilize the fracture. The animal returned to the show ring in six months, although complete healing was delayed. (C) A radiograph at 10month follow-up shows complete healing.

FIG. 36-3 A third-degree open fracture of the tibia is stabilized with minimal internal fixation (three screws [A] and an external skeletal transfixation [B]).

POSTSURGICAL MANAGEMENT

The management of the wound following definitive fracture treatment is most important. The decision to close a wound or leave it open often will determine success or failure of the fracture repair. Although each case will present slightly different problems, some basic rules should be followed and remembered. All open fractures present with contaminated wounds. Wounds presented or dealt with after the 6 hour "golden period" can be considered to be infected. In my opinion, closure of a wound should be considered only with a well-debrided, clean first-or second-degree open fracture. These wounds must have good vascularity, no tension or dead space when closing, and no devitalized tissue within their boundaries. Primary closure is also performed when closed suction drains can be used to control dead space. All other wounds are best left open. Following surgical debridement, the wound is lightly packed with sterile Vaseline gauze sponges. The wound is bandaged with sterile cotton roll and the animal is recovered. The dressing is changed in 2 to 4 days in an aseptic manner. If further debridement is needed, the patient is returned to the operating room and another surgical debridement is carried out. Additional loose packing of the wound is performed and bandage changes repeated as needed. When the bed of the wound is covered with granulation tissue, the immediate threat of infection is gone. At this time, the wound can be left to granulate closed (skin transplants are rarely used in the dog) or a delayed primary closure is carried out by returning the patient to the operating room and closing the wound after careful inspection and freeing of the skin edges to prevent tension in the suture line.

Occasionally, large bone and soft tissue defects are present. These wounds can be managed with a massive cancerous bone

graft after the wound bed is covered with granulation tissue, usually within 10 to 14 days. In this instance the graft (see Chapter 39) is used to fill the entire wound with cancerous bone right up to the skin edges. The wound is covered with Vaseline gauze and kept under a sterile bandage, which is checked by changing as needed (every 2 to 4 days). When gaps exist in the fracture fragments, cancerous bone grafts should be used either immediately with good vascularity or after a 10 to 14-day delay when dealing with impaired circulation. Bone grafts tend to help speed union in all fractures, but especially in open fractures. If the graft does not take because of poor vascularity, it undergoes coagulation necrosis and is exuded from the wounds. Open fractures respond well to good surgical debridement and wound care. Stabilization of the fracture allows more rapid healing of the soft tissues and seems to control infection. Implants can and should be used for correct indications in open fractures, along with cancellous bone grafts.

SECTION TWO
WOUND BALLISTICS

PAUL BERG

- History
- Wound Severity
- Physical Property of the Missile
  Velocity
  Mass
  Ballistic Shape
  Design and Composition
  Yaw
- Reaction of the Tissues
- Infection in Bullet Wounds

Wound ballistics is that branch of science that deals with the motion of missiles within the target tissues.

Proper management of bullet wounds requires a working knowledge of physical factors involved in the creation of such injuries and the way in which they interact. (4,9) Such familiarity has already been the basis of a study reporting the capacity to predict the character of wounds created by the military small arms and ammunition used in the Spanish-American War. (34) This was a welcome change from the prior practice of using surgical exploration or autopsy findings as determinants of wound severity. Because of such investigations, it is no longer sufficient to lump bullet casualties in that sweeping category of "penetrating wounds" in which wounding capability is largely determined by damage to tissues and organs lying directly in the path of the penetrating agent.

The creation of a ballistic missile wound is a very complex phenomenon that results from the action of the missile and the reaction of the tissue. Thus, the veterinary surgeon must know the wound-creating capabilities of the firearms and ammunition available and in general use in his area (Tables 36-1 through 36-3). He must also be aware of the energy potential of each cartridge and the types, composition, construction, and ballistic properties of the projectiles loaded into these cartridges (see Figs. 36-6, A and B. 36-7, and 36-10). High-velocity rifle wounds, for example, invariably result from the use of hunting ammunition (Fig. 36-4) which, through design and construction, produces devastating wounds when compared with damage resulting from the use of military ammunition.

FIG. 36-4 Nonmilitary type projectile fragments resulted from abrupt deceleration on striking the proximal humerus. Fragmentation of a bullet and further disintegration of the fragments augment its "wounding power" and increase wound severity. (Hampton OP: The indications for debridement of gunshot bullet wounds of the extremities in civilian practice. J Trauma 1:368, 1961)

TABLE 36-1 Bullet Mass, Velocity, and Energy Level of Some of the More Common Handgun Cartridges

TABLE 36-2 Bullet Mass, Velocity, and Energy Level of Some of the More Common Rifle Cartridges

Finally, the clinician must know the destructive effects of the various rates of retardation (deceleration) to projectile flight offered by tissues of varying density. It is only by understanding the interaction of all of these factors that the veterinarian can predict wound severity with any degree of accuracy.

HISTORY

Early military weapons used black powder as a propellant, were loaded through the muzzle, and delivered a round lead ball at low velocity (see Fig. 36-8, I). These firearms and early breech-loaders were of large bore (caliber) and were very effective when adversaries were at close quarters. Wounds of that era were usually relatively simple. Tissue injury, although sometimes massive, was restricted to an area along and in close proximity to the bullet track.

As early as 1848, some observers noted the explosive nature of some wounds and associated wound severity with the tissue water content. These observations were reported by others and further amplified, but they could not at that time explain the disparity of damage within comparable tissues.

While working with contemporary modern smallcaliber bullets driven by nitrocellulose propellants, Woodruff,(55) in 1898, confirmed the extreme variation in degree of tissue damage and was the first investigator to use the term "cavitation" to describe the formation of a temporary cavity in the wake of bullet passage. This offered a rational basis for explaining the explosive effect of highvelocity missile wounds.

Other military surgeons have confirmed that wound damage and consequent treatment modalities can be predicted when some of the properties of moving projectiles are understood.(34) This would include the Krag magazine rifles used during the Spanish-American War, which launched a .30-caliber projectile weighing 200 grains (3.18 g). These long bullets were well stabilized by the rifling and maintained a point-on flight before and after impact. Wounds produced during that conflict were less severe than those recorded in any other war, and the reported predictability of wound severity is biased on that account.

During the two world wars, lighter, shorter, pointed bullets of similar caliber driven at velocities between 2400 and 2700 feet per second (fps) dramatically magnified tissue damage. Studies of rifle wounds published by the combatant nations in both wars documented the explosive effect of high-velocity missiles and confirmed the relationship between high velocity and wounding power.

 TABLE 36-3 Kinetic Energy Produced at Any Given Velocity By Bullets of Various Weights

American military surgeons repeatedly demonstrated that blood vessels. remote from the bullet's course were disrupted, with wide separation of fascial planes.(3,4,9) Damage was most severe in tissues of greater density, such as fluid-filled structures or bone.(25) Head wounds showed massive laceration, extensive comminution, and fragmentation of the skull accompanied by herniation or avulsion of the brain.(33) Bone splinters acted as secondary missiles. These studies emphasized the correlation between tissue density and wound severity.(1)

In Vietnam, the .223-caliber (5.56 mm) M-16 rifle saw widespread use. It launched a 55-grain projectile at a velocity of 3250 fps. Dimond and Rich examined these casualties and found that entrance wounds were small and related to bullet diameter, while exit wounds were devastating with much tissue loss. This extensive damage was attributed to the increased velocity, instability of the bullet in flight and in the tissues, and bone fragments as secondary missiles.(1)

WOUND SEVERITY

Until recent years sports writers and army ordnance personnel judged the wound-producing potential of various bullets by their ability to penetrate 1-inch thick pine boards spaced 1 inch apart. Actual tissue damage produced by the bullets so tested showed these studies to be imprecise. The path and motion of a spinning projectile are greatly affected not only by its own physical makeup but in large measure by the properties of the traversed structures. Tissues of different densities variably influence the bullet retardation and drastically alter the manner in which kinetic energy is transferred.(29,50) It is tissue absorption of the kinetic energy shed by the bullet that is the ultimate determinant of wound severity and not the kinetic energy potential possessed by the bullet. This interaction between missile action and tissue reaction, which results in bullet deceleration and energy release, is summarized below:

SEVERITY OF INJURY
Action of missile (physical properties):
Velocity
Mass
Ballistic shape
Design and composition
Yaw and presented area

Reaction of tissues:
Elasticity
Cohesiveness
Density

PHYSICAL PROPERTIES OF THE MISSILE

Modern cartridges are single units that bring together in one container all the components needed to launch a bullet through the air to its intended target. Fig. 36-5 is a cutaway drawing showing the cartridge case (A) lying within a corresponding chamber (B) cut into the steel barrel (C). Completing the steel envelope enclosing the cartridge is a breeching mechanism called the bolt (D). When the firing pin (E) is released, it is spring-driven against the primer (F), releasing its flame through

the 2. primer hole (G) and igniting the propelling powder charge (H). The cartridge case is not merely a method for carrying all the components in one convenient package to allow ease of loading. When the cartridge is fired, the burning powder produces gas that builds up the internal pressure, forcing the thin walls of the brass cartridge case tightly against and gripping the chamber walls. The case head is pressed against the bolt face. These characteristics constitute the primary obturation that prevents gas from escaping to the rear. (3)
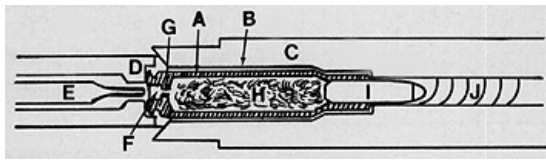

FIG. 36-5 A schematic view of the components of a cartridge contained within the solid steel envelope formed by the barrel and breeching mechanism of the typical rifle.

As increasing volumes of gas are produced by combustion of the progressive burning powder, the increasing pressure is transmitted equally in all directions. Since the only movable component of the cartridge is the bullet (I), which is held in the cartridge neck by friction, it is forced forward at increasing velocity, engaging the rifling (A) cut into the barrel. The rifling twist is calculated to be approximately one complete turn in 10 inches for the average hunting rifle in general use and imparts a spin about its longitudinal axis to the bullet. This spin, roughly 200,000 revolutions per minute, stabilizes the bullet in nose-on flight so that air resistance is minimal, giving stability and consistency of trajectory, which increases range and striking velocity.

VELOCITY

Velocity is the one property common to all missiles and is the most important single factor responsible for woundcreating capability.

In explaining bullet injuries it is convenient to separate projectile flight from muzzle to target into three phases:

1. The initial velocity, measured at a point approximately 15 feet from the muzzle, is the speed transferred to the projectile by the combustion of the propelling charge. Its only importance is that it delivers the missile to the target tissue with sufficient velocity at impact to produce injury. Wound severity decreases as the distance from the launching device increases. Wounds created by bullets with initial velocities less than 2000 fps (616 m/sec) are considered to be lowvelocity wounds, while those driven at greater velocities are high-velocity wounds.

2. Impact velocity is the speed at which the bullet meets target tissue and determines the wound character. Wounds that occur when impact velocities are low show less tissue damage and are free from the explosive effect. There is a transitional zone between low and high velocity injuries in which destruction becomes increasingly more extensive and the explosive effects begin to appear. Maximum tissue destruction with injury remote from the bullet track characterizes high-impact velocity wounds.

3. Residual (remaining) velocity is that velocity retained by the missile after it has passed through the tissues. It is never known in clinical cases but is always measured in experimental studies. The difference between impact velocity and residual velocity forms the basis for calculating the kinetic energy expended in wound production. When the bullet ends its flight within the tissues, all the kinetic energy generated by the impact velocity is used in producing the wound.

In exploring the relationships between mass and velocity which can be used to explain the extent of damage in bullet wounds, three major formulas have been considered.

Momentum, a function of mass times velocity, is still used to define the performance of large-diameter projectiles driven at velocities in the intermediate transitional zone between low and high.

Kinetic energy, which equals 0.5 times mass multiplied by the square of the velocity, is the relationship best able to explain all the physical factors associated with the wound and its formation. This formula is the one currently in favor with most ballisticians.

Power is the rate at which the work is done and is a function of mass times velocity cubed. It has little application in the field of wound ballistics today.

Any moving projectile has kinetic energy. It is seldom necessary to compute this energy because convenient tables are readily available for all commercially produced cartridges (Table 36-2). Nevertheless, the kinetic energy equation should be studied to determine the contribution of each of its elements to the magnitude of tissue destruction. (13)

Kinetic energy (KE) = $mv^2/2$
m= mass in pounds= bullet weight in grains/7000grains/lb v = velocity in feet per second

Note that kinetic energy varies with the square of the velocity but varies directly with the mass. Thus, doubling the velocity increases the kinetic energy fourfold while increasing the mass produces a much smaller effect. This affirms the status of velocity as the most important single factor in making the bullet capable of producing damage (Fig. 36-6, A).

Although velocity and mass determine the bullet's kinetic energy, its wounding potential depends on the transfer of that energy to tissues. This potential is realized by the rate and degree of bullet deceleration by tissue elasticity, cohesiveness, and density. This tissue resistance causes the projectile to shed energy to surrounding structures, which are displaced backward, forward, and radially, producing the temporary wound cavity under the pressures of 100 atmospheres to 200 atmospheres (1500-3000 psi) characteristic of high-velocity missile wounds.(11)
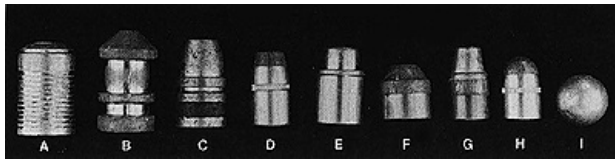
Where tissue resistance is sufficient to cause total dissipation of the projectile's kinetic energy, the bullet remains within the tissues and the wound is called penetrating. In a perforating wound, the energy imparted is the difference between that possessed at entry and that remaining at exit.

Retardation varies directly as the square of the velocity. Doubling the velocity multiplies the deceleration four times. This, in large part, explains the devastating but sometimes superficial wounds created by very high velocity projectiles.

FIG. 36-6 (A) All the rifle cartridges pictured here are .30 caliber. (From left to right): (a) Representative handgun cartridges. From left to right:

MASS
Kinetic energy varies directly with the mass of the bullet. Doubling the weight only doubles the energy. Most hunting and military bullets vary in weight between 150 grains and 200 grains, except those cartridges used for large dangerous game. At the usual initial velocities ranging from 2000 fps to 3000 fps, corresponding kinetic energy levels fall between 1800 and 3500 foot pounds (ft-lb).

Retardation in any medium varies inversely with the bullet mass; thus, in cartridges with comparable velocities, at any given distance from the firearm, the heavier bullet will have the greater impact velocity and will penetrate tissues further if of a nondeforming type.

BALLISTIC SHAPE
Bullets of different shapes, weights, and calibers do not behave alike in passing through the air. Some are retarded or slowed down more rapidly than others. A number is determined for each bullet that represents the ease with which it penetrates the atmosphere. This number is the ballistic coefficient and is found by dividing the sectional density (its weight divided by the square of the diameter) by a form factor related to the bullet's shape. Controlled bullet flight is possible because of its ballistic coefficient and the spin imparted to it by the rifling. Figures 36-7 and 36-8 show the major bullet shapes in general use.

The shape of the bullet is important to its performance while passing through the atmosphere and when it makes the transition into a material more dense than air. Bullets are loosely classified as pointed (Fig. 36-7, F), round-nosed (Fig. 36-7, A and C and Fig. 36-8, H), flat-nosed (Fig. 36-7, E and Fig. 36-8, A), wad-cutter (Fig. 36-7, B), and boat-tail (Fig. 36-9, D). Wad-cutters may be flat across the entire face or may have flat surfaces surrounding a central projection. Round-nosed bullets are retarded more rapidly in air and tissues than sharp points and consequently they penetrate less well. Flat nosed bullets have the least penetration of all.

DESIGN AND COMPOSITION
Bullets are designed to fit a specific purpose. Military projectiles have a lead core fully surrounded by a copper zinc alloy jacket except for a small exposed lead area at their bases (Fig. 36-7, C and J). Since these are supposed to be nonexpanding, the jackets are sometimes drawn thicker at the point than at the base ends. Three major shapes are used by the military: flat base with rounded nose used in handguns (Fig. 36-7, C); flat base with pointed nose (Fig. 36-9, A); and tapered base with pointed nose (Fig. 36-9, D) used in rifles.

Soft-point bullets are jacketed, but the lead core exposed at the tip so that they will mushroom or expand upon impact (Fig. 36-7, E and F and Fig. 36-9, E and G). The principle behind this design is to have a small caliber for high velocity with an enlarging point at impact, which greatly increases retardation and energy transfer. Soft-point bullets vary in shape and construction. Some are flat-nosed (Fig. 36-7, B and E), others round-nosed (Fig. 36-7, A and C), and still others are sharp-pointed with varying amounts of lead exposed. Manufacturers have attempted to design bullets that will expand equally at hunting ranges at all striking velocities.

Some design features used to control expansion are varying the thickness of jackets, the hardness of cores, v {a and the amount and shape of the exposed lead tip (Fig. 36-8, D through H). Despite these innovations, some bullets fail to expand well at long range even though expansion is adequate at short range. Conversely, bullets that expand as designed at long range may expand too rapidly or disintegrate at close range, leaving very large superficial wounds.

FIG. 36-7 (Top) The major types of handgun bullets. (A) Roundnose, flat-base bullet made of 90% lead/10 tin alloy. It is the type projectile most often used by police forces in their 38 special cartridges. (B) Flat-nose, flat-base "wad-cutter" lead-tin bullet used primarily in target shooting to punch clean holes in the target. (c) Round-nose, fulljacketed military type bullet with a lead core. (D) Jacketed, hollow-point bullet designed to increase diameter on impact. (E) Jacketed bullet with lead core exposed at the up. (Bottom) The main types of rifle bullets in general use. All have lead cores. (F) Jacketed soft-point bullet with lead exposed at tip. (G) Jacketed hollow-point bullet. (H) Jacketed bullet with bronze wedge inserted in up. (I) Paragon jacketed bullet designed to expand but maintain integrity of the mass within the base portion. (J) Fulljacketed military type bullet.

FIG. 36-8 (A, B. I) Solid lead-cast projectiles in .50 caliber used in muzzle-loading rifles. The circumferential grooves are designed to hold lubricant. (C) Revolver bullet cast of 90% lead and 10% tin. (D, F. G. H) Jacketed soft-point bullets with various nose shapes designed to expand in diameter but retain mass without excess fragmentation. (E) This bullet has a hollow point not visible in this photo. A conical cavity at the tip ensures rapid expansion in tissue.
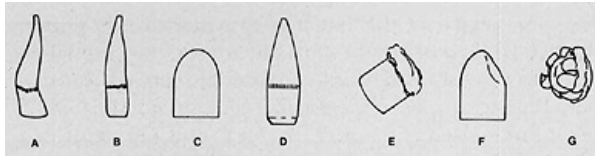

FIG. 36-9 (A, B) Military fulljacketed rifle bullets recovered from tissue show distortions resulting from deceleration.. Compare these with the unfired .30-caliber 150-gr bullet in D. Most of the mass remains. (C, F) Before and after sketches of the .45-caliber auto pistol bullet. The dent in the upper right surface is where it came to rest against bone. (E) Jacketed soft-point pistol bullet after firing. At low velocities expansion is minimal. (G) Jacketed soft-point rifle bullet constructed to expand progressively. The copper jacket opens like a banana peel.

Hollow-point bullets are jacketed bullets in which the jackets are not completely closed at the tip and no lead is exposed (Fig. 36-7, D and G). These behave in a fashion similar to soft-point jacketed bullets, with the points expanding presumably through the wedging action of the tissues while the bases remain unchanged. Some hollow-point bullets have bronze wedges inserted in the tip to facilitate expansion (Fig. 36-7, H). Expansion of hollow-point bullets is controlled by thickness and hardness of the jacket and by hardness of the cores. Bullet jackets are made with thick walls that taper toward the point. This offers increasing resistance to expansion as the point expands and prevents excess expansion as well as disintegration.

Partition-core jackets are designed to maintain the base portion intact as the point expands or fragments (Fig. 36-7,1). The intact portion usually retains 60% or more of the total projectile weight.

Cast lead alloy bullets (Fig. 36-7, A and B) cannot be driven at high velocities; thus, unless they are fired at very close range, they do not expand reliably nor do they break up with certainty.

YAW

If any elongated bullet were fired from a barrel with a smooth bore, it would tumble end over end. Under optimum conditions of bullet design and manufacture associated with the appropriate twist of rifling, the bullet: follows its trajectory and penetrates the air with least retardation. The sole purpose of rifling is to give adequate rotation to the bullet to keep it stable in flight. The twist or pitch of rifling required depends on the sectional density of the bullet (weight divided by the square of the diameter). Long bullets require a faster spin than short ones.

Any deviation of the longitudinal axis of the bullet from the line of flight is called yaw. Yaw results from inherent or induced asymmetry of the projectile. Inherent asymmetry occurs during the manufacture of the bullet when imperfections in the jacket or core or defects in the bonding of dissimilar materials result in an eccentric center of mass. The center of gravity is not in the axis of revolution. Induced asymmetry is produced in several ways. Imperfections or wear in the rifle barrel can distort the bullet during its flight within the barrel. Even if the bullet and barrel are within normal tolerance, a projectile abruptly launched into the atmosphere by 50,000 psi of gas pressure is subjected to stresses of great magnitude. Unequal fins formed of metal displaced by the rifling may be directed rearward beyond the base. The blast of escaping gas contributes to the instability. Hot gases under great pressure may deform lead cores.

In the early stages of flight the bullet usually wobbles considerably, which is further aggravated by disparity between the center of gravity and the center of form. While the bullet is passing through the rifling and receiving its rotation, it is supported on all sides by the barrel and is forced to rotate around its center of form. When it emerges into the atmosphere, it will revolve around its center of mass. It is almost impossible for a manufacturer to get these two centers to coincide. Should the bullet jacket be thicker on one side than the other or if the core is not uniformly dense, the bullet will be eccentric during its entire flight.

After the initial phase of instability there is a second stage in the trajectory in which the bullet is most stable. Toward the farther end of the trajectory there is another phase of instability. Yaw is a major factor in explaining the apparently aberrant bullet wounds seen in veterinary practice. Because animal tissues have a density at least 800 times that of air, yaw is magnified in proportion to the sudden increase in density. This increases the angle of presentation of the bullet by as much as 170¡ from point on flight, and since deceleration varies as the square of the angle of yaw, a highvelocity bullet may be stopped abruptly within the tissues, causing enormous destruction because of energy transfer. The forces of spin may still be operating, and the bullet, which is point on at impact, may yaw 170¡ in a few inches, increasing retardation 172 times, and reestablishing point on flight in a few more inches. This may result in a wound with small entrance and exit holes with massive destruction and bone shattering between.

REACTION OF THE TISSUES

The second aspect of wounding that contributes to its severity is tissue retentivity. It is not merely the projectile's energy upon impact but rather that which is transferred to the tissues that determines wound extent. Thus, if the bullet penetrates the body but is decelerated to zero and remains within the animal, all its kinetic energy was useful in producing the wound.

As the projectile moves through the tissues, the tissues that are penetrated offer a resistance proportional to their elasticity, cohesiveness, and density. These tissue properties tend to oppose the bullet's inertia and slow it down. The characteristic pattern of bullet damage is set by these tissue properties.

Muscle (specific gravity 1.02 to 1.04) and liver (specific gravity 1.01 to 1.02) have similar densities but react differently to the passage of high-velocity missiles. Skeletal muscle fibers are organized into distinct bundles within connective tissue envelopes. Each muscle fiber is enclosed by a sarcolemma and connective tissue endomysium. Several fibers may be grouped into a perimysium surrounded fasciculus. Several fasciculi wrapped in epimysium form the definitive muscle. The amount of connective tissue varies with the muscle. It includes collagen fibers, elastic fibers, reticular fibers, fibroblasts, and histiocytes. Arteries, veins, and lymphatic vessels form capillary plexuses around the muscle fibers. Nerves accompany the blood vessels. Liver, on the other hand, is covered by thin peritoneum superficially and a thin fibrous capsule which sends septae deep. Any other connective tissue is limited to the arteries, veins, lymphatics, and bile ducts. The fine reticular fibers that support the reticuloendothelial system offer little resistance to disruptive forces. Both liver and muscle absorb the same amount of energy per centimeter of tissue, but the residual damage to the liver is greater, with.much tissue loss from the permanent cavity. An explanation for this phenomenon has been found in high-speed photographs taken of missiles passing through water, gelatin, and tissues. Early workers explained the explosive cavity through the "accelerated particle theory." In this theory, the bullet's energy is considered to be transferred to the soft tissues in front and to each side. Momentum is imparted and these tissue particles are forced away from the bullet path to act like secondary missiles. Once set in motion, the particle movement continues until its inertia is overcome by tissue resistance, leaving behind a large cavity. This temporary or "explosive" cavity will, at its maximum size, be almost 30 times that of the permanent wound track. This temporary cavity exists for no longer than several milliseconds, during which it undergoes several pulsating reductions to its permanent size, restoring the tissues to near their original positions.[14,27]

Soft muscle tissues in the path of a high-velocity bullet are pulped.[17] As the cavity expands behind the advancing particles, its walls become quite irregular because of the differential stretching and tearing of muscle and connective tissue, the separation of fascial planes, and the interruption of smaller blood vessels.[29,36] Much of the tissue that is missing from the permanent wound track was blown out in large quantities through tissue "splash" at the bullet entry and exit sites.[19] This loss of tissues occurs in all high-velocity projectile penetrations and perforations. Although muscle tissue may be displaced a considerable distance radially, damage to muscle fibers themselves does not extend very far peripherally.[1,11] Most of the damage is done by the capillary disruption and compromised blood supply. Vascular damage may be extensive for a considerable distance peripherally, with collections of blood filling in the fascial planes between separated muscle fibers.[36] Unless larger blood vessels are directly struck by the bullet, they remain intact when viewed macroscopically. Blood vessels of this size have a good bit of elastic tissue in their walls and are stretched aside by the expanding temporary cavity only to snap back to their resting places when pressures return to normal. There have been reports of intimal tears and thrombosis in some of these vessels in the postinjury period.[36]

Large nerves, unlike blood vessels, when stretched may be severely impaired in function even though there is no visible defect.[20] Histologic examination of these nerves has revealed severe damage, severing, and separation of the fibers.

Bullet injuries of the lungs[6,7,12,15] and heart[16,21] are discussed in detail elsewhere.

Bone (specific gravity 1.11 or greater) is a support/ protective structure of considerable variability in density. There are two types of bone structure discernible in various proportions in the long and flat bones. Compact (cortical) bone is the denser part, which forms the outermost shell of all parts of the skeleton. Its thickness and density are determined by the stress to which the bone is exposed during its life. The long-bone shafts have a thicker layer than do the ends. Spongy (cancerous) bone is preponderant in the long-bone ends and is found separating the inner and outer compact layers of the flat bones. It is much less dense than cortical bone, consisting of a complicated pattern of osseous spicules and leaves that cross and connect apparently at random.

Damage to bone may result from the bullet striking the long bone directly. The effects of such contact depend on the type of bone structure that is struck, the surrounding and supporting structures, and the physical characteristics of the missile. The low-velocity handgun-generated fractures most often reported in civilian studies show great variability in degree. Some of the variation can be explained by analyzing such a wound.

The .45-caliber (auto., ACP, or govt.) cartridge has a legendary but undeserved reputation as a "man-stopper." This pistol delivers a 230-grain full-jacketed projectile (Fig. 36-6, B) at a muzzle velocity of 850 fps, and the kinetic energy at the muzzle is 370 ftlb (see Table 36-1). Penetration of the skin requires approximately 150 fps, and penetration of bone causes another loss of 200 fps. This drops the remaining velocity to 500 fps and energy to approximately 120 ft-lb (see Table 36-3). These figures will be further reduced by the retardation of any soft tissues traversed before the bone is struck. To further detract from the legend, most such wounds seldom are inflicted at point-blank ranges, and the impact velocity is almost certain to be somewhat less than the muzzle velocity. Given these statistics, it is not surprising that the .45-caliber automatic pistol and ammunition are not effective wound-producing agents, since the bullet may not fracture bone in the splintering, shattering manner usually seen in high-velocity rifle injuries. Indeed, if the .45-caliber automatic bullet or one similar strikes the distal femur or any other area of cancellous bone, it may simply punch out a hole of roughly bullet diameter without fracture or, if the velocity has dropped enough, the bullet may merely come to rest against the cortex without visible bone injury.[31] If the bullet contact is in an area devoid of spongy bone where compact bone is thickest, as in the midshaft femur or distal radius,

the bone may show several cracks radiating from the point of contact. Figure 36-7, A and B shows a low-velocity, large-caliber projectile of expanding type that has come to rest against the caudal surface of the radius and produced such an injury. As the velocity increases, the cavitation also increases and the bone "explodes," as does soft tissue. When a high-velocity missile (see Table 36-2) launched by a shoulder weapon strikes bone, fragments fly out into the temporary cavity. Most, which remain attached to the periosteum, return to reasonable proximity to their original positions. Rarely, a few are detached fragments that become secondary missiles and may come to rest at some distance from the parent bone (Figs. 36-10 and 36-11). Classification, management, and complications of missile-induced bone damage in animals have already been well reviewed.(45,49)

Another and less severe kind of fracture occurs when a high-velocity bullet passes near the bone but does not contact it directly. This has been called an "indirect fracture." Such injuries are caused by the high pressures suddenly launched against the bone by the leading particle edge of the rapidly expanding temporary cavity. They are usually simple fractures instead of the dramatic comminution resulting from direct contact between rigid bone and a high-velocity rifle bullet. Experimental studies(9) using high-velocity projectiles to create indirect fractures have shown the humerus to be much more resistant than the femur to this type of injury. Whether this results from architectural differences, better insulation of the humerus against damage by muscle and fascia, or both is not clear. These fractures appear, during microsecond roentgenography, as if the bone had been struck a substantial blow on the side facing the cavity radiating from the bullet track. The incidence of indirect fractures varies directly with bullet impact energy. At velocities less than 2000 fps, standard weight bullets do not produce indirect fractures.

FIG. 36-10 (A) Cranial-caudal view of a large-caliber revolver bullet shot at low velocity, at rest against the distal radius. Note that the bone fragments are not distracted to any degree. (B) Lateral view shows the expanding nature of the bullet. The lead particles shed along the track are clearly visible. The concavity in the bullet base and the barrel-shaped sides indicate a lead bullet.

Damage to the flat bones and contained structures of the skull varies with the muzzle energy and with the angle of presentation (yaw) of the projectile, especially after its deformation. At low velocities small holes of bullet diameter or slightly larger are present at entry and exit sites. Cavitation is small at the lower velocities but damage may be severe because bone chips are usually driven into the brain. They sometimes follow the bullet track and sometimes create new injury paths. Ricochet may occur (Kirkpatrick and DiMaio(33)) when the bullet penetrates one cortex, traverses the brain, and rebounds from or follows the contour of the inner surface of the opposite cortex. There is ample evidence of increased intracranial pressure even in low-velocity wounds, and cerebral edema is common.

As the velocity and energy increase, cavitation and concomitant pressure cause extensive separation of the skull along suture lines, with herniation or excavation of brain tissue.
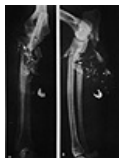

FIG. 36-11 (A) Cranial-caudal view of radius and ulna. "Explosive" effect of high-velocity missile produces secondary missiles from bone fragments. (B) Lateral view of radius and ulna shows wide distraction of bone fragments and the disintegration of the projectile. Each of these bullet fragments creates its own "accelerated particle" effect and the energy transfer to the tissues is cumulative.

Very low velocity projectiles such as those driven by spring-loaded, smooth-bore air guns commonly used by children rarely produce significant wounds unless they can enter the body through an existing aperture.(32) Figure 36-12 illustrates such a pellet that penetrated the globe, causing panophthalmitis and ultimate loss of the eye.

Similarly, the .177-caliber (4.5-mm) air rifle launches a waisted pellet weighing 10 g through a rifled barrel at 400 fps to 800 fps. The propelling medium is usually compressed air or CO2 gas cylinders. This pellet is capable of kiting small birds and rodents up to 15 yards away.(32) At very close range it may penetrate the cranial vault of the cat.

Most veterinarians who treat hunting dogs are familiar with incidental radiographic findings of multiple "bird-shot" pellets scattered throughout muscular tissues, the abdominal cavity, and thorax. Even though numerous, these pellets rarely cause clinical signs. There have been reports of embolism of the middle cerebral artery in humans as a result of thoracic shotgun wounds with small diameter bird shot.(2,54) The suspected route of dissemination began with penetration of the left heart, thoracic aorta, pulmonary veins, or left atrium.

FIG. 36-12 A 5-gr BB pellet projected at less than 300 ft/sec by spring piston power is not normally considered capable of producing significant injury. Here the missile has penetrated the ocular soft tissues after passing, unimpeded, through one of the body's natural apertures, causing loss of vision in that eye.

In a 1968 review of 33 cases of arterial bullet embolism in humans, there were two carotid emboli and seven embolizations to the upper extremity; the rest were in the lower extremity.(55) Bullet embolization to the heart and other migrations have also been recorded.(6,39,40,46,50,53)

The close-range shotgun wound is an exception to the rule regarding low-velocity injuries. A 3-inch magnum shotshell can deliver 17/8 OZ (816 gr) of No. 4 shot (253 pellets) at a muzzle velocity of 1200 fps. This translates to a muzzle energy 2600 ft-lb, almost exactly the energy level of the .308-caliber Winchester cartridge with 150grain bullet. In addition, every shotshell has a composition overpowder wad or plastic shot cup-wad combination separating the propellant powder from the shot.

This functions to keep the expanding gas behind the shot charge. At close quarters, this wad has not fallen behind the shot. It is driven into the wound, adding its mass to the energy transfer and burying within the tissues a foreign body that must be removed. Shotgun pellets are spherical and decelerate rapidly, causing severe damage over a wide area because of devitalization secondary to vascular disruption. There may be widespread skin and muscular avulsion.

Shotgun wounds may be considerably less severe than the "magnum" injury described above because of the great variety of barrel lengths, muzzle constrictions (chokes), distance from muzzle to target, weight and size of shot, energy level to which the shotshell is loaded, and the shot pattern at the target range. For example, a 12-gauge shotshell with 1 oz of No. 9 shot fired at 25 yards would seldom need debridement.

INFECTION IN BULLET WOUNDS

Even though it has been shown repeatedly that bullets are not sterilized by the gases of combustion upon being fired, it is stir a firmly held and widespread belief Contamination must always be suspected in gunshot injuries and may occur in the following ways: The bullet punches out a small piece of skin and hair and carries it into the wound. The temporary cavity, which continues expanding after the projectile perforates, creates a negative pressure that sucks contaminated material into the wound track through both the entry and exit holes. A third mechanism for contamination involves tissue that is temporarily forced out of either of the perforations but remains attached. With equalization of pressures, this contaminated elastic tissue snaps back into the wound.

Military surgeons established the time-tested classic technique of managing gunshot injuries. It emphasized wide surgical debridement with enlarging incisions, removal of devitalized tissue, thorough irrigation with physiologic solutions, and delayed primary or secondary closured Antibiotics were routinely employed. In combat situations surgeons dealt primarily with high-velocity bullets delivered from rifles or machine guns and with mortar or artillery fragments, which created similar wounds. As impact energies increased, the size of temporary cavities and associated forces increased in proportion. In addition to the direct damage to muscle fibers, surrounding connective tissue, blood vessels, and bones were injured to the outer limits of the "explosive" cavity, leaving a significant amount of devascularized tissue at a considerable distance from the permanent wound track. Young military surgeons repeatedly learned the appropriateness of excising all devitalized tissue back to fresh bleeding muscle margins and packing the wound. After reexamination in 3 or 4 days, secondary closures were performed if the wound was clean.

When military surgeons, trained in these precepts, returned to civilian life, they encountered a class of firearm injuries with which they were unfamiliar. Few of the combat wounds were created by low-velocity handgun bullets, but this type of injury was most common in urban civilian medical practices.(24) These wounds usually involved bullets with velocities less than 1200 fps (see Table 36-1). In recent years there has been a pronounced bias toward conservative treatment of lowvelocity handgun wounds(7,26,55) and a reaffirmation of the principles of high-velocity wound care learned in World War II.

In general, civilian low-velocity extremity wounds rarely require debridement in the classic sense.(30) All that may be required is thorough but gentle irrigation with physiologic fluids to remove surface debris and contaminants.(37) Any obviously devitalized exposed skin, muscle, and fascia may be minimally excised. Foreign bodies such as shotshell wads must be removed, but probing of the wound is avoided. If a comminuted bone fracture is present, only small fragments with no soft tissue attachments should be removed, and periosteum should be preserved.(28)

Low-velocity gunshot injuries of joints are exceptions to the general trend toward conservative treatment of such wounds.(5) It has been shown that lead is dissolved by synovial fluid and causes migration of the solute to the subsynovial tissues, resulting in periarticular fibrosis. Lead-induced lysis in the cartilage may ultimately lead to hypertrophic arthritis. Chronic lead poisoning has been reported as a delayed complication.(35) Such findings man date surgical intervention with removal of the offending bullet fragments as the only appropriate course of action.

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