TABLE *5-5*

ALEXANDER FLEMING'SPERCENTAGE OF CASUALTIES WITH BACTERIAL SPECIESIN WORLD WAR I

Species	Time After Infection Diagnosed		
	1–7 days	8–20 days	>20 days
C. *perfringens*	81	**34**	18
Streptococcus	*80*	91	84
Staphylococcus	**32**	29	**70**
Coliforms	29	32	70
C. tetani	17	9	*0*
Other	17	17	**6**
Total number of casualtics	127	56	27

Source: Reference 35

from the wounds, produced by the spore-bearing and intestinal coliform bacilli that grew in the old blood within the permanent **cavity,** but not in the surrounding soft tissue.

- During the second and third weeks, the discharge became more **purulent;** the **earlier** flora were replaced by pyogenic cocci, which caused clinical signs of invasive sepsis in and around the permanent cavity.
- During the final phase before the wounds healed, the discharge became less copious as the pyogenic cocci disappeared.

The **abundance** uf C. *perfringens* that Fleming initially cultured from the wounds (the bacteriological correlate of the "heavily manured soil" in Flanders **fields)** is reflected in his simultaneous determination of the bacterial flora found on the soldiers' clothing: 83%had C. *perfringens,* 42%had streptococci, and 33% had other clostridia. No doubt a similar flora existed on the soldiers' skin. Clearly, the wound is first contaminated with the flora that the bullet or fragment collects as it passes through the soldier's clothing. To a lesser extent, contaminants are also aspirated into the wound tract if temporary cavitation occurs. But the sources of the pyogenic cocci and especially the staphylococcithat dominated the latter phase remained to be determined.

World* War *I—Gas Gangrene. Gas gangrene—caused by the anaerobic fecal bacteria C. *perfringens,* other clostridia, and anaerobic streptococci—first achieved prominence during World War I. The exact prevalence of this most-feared of all wound infections is unclear, although at its peak early in the war, 10%of all casualties may have developed it.[36] Gas gangrene's prevalence fell to about 5%late in the war: In France in 1918, there were 221 cases among 4,377 hospitalized casualties. Although it afflicted only a small fraction of the total casualty population, gas gangrene was an important medical problem; even with optimal care, it was a major cause of death. Among **363** casualties in France who died **of** their wounds, gas gangrene was second only to shock and hemorrhage as the leading cause of death.[37]

A battlefield study performed in 1918 provides important data on the epidemiology of gas gangrene that remain useful today:

- Although only 51%of all wounds in this study occurred in the skeletal muscles of the shoulders, arms, hips, buttocks, thighs, and calves, 88%of all cases of gas gangrene occurred there.
- In the first 48 hours after wounding, a linear relationship exists between the probability

of developing gas gangrene and the time interval between wounding and surgery. The median time between wounding and surgery in casualties who developed gas gangrene was 40 hours.

- Fifty-four percent of all casualties in this study had wounds that cultured positive for anaerobic bacteria. (Fleming had found an 81%-positive culture rate for C. *perfringens* early in the war.)
- Two-thirds of the casualties with wounds that cultured positive for anaerobes showed no clinical evidence of gas gangrene at all.
- Only 3% of the casualties who cultured positive for anaerobes developed gas gangrene after surgery. The remainder of those who had cultured positive (about 90% of the total cases of gas gangrene) also had clinical evidence of gas gangrene at the time the cultures were made.
- C. *perfringens* was present in about 80% of casualties who developed gas gangrene. About two-thirds of the casualties also had other anaerobes.
- Streptococci, both hemolytic and nonhemolytic, were present with equal frequency in both wounds that did and wounds that did not develop gas gangrene.

And the conclusions from this research also remain valid today:

- The most important factor in preventing gas gangrene is early operation. (This is a function of rapid evacuation.)
- Most wounds are contaminated with anaerobic bacteria, but do not develop gas gangrene. (All subsequent studies agree on this point.)
- Many cases of gangrene are due to anaerobes other than *Bacillus welchii.* (This is the same bacterium that Fleming called *Bacillus aerogenes capsulatus,* which now is named C. *perfringens.)*
- In most cases of gangrene, *B. welchii* is associated with other anaerobes. (All subsequent studies agree that polymicrobial infection is the rule.)
- The streptococci (both hemolytic and nonhemolytic) are apparently of little importance in the etiology of gangrene. (We know now that anaerobic streptococci—peptostreptococci—do cause a small fraction of all cases of gas gangrene.)[37]

World War 11—The Pre-Antibiotic Era. Studies carried out early in World War II extended the World War I–observations of the bacterial flora of battlefield wounds. The wounds of 105 casualties who had been evacuated from Dunkirk were cultured on admission to English hospitals. Some of the casualties had been wounded as long as 3 weeks before. Others had been wounded only a day or so before. None of the casualties had received surgical wound care, and therefore the whole population constitutes an untreated control group. The bacterial flora found in the initial wound cultures are shown in Table 5-6.[38]

Unfortunately, these results cannot be stratified by time after wounding, and thus a direct comparison with Fleming's work is impossible. Nevertheless, certain comparisons can be made between these results and those shown in Table 5-5.

- While clostridia were present in about 40% of the wounds, no cases of gas gangrene occurred in either population.
- Pyogenic cocci, and especially coagulase-positive staphylococci, predominate in both flora. (The worldwide pandemic of streptococcus infections during World War I perhaps explains the lower prevalence of hemolytic streptococci in this early–World War II sample compared to Fleming's finding.)
- *P. aeruginosa* (a latter-day scourge of intensive-care wards) first became prominent at this time, but it may have been entirely absent from Fleming's population.

Further epidemiological interpretation of these data later during World War II found that most of the species present during the first few days after wounding (including the clostridia) were contaminating saprophytes, and were lulled off by host defenses or by other bacteria.[39] The pathogens that caused the most infections were the pyogenic cocci, many of which were introduced into the wound not only at the time of injury but also during the medical treatment. The researcher estimated that (a) almost all serious infections in battlefield wounds were caused by hemolytic streptococci or *Staphylococcus aureus* or both, and *(b)* gas gangrene had a prevalence of only a few percent.

World War II—The Early Antibiotic Era. The experience that medical officers gained in treating soft-tissue and orthopedic war wounds during late 1944 and 1945 provided evidence showing both penicillin's alteration of the bacterial flora in battlefield wounds and its potential limitations as a therapeutic agent. Perhaps the most interesting study done during this period documented the bacterial flora in thirty-six casualties who had soft-tissue and orthopedic wounds in their extremities.* Twenty-seven casualties had grossly infected wounds and nine had wounds that

TABLE 5-6

WOUND BACTERIA IN EARLY WORLD WAR II CASUALTIES

Bacteria	Percentage of Casualties with Given Species
Streptococci	
hemolytic	31
viridans and nonhemolytic	18
Staphylococci	
aureus	54
albus, micrococci	19
Gram-negative cocci	1
Diptheroids	8
Gram-negative bacilli:	
coliforms	25
Proteus	7
P. *aeruginosa*	8
Hemophilus	1
Spore-bearing:	
anaerobic	14
C. *perfringens*	23
C. *sporogenes*	10
C. septique	4
other clostridia	5
Sterile	11

Source: Based on data contained in Table 1, reference 38

appeared not to be infected. The wounds were 2 4 5 days old when studied. All casualties had received initial wound debridement, all had received a sulta drug as part of their initial wound care, and all but five had received systemic penicillin both as part of their initial wound care and during their convalescence.

The bacteriological studies included both speciation and a determination of the cultured organisms' sensitivities to the antibiotics then available. Infected wounds contained five or six species of bacteria. "Clean" wounds contained two or three species. The researcher distinguished among *true pathogens* (that is, toxigenic clostridia, coagulase-positive staphylococci, and beta-hemolytic streptococci), *wound pathogens* (that is, Gram-negative organisms, nontoxigenic clostridia, and *so* forth) and *commensals* (that is, the diphthei-oids, nonhemolytic coagulase-negative staphylococci, and so forth). Wound pathogens were distinguished from true pathogens as those bacteria unable to mount a "direct attack upon living tissue."[40] The distinction between invasive and toxigenic necrosis of living tissue (a function of true pathogens) and the septic decomposition of devitalized tissue (a function of wound pathogens) is important. It suggests that Fleming's first phase of wound infection represents only the action of wound pathogens upon blood clots and dead muscle.

The incidence of potentially invasive or toxigenic bacteria (the true pathogens) was: toxigenic clostridia, twelve; coagulase-positive staphylococcus, eleven; and beta-hemolytic streptococcus, seven. True pathogens were present in twenty-four of the twenty-seven clinically infected wounds and absent in eight of the nine "clean" wounds. Although there was only a single completely penicillin-resistant organism among the true pathogens—a staphylococcus (a harbinger of things to come)—local wound suppuration continued unabated.

The researcher's conclusions remain valid:

> Wound suppuration [is] not controlled by chemotherapy alone. . . . Invasive sepsis is controlled by the systemic use of chemotherapeutic agents. . . . Anaerobic infection is controlled by the excision of dead tissue protein and the avoidance of primary wound closure. Aerobic wound infection is controlled by preventing wound exudation through the use of splints, pressure dressing, and secondary closure of clean wounds.[40]

The researcher also offered the following practical advice regarding making decisions in the management of contaminated wounds: "The gross surgical pathologic condition of the open wound is more directly and accurately informative than any reasonable bacteriologic analysis."[40]

World War II—Anaerobic Infections. Although gas gangrene was much less prevalent during World War II than it had been during World War I, many new observations were made based on campaigns fought in the Africa, which established the currently accepted understanding of these infection~:~'

- About 30% of the wounds incurred in the Middle East contained anaerobic bacteria. Between 2.5%–5.0% of these contaminated wounds (that is, about 1% of the total wounded) developed clinical infections associated with anaerobic bacteria.
- In about 60% of the casualties with clinical infections, clostridia multiplied in necrotic

tissue, produced gas, spread along fascial planes, but did not invade normal muscle. This disease is *anaerobic cellulitis.*

- In about 30% of the cases with clinical infections, clostridia invaded and destroyed normal muscle. This disease is classical gas gangrene: *clostridial* or *anaerobic myositis.*
- In about 10% of the cases with clinical infections, anaerobic streptococci rather than clostridia caused muscle necrosis. This disease is *streptococcal myositis.*
- Different toxigenic clostridia were found to have different clinical characteristics. *Clostridium edematiens* had an incubation period of more than 5 days, while the more-common C. *perfringens* had an incubation period of about 1 day.
- About two-thirds of the casualties who had clinical infections also had suffered an injury to a major artery. But interestingly, in this study, the presence or absence of the vascular injury had little influence on the incubation period, the symptoms, or the end result of the infections.
- The magnitude of tissue damage predicted the casualty's outcome (Table 5-7).
- As Fleming had found during World War I, the soldiers' clothing was the source of most of the contamination: ninety-four samples taken from fifty sets of service dress cultured positive for one or more clostridial species.
- Fifty percent of the casualties with anaerobic during this obscrvation period—a rate not that observed at the end of World War I. Medical officers obtained the best survival rates (70%) with surgery combined with antitoxin and sulfa drugs. Sulfa drugs by themselves were not effective.

TABLE 5-7

CLOSTRIDIAL SEPSIS: WOUND SEVERITY AND FATAL OUTCOME IN WORLD WAR II

Type of Injury	Outcome (N)	
	Fatal	Recovered
Traumatic amputation	4	1
Bony injury	4	15
Muscle laceration only	6	16
Minor injury	0	1

Source: Reference 41

These extensive observations with anaerobic bacterial infections led to several conclusions that, more importantly, helped develop the concepts that led to understanding these infections:

> Anaerobic infections are not bacteriological but clinical entities. . . . [The anaerobic bacteria's] absence from war wounds is a matter for surprise rather than satisfaction, their presence for resignation rather than alarm. . . . [T]he vast majority of these [anaerobic] organisms, including those of medical and veterinary importance, are primarily and essentially saprophytes. . . . [A]ll or nearly all [anaerobic bacteria] require special environmental conditions in their host before they can produce those effects that we speak of as a disease, before, indeed, they can even grow.[41]

The first 6 weeks of the Normandy Campaign saw one of the only studies in the history of combat-casualty care in which the experimental design allowed for a concurrent control group. The purpose was to ascertain the extent to which prophylactic penicillin would prevent clostridial wound sepsis. Out of about 4,000 British battle casualties, 436 were treated by injections of penicillin. 100,000 units as soon as possible and 50,000 units every 4 hours until their surgery. These casualties' wounds were the most likely to develop gas gangrene (that is, they included extensive lacerations of the muscles of the buttocks or thighs, compound fractures, gross contamination, long delay in providing initial care, and so forth).[42]

The results clearly indicated that penicillin markedly reduced the probability of clostridial sepsis. Only two casualties of the 436 who had received penicillin (0.46%) but twenty-eight of the nearly 3,500-member control group (0.81%) developed clostridial sepsis. Since the penicillin-treated casualties had wounds that were likely to develop gas gangrene, the difference is even more dramatic. The absence of clinical infection did not indicate that clostridia were absent from the wounds: All but one clinically benign but "dirty" wound that had been treated with penicillin grew clostridia in cultures. Penicillin did more than just prevent gas gangrene; only a small proportion of the wounds contained *Staphlococcus aureus* or *Streptococcus hemolyticus,* and about 40% of the penicillin-treated wounds that were "clean" were also sterile. The researchers cautioned that a short or inadequate course

of penicillin may not totally abort clostridial wound sepsis. Profound or protracted toxemia occurred in several casualties, even though there were no local signs of clostridial sepsis. Presumably, clostridia produced their toxin even though the bacteria did not invade living muscle.

The striking difference in the prevalence of clostridial sepsis in casualties wounded while fighting over the same terrain in the two world wars is difficult to explain. Certainly, the use of antimicrobial drugs alone cannot explain the marked reduction of clostridial sepsis; the Normandy study's control group had a prevalence of only 0.8%—less than one-fifth the rate that was reported[37] at the end of World War I. Nor can differences in surgical techniques explain it; the techniques of soft-tissue wound management that were practiced near the end of World War I were surely at least as exacting as those practiced late in World War II. Could the toxigenic species of clostridia have become more benign during the period between the wars?

Korean War. The most valuable data regarding the bacteriology of battlefield wounds that has been obtained since World War II was performed by U.S. Army researchers near the end of the Korean War. One study determined the bacterial flora in skeletal muscle that was removed during the debridement of soft-tissue and bony wounds. Researchers examined 42 wounds in thirty-three casualties in the summer of 1952, and 112 wounds in sixty-nine casualties in the winter of 1952–1953 (Table 5-8). The average time between the casualty's wounding and the researchers' removing tissue for culture was about 4 hours in the summer and 8 hours in the winter. All casualties were given 300,000–600,000 units of penicillin "shortly after injury."[43]

Three of the observations that emerged from this study require comment:

- The high prevalence of hemolytic streptococci during winter no doubt reflects the expected increase in upper respiratory infections.
- No cases of gas gangrene occurred in the study group (and the overall incidence for American troops in the Korean War was less than 0.5%).
- Both the striking winter decrease in Gram-negative bacteria and the less-dramatic winter decrease in clostridia perhaps reflect a winter reduction of fecal contamination in the soldiers' environment. The fundamen-

TABLE 5-8

BACTERIAL FLORA AT THE TIME OF SURGICAL CARE IN KOREAN WAR WOUNDS

Species	Percentage of Wounds Containing Bacteria	
	Summer	Winter
Sterile	11	19
Staphylococcus		
hemolytic	17	46
nonhemolytic	12	33
Streptococcus		
beta-hemolytic	0	61
non-beta-hemolytic	59	76
Total Clostridia	84	36
pathogenic, including C. *perfringens*	44	21
Gram-negative bacilli	69	12
Bacillus species, including *B. subtilis*	10	62

43

tally different summer and winter flora indicate that medical officers must choose carefully when considering effective antibiotic prophylaxis.

Several ancillary studies done at the same time showed:

- The larger the wound, the more likely it was to contain pathogenic clostridia. This effect was not found for aerobes.
- Soil, rather than the soldier's skin or clothing, was more likely to be contaminated with clostridia.
- Fifty-five percent of surgically removed rifle and machine **gun** bullets grew clostridia, and clostridia were cultured from 25% of shell fragments and 39% of grenade fragments.
- In the doses that were employed, penicillin inhibited the *in vitro* growth of only one-half to three-fourths of the isolated clostridia.

The authors of these studies emphasized that the bacterial flora "illustrate wound contamination and early proliferation of bacteria, rather than infection."[43] Unfortunately, they did nut tell how many, if any, of the casualties in these studies actually developed clinical wound sepsis.

With few exceptions, studies of bacterial wound flora done before the Korean War described observations that were made at only one point in time. In the spring of 1953, researchers followed eleven casualties who had received state-of-the-artcombat-casualtycare and studied how their flora changed over time. They cultured skeletal-muscle biopsies that were taken at the time of initial wound surgery and again, under sterile conditions, on every second day until surgeons closed the wounds between the fifth and ninth days. The casualtics had **at** the time of initial wound surgery, but not afterwards.

> All wounds contained a rich flora of Gram-positive and Gram-negative aerobes on initial culture. Without exception, these organisms persisted in the wounds during the first week of healing. . . . Nine of **the** 11 wounds studied contained **one** or more species of clostridia at the time of initial debridement. Clostridia were absent from two-thirds of the wounds when studied following initial surgery.[44]

The failure to achieve sterilization in any of the wounds might be thought to reflect inadequate wound surgery. However, the surgeon purposely excised healthy-appearing tissue (afterhe had performed what he judged to be an adequate debridement) on six casualties. Five of the six specimens contained bacteria of the same species that were found during debridement of the "devitalized tissues. Two of the eleven casualties developed wound sepsis from their "clostridial and rich aerobic flora." The authors concluded that "adequate debridement was not performed" in these failures. But the clear implication from this work is not that the wounds were inadequately debrided; it is rather that surgery probably cannot sterilize a battlefield wound. Debridement reduces bacterial contamination and augments the casualty's defenses against infection by eliminating abnormal tissue.[44]

Vietnam War. Our understanding of soft-tissue wound infections advanced less than might have been expected during the Vietnam War, given the high level of medical sophistication compared to other wars. Complications of soft-tissue wounds were less frequent during the Vietnam War than they had been in prior American wars. There was less interest in the problem of wound sepsis than there had been in World War I, for example, which is not surprising. Although this favorable situation no doubt reflected the general excellence of surgical care and the liberal use of antibiotics both prophylactically and therapeutically, it is a mistake not to recognize that it was the nature of the war itself—largely low-intensity counterinsurgency operations—that made the general excellence of the medical care possible.

During the battle of Dak To in November 1967, a rare instance when a battlefield in Vietnam had the scope and intensity reminiscent of World War I and World War 11, wound sepsis became a serious problem:

> The 24-hour-old wounds were uniformly purulent and the extremity wounds were often accompanied by rather marked swelling. After the first 24 hours, patients frequently became quite febrile, and while cellulitis was the rule, lymphangitis was rare. The casualties from the 173d Airborne Brigade with 2- or 3-day-old wounds demonstrated the same findings, but their fever and inflammation were more severe.[45]

The following databases clearly seem to apply to a much more benign environment than Dak To. One study followed 112 soft-tissue wounds in 110 casualties (Table 5-9). Cultures were taken at the time the casualties were admitted, but before surgery was performed. "The vast majority of patients received penicillin and streptomycin,"[46] but the researchers provided no information regarding dosages and times of administration of the antibiotics. Several striking differences seem to exist between these data and those published during previous wars:

- *Streptococcus pyogenes* was totally absent and

TABLE 5-9

BACTERIAL FLORA IN VIETNAM WAR COMBAT WOUNDS

Species	Percentage of Wounds Containing Species
No Growth	34
A. aerogenes	33
Staphylococcus aureus	30
P. aeruginosa	14
Proteus sp.	14
E. coli	11
Enterococci (group D beta-hemolytic streptococci)	7
Staphylococcus epidermidis	6
Clostridium sp.	2
Others	4

Source: Reference 46

clostridia were nearly absent, in marked contrast to the high prevalence of these organisms in wounds of previous wars. Clostridia were known to be present in all types of soils in Vietnam. Whether penicillin was responsible for the absence of clostridia in wounds is not known. The absence of S. *pyogenes* probably reflects climatic conditions: This species was also absent from Korean summer cultures (Table 5-8).

- Nearly three-fourths of the isolates were Gram-negative. Although high, these data are comparable to the Korean summer cultures.
- One-third of the cultures showed no bacterial growth. This figure is much higher than that from previous wars. It may reflect the fact that cultures were taken from wound edges, rather than from actual tissue. Or the wounds may have been sterilized by the antibiotics.

Evidence from another study supports the suggestion that the pathogens that caused such severe problems in previous wars were much less prevalent in Vietnam.[47] Clostridia and beta-hemolyticstreptococci were essentially absent from cultures taken from 1,531 wounds when casualties from Vietnam arrived at fourth-echelon hospitals in Japan. All the patients had received initial wound surgery and a variety of antibiotics, so whether the absence of these pathogens reflects effective prophylaxis or decreased bacteria in the environment is unclear. However, these data do suggest that the environment and climate of the battlefield determine both the ambient bacterial flora and the consequent likelihood of wound sepsis.

One effort during the Vietnam War sought to *(a)* quantitate the bacterial counts in battlefield wounds and *(b)* determine whether applying topical antimicrobial drugs to open soft-tissue wounds could lessen the likelihood of sepsis.[8] The study population consisted of 245 wounded Vietnamese soldiers who were randomized into seven treatment groups (controls, saline irrigations, and various protocols for the topical

TABLE 5-10

BACTERIAL COUNTS DURING TREATMENT IN VIETNAMESE BATTLEFIELD WOUNDS

Species	Percentage of Wounds Containing $10^3/10^6$ Organisms per ml of Wound Exudate — Day of Culturing Bacteria			
	0	2	5	8
Staphylococcus aureus	46/17	37/29	45/30	62/40
Pseudomonas	10/5	31/26	45/39	40/30

Source: Reference 8

application of Sulfamylon, Polybactrin and Neosporin). All casualties received parenteral penicillin and streptomycin throughout the study. Cultures were taken from the wounds when the casualties were admitted, before their initial wound surgery, and on the second, fifth, and eighth days after surgery, using sterile technique (Table 5-10).

Unfortunately, this study did not report the clinical outcome of these casualties' wound-healing. Since only a few of the wounds had counts of *Staphylococcus aureus* that are known to be associated with invasive sepsis in animal models, invasive sepsis might have been uncommon in this population. Clearly, all casualties must have had surface infections, but the study did not report what happened when (or if) the wounds were surgically closed. While the details of surgical care were not specified, whatever was done surgically did not sterilize—or even decrease—the bacterial counts; *Pseudomonas* proliferated continuously. Nor did any of the antibiotics used either topically or systemically appear to decrease the bacterial counts.

TABLE 5-11

BACTERIAL SPECIES FOUND IN SOFT-TISSUE WOUND INFECTIONS DURING THE YOM KIPPUR WAR

Total Casualties = 10 Total Isolates = 41	Positive Cultures
Various Gram-negative bacilli other than Pseudomonas	15
Pseudomonas	12
Enterococci	6
Staphylococcus aureus	4
Streptococcus pyogenes	2
Clostridia	2

Source: Reference 48

Yom Kippur War. Research performed by Israeli medical officers during the 1973 Yom Kippur War yielded important information on the differences in the bacterial flora responsible for *(a)* the simple wound contamination that was found in cultures taken at the time of initial wound care and *(b)* the clinically apparent soft-tissue wound infections that were seen days to several weeks after wounding.[48] Bacterial species were cultured from the 10 of 178 casualties who had infected soft-tissue wounds, an unreported number of which were multiple (Table 5-11). The frequency of the species seen in the these infections, which also represents the flora of infected fracture wounds, is very different from the flora found during the pre-antibiotic era of the two world wars. Gone are the large numbers of wounds infected with pyogenic cocci and clostridia. They have been replaced by a large number of infections caused by Gram-negative pathogens, at least some of which are nosocomial. In a companion study, the investigators state their firm belief that the antibiotics administered in the field were primarily responsible for the changes in the

Insofar as the data permit comparison, the soft-tissue wound infection rate changed little, compared to late-World War II or the Korean War; only the bacterial species causing infection changed.

TABLE 5-12

BACTERIAL COUNTS OVER TIME IN MASSIVE SOFT-TISSUE WOUNDS IN GOATS

	Bacterial Counts Over Time (Hours) After Wounding				
Species	9	16	25	36	48
C. perfringens	3×10^3	4×10^4	9×10^6	3×10^7	dead
S. *aureus*	1×10^4	4×10^5	1×10^4	6×10^4	dead

Source: Reference 51

The Bacteriology of Penetrating Wounds in Experimental Animals

Several of the many experimental-wound studies performed at Edgewood Arsenal may help medical officers understand the bacteriology of penetrating wounds.

A study using goats with extensive soft-tissue wounds emphasized the value of distinguishing between *qualitative* assessments of bacterial flora (that is, the presence or absence of a given species) and *quantitative* measurements of the actual number of bacteria present in a wound. Kesearchers wounded each goat by detonating a small explosive charge near the animal's thigh. Bacterial cultures revealed little change in the flora over several days, even though the goats' deteriorating clinical status suggested invasive sepsis. A different picture emerged when bacterial counts were made: The number of bacteria per gram of tissue increased from 10^2 immediately after wounding to 5×10^3 at 6 hours, 12 hours, and to 10^6 at 18 hours. Death occurred in most untreated animals when the quantitative measurements found more than 10^6 bacteria per gram of tissue, even though the bacterial species found in the wound when the animal died were the same as those found in the wound immediately after the animal was wounded.[50]

A companion study using a similar experimental model studied bacterial speciation and measured the growth of C. *perfringens* and *S. aureus* in a group of untreated control animals (Table 5-12).[51]

Although studies like these are difficult to perform, they are valuable because they allow investigators to quantitate the effect of a given therapeutic intervention — whether surgery or an antimicrobial agent. Subsequent research done at Edgewood that studied the bacteriology of penetrating wounds made by fragments and spheres illuminates some of the difficulties inherent in such investigations. Although *C. perfringens,* S. *aureus,* and even anaerobic streptococci, among other pathogens, were present in most wounds, there was "little consistent correlation between the organisms recovered from the wounds and the [experimental animals'] clinical course."[16] Many of the animals developed minimal, well-localized infections, and quantitative bacterial counts alone would mislead as to their extent. For example, many instances of C. *perfringens* infection contained so few organisms that the relationship between bacterial count and clinical outcome could not be determined. This study shows that the mere presence of a penetrating soft-tissue wound does not necessarily indicate bacterial contamination that will automatically progress to life-threatening sepsis. Many — in fact most — of the experimental wounds healed uneventfully.[16]

Since this pioneering work at Edgewood, many additional investigators have reported on the bacterial flora in experimental penetrating soft-tissue wounds. One of special interest combined sophisticated bacteriological studies with relevant wounds that were created under realistic controlled circumstances.[52] The investigators shot sixty-four swine (although only forty-seven were used in the study) through the soft tissues of their posterior thighs *(a)* in the field, *(b)* at ranges of 30 or 100 m, and *(c)* with a variety of military small arms including the 5.56-mm M193 ball and the 7.62-mm M43 ball. Cultures were taken *(a)* when the wounds were debrided 6 hours after wounding and *(b)* when the dressings were changed 72 hours after wounding. One-half of the animals received parenteral penicillin every 8 hours.

Important differences regarding both bacterial

counts and wound morphology appeared between the 5.56-mm and 7.62-mm bullets. When the wounds were debrided, only one of the 7.62-mm wounds contained a measurable number of bacteria (in this instance, 10^4 E. *coli*), while 50% of the 5.56-mm wounds contained various species with counts ranging between 10^2 and 10^4. None of the latter animals had received penicillin. Twelve of the swine were studied at 72 hours. All the 7.62-mm wounds were apparently sterile, but the 5.56-mm wounds were invasively infected (with bacterial flora of soil or fecal origin) and contained more than 10^5 bacteria per gram of tissue.

Wound morphology was also strikingly different in the 7.62-mm and 5.56-mm groups. The en seton wounds made by the 7.62-mm bullets appeared benign; the dimensions of the wounds of entrance and exit were the same. However, the exit wounds made by the 5.56-mm bullets (especially those made at the 30-m target distance) were more often than not "explosive," with dimensions many times larger than their corresponding wounds of entrance. The huge exposed surfaces of the large wounds of exit became the sites of invasive sepsis.

This study has several important implications for military surgeons who may treat battlefield wounds:

- Benign, perforating, (en seton) soft-tissue wounds that the 7.62-mm bullets made frequently healed without any therapeutic intervention being necessary. This study shows why: Bacterial contamination is insufficient to cause infection.
- The greater the tissue damage, the greater will be the potential for bacterial contamination. Yet the invasive sepsis that developed in the 5.56-mm wounds appears not to have been caused by the contamination that occurred at the time the animal was hy secondary contamination from the animal's environment that occurred many hours after wounding.
- Penicillin prevented the growth of the bacterial contamination that occurred at the time of wounding, but was ineffective in preventing the later colonization of the open wound.

AN OVERVIEW OF MANAGEMENT CONSIDERATIONS

The military surgeon's goal in soft-tissue wound management is to to return the combat casualty to duty at the earliest possible moment. The medical factor still most likely to delay early return, however, is the wound's failure to heal because of sepsis. Ideally, prophylactic interventions will prevent a contaminated wound from becoming infected and an infected wound from becoming septic, but if prevention fails, therapeutic interventions will have to be employed.

The potential for wounds to become infected or septic can be lowered by (a) decreasing the magnitude of bacterial contamination and *(b)* eliminating those factors that decrease the casualty's resistance to bacterial infections. Interventions that both decrease contamination and augment the casualty's resistance include (a) surgery, *(b)* mechanical irrigation, *(c)* antiseptics, and *(d)* antibiotics. Of course, civilian surgeons face many of these same situations every day, but there are aspects that are unique to soft-tissue wound management in combat casualty care.

Surgery

Surgical interventions range among *(a)* wound incision (that is, simply opening the wound tract), *(b)* simple wound excision (that is, excising all or part of the permanent cavity's wall, cutting from the inside out), and *(c)* total wound excision or excision en bloc (that is, entirely excising the tissue around the permanent cavity, cutting around the damaged tissues but never entering the permanent cavity itself). The distinction between simple wound excision and total wound excision is of academic interest only: Excision en bloc is hardly ever a practical possibility. Even the distinction between incision and excision may be more theoretical than practical, because performing wound excision is impossible without first performing wound incision. Furthermore, except when incising a grossly suppurative permanent cavity (that is, when draining an abscess), the surgeon will usually trim injured tissue from the permanent cavity's walls. Because both incision and some degree of excision are *(a)* part of the usual surgical management of penetrating soft-tissue wounds and *(b)* included in the term *debridement* (both as it has been used in the U.S. Army since World War I and compatible with its contemporary civilian use), this textbook uses debridement to describe the surgical management of penetrating soft-tissue combat wounds.[53]

liemoving dead or devitalized tissue is the usual

rationale for performing debridement, but wounds usually contain little truly dead tissue. They do, however, contain significant amounts of damaged tissue: the ecchymotic, suffused, edematous tissue in the zone of extravasation. This is the tissue most likely to be contaminated by foreign material — including bacteria and soil. Therefore, debriding a layer of the zone of extravasation lying just outside the permanent cavity will both decrease the bacterial count and augment the casualty's ability to resist infection. The famous four Cs criteria-color, consistency, contractility, and circulation — while they do not absolutely identify dead tissue, do actually identify the tissue most likely to **be** Contaminated and thus at risk to develop sepsis.

But there should be no doubt as to whether debridement can sterilizea wound: It cannot. Neither can debridement sterilize an infected wound: Infection cannot be excised.

Irrigation

Large foreign bodies, blood clots, and small pieces of detached muscle and fat are easily removed from the walls of a permanent cavity by conventional irrigation (that is, lavage with large volumes of saline at low pressure). But bacteria, because of their *(a)* small size and consequent low hydraulic drag and *(b)* surprisingly great physical adherence to tissue, resist being removed by conventional irrigation, even when saline is squirted forcefully from a bulb syringe. Bacteria can be removed from tissue only if the irrigation solution floods the wound margins at a pressure of 7 psi or greater.[54] Commercial devices are available for this purpose, but a 35-ml syringe ejecting through a 19-gauge needle can obtain a similar effect.[55] Devices such as the Water Pikfrequently use a high-pressure pulsatile jet. Extensive experimental work done by the U.S. Army Medical Research and Development Command has shown the value of such devices as adjuncts in the mechanical cleansing of wounds.[56] Earlier concerns that high-pressure irrigation would drive the contaminating bacteria into deep tissue recesses have been dispelled by studies showing that the benefits from physically removing the bacteria outweigh any decrement in the casualty's ability to resist infection.[57] Wounds have also been successfully decontaminated using ultrasound waves. In response to the cyclic high- and low-pressure phases of the sound waves, microscopic air bubbles expand and collapse explosively and strip particulate matter from the tissue.[58]

Modalities such as high-pressure irrigation and ultrasound, applied after the permanent cavity is opened, might seem to be attractive alternatives to excision, but their value to military surgeons is moot: Such devices are unlikely to be available in combat-zone hospitals. Battlefield medical facilities may lack even copious quantities of irrigation fluid for conventional wound lavage.

The wound must be incised before any irrigation technique can be employed, although attempts to circumvent this prerequisite occasionally occur. Some have tried to irrigate without incising by placing the nozzle of a syringe directly into the wound of entrance or exit and squirting vigorously. Obviously, the convoluted geometry of most permanent cavities precludes anything other than inadequate lavage. More recently, others have suggested that the permanent cavity could be scrubbed by pulling a sponge or gauze through it, but an unanesthetized casualty may not tolerate a surgeon's insinuating a gauze through a long permanent tract. Cleansing a wound by direct mechanical trauma may actually impair the casualty's resistance. In one experimental study, the percentage of infected wounds was increased from 0% in the controls to 40%–70%in sponged animals, depending upon the **sponge's** roughness.[59]

Antiseptics

Antiseptics have a long and controversial history in military surgery. Surgeons in World War I managed grossly septic open wounds by irrigating them frequently with corrosive chemicals. The best-known (but now obsolete) regimen used Carrel's technique and Dakm's 0.5% sodium hypochlorite solution. Although Dakin's solution killed bacteria and digested dead tissue, it also injured living tissue in the wound. Furthermore, the procedure required that the wound be exposed frequently, with the attendant possibility of secondary contamination with hospital bacteria.

While using antiseptics as therapeutic agents in treating grossly infected wounds seems to be reasonable, using an antiseptic prophylactically is not. Any chemical capable of killing bacteria will also kill mammalian cells. But nontoxic detergents (such as Pluronic polyol F-68), because of their ability to reduce the bacterial count in experimentally contaminated wounds, might be useful adjuncts in debridement.

Today, surgeons use antiseptics — specially those based upon iodophors (that is, complexes of elemental iodine and polymers of polyoxyethylene or polyoxypropylene)—in managing suppurating wounds. The goal remains to reduce the wound's bacterial count until secondary closure can be performed safely.