Chapter 3

THE EVOLUTION OF WOUND BALLISTICS: A BRIEF HISTORY

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INTRODUCTION

Some think that wound ballistics is uncomplicated. After all, what could be simpler than the study of a little hole? Yet, if wound ballistics is straightforward, why, both now and in the past, have there been controversies regarding the wounding done by high-velocity versus low-velocity projectiles, incision versus excision of wounds, primary closure versus delayed primary closure, among many examples? If wound ballistics and its practical application, military surgery, are uncomplicated, why has one of the recurrent themes of military history been the lament that the surgical lessons of past wars—lessons based on an understanding of wound ballistics—have been forgotten by the beginning of the next war, with dire consequences for the first casualties? Fortunately—and in marked contrast to other types of military trauma (biological, nuclear, and chemical), in which actual experience with medical management is limited or even nonexistent—there is a rich store of knowledge dating back almost five centuries that can be used to understand the nature of ballistic injuries and the management of battlefield wounds.

The fact is that the simplicity of wound ballistics is deceptive. One need only look at the history of military surgery with its attendant confusion, disarray, and controversy, to see its true complexity. The nature of wounds changes with the new weapons that are introduced in each succeeding war, and the evolution of wound ballistics is mirrored in the response of military surgeons to the injuries caused by these newer, more destructive weapons. The new weapons—higher-velocity bullets, deforming bullets, fragmenting munitions, and so forth—not only cause new problems for military surgeons, they also provide new insights into the nature of ballistic injuries. These developments in the types of wounds that occur and the medical response to them are tantamount to the experimental variables that scientists introduce in their laboratories. Thus, considerable understanding of wound ballistics is possible by reviewing the history of military surgery. To ignore the past and to base an appreciation of wound ballistics on narrow personal experience risks repeating the mistakes of the past.

In this volume, wound ballistics is treated in three chapters, which are designed as a unit. First, important concepts of wound ballistics are developed in the context of the history of military surgery, and, to a lesser extent, as a result of the successes of experimental and theoretical wound-ballistics research. Second, the basic physics and biophysics of wound ballistics are synthesized with modern experience. And third, the medical aspects of wound ballistics as they apply to managing soft-tissue wounds are considered. The specific aspects of penetrating injuries of the viscera are the subjects of other volumes of this series of textbooks.

WOUND BALLISTICS: THE MANAGEMENT OF PENETRATING INJURIES

Wound ballistics began as an empirical rather than an experimental study. During combat, military physicians have never had a dearth of wounds to observe and treat, and the relationship between certain kinds of munitions and the wounds they caused was often readily apparent, even if not always understood. Until the twentieth century, gunshot wounds to the head or trunk were usually fatal; only since the last decade of the nineteenth century have the wound ballistics of specific organs been investigated. The observations in the historical anecdotes that follow were based primarily on wounds of the extremities.

Penetrating wounds made by projectiles called *shot* that were fired from small arms were first described in the fourteenth century. These wounds contained tissue that was torn or lacerated rather than cut (such as wounds from swords or spears) or crushed (such as the massive mutilating blunt wounds made by cannonballs). They also usually contained a large foreign body (the shot) and were much more likely to become inflamed and to suppurate than other penetrating wounds were.

The prevention and treatment of sepsis have always been dominant issues in wound ballistics. Medieval physicians believed that infection resulted from a poisoned projectile or from the contamination of the wound path with gunpowder, and treated the wound not only by aggressively removing the projectile but also by destroying the tissues surrounding the wound path with boiling oil or a hot cautery. Unfortunately, these treatments traumatized and contaminated what was already a dirty wound, further lowering the casualty's ability to resist infection.

Pioneers Who Advanced the Management of Ballistic Injuries

Ambroise Part!. The poisoned-wound theory was not disproved until the sixteenth century, when the French surgeon Ambroise Par6 found himself improvising a treatment during his first military campaign. He knew that the standard surgical practice involved pouring a scalding mixture of oil and treacle into the wound as the first dressing. As he went on his rounds, Pare ran out of boiling oil and had to resort to a *digestive,* a substance that promoted suppuration and the discharge of *laudable pus.* Physicians at that time encouraged these processes, believing that unhealthy humors or fluids were eliminated from the injured body along with the laudable pus. Pare wrote:

> At last my supply of oil ran out, and I was obliged to use in its place a digestive made of yolk of egg, oil of roses, and turpentine. That night I could not sleep well, thinking that I might find the wounded, who had been deprived of the oil, dead from poisoning through the lack of proper cauterization. It made me get up very early to go to see them. Beyond all my hopes, I found that those who had received the application of the digestive on their wounds were feeling little pain, they were without inflammation or swelling, and they had rested quite well during the night. The others, to whom application of the oil had been made, I found had a fever, with great suffering, and with swelling and inflammation around the wounds. And then I resolved never again so cruelly to burn poor men wounded with gunshot.'

By the early eighteenth century, empirical observations of gunshot wounds began to take on a modern tone:

> [The] opening of entrance was described as dark, torn, and depressed, tending to be associated with ecchymosis; the opening of exit was often wider and less crushed. If the wound involved the soft parts alone and was superficial, the bullet path was split open: if deep, incisions in the long axis of the extremity were made on both sides. When the wound had been laid open, it was scarified [abraded]. . . . If [the bullet] could not be easily drawn out after the tubular crushed wound had been converted by a broad incision into a gaping, crater-like structure, it was left in place. . . . If the bones were splintered, any loose pieces were extracted. [2]

The creation of this "gaping, crater-like structure," which was intended to allow laudable pus to drain out of the wound and therefore aid the natural healing process, was itself, though unintentionally, suppurative. Eighteenth-century surgeons continued to use digestives in local wound treatment, and began to emphasize emetics and other internal treatments as well.

John ***Hunter.*** By this time, the most common small arm on the battlefield was a smooth-bore musket that fired a round lead ball (Figure 3-1). The English surgeon John Hunter (the "founder of modern surgery") was one of the first to recognize that the velocity of the projectile was a determinant of the nature of the wound:

> Gun-shot wounds . . . are in general contused wounds, from which contusion there is most commonly a part of the soluds [*sic*] surrounding the wound deadens. . . which is afterwards thrown off in form of a slough, and which prevents such wounds from healing by the first intention. . . . When the velocity is small, the deadened part of the slough is always less . . . while when the velocity is great, the contrary must happen. . . . Velocity in the ball makes parts less capable of healing, than when it moves with a small velocity. [3]

Hunter, of course, could not measure the velocity of the projectile. What he called "great" velocity was only about 180 meters per second (m/s), lower than the velocity of a modern pistol bullet. (In modern usage, *high* velocity is defined as faster than 700 m/s.)

Finding the projectile and other foreign material that was embedded in wounded tissue was not often easy. Hunter tended to be less willing than most of his contemporaries were to search and further traumatize the tissue:

> It has been hitherto recommended, and universally practiced by almost every surgeon, to open immediately upon being received . . . the external orifice of all gun-shot wounds . . . [because] there was an immediate necessity to search for after [*sic*] those extraneous bodies [such as the ball, clothing, and body parts] . . . [but] the impossibility of finding them. . . . without dilatation gave the first idea of opening the mouths of the wounds. . . . [I]t was oftener impossible to find [the foreign bodies] than

Fig. 3-1. Some bullets of historical importance are, from left to right: musket ball, 69-caliber smooth bore, dating from about 1840; Minie bullet, 55-caliber, dating from about 1555; blunt-nose, 30–40 Krag-Jorgensen, dating from about 1892; spitzer, 1903 Springfield, dating from about 1906.
Source: Division of Armed Forces History, National Museum of American History, Smithsonian Institution, Washington, D.C.

> could at first have been imagined, and when found that it was not possible to extract them.. . . [Y]ou can gain nothing by opening immediately, but will only increase the inflammation.. . [which] may be too much for the patient [3]

If the foreign material were not expelled by the body in its slough, Hunter recommended making a later incision *(a)* if "a ball, or broken bone [were] pressing upon a large artery, nerve or vital part," *(b)* if "an artery [were] wounded," *(c)* "in a wound of the head," or *(d)* "where there are fractured bones in any parts of the body that can be immediately extracted."[3] Hunter also noted that gunshot wounds may contain dead tissue and that they commonly become inflamed. The treatment of such wounds, he urged, should be individualized.

Pierre *Joseph Desault and Dominic Jean Larrey.* The great French military surgeons Pierre Desault and Dominic Larrey made important contributions, both to the management of individual wounds and to the organization of the medical service fur the mass casualties that characterized the wars of the Napoleonic era. Desault and Larrey are historically associated with the surgical procedure known as *débridement* (from the French, meaning "to unbridle"), which they defined as an incision "[to] relieve tissue tension and [to] establish free wound drainage."[4] Debridement had been introduced several centuries before, but because of Desault's and Larrey's great prestige, this process of wound incision became the predominant surgical intervention used to manage penetrating wounds.

It is to Larrey more than to anyone else that we owe the concept that a penetrating missile wound is a *dynamic entity* (that is, the condition of the wound changes over time). For example, when confronted with a badly injured extremity, Larrey believed that it was far better to amputate immediately through uninjured tissue than to wait until suppuration or which mandatory. The need to care for large numbers of casualties as soon as possible after they were wounded dictated that surgeons opt for standard, aggressive wound management rather than take the time to develop individualized treatment plans. Immediately amputating a badly injured extremity would not only allow surgeons to treat more casualties, but would also allow them to treat a wound definitively before the otherwise healthy soldier's condition had deteriorated. This philosophy of active intervention differed from Hunter's conservative approach.

The Nineteenth Century

Conoidal Bullets. By 1850, smooth-bore muskets and their soft lead balls had begun to be displaced in favor of muzzle-loading rifles that fired small-caliber, high-velocity, cylindro-conoidal projectiles known as Minie bullets (Figure **3-1**). Armies also began to use shrapnel-filled explosive shells. As a result, military surgery and the study of wound ballistics began to change dramatically. The wounding effects at longer ranges of the new conoidal bullets were compared with those of lead musket balls:

> [T]he opinion being generally expressed by surgeons [is] that wounds caused by the elongated missile [conoidal bullet] are more severe and dangerous than those resulting from the spherical ball. . . . [I]t opposes less frontage to the resistance of the air and its velocity suffers less retardation. . . . [R]otation upon its long axis tends to give it a steadier flight. . . . [I]ts pointed apex enables it to pierce more easily. . . . [A]dding the factor of velocity, we have a missile deadly in its effects.[5]

At close range, however, quite the opposite effect occurred:

> It is probable that the effects produced by round bullets (musket balls) at very close quarters are equally if not more destructive than those produced by elongated missiles; the initial velocity in the two cases does not vary greatly, and, in short distance, the advantage of form as a destructive element is on the side of the round ball.[5]

The guidelines of wound management that Hunter had established continued to be the standard of care:

> [B]alls and foreign bodies were extracted, bleeding vessels secured, and splinters of bone removed. . . . [I]t was not unusual to enlarge the wound.[6]

Civil War casualties sometimes had the benefit of anesthesia, but no procedures were done under sterile conditions. The surgeon's bare finger was considered to be the "surest and most intelligent probe" for finding foreign bodies. Wound dressings were examined every **2–3** hours for maggots and surgeons continued to worry about "hospital gangrene, traumatic erysipelas, and pyemia."[6]

Artists who visited Civil War hospitals painted pictures of wounds (color photography had not yet been invented), which give us an idea of the actual appearance of the wounds of entrance and exit made by musket balls and conoidal bullets (Figures **3-2** and **3-3**). Surgeons also compared the wounds that the two types of projectiles made:

> [T]he track of a small conoidal ball passing swiftly through a muscle is generally more cleanly cut than

Fig. 3-2. Paintings of wounds made by a spherical ball in a Civil War casualty. Upper: wound of entrance; lower: wound of exit. The wound of entrance is quite large compared to those made by modern bullets. The even larger wound of exit suggests that the bullet deformed during its trajectory through the casualty's soft tissue.
Source: Plate 39, reference 6

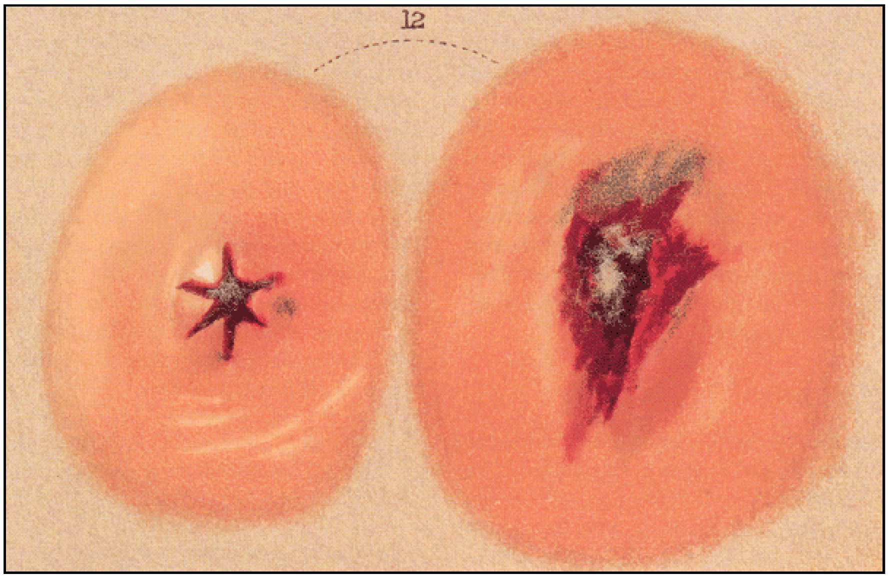


Fig. 3-3. Paintings of wounds made by a conoidal bullet in a Civil War casualty. The source contains the following legend: "Shot flesh wound made by conoidal ball—entrance wound to left, exit to right—typical representation of the effect of a conoidal ball of high velocity." The small wounds of entrance and the large (almost explosive) wounds of exit appear similar to twentieth-century wounds.
Source: Plate 40, reference 6.

> that made by a large or round ball; but in all shot wounds there is usually found an irregular channel with contused and lacerated walls, more or less devitalized by contact with the missile, the area of injury gradually shading off by concentric layers until lost in healthy tissues.[6]

When conoidal bullets were first used, not much was known about the effects that bullet deformation and fragmentation had on tissue. Because both the musket hall and the conoidal bullet sometimes deformed upon impact (Figures 3-4 and 3-51, a distinction between the two in this regard was not immediately obvious. Civil War surgeons observed that whether or not a projectile deformed determined the kind of wound it might cause. This question of bullet deformation was one of the first that the new experimental science of wound ballistics addressed. Writing in the 1890s about the wounds caused by projectiles that had been used during the Civil War, the American military surgeon Louis La Garde noted that "the [round] bullet was capable of causing extensive damage, though less than that observed from conoidal rifle bullets." This was especially apparent in wounds in which bone was hit

> Wounds produced in soft parts were not attended much contusion and laceration as with the use of old spherical balls. The amount of devitalized tissue surrounding the bone wounds, however, resembled the effects of an explosion.'

Conoidal bullet wounds were the first to demonstrate *explosive* effects in tissue. They were described as

> characteristic lesions. . . notably seen in the proximal ranges—from the muzzle up to about 350 yards. . . . [T]he wound of entrance presented no special features. . . . The point of impact against resistant bone showed loss of substance. . . larger spicules of bone were driven into the soft parts.. . . Pulpification of soft parts was noticed at some distance from the tract of the bullet. . . . The wound of exit was irregular, and measured as much as 3 and 4 inches in its longest diameter.[7]

Jacketed Bullets. After the Civil War, weapons designers developed military bullets that were *jacketed* (that is, the lead core was surrounded by a layer of hard metal, such as steel or a copper alloy) in order to increase the muzzle velocity—and thus the range—of small-arms projectiles (Figure 3-1). Surgeons during the Russo-Japanese and the Spanish-American wars had found that the faster, jacketed bullets were frequently not as destructive to human tissues as the slower, softer bullets were. La Garde, writing from his historical perspective in the early 1900s, observed that "Injuries inflicted outside the zone of explosive effects

Fig. 3-4. A deformed spherical ball found in the soft tissue of a casualty's upperarm.
Source: Plate 78, reference 6

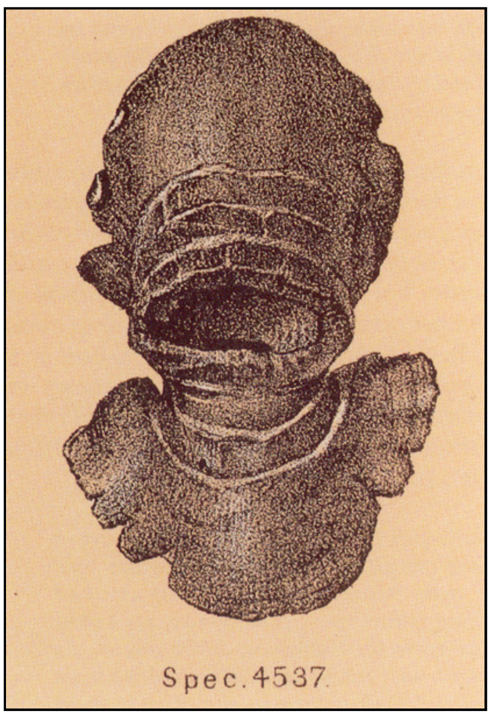


Fig. 3-5. A deformed conoidal bullet found in the soft tissue of a casualty's cheek.
Source: Plate 78, reference 6

upon the shafts of long bones always show less comminution with the small bullet of hard exterior."[7] There were also characteristic differences in the behavior in tissue between the older projectiles and the new jacketed bullets:

> [T]he leaden bullet [round ball or conoidal bullet] was so soft that it often separated into a number of fragments.... [T]he steel-jacketed bullet.. .seldom encounters resistance enough in the human body to disintegrate it. . . .
>
> [T]he small frontage of the jacketed bullets cause them to inflict injuries resembling subcutaneous wounds when the soft parts alone are traversed, and . . . the small wounds of entrance and exit and the narrow tract of the missiles were favorable circumstances to rapid healing.'

Dumdum Bullets. From a military perspective, however, the unexpectedly humane features of the jacketed bullets were less desirable because the wounds to nonvital areas were less severe. In the early 1890s, at their military arsenal in Dum-Dum, near Calcutta, the British experimented with ways to take advantage of the effects of both the old, soft bullets (that is, their tendency to deform or fragment, causing destructive wounds) and the new higher-velocity, jacketed bullets (that is, their greater range). Making ad-hoc modifications in the field, they simply removed about 1mm of the jacket at the tip of the bullet and exposed the soft lead in [illegible] became known as *dumdums*.[8] Responding to the soldiers' need for a more lethal bullet, the British armament industry created hollow-point bullets, which also were known as dumdums (Figure 3-6).

Verbal charges and countercharges, particularly between Germany and Great Britain, alleging that dumdum bullets caused unusually devastating wounds, created a heated political climate among the fifteen governments represented at the Hague Convention of 1899. The Third Declaration of that convention agreed to ban the use of deforming bullets in wars between signatories. Although the ban did not apply to countries that had not signed the declaration, the practical result was that all military bullets were expected to have full metal jackets.

Antisepsis. Civil War surgeons used general anesthesia, but sterile techniques—antisepsis and asepsis—were not introduced until after the war. Joseph Lister's first paper describing the use of carbolic acid to achieve antisepsis appeared in 1867, but his principles were not generally accepted for another 20 years.

In 1881, the Russian surgeon Carl Reyher reported the first well documented use of antisepsis in the management of penetrating trauma sustained on the

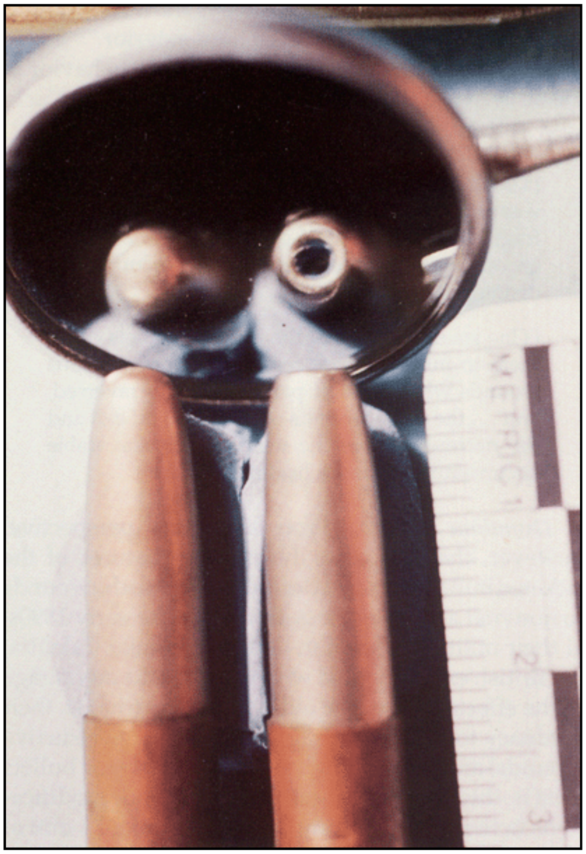


Fig. 3-6. The Mark II bullet, left, which British soldiers modified in the field at Dum-Dum, India, by cutting away about 1 mm of its jacket to expose the tip of the bullet's soft lead core, and the Mark V bullet, right, which was the British armament industry's response to the soldiers' need for a manufactured deforming bullet. Its copper and nickel jacket is folded back at the bullet's nose, exposing a 0.35 x 0.1-in lead-lined cavity.
Source: P. M. Dougherty

battlefield. He found that when antisepsis technique was applied to very fresh wounds, the mortality rate among his patients fell to 50% of that when conventional treatment was applied to day-old wounds. Reyher was said to have also performed wound excision on those casualties whom he treated with antiseptic techniques, so it is not clear what antisepsis alone accomplished to reduce mortality from infection. However, he was one of the first to recognize that battlefield wound sepsis has an iatrogenic component, and he divided casualties into two groups: those whose wounds had been "fingered" and those whose wounds were "unfingered."[9] His observation implies that at least some of the problems of wound sepsis are caused not by bullets but surgeons probing the wounds with their unsterile fingers.

By the end of the nineteenth century, the medical community thought that antiseptic techniques had resolved the problems of wound sepsis. They were rudely awakened at the onset of World War I to find that their approach was ineffective.'"

World War I

Spitzer Bullets. After the turn of the century, weapons designers turned their attention to increasing the effective range of jacketed projectiles by making them more streamlined. They developed bullets that had a *spitzer* (or pointed) shape, which has continued to be the basis for all subsequent bullet designs (Figure **3-1).** This seemingly minor modification also caused the bullet to behave differently in tissue. After examining the wounds made by this new bullet in World War I, a British surgeon compared them to those made by the old blunt-nosed bullets:

> The so-called "normal" bullet wound [made by blunt-nose, cylindrical, jacketed bullets] . . . that was characterized by a tiny aperture which might have been made by a gimlet or a trocar, is in this war quite rare, and even if the entry is of this nature, the exit [of a wound made by a spitzer bullet] is almost always ragged and large. In many of the cases bullets tear the soft tissue to rags, and blow out the muscles and fascia through great rents in the skin. . . . [S]uch injuries as these are always due to the discharge of the rifle at close quarters, and generally within fifty yards. When a large bone is struck, the damage is yet greater."

Although they may not have intended to do more than improve the projectile's aerodynamic properties, weapons designers were now becoming aware of the important relationship between bullet stability and wound severity. For example, the explosive effects of the spitzer bullet occurred because its center of mass was located further back than it would have been in a blunt-nose bullet, which increased its tendency to "turn over within the body."" Surgeons noted that these explosive effects occurred at some distance from the projectile's path through tissue:

> [T]he main injury is done by a force of a divulsive or expanding nature, so that the tissues are torn asunder from within instead of being crushed slowly from without. . . . [T]he injury, instead of being limited to the tissues on either side of the bullet track—as it would be if the wound were not made by a bullet but by a trocar—is diffuse in every direction, and radiates through all the surrounding structures. . . . [I]n the case of the brain enclosed in

> the skull, or the liver enclosed in a strong capsule, explosive effects are typical. . . . [T]hese same effects are produced in every other part of the body and limbs also. . . . [T]he missile has not only shattered the tissue in the line of its flight, but the divulsive force has separated the fascia from the skin, and split the muscles from each other along their intermuscular plane. . . . [T]he effect of the injury may, indeed, spread up and down a great part of the length of the limb, and vessels may be burst and extravasation of blood may be found far from the obvious tract of the missile."

The fragmentation of explosive shells also caused devastating injuries and their treatment, at least at the beginning of the war, was frequently unsatisfactory:

> The wounds caused by high-explosive shell fragments . . . are so infinitely various. . . . [A]ll shell fragments being rough and jagged, they tear away parts of the clothing and carry the latter into the extreme depths of the wound. . . . [L]arge fragments tear away portions of skin and muscle from the limbs or trunk. . . the whole of the calf or thigh may be destroyed . . . tissues are crushed and lacerated . . . vessels are pulped, and extensive areas die. Nothing is more striking than the immense amount of destruction wrought by even quite small pieces of a shell burst. . . for the wound in the tissues may be ten times as large as the missile. . . . [B]ombs and grenades are especially likely to cause multiple wounds. . . . At very close quarters, quite small, sharp-edged strips of metal may penetrate very deeply. . . . These wounds are especially liable to be infected?'

Developing protocols for the optimal management of penetrating missile wounds is a goal of wound-ballistics theory. Conversely, the failure to obtain adequate results in treatment may provide useful insights into the deficiencies of the theory.

During World War I, surgeons found that when they applied not only the current civilian concepts of wound management but also the experiences of prior small wars (which had been fought with different weapons under different conditions), their efforts in the first months of the war met with dismal failure. Foremost among the factors leading to these failures was their lack of understanding that the battlefield milieu was an important determinant of the surgical treatment of penetrating wounds.

Environmental Factors in Wound Contamination. When dirt and other foreign matter entered the wounds that were seen in World War I, serious infections were almost certain to develop. Battlefields are filthy places, but the soil at the western front seemed to be particularly so:

> [M]ud and dirt pervade everything; and bacteriological investigations of the soil, of the clothing, and of the skin demonstrated the presence of the most dangerous pathogenic organisms in all three."

Sepsis, including gas gangrene, was common. Surgeons came to realize that there was a relationship between local environmental conditions and the nature of wound management. One surgeon compared

> the fields of war in South Africa and in France. . . . In the former . . . the soil was almost entirely free from all pyogenic bacteria. . . . At the present seat of war [France] . . . [the soil] is more heavily manured with the excrements of man and animals than almost any other land. . . . [E]very form of micro-organism flourishes. . . [and] spore-bearing pathogenic organisms abound."

Surgical Treatment of Penetrating Wounds. Most wounds seen at the beginning of World War I were massively contaminated, and the majority were clinically infected when they were first seen at a surgical facility. For these casualties, surgical care consisted of opening the wound to allow the free drainage of **pus,** a practice that was combined frequently with irrigating the wound with an antiseptic solution in an effort to sterilize it. As the war progressed and hospitals filled with septic casualties, surgeons became increasingly dissatisfied with this passive approach. Some sought to mechanically sterilize the wound before it became septic:

> [N]o antiseptic lotion can possibly, by its mere application to the soiled tissue, ensure healing without suppuration. In a contused and lacerated wound, such as we get from bombs, high explosive shells, and often from shrapnel, nothing short of complete excision of the soiled and devitalized tissues can be relied on to secure the healing by first intention that should always be regarded as our ideal.[12]

The French termed this excision of damaged or devitalized and contaminated tissue *épluchage,* (that is, "to pare" or "to trim"). This **type** of surgery was quite different from debridement, in which the emphasis was upon opening the wound by incision. During World War I, the term "debridement" gradually came to be interpreted by Americans to include both of these formerly distinct meanings.

The official U.S. Army history of medicine in World War I described the evolution of these wound care concepts:

> Following the disastrous practice in the early months of the war of abstention from surgical intri-

> vention, it was for a time considered sufficient to remove projectiles and superficially clean the wound channel. Experience soon showed the inefficiency of these procedures. This tentative period lasted nearly two years, 1914 and 1915. In 1915 the method of debridement was initiated; in 1916 it was practiced, and in 1917 and 1918 it was elaborated and improved. This practice was dependent upon careful observation of the pathological factors involved in wounds produced by projectiles."

The word "debridement" is used definitively in this history, establishing it in the American medical lexicon.

> debridement of tissue—that is,. . .[the] free incision and excision of injured and contaminated tissue and . . .[the] removal of the foreign material carried by the missile into the wound."

By the end of World War I, American surgeons recognized debridement as the most important single step in the management of penetrating injuries:

> Physical disinfection consists of ablation of necrotic tissue and removal of foreign bodies. This method, known as debridement, constitutes the greatest advance from a surgical standpoint in the recent war.[13]

Regardless of the nature of the initial surgery, the surgeon's goal was to obtain healing of an open wound. With the gaping, infected wounds that most casualties had, wound closure involved *(a)* the formation of granulation tissue, *(b)* fibrosis, *(c)* contracture, and *(d)* epithelization. This process usually took many months and resulted in a nonpliable and grossly deformed wound. Spontaneous closure of this sort, known as healing by *secondary intent,* prolonged the period that a wounded soldier was unavailable for duty, and therefore was not appropriate in a war of attrition.

Many surgeons attempted to accelerate the healing process after several weeks by closing the wound with sutures. This procedure was known as *secondary closure.* Unfortunately, wound to pcrsistent sepsis, while uncommon, was an occasional complication.

A few surgeons employed wound excision and immediate closure as an alternative method. If a wound could be mechanically sterilized before sepsis developed, then perhaps it could be safely closed immediately. This procedure, called *primary closure,* was successfully employed by only a few surgeons in World War I, who obtained healing in more than 90% of their patients.[13] Successful primary closure depended upon satisfying the following strict criteria: *(a)* the wound was less than **12** hours old, *(b)* the wound could be completely excised, *(c)* the casualty could be kept at complete bed rest, and *(d)* the casualty could be observed until healing was complete. When surgeons attempted primary closure without satisfying these criteria, the procedure failed in two-thirds or more of the casualties, and severe wound sepsis frequently developed.

The success of primary closure depended upon adequate wound excision. During the initial surgery, the surgeon had to be sure that most (if not all) of the contaminated and injured tissue around the wound tract was cxciscd. **A** tcchniquc that dcvclopcd late in World War I involved leaving the wound open after the initial surgery and then reinspecting it within 4–6 days, which was enough time for sepsis to appear but not enough time for the wound to become indurated with granulation tissue. If there was no evidence of sepsis, the wound was closed with sutures. This approach, called *delayed primary closure,* was widely utilized by the end of World War I, and remains the standard method by which the military surgeon closes penetrating soft-tissue injuries.[13]

While penetrating injuries to the gut, the chest, and the brain tend to be far more serious than injuries to the soft tissues (skin, fat, and muscle), the wounds that caused the greatest mortality and morbidity—before antibiotic drugs were available—were *open comminuted fractures of the extremities* (that is, open wounds that involve both splintered bone and bony penetration of the soft tissues). In World War I, the standard treatment for these ballistic wounds was to splint the limb and irrigate the open wound with antiseptic solutions. This treatment resulted in a high incidence of osteomyelitis and nonunion of the fractured bone. The military medical system needed simpler. more effective procedures to care for mass casualties with open comminuted fractures. During the Spanish Civil War in the 1930s, the surgeon Raspall José Trueta developed a closed-plaster technique for treating these casualties:

(a) thoroughly wash the wound,
(b) incise and excise the devitalized **tiseue,**
(c) allow the wound to close by secondary intention rather than by suturing it,
(d) establish dependent (downward) drainage of the wound, and
(e) immobilize the limb by plaster cast until the soft-tissue wound and the bone heal.[14]

With the exception of step *(c),* which some might (in retrospect) consider retrogressive, Trueta's regimen was used successfully to treat thousands of open comminuted fractures in the early years of World War II.

Trueta himself, who performed more than 1,000 of these procedures, believed that step *(b)* was the most important:

> The excision of all devitalized tissue is the basic factor in the treatment of war wounds. The patient's progress, good or bad, bears a direct relation to the skill and thoroughness of this excision. . . . [T]he chief cause of the many surgical disasters of the War of 1914–1918... was that the technique of excision was not properly understood.[15]

World War II

Surgical Wound Management. Soft-tissue wound management as practiced by the British in the first years of World War II strongly depended upon their World War I experience. The British maintained the semantic distinction between epluchage (which they called primary *wound* excision if it was performed soon after wounding) and debridement:

> Debridement is the very antithesis of primary wound excision. Wound excision is a meticulous process, often time-consuming, and only to be carried out soon after wounding. Debridement simply implies enlargement of the wound in order to effect free drainage combined with rapid removal of foreign bodies and obviously dead tissue. The latter is the only local treatment permissible when more than eighteen hours have elapsed since the infliction of the wound.[16]

Nevertheless, the British still performed thorough surgical excision

> if the muscle in any part of the wall of the wound shows evidence of altered color or consistence, fails to bleed when it is cut, or does not contract when it is pinched with the forceps.[16]

These criteria, which date back to at least World War I, have become known as the four Cs:

- Color—the tissue is darkish
- Consistency—the tissue is mushy
- Contractility—the tissue fails to contract
- *Circulation*—the tissue fails to bleed'?

The dynamic nature of the wound—as Larrey had noted over a century earlier—was a crucial consideration to **these** British surgeons:

> Primary excision is the treatment of election for recent wounds, but unless the surgeon is quite sure that the wound is recent (signs of inflammation have not [yet] developed) he should not even contemplate carrying out this procedure.[17]

The likelihood that initial wound surgery will be performed to drain an infected wound, rather than to prevent infection from occurring, increases with the time that elapses between wounding and surgery. The British emphasis on the management of infected wounds was understandable given their disastrous Dunkirk retreat, with its prolonged and difficult evacuation of casualties. Just as the battlefield milieu influences the nature of wound care, so also do the combat conditions and the tactical posture (for **ex**ample, slow evacuation during **a** retreat versus more rapid evacuation during victorious advances).

The techniques that had been developed during World War I and **the** Spanish Civil War to obtain soft-tissue wound closure (that is, secondary closure and especially delayed primary closure) might have been expected to have been applied immediately in World War II. The need for wound closure was especially great with open comminuted fractures. The major drawback of Trueta's five-step regimen was that the required immobilization of casualties with these injuries frequently was not possible. The plaster casts usually disintegrated and the soft tissue commonly failed to heal. The alternative approach—skeletal traction in the presence of an open wound—was impracticable during evacuation and undesirable in a combat-zone hospital. The World War I wound closure techniques appear to have been downplayed by American military medical authorities during the initial stages of World War II. In fact, Edward Churchill, the surgical consultant to the North African theater, found shortly after his arrival there early in 1943 that

> steps were underway to FORBID this procedure [secondary closure and, by implication, delayed primary closure] from being undertaken.[18]

Wounds were expected to heal by secondary intention. The origin of this attitude is unclear, but within a few months both secondary and delayed primary closures were widely performed.'*

The theoretical basis for wound closure changed significantly between the two world wars. In World **War** I, **the** wound was **not** considered to be **ready** for closure until bacteriological studies showed that contamination had been reduced below an arbitrary minimum. In World War II, the wound was closed if it appeared clinically clean. In essence, the policy in World War I was to sterilize the wound so that it could be closed; in World War 11, the wound was closed so that it would not become infected.[18]

Antibiotics. World War II saw the introduction of antimicrobial drugs—the sulfonamides and penicillin. Medical personnel hoped that these miracle drugs would bring about revolutionary changes in wound management.

Sulfa drugs were used extensively in the treatment of casualties at Pearl Harbor. Doctrine soon mandated that sulfa be applied to all wounds. Initial reports suggested that infection could be prevented by simply applying sulfa topically to the wound, but by 1943the wisdom of this intervention was being questioned:

> The extensive application of sulfa to wounds was certainly one aspect of wound management that contributed to infection and suppuration.'*

In retrospect, it is clear that sulfa is not a good antibiotic; it **is** merely *bacteriostatic* (that is, it arrests or retards the growth of bacteria) and does not sterilize the wound. Opening the wound to apply the sulfa topically could have contaminated it further, and packing sulfa powder into a contaminated wound could have aided, not prevented, suppuration.

The introduction of penicillin in 1943raised hopes that the extent of wound excision could now be decreased. However, controlled studies are nearly impossible to conduct on the battlefield. Clinical trials with what are now recognized as inadequate doses of penicillin (15,000–150,000 units daily) demonstrated inconclusive benefits, except in those instances when penicillin was used successfully *(a)* as an adjunct in secondary closure by suture, and *(b)* prophylactically, and was shown to prevent gas gangrene in severe wounds.[19] The official doctrine about 1944concerning soft-tissue wound care stated:

> Chemotherapy has been recommended: (1) as a substitute for adequate wound surgery, seeking to delay and minimize operative procedures; (2) as an adjunct to established and progressive surgical measures designed to achieve better results with an increased margin of safety. The latter has been and will continue to be the policy governing the management of the wounded in this theater.. . . The use of penicillin as an adjunct to surgery outlined in this circular is defined as therapy rather than prophylaxis. . . .[P]enicillin does not sterilize dead, devitalized or avascular tissue, nor does it prevent the septic decomposition of contaminated blood clots. . . . These limitations demand that surgical wound management retain the principles of excision of devitalized tissue, dependent drainage of residual dead space, evacuation of pus and delayed or staged closure of contaminated wounds.[19]

As the war proceeded, the need to excise tissue was emphasized repeatedly, and was illustrated in the slogans "When in doubt cut it out" and "If a little bit is good, a lot will be a lot better." And therein lay the problem that faced the battlefield surgeons: the potential that too much tissue would be removed. Since surgeons were not able to follow their patients and to know the results of their surgical procedures (because most casualties are evacuated to the next echelon of care as soon as they are able to be moved) most surgeons probably tended to err, in retrospect, on the side of excessive excision. By the end of World War II, excessive surgery was condemned:

> The unnecessary method of excision en *bloc* ([that is, the] aseptic excision of the tract from outside without cutting into it) was again repeatedly described during the period 1939–1945. Excision of living tissue caused needless mutilation.]'

By 1944, some categories of gunshot wounds were thought not to require any surgery. For example, the incision and excision of *en seton* bullet wounds of the extremities (that is, perforating wounds not involving neurovascular structures or bone, and with little external evidence of tissue damage) were considered to be "cardinal sins of war surgery."[21]

There is general agreement that soft-tissue and orthopedic wound management in World War II was better than it had been in World War I. The mortality rate for soft-tissue wounds of the lower extremities in World War II was 0%–0.3% for the Fifth U.S. Army in Italy, much lower than the overall rate of 6.1% for mortality from soft-tissue wounds during World War I.[22] Prevention of wound sepsis was probably an important factor in making this advance possible:

> [U]p to that time [June 19441 at least 25,000 soft-tissue wounds [had] been closed by delayed primary closure.. . . In at least 95%. . healing occurred with no loss of life or limb and without serious complications. The most usual explanation in the 5% [who had] unsuccessful closure was failure to remove dead tissue[20]

The German Army during World War II, however, continued to rely on older methods and did not have such successful results:

> [T]he Germans assumed . . . that all penetrating wounds received in combat would become infected and that pus was anticipated. . . . [Wound] surgery consisted of no more than incision of skin and fascial planes, the removal of gross debris and devitalized tissue, and usually trimming of devitalized edges of the skin wound. The careful wound excision practiced by Allied surgeons was done in German hospitals only in rare instances.[23]

It is not clear whether the better treatment results that Allied surgeons obtained in World War II were due to *(a)* more complete mechanical cleansing of the wound at the time of initial surgery, *(b)* the use of penicillin and sulfa drugs, *(c)* the conditions of the battlefield (that is, less mud and dirt), *(d)* more rapid evacuation from the fewer casualties would have had gross wound sepsis when they were first seen by physicians), *(e)* the less severe nature of the wounds, *(f)* the overall health of the troops (as the World War II history suggests), *(g)* the fact that, unlike World War I, World War II was not "fought during a pandemic of hemolytic streptococcus"[18] or, *(h)* some combination of these factors. These variables interact in a manner that makes analysis difficult, and wound-ballistics experimentation is needed to separate and analyze them.

The first efforts to collect data on wounds in a systematic fashion were made in World War II. The U.S. Army's leading wound-ballistics expert, Brigadier General George Callender, deplored the "startling lack of information" concerning the actual nature of combat wounds in a paper that provided much of the impetus for this data-collection effort.[24] The classic "Study on Wound Ballistics—Bougainville Campaign," a chapter in the standard text *Wound Ballistics,* was a result of Callender's concerns. The Wound Data and Munitions Effectiveness Team (WDMET) continued this effort during the Vietnam War.

Post–World War II

Our understanding of the nature and treatment of ballistic injuries has been extended only marginally since World War II. The surgical doctrine that was followed in the Vietnam and Middle-East conflicts has emphasized thorough wound excision combined with delayed primary closure. The preamble of the instructional document prepared for U.S. Army surgeons in Vietnam clearly states that

> [d]ebridement is the surgical technique of excising devitalized tissue. The experience of several wars has demonstrated that proper debridement is the key to surgical treatment of soft-tissue wounds and provides the best means of reducing morbidity and mortality.[25]

Some think that this approach has resulted in excessive excision of tissue, but its success can be seen in the very low incidence of soft-tissue wound sepsis during that war. Among American forces in Vietnam, the early infection rate of extremity wounds (that is, those infections that developed within the first week after wounding) was only 4%–5%.[26] During the Yom Kippur War, the total soft-tissue wound-infection rate among Israeli casualties was only 6%.[27]

The role of antimicrobial drugs as adjuncts to the surgical management of soft-tissue ballistic injuries sustained on the battlefield has not been clarified significantly. Most casualties in Vietnam who had penetrating trauma received penicillin or tetracycline, so the effect of surgery alone could therefore not be determined. An Israeli study of casualties wounded in the Yom Kippur War found that, while all casualties had received prophylactic antibiotics, the antibiotic used was effective against the offending pathogen in only one-third of the 6% who developed wound infections. Since penicillin was the most commonly used prophylactic antibiotic, Gram-negative organisms, not unexpectedly, were commonly encountered in infected wounds. The researchers concluded that

> the practice of antibiotic wound prophylaxis may contribute to the incidence and nature of infection in battlefield wounds. . . . The temptation to "sterilize" the wound with massive doses of antibiotics . . . favors a false security with less reliance on good surgical technique.[28]

Weapons development since World War II has been characterized by two design trends: firearms that shoot small-caliber, high-velocity bullets, and explosive munitions that produce large numbers of small, fast-moving fragments. Both developments are predicated on *(a)* the assumption that wound severity is determined by kinetic energy, which some believe is an oversimplification, and *(b)* the fact that greater kinetic energy can be more readily obtained by using high-velocity, small-size projectiles rather than massive, low-velocity projectiles. Wound management has been influenced by the corollary assumptions, which also may be oversimplified, that *(a)* kinetic energy kills tissue, and *(b)* all dead tissue must be removed in the optimal treatment of penetrating wounds.

The wounds produced by bullets fired by the M16 assault rifle in the Vietnam War are frequently used to illustrate the relationship between kinetic energy and wound severity. This cause-and-effect relationship is flawed, however: The kinetic energy of the bullet fired by the M16 rifle (that is, 1,650 joules) is nearly identical to that of the conoidal bullet fired by the muzzle-loading rifle of the 1850s (that is, 1,665 joules), and has lower kinetic energy than any bullet fired by a military rifle fielded since then. The wounding potential of the bullet fired by the M16 rifle depends upon its fragmentation in tissue and not on its kinetic energy and velocity. This information appears in the WDMET data that were published but not publicized during the 1960s: "In almost all cases in the series involving 5.56 x 45 mm bullets, the projectile fragmented after striking the body."[29] In a very real sense, M16 ammunition is the contemporary equivalent of a nineteenth-century dumdum.

WOUND BALLISTICS: THE THEORETICAL AND EXPERIMENTAL SCIENCE

The problems encountered by battlefield surgeons in their treatment of ballistic wounds have always driven the scientific advances made in wound ballistics laboratories. The Swiss surgeon Emile Theodor Kocher (who is regarded as the founder of wound ballistics as an experimental science), the German pathologist Paul L. Frederich, the American physician Charles Woodruff, and the American military surgeon Louis La Garde were among the first researchers to investigate systematically the individual projectile variables that determine the nature of ballistic wounds, as well as the special treatment problems these wounds present. Contemporary wound ballistics has become a rigorous and specialized field; it studies an array of projectile effects on tissue, and uses the most sophisticated scientific technologies to support its findings.

Early Rcscarch

Emile Theodor Kocher. Although no doubt others had observed the effects of military projectiles in tests involving animate and inanimate objects, Theodor Kocher appears to be the first who systematically investigated the individual variables that are the determinants of wounding. Kocher is well known in the history of medicine for his contributions to orthopedics and surgery: He was the first surgeon to win the Nobel Prize in medicine (in 1909, for his work on the thyroid gland). He is less well known for his accomplishments in experimental wound ballistics, which were performed during 1874–1879 in Thun, Switzerland[30, 31] Much of our understanding of Kocher's contributions to wound ballistics comes from the research of Dr. Paul J. Dougherty.[32]

Though Kocher, who was a member of the Swiss militia, never saw a war wound until he was invited to tour a German military hospital early in World War I, he knew about the "explosive" injuries that conoidal bullets made. He sought both to *(a)* systematically determine the mechanisms that caused ballistic wounds and *(b)* provide a rational treatment for explosive gunshot wounds. An explanation then current was that a bullet's rotation—imparted by a rifle barrel's grooves—caused centrifugal forces that ripped apart the tissue. Kocher disproved this, showing that the wounding effect was no different from that of a conoidal bullet fired from a smooth-bore barrel. Kocher also obtained the equivalent of the explosive wounds that he had previously observed in cadaver skulls—small wounds of entrance, enormous wounds of exit, and separated cranial sutures—by shooting into water-filled metal cans. The cans had small entry holes, very large exit holes, and the inelastic seams of the cans were ruptured.[33] He fired equivalent shots into empty metal cans and demonstrated the resulting small entry and slightly larger exit holes and intact seams. This indicated to Kocher that hydraulic or hydrodynamic factors, which subsequently came to be known as *cavitation,* were responsible for the explosive effects in tissue. He noted that muscle seemed to act like a fluid; it stretched, transmitting the energy of a bullet rather than rupturing, as did inelastic tissues such as bone.[32] In soft-tissue injuries where a bone was not struck, however,

> a different effect was observed. In the shots to the extremities small entry and exit holes were observed if a bone was not struck. The exit holes tended to have split skin, which was along the axis of least resistance, along fascial planes. Skeletal muscle showed this same effect when it was dissected out.[33]

Kocher emphasized the importance of projectile deformation as a major determinant of wounding potential, and was able to separate the variables of velocity and deformation. In his experimental design, he variables of linear arid ity, bullet composition, and target media. He changed only one variable at a time, and noted its effect on both the target and the projectile. He reported only what he observed and did not speculate about his observations.[32] In his 1879 studies he *(a)* compared bullets of varying degrees of hardness; *(b)* obtained (from the arsenal at Thun) early chronograph-measurements of muzzle velocities; *(c)* introduced the technique of "reduced-power loading," which is still used in ballistics laboratories today to simulate varying target distances by reducing bullet velocity in measured steps; and *(d)* caught his projectiles in water-filled tanks and compared their deformation and fragmentation.[34]

Kocher was the first researcher to study the effects that varying a projectile's velocity had on a target. He demonstrated that the destructive effects seen in water-filled cans seemed to depend upon the projectile's velocity. He predicted that less severe wounds would be made with solid, nondeforming bullets (made of metal harder than lead), regardless of their velocities.

Kocher was also the first to suggest that, in order to reduce their wounding potential, the core of military bullets should be made of metal so hard that they would not deform in tissue. In 1875, he wrote that "the goal of weapons designers should be to design a firearm that would incapacitate rather than cause inhumane destruction."[33] In a speech delivered at the Eleventh International Medical Congress in Rome, Kocher recommended that "from the standpoint of humanity,"[35] a projectile should have *(a)* a 5–6-mm diameter, *(b)* a hard steel point to prevent deformation, and *(c)* a tapered point to moderate the damage as the bullet passed through tissue.

Another of Kocher's contributions to wound ballistics was his modification of the gelatin tissue simulant, which was used in lieu of living animal tissue. He devised a gelatin and concrete "sandwich"—a 3-cm concrete block covered on both sides with 3-cm gelatin plates—that he thought was analogous to soft tissue and bone. After he fired into it, he found a small entry hole through the first layer of gelatin, a large (10–15-cm diameter) defect through the concrete, and an exit hole through the gelatin that was somewhat larger than the entry, with pulverized concrete throughout the exit canal. He described these experimental findings as being similar to a compound fracture.[34]

Political Influences on Science. The flurry of ballistic experiments that occurred in the last quarter of the nineteenth century were stimulated by the controversy over deforming bullets, such as the British dumdums, that had just been developed. Some of these early experiments were marred by extremely emotional political considerations. Hostilities between Germany and Great Britain were intensifying, and the Germans conducted experiments to show that deforming bullets fired into long-dead cadavers caused especially massive wounds, and should therefore be banned. However, the bullets that the Germans used in these experiments had higher velocities and much more lead core exposed at the tip than the dumdum bullets did. British and American investigators countered by citing anecdotes to show that the then-new jacketed bullets caused just as much damage as the did.[8] Because both sides used evidence to support their desired conclusions, science was lost to political controversy, and important methodological standards—such as comparing bullets of like velocities and designs and using similar tissue simulants in comparable experiments—were ignored.

Paul L. Frederich. One study of permanent worth was conducted during this period, however: The German pathologist Paul L. Frederich investigated the temporal relationship between wound contamination and invasive sepsis. This study provided the scientific basis for the concept that a penetrating wound is a dynamic entity, which Larrey had introduced 70 years before. (Frederich did not refer to Larrey's concept in his paper; it is possible, due to the political enmity between France and Germany, that Frederich was unaware of Larrey's work.) In his landmark study, Frederich contaminated an experimental wound in a rat triceps with soil, and sutured the wound closed. He then periodically examined biopsies removed from more proximally situated muscle for microorganisms. None were apparent before 6 hours had elapsed. He concluded that surgical manipulation of the contaminated area might be curative for up to (but not later than) 6 hours after wounding. Frederich demonstrated that excision of 1–2 mm of the contaminated wound lining within 6 hours prevented invasive sepsis and death (Figure 3-7). In his historic paper, which has been translated and interpreted extensively (but not always accurately) since its publication, Frederich concluded:

> [I]n each so-called "spontaneous infected" wound, the infection process is very nearly a localized one. It is important for arriving at a therapeutic and diagnostic judgement to keep in mind that in the great majority of instances this process will remain so until at least the sixth hour after wounding, and often longer. This span of time represents, to a certain extent, the germination time of the infection (the infection's latency period and incubation time).
>
> The most reliable means of attaining an infection-free healing process through medical treatment is to apply at this time [during the first *6* hours] a precise freshening [in the original, *anfrischung*] in addition to a complete distension or opening up of the wound area.
>
> Where the circumstances forbid or do not indicate this treatment method (due to time, wound size, [or the] lack of assistance, skillful anesthesia, or aseptic instruments and equipment), a more-or-less open management is the best prevention of a serious infection.
>
> The use of antiseptics is only sensible if the wounded area is by-and-large accessible to them, if they are used within the indicated germination period, or if the infection is produced as a result of bacteriological agents and not chemical substances. In the case of progressive or generalized infections, antiseptics are futile and often detrimental. The sum total of their effect is little more than to prevent the use of open management.[36]

Frederichs most important conclusions are that *(a)* wound contamination is not synonymous with wound infection and *(b)* if the contaminants can be removed during their latency period, infection will not occur. This latency period, approximately 6 hours, was subsequently called by others, but not by Frederich himself, the *golden* period. Although the word he used to describe his infection-prevention process was *freshening,* Figure 3-7 shows quite clearly that he actually practiced wound excision. By World War I, Frederich's concept of freshening had been exaggerated: His experiments were commonly thought to demonstrate that one approach to managing a contaminated war wound was to completely excise it during the golden period "as though it were a neoplasm." This is the origin of the concept of Frederich's *tofaler Wundexzision,*[37] that **is,** Frederichs complete wound excision (and the equivalent expression in French and English, *wound excision en bloc).*

Frederich's own conclusions were sound and reasonable. Complete wound excision, however, is rarely, if ever, either a practical possibility or sound medical practice in treating combat casualties. Fortunately, a lesser degree of excision may accomplish the same result. Even more importantly, he also recognized that if excision were not possible, simply leaving the wound open was therapeutically sound.

Charles Woodruff. Two seminal communications that appeared in English in 1894 and 1898 advanced the understanding of explosive wounds and supported the observations that Kocher had made in the 1870s. Victor Horsley published evidence that hydrodynamic effects are the origin of explosive wounds of the skull.[38] Charles Woodruff was the first to suggest that it is the transfer of kinetic energy from the projectile to the tissue—and not the projectile's amount of energy (or velocity) on impact—that determines the nature of the ballistic injury. He studied the wounding ability of fully jacketed bullets, and inferred the behavior of the older, larger lead balls:

> The energy or ability to do work is proportional to the mass and the square of the velocity [MV^2]; hence the new bullet, though smaller, has much greater energy than the old, and can do more **work,** though it rarely gives up all its energy, because it passes entirely through the body.... The slow, large bullet ... has less energy than the new... [and] is so large [that] it can not plow its way through the tissues like a small bullet.... [I]t is therefore stopped, gives **up** all its energy, and delivers a far greater blow than the new bullet.[39]

Woodruff noted that bullets that transfer more of their kinetic energy are more likely to cause explosive effects, as though the bullet itself had exploded within the tissue. He suggested that the interaction of bullet **and** tissue can be understood

> almost exclusively by the capability or incapability of the tissues to take up and transmit vibration or wave motions, [and explained that] tissue may be set into such violent vibrations that, like a pane of glass, it may be strained beyond its limit of elasticity, and may fly to pieces.... The particles of tissue moving away from the bullet track., even after the bullet has passed, must then form a vacuum or cavity. This cavitation is the basis of the explosive effects. . . . The enormous extent of the cavity or vacuum thus formed depends solely upon the velocity of the particles [of tissue] moving outwards from the track of the bullet. **As** soon as the particles are brought to rest [that is, as soon as the cavity reaches its maximum expansion] they are acted upon by the forces driving them back, for they now surround a vacuum. They rush back again to the trark of the bullet, and come together with great force.... They [the particles of tissue] thus vibrate back and forth until their energy is dissipated."

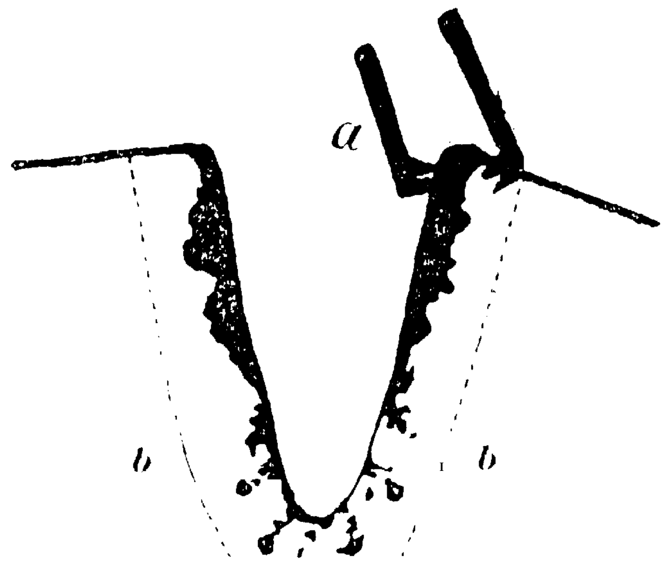
Woodruff compared a fast-moving projectile's passage through tissue with the cavity that would be seen in water around the rapidly rotating propeller of a ship.[39] He suggested that this phenomenon, cavitation, is possible only in an incompressible (that is, liquid) medium. It is the hydrodynamic effect (that is, the moving fluid)—rather than the hydrostatic pressure (that is, the pressure wave moving through a fluid at rest)—that causes the tissue damage.

Another of Woodruff's insights was that the collapse of the cavity itself causes damage. Contemporary Swedish ballistics experts suggest that this phenomenon (implosion contrasted to explosion) is a major source of the tissue damage associated with cavitation.

Louis A. La Garde. Louis A. La Garde dominated American wound ballistics in the two decades before World War I. He wrote *Gunshot Injuries* (Figure 3-8), a comprehensive survey of clinical, experimental, and theoretical wound ballistics that remained the best-known treatise in English on that subject until Beyer's *Wound Ballistics* was published in 1962. One of his experimental contributions was to challenge the notion that bullets (and, by implication, fragments from cxplosivc munitions) wcrc sterilized by being shot out of a gun barrel. La Garde disproved this belief by shooting bullets that had been contaminated with anthrax bacilli into animals, who later developed the disease.[40]

La Garde's research using animals, cadavers, and tissue simulants allowed accurate predictions to be made regarding the nature of the wounds made by both the round-nose jacketed bullet (the Spanish-American War) and the pointed jacketed bullet (World War I).[41] It **is** doubtful that any of La Garde's experi-

Fig. 2.
(Grobes Wundschema).



a = „inficirter" Pincettenarm, b = idealer Anfrischungsschnitt.

Fig.3-7. This is a reproduction of Figure 2 in Frederichs paper. The original caption, translated from German, reads: "Drawing of **a** Wound a = 'nonsterile' forceps; *b* = idealized wound-freshening." His drawing clearly shows that the procedure Frederich called "freshening" is equivalent to the procedure we call "excision" today.
Source: Reference 36

mental findings were used by military surgeons in those wars, however, and there has been little interaction between weapons designers and medical officers since that time.

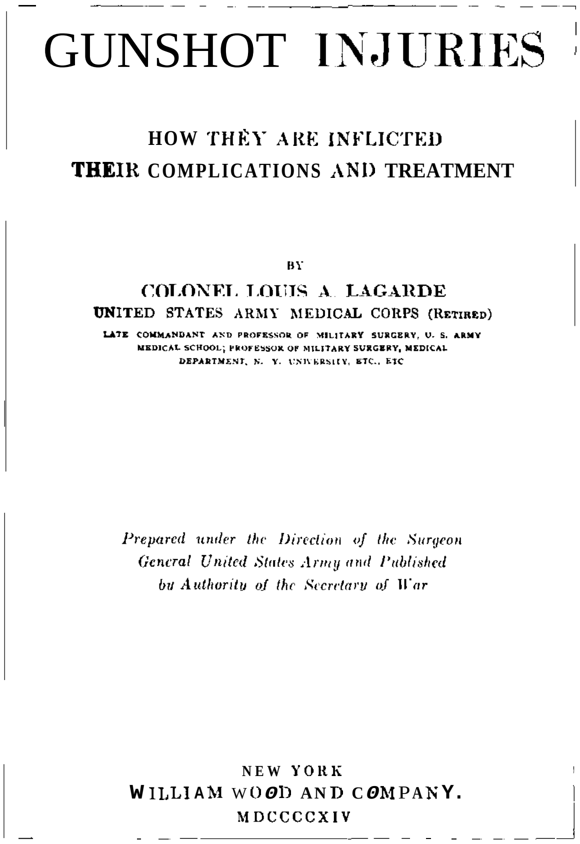
Modem Research

Louis Wilson. Ballistics researchers were ready for the vast amounts of wound data that became available as a result of World War I. **to** describe the injuries they saw in terms of physics as well as simply those of pathology. An American medical officer, Louis Wilson, proposed that a ballistic wound could best be understood in terms of energy transfer. He wrote:

> The wounding effect of a bullet depends upon *(a)* the amount of energy it transmits to the tissues, *(b)* the velocity of the transmission, *(c)* the direction of the transmitted energy, and *(d)* the density of the tissues. The first three of these factors depend almost entirely on the energy, velocity and shape of the bullet. . . . The proportion of the energy transmitted [of the total available on impactl depends on the [cross-lsectional area of the bullet, the shape of its head, the character of its surface.and the relative densities of the tissues struck.[42]

Whether Wilson actually had the experimental data to justify these conclusions is unknown, but his ideas led to the development of the lightweight high-velocity projectiles that are common today.

George Callender and Ralph French. In the 1930s, the U.S. Army began conducting wound-ballistics research at Aberdeen Proving Ground in Maryland. George Callender and Ralph French built upon Wilson's energy-transfer hypothesis, measuring both impact and exit velocities of projectiles and, thus, calculating an amount of energy transfer that they could qualitatively correlate with aspects of tissue destruction.[41]



GUNSHOT INJURIES

HOW THEY ARE INFLICTED
THEIR COMPLICATIONS AND TREATMENT

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Prepared under the Direction of the Surgeon General United States Army and Published by Authority of the Secretary of War

NEW YORK
WILLIAM WOOD AND COMPANY.
MDCCCCXIV

Fig. 3-8. The title page of the second edition of Colonel Louis A. La Garde's famous book. Note that he was commandant of the U.S. Army Medical School.
Source: Reference 7

The aspect of projectile-target interaction that is probably of greatest interest in contemporary wound ballistics—cavitation, the putative source of the mysterious explosive effect that was first described in the nineteenth century—was not even mentioned by Callender and French in their early writings. This might have been because neither they nor anyone else had yet visualized the cavity that Woodruff (and others) hypothesized followed a high-velocity missile as it passed through tissue. In fact, it was not until 1941 that a group of English investigators led by Solly Zuckerman conclusively demonstrated the phenomenon, using sophisticated photographic techniques for that era. That paper begins:

> The fact that the amount of tissue destruction caused by small high-velocity bomb splinters may be out of all proportion to their size has been recognized for some time.[43]

After reproducing photographs showing large cavities in gelatin blocks that occurred "with explosive violence" several hundred microseconds after a rapidly moving missile (700–1,000 m/s) passed through, the paper concludes:

> As the missile passes through the block it imparts motion to the particles in its track, and these fly off radially, imparting their momentum in turn to further particles (and so on)."

The term by which this phenomenon is now known, *temporary cavitation*, was not used by these researchers.

E. Newton Harvey. Like other research efforts in World War II (such as those that led to the development of radar and the atomic bomb), certain wound-ballistics studies that had been started in wartime England were continued in the United States. The National Research Council held a conference on wound ballistics in late 1943, which resulted in support for several ballistics-research contracts. One of these studies, conducted by E. Newton Harvey, is still an important source of information on the physical aspects of projectile-target interaction; Harvey's group wanted "to predict exactly what damage may be expected from the impact of a known mass moving with any known velocity."[44] To do *so*, they would need to *(a)* relate injury to the physical characteristics of the projectile, and *(b)* study the nature of the damage to tissue. Some of their conclusions were:

- A sonic shock wave precedes the passage of a projectile, and (depending on the physical characteristic of the tissue) may or may not cause injury.
- A wound consists of a permanent cavity (the hollow path left by the projectile as it cuts through the target), as well as the surrounding tissue that was stretched by a temporary cavity. And, most importantly,
- The size of the temporary cavity is determined by energy transfer (that is, if other factors are the same, the higher the projectile's velocity, the larger the temporary cavity will be).

Not all contemporary ballisticians view Harvey's work as the scientific foundation of modern wound ballistics. Some believe that his interpretation of the damage done by temporary cavitation is exaggerated.[45]

Harvey's group published some of the first studies of animal survival following soft-tissue gunshot wounding; they noted "the absence of dead tissue in the wound" and that many of the wounds healed naturally without any care being given. Ironically, they wanted to understand the nature of wounding not so much to improve the care of the wounded, but rather to

> predict the degree of incapacitation [that] may result from a hit by a missile . . . [*so*] as to test the casualty-producing effectiveness of [American] weapons."

Much of the wound-ballistics research since World War II at Aberdeen Proving Ground and the nearby Edgewood Arsenal has had the improvement of weapons effectiveness as its goal.

An important post–World War II study done at Edgewood investigated why penetrating wounds sustained on the battlefield were *(a)* likely to be contaminated, and *(b)* at risk to become septic.[46] Dziemian and Herget showed (with gelatin tissue-simulants) that temporary cavitation was frequently associated with the aspiration of foreign material into the wound tract. This was especially likely to happen if the cavity (with its subatmospheric pressure) was connected to the outside through the wounds of entrance or exit. These researchers concluded that, because *(a)* high-velocity projectiles capable of causing large temporary cavities are common on a battlefield, and *(b)* the battlefield environment has a ready source of material capable of being aspirated into the cavities and contaminating those wounds, then *(c)* the likelihood of increased sepsis in war wounds is understandable.

D. ***Lindsey and J. A. Mendelson.*** Many of the researchers at the Aberdeen-Edgewood complex used animal experimentation and mathematical models to predict the wounding effects of various projectiles. During the decade before the Vietnam War, D. Lindsey and J. A. Mendelson attempted to determine the natural history of untreated penetrating missile wounds. Building upon the work that Harvey began, they investigated how the natural course of healing might be altered by various therapeutic interventions such as using antibiotics and debridement. These studies concluded that

- undebrided missile wounds of nonvital areas may indeed lead to a fatal result, and
- many of the high velocity missile wounds healed quite uneventfully and extensive soft tissue necrosis was not an inevitable accompaniment of them.[47,48]

The same investigators also made exhaustive measurements of bacteriological, histopathological, and biophysical phenomena. From their measurements of the biophysical interactions, they prepared a series of elegant diagrams correlating the absorption of energy and tissue damage as functions of the depth of the wound tract. But none of these studies appears to have had any influence on wound management in the war then going on in Vietnam. Some military medical officers considered experimental wound-ballistics research to be too esoteric, and the same attitude exists today.

Contemporary Wound-Ballistics Research

Since World War II, strong but short-lived research efforts have appeared in several countries. British clinical researchers in the 1960s, for example, showed that, in sheep, penicillin (used as the sole therapeutic intervention) could prevent death from experimental gas gangrene.[49]

Returning to the work that Harvey's group had done in the 1940s, reseachers at Aberdeen in the early 1970s performed a flurry of wound-ballistics experiments to investigate their possible clinical importance. They studied organ-specific aspects of temporary cavitation, especially as they apply to the lungs and large arteries. Joseph Amato demonstrated, using X rays with a pulse of less than 0.1 microsecond, the formation of a temporary cavity within a goat's thorax.[50] Amato and Norman Rich, in another study, shot the femoral arteries of mongrel dogs with high-velocity projectiles to demonstrate *(a)* the shearing effect on the artery and *(b)* the

> significant additional injury ... caused by the crushing effect of the temporary cavitation. . . [and the] rapid acceleration of the tissue [which is] proportional to the transfer of energy expended in the formation of the temporary cavity."

Confirming Harvey's earlier observations, Rich also found that the temporary cavity caused by a high-velocity bullet can *(a)* be many times larger than the permanent wound tract, and *(b)* cause arterial thrombosis or fracture a bone without the bullet's actually having hit these structures.[52]

Swedish researchers in the 1970s and early 1980s attempted to determine—as Kocher had done a century ago—the modifications that might make bullets less destructive. Going beyond researchers of the Callender-and-French discipline, who concentrated on the qualitative relationship between energy and tissue damage, Swedish investigators have striven to find an exact quantitative relationship between the two, using the amount of debrided tissue as an index of tissue damage.[53] Some researchers dispute this assessment, saying that it has no practical clinical application; others agree that the quantitative approach has considerable value.

Six international wound-ballistics symposia have been organized as a result of research, and hundreds of papers have been added to the literature.[54, 55, 56] The most recent International Wound Ballistics Symposium was held in China in 1988. China currently has the most active research programs, perhaps because the animal-rights movement is not as strong there as it is in western countries.

Finally, American wound-ballistics research has undergone a resurgence due to the efforts of Colonel Martin Fackler. His contribution has been to emphasize observables such as bullet deformation and fragmentation rather than intangibles such as energy and temporary cavitation, and he has sought to make complicated aspects of projectile-target interaction understandable.[57]

SUMMARY

Military surgeons over the past 500 years have observed certain common problems as they have managed ballistic injuries. The evolution of the surgical management of these injuries has included these observations, which valid theories of wound ballistics must incorporate:

- Untreated penetrating wounds sustained on the battlefield are likely to develop sepsis.
- The likelihood that sepsis will develop seems to be related to *(a)* the condition of the battlefield, *(b)* the ability to provide timely care, *(c)* the presence of foreign material in the wound, *(d)* the presence of dead tissue in the wound tract, and *(e)* the ballistic characteristics of the projectile.
- Surgical removal of foreign material and dead tissue seems to decrease the likelihood of sepsis.
- Primary closure of war wounds is usually unsatisfactory.
- The more a projectile deforms or fragments in tissue, the more damage it will do.
- Projectiles with higher velocities tend to cause more tissue damage than slower-moving projectiles.
- The more unstable a projectile is in tissue, the greater the tissue damage will be.
- Projectiles of irregular shapes, such as fragments from an explosive munition, may cause torn, jagged wounds.
- These factors may interact and modify the observed tissue damage.
- Under certain conditions, tissue damage is out of proportion to what would be expected from dirert physical contact with the projectile, and has been likened to the effects of an explosion.

Although wound-ballistics researchers at first tried only to replicate battlefield wounds in controlled environments, the field soon expanded to include laboratory studies of the physical mechanisms that determine the way projectiles behave in tissue. Before long, laboratory evidence showed that a projectile's velocity, deformation, and stability combine to determine the severity of the wound that it caused.

Measuring physical parameters, such as the projectile's velocity, could obviously not be done during a battle, but was ideally suited to the laboratory and could result in a unifying physical concept (such as transferof energy) that might explain the projectile's behavior in tissue. The history of wound ballistics has been dominated by the study of these physical param eters, sometimes to the exclusion of more practical clinical questions.

One of the most valuable contributions that wound-ballistics researchers have made is their provision of a clearer understanding of the explosive effects of projectiles in tissue, which had been observed by military surgeons for more than a century. This phenomenon of temporary cavitation could only have been demonstrated in the laboratory.

Questions of wound management have been more difficult to study, although wound-ballistics researchers have not ignored them. Tissue simulants, or even conscious but chronically instrumented laboratory animals, do not provide completely accurate models of wounding effects and their treatments. Therapeutic questions are probably best answered during actual combat conditions, but military surgeons should not ignore the contributions that have been made in wound-ballistics laboratories.

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