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Gunshot Wounds: Epidemiology, Wound Ballistics, and Soft-Tissue Treatment

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Abstract

The extremities are the most common anatomic location for gunshot wounds. Because of the prevalence of gunshot injuries, it is important that orthopaedic surgeons are knowledgeable about caring for them. The most common injuries seen with gunshot wounds are those of the soft tissues. Nonsurgical management of patients who have gunshot wounds with minimal soft-tissue disruption has been successfully accomplished in emergency departments for several years; this includes extremity wounds without nerve, intra-articular, or vascular injury. Stable, nonarticular fractures of an extremity have also been successfully treated with either minimal surgical or nonsurgical methods in the emergency department. Indications for surgical treatment include unstable fractures, intra-articular injuries, a significant soft-tissue injury (especially with skin loss), vascular injury, and/or a large or expanding hematoma.

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Gunshot wounds remain a significant clinical problem in the United States.[1-9] In 2006, there were 29,569 firearm-related deaths and approximately 66,000 nonfatal injuries that received care in the medical system; these numbers exceed the total number of Americans killed or wounded in Iraq and Afghanistan during the present conflict. Because of the prevalence of gunshot wounds, it is important that orthopaedic surgeons are knowledgeable about treating these injuries.

Epidemiology

Gotsch and associates[1] estimated that there were 180,533 fatal gunshot wounds and approximately 411,000 nonfatal gunshot wounds in the United States from 1993 through 1998. During this period, there was a 41% decline in the annual nonfatal injury rate (from 40.5 to 24 per 100,000) and a 21% decline in the fatal injury rate (from 15.4 to 12.1 per 100,000). This decline corresponded with an overall decrease in violent crime of 21%. The stated cause for injury was assault in 57%, self-inflicted in 20%, unintentional in 13%, and unknown in 10%. The average number of self-inflicted fatal injuries exceeded those from assault (18,227 versus 15,371 per year) during the study period.

From 1998 through 2006, there has been a further decline in violent crime from 566.4 to 473.5 incidents per 100,000 (16.5%) and in murder from 6.3 incidents to 5.7 per 100,000 (9.5%).[8] Deaths caused by firearm-related injury in the United States also decreased, from 35,957 (13.5 per 100,000) to 29,569 (10.5 in 100,000).[8]

Gotsch and associates[1] also found that the rate of firearm-related injury was seven times higher in males than in females. The annual rate of fatal and nonfatal firearm-related injury was highest in African-American males 20 to 24 years of age (166.7 fatal injuries and 690 nonfatal injuries per 100,000; comparable rates for the general population were 13.4 fatal injuries and 30.1 nonfatal injuries per 100,000). These demographics also explain why the concentration of patients with gunshot wounds is higher in trauma centers in cities with a high African-American population, such as Detroit, Los Angeles, Philadelphia, Chicago, and New Orleans.[8]

There is an economic as well as a human cost in caring for patients with gunshot wounds. In a 1994 study, Hakanson and associates[5] reported that the average cost of treating a gunshot-related orthopaedic injury was $13,108 per patient. Brown and associates[3] found that orthopaedic patients treated for gunshot wounds in New Orleans at an inner city

Table 1
Anatomic Distribution of Gunshot Wounds

	Detroit, Michigan	Cordoba, Argentina
	(*N* = 1,505)	(*N* = 1,326)
HEENT	11.7%	12%
Abdomen/pelvis	16%	12%
Upper extremity	16.2%	18%
Lower extremity	26.2%	45%
Spine	5%	Not reported

HEENT = head, eyes, ears, nose, and throat.

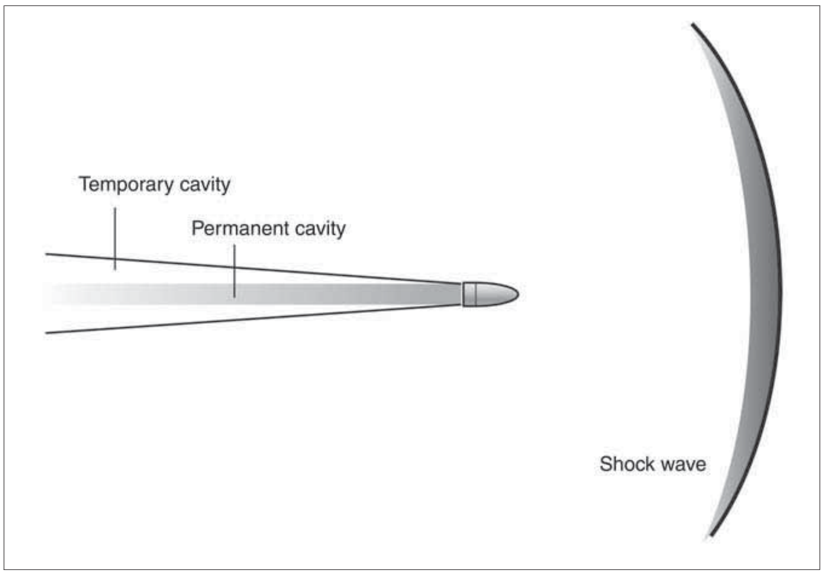

Figure 1 Projectile-tissue interaction.

level I trauma center accounted for 24% of all admissions and 26% of all orthopaedic trauma surgical cases.

The most common location for nonfatal gunshot wounds is the extremities (Table 1). Gotsch and associates[1] reported that extremity wounds represented 46% of nonfatal wounds due to assault and 71.8% of unintentional wounds. A series from Cordoba, Argentina, found that 63% of gunshot victims had injuries to the upper or lower extremities.[4] A review of records at Henry Ford Hospital in Detroit, Michigan, from 2001 to 2006 found that 42.4% of all patients admitted with a diagnosis of gunshot wounds had extremity wounds. This figure increased to 50.2% if pelvic and spinal injuries were included.

Some patients with gunshot wounds are treated in the emergency department as outpatients. The percentage of gunshot wounds treated on an outpatient basis is approximately 45% to 60%.[1,6] Gotsch and associates[1] reported a ratio of 1:1.2:1 for deaths, hospital admissions and transfers, and emergency department treatment and discharges, respectively.

Wound Ballistics

Wound ballistics is the science that studies the effects of penetrating projectiles on the body.[9-23] Three observable phenomena occur when a bullet strikes tissue.[9,10,13-19] First, tissue is crushed by the projectile as it passes through, leading to a localized area of cell necrosis that is proportional to the size of the projectile. This area of the projectile's path is called the permanent tract or permanent cavity (Figure 1).

There is a second area in which elastic tissue is stretched, causing a temporary cavity (Figure 1). The stretch occurs because of a lateral displacement of tissue that occurs after the passage of the projectile. There is a transient increase in pressure of a few atmospheres for a few milliseconds in duration.[15,16] This transient lateral displacement of tissue, such as skeletal muscle, vessels, and nerves, macroscopically appears as blunt trauma.[9,11,16-20] Inelastic tissue, such as bone or liver, may fracture in this area.

A third component, known as the shock wave (Figure 1), is a pressure wave that travels at the speed of sound preceding the bullet in tissue.[9,16-18] This pressure wave is of very short duration, a few microseconds, although it may generate pressures of up to 100 atm in magnitude. The shock wave has not been shown to cause tissue injury.

Grundfest and associates[21] used cadaver skin to test threshold velocities for penetration. The skin was stretched over a frame during testing, thus altering the behavior seen in vivo. The authors used steel ball bearings from 1/16 to 1/4 inch in size, as well as 11/64-inch lead spheres fired from an air rifle. The authors found that increasing the size of the projectile also required increasing the velocity needed to perforate the skin.

Fackler and associates[11] studied healing of soft tissue using a large porcine animal model. These investigators fired a solid, nondeforming 5.56-mm bullet into the thighs of the animal models. Exit wounds were larger than entrance wounds and were produced by splits in the skin caused by the larger temporary cavity produced as the bullet yawed through tissue. The larger wound allowed for better exposure of the wound path and free drainage of wounds. Additionally, the authors found skin vasospasm, which produces blanching, soon after wounding. This area did not revascularize for several hours. If the loss of blood supply is a criterion for excision, the transitory nature of the blanching shows that viable tissue would be sacrificed in this area if evaluated soon after wounding.

In another study, Fackler and associates[12] found that projectile shape was important in determining the appearance of a skin wound. The authors fired a solid, nondeforming bullet point-first and then base-first, noting the different appearance of the skin wound in each instance. The bullets were fired at more than 5,000 ft/s. For the projectile traveling base-first, large skin splits were produced by an early temporary cavity. No such effect was seen with bullets traveling point-first through the skin.

Injury to skeletal muscle has been studied using animal models.[10,11,13,15-19] Muscle that is touched by the projectile in the permanent cavity has a microscopic rim of tissue that is actually necrotic. If the blood supply to the muscle remains intact, this tissue can heal over time without surgical intervention. The area of cell death sloughs,

Figure 2 Direct bullet fracture.

and as long as the wound can drain, this tissue will heal spontaneously.

Surrounding the path of the projectile is an area damaged by stretching of the tissue, causing a temporary cavity. The stretched area of temporary cavity may split along fascial planes. The gross appearance of this area is that of bruised or contused tissue. Bruised skeletal muscle ordinarily heals uneventfully. Microscopically, there are disrupted skeletal muscle fibers and capillaries. After a period of time, there is leukocyte infiltration, followed by inflammation and healing.[15,19,20]

When a bullet fragments, many permanent paths are formed; thus, the region stretched by the temporary cavity is perforated in multiple places. Tissue weakened by these tiny perforations often is split by the temporary cavity stretch, and pieces between perforations are detached. This perforated tissue often greatly increases the size of the permanent cavity.[13]

If the muzzle of a firearm is in contact with a living body when it is fired, the high-pressure gas that pushes the projectile out of the barrel passes into the tissues through the hole formed by the projectile, often causing an increase in tissue displacement and disruption.

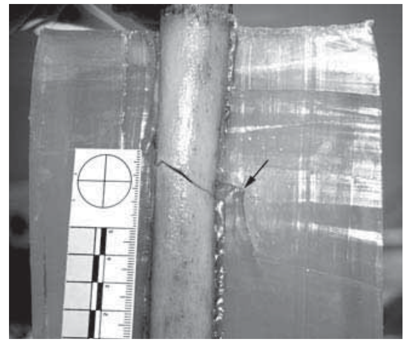

Figure 3 Indirect fracture to bone. The shot line is 8 mm away from the bone (*arrow*).

Bone injury is common with gunshot wounds to the extremities. Fractures may occur either when the projectile strikes bone or, rarely, indirectly by the temporary cavity.[24-32] Direct fractures (Figure 2) occur when a projectile strikes the bone.[24-28,30-32] Because of the density and relatively inelastic behavior of bone, fracture line propagation may occur well beyond the area crushed by the projectile itself, leading to bone comminution and the production of secondary missiles from the bone itself. Because the secondary missiles of bone disrupt tissue before it is stretched by the temporary cavity, there is the effect of increasing comminution around the bullet path, possibly causing increased soft-tissue disruption, similar to the synergism between bullet fragmentation and temporary cavity stretch.

Indirect fractures (Figure 3) may occur when a projectile passes close to the bone in soft tissue and a strain occurs to such a degree as to cause a fracture. Indirect fractures are almost always simple fractures.[15,29,30]

Figure 4 Incomplete fracture. An eccentric divot hole is shown.

Clinically, indirect fractures to bone are rare when compared with those formed when bone is struck directly by the projectile.

Clasper and associates[30] used sheep femora and hindlimbs and fluorescein to study contamination of both direct and indirect fractures. The authors found massive fluorescein contamination for specimens with direct fractures, although only 3 of 14 bones with indirect fractures had medullary fluorescein contamination. Periosteal contamination was less with indirect fractures than with direct fractures. The authors concluded that although contamination occurs with all gunshot fractures, it is more extensive with direct fractures.

Rose and associates[28] proposed a classification of incomplete fractures caused by gunshot wounds, describing "drill hole" and "divot" fractures (Figure 4). The drill hole fractures are caused by bullet perforation of both cortices yet have minimal comminution surrounding the bullet tract. The divot fracture is described as an eccentric perforation of a diaphyseal long bone.

There are common misconceptions about wound ballistics.[9] First, some authors have exaggerated the effects of velocity, using it as the sole criterion for increased injury or as a means to classify gunshot wounds. Velocity is only one of several factors involved with the production of a wound. The introduction of the M16A1 rifle (with its smaller bullet) during the Vietnam War was heralded as producing equivalent wounds or causing equivalent incapacitation as the older M14 rifle, reportedly because of the weapon's higher muzzle velocity of an advertised 3,200 ft/s. The M193 bullet fired from the M16A1 rifle was 5.56 mm in diameter and weighed 3.6 g, compared with the 7.62-mm bullet fired at a velocity of 2,700 ft/s weighing 8 g. Later testing in the laboratory found that the increased severity of wounds sometimes seen with the M16A1 rifle were caused by bullet fragmentation, not the modest 10% increase in velocity.[13] The greatest increase in muzzle velocity for military rifles occurred in the late 19th century, when the armed services of several nations, including the United States, changed from a solid lead bullet to a full metal-jacketed bullet. This change resulted in an increase of muzzle velocity from about 1,000 ft/s to 2,000 ft/s;[23] however, wound severity decreased because bullet deformation was limited by the jacketing.

A second misconception is the idea that kinetic energy or "energy deposit" is directly proportional to wound severity.[9] Kinetic energy is the amount of potential energy available for work, and "energy deposit" is a description of how much energy is lost or deposited in tissue. Although the projectile's velocity and weight can be measured as it enters and exits a body or tissue medium, this does not describe how this potential energy is used. The potential energy may be used for the crush or stretch but also may be consumed in mechanics that may not cause any tissue injury. Examples where energy may be consumed but not cause tissue damage include the shock wave, bullet heating, and bullet deformation.

Treatment of Soft-Tissue Injury

Initial evaluation of a patient with a gunshot wound should include a thorough history and physical examination. After all clothing has been removed, the extremity should be inspected for entrance and exit wounds. The limb also should be inspected for swelling, deformity or shortening, and ecchymosis. The limb should be palpated for crepitus. Examination of distal pulses should be done to assess vascular status. In an awake patient, motor and sensory status should be evaluated. If the patient is not able to comply, this fact should be documented, with a note to recheck if the patient's condition improves.

Biplanar radiographs should be taken of the injured limb, covering the path of the bullet. Standard long bone radiographs, including both above and below the joint, should be taken if the long bone is included in the bullet path. If an articular wound is suspected, standard views should be taken of the joint. The most common gunshot injury is to the soft tissues of skin, subcutaneous fat, and skeletal muscle.

Skin

Skin wounds have three general patterns: a punctate wound about the size of the penetrating bullet (Figure 5); a wound that contains splits in the skin but has negligible skin loss and can eventually be closed without resorting to more extensive skin grafting or flap coverage (Figure 6); and a wound in which there is skin loss that requires the use of partial-thickness skin grafting or flap coverage (Figure 7).

Patients with perforating, nonarticular wounds without a fracture or vascular injury may be candidates for outpatient treatment. Under controlled circumstances, simple perforating wounds have been shown to heal uneventfully with simple dressing changes.[11,17] Successful treatment with local wound care has been reported by several authors.[33-35] Simple fractures with minimal soft-tissue disruption also have been treated without resorting to the operating room by treating the soft tissues with local wound care.[36-39]

Simple splits in the skin[11] are produced from dilation caused by the temporary cavity, a projectile that is traveling sideways and presenting the long axis of the bullet to the skin, or bone becoming a secondary missile and causing a more extensive wound. The splits produce an exit wound that will allow for free drainage of the wound, preventing the formation of an abscess or a hematoma.

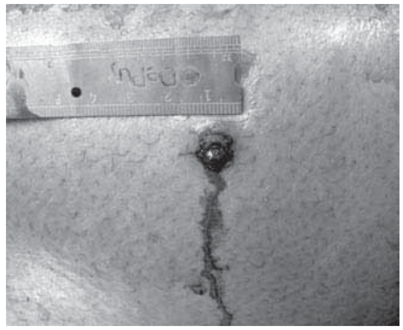

Figure 5 Simple perforating skin wound.

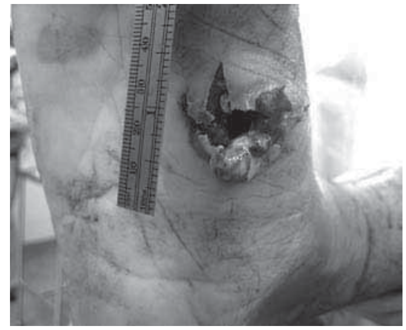

Figure 6 Skin splits.

Figure 7 Extensive wound caused by a shotgun.

More extensive wounds with skin loss may be produced from shotguns or bullet or bone fragmentation. Initial treatment of more extensive wounds should be done in the operating room. Longitudinal incisions of the skin and underlying fascia should be made to relieve pressure, remove a hematoma and debris, and expose the underlying muscle. Surgical removal of skin rarely is indicated for the initial surgery, other than trimming irregular edges. As described previously, blanching may give a false impression of nonviable skin if seen soon after injury and may lead to excision of viable skin.[11]

The use of negative-pressure dressings (vacuum-assisted closure) for the initial management of more extensive wounds has been promoted to potentially reduce the size of the defect needing coverage, promote local growth factors, and remove debris and nonviable tissue from the wound.[40] However, a randomized study comparing this method with standard dressing changes is not available in the literature. An early consultation should be made with a plastic surgeon or a hand surgeon who is skilled in extremity soft-tissue coverage. The wound should be stable before soft-tissue coverage.

Skeletal Muscle

One of the most controversial aspects in caring for gunshot wounds is the treatment of skeletal muscle. Studies have shown that a relatively minimal margin of necrosis occurred in skeletal muscle if the blood supply remained intact.[17-19]

Excision has been recommended for skeletal muscle that would not survive, thus acting as a bacteria medium. Identification of tissue that needs to be excised is imprecise, at best. Scully and associates[41] evaluated 60 biopsies taken from the initial wound excision of 12 war wounds during the Korean War. The surgery took place between 3 and 8 hours after the time of injury. The samples were graded by the surgeon as to the presence of color, consistency, contractility, and bleeding (circulation). The samples were then evaluated by a pathologist who graded the degree of muscle fiber damage. The authors found a correlation of microscopic damage with consistency, contractility, and bleeding. Color was not found to correlate to the degree of soft-tissue damage. Furthermore, time was not found to be a factor in determining tissue viability.

For wounds in which there is a simple perforation of the limb, there is a small rim of cell death. The wound tract will heal uneventfully if allowed to drain.

For wounds in which there is more extensive skeletal muscle injury, a more formal exploration of the wound is warranted. The wound can be enlarged by using longitudinal skin incisions as previously described. Macroscopic evaluation of skeletal muscle will determine what tissue needs to be removed. A simple analogy for surgeons is muscle that looks like hamburger should be excised, and muscle that looks like steak should remain.

The term "débridement" is derived from the French verb "débrider," which means to unbridle or release. As noted by Fackler,[42] the original translation of works from the Napoleonic Wars by Larrey and Desault showed that incision, to allow free drainage of the wound and to relieve swelling (compartment pressure), was the technique used by these surgeons for extremity wounds.

Hampton[43] had a similar description: "Débridement of any wound is designed to relieve the area of excessive tension, rid it of dead tissue and massive hematoma and provide excellent drainage." He speculated that relief of tension was the most important contribution of wound débridement.

Compartment syndrome occurs when there is swelling inside a relatively closed space, such as the anterior compartment of the leg, which is surrounded by fascia and bone.[41,44-47] The swelling occurs as a result of direct trauma, hemorrhage, or ischemia, such as with a vascular injury. A hematoma inside a compartment may lead to pressure and ischemia of muscle. The diagnosis of compartment syndrome is primarily clinical.

Compartment syndrome associated with gunshot wounds has been reported in the forearm, leg, and thigh.[44-48] Forearm compartment syndrome has been well documented and is present in up to 10% of patients.[44] Longitudinal incisions to release pressure within a compartment, as well as to expose tissue, have been recommended by military surgeons at least since the time of the Napoleonic Wars.[42]

The amount of swelling present in a compartment after a gunshot wound may range from minimal to involvement of the entire compartment. Involvement of the entire compartment is rare but does occur when patients have extensive soft-tissue injury or vascular injury causing ischemia. Patients with a large hematoma, vascular injury, or excess swelling at initial evaluation are candidates for more formal surgical treatment of the soft tissues.

Infection

Infection has been documented to occur in 1.5% to 5% of patients with gunshot injuries. Bullet wounds are contaminated wounds. Bullets themselves, when fired, do not become sterile after heating and friction encountered in the barrel. LaGarde[49] created contaminated wounds by firing bullets contaminated with anthrax into an animal model. The animals developed an anthrax infection. Dziemian and Herget[22] placed barium sulfate dye on the surface of an ordnance gelatin block. After shooting through the surface into the gelatin, the dye coated the entire path of the projectile, showing that surface material is brought into the wound.

The discovery of penicillin in 1929 by Fleming led to its use during World War II in caring for the war wounded. Fisher and associates[50] compared 3,471 wounded soldiers with 436 who had wounds at risk for developing gas gangrene (open fractures, more extensive soft-tissue injury, long delay to care, wounds to the buttock or thigh). Those with wounds at risk were treated with penicillin, whereas those without risk were not. Infection developed in 28 of 3,471 untreated wounds (5 with gas gangrene) and in 2 of 436 treated wounds (0 with gas gangrene).

Patzakis and associates[51] divided 310 patients with open fractures (78 caused by gunshot wounds) into one of three treatment groups: no antibiotics, penicillin and streptomycin, and cephalothin. Four of 78 wounds (5%) became infected, 1 with osteomyelitis. The authors attributed the infection to severity of injury in three of the patients who had shotgun wounds with extensive soft-tissue damage. A fourth infection was in the no-antibiotic group.

Hansraj and associates[52] compared the use of ceftriaxone to cefazolin for nonsurgically treated gunshot fractures with minimal soft-tissue disruption (wound < 1 cm), with 50 patients in each group.

Follow-up was 59%, and the authors reported no infections from the emergency department cultures taken. The authors concluded that the 1-day ceftriaxone regimen is more cost effective than the 3-day cefazolin regimen.

Knapp and associates[53] reported a prospective study of 186 patients with 218 gunshot fractures. All fractures were treated nonsurgically and were considered to be "low velocity" based on the appearance of the wound and history. Wounds larger than 1 cm associated with the fractures were excluded. The authors compared the use of oral antibiotics (ciprofloxacin 750 mg twice daily) with intravenous antibiotics (cephapirin sodium 2 g every 4 hours and gentamicin 80 mg every 8 hours). There were two infections in each group (four total). All infections were associated with fractures of the distal tibia.

The prevalence of infected gunshot wounds in the nonmilitary setting is low. None of these studies show the superiority of any particular antibiotic regimen; rather, it is the use of antibiotics that helps reduce infection.

Summary

Gunshot wounds continue to be a major clinical issue for orthopaedic surgeons, particularly those who provide care in large urban level I trauma centers. Variables involved with the severity of a gunshot wound include bullet diameter, bullet shape, bullet composition, velocity, and the type of tissue struck. Changing one of the variables may alter the appearance of the wound. Patients with extremity wounds and minimal soft-tissue disruption may be candidates for nonsurgical, outpatient management. Criteria for surgical treatment include severe soft-tissue injury, comminuted fracture, vascular injury, a large hematoma, compartment syndrome, intra-articular injury, and an unstable fracture. Formal surgical treatment should consist of longitudinal skin and fascia incisions to extend the wound and allow exposure, followed by removal of the hematoma and foreign material. Excision of skin should be minimal in most instances and should consist of trimming the irregular edges. Excision of skeletal muscle also should be done for tissue that appears nonviable. The wound should be irrigated to remove debris and bacteria from the tissue surfaces. The surgical extensions can be closed if undue tension is not present, but the wound itself should be left open and covered with a sterile dressing.

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