Abstract—Background and Objectives: This report provides an overview of advances in wound repair devised by our research team during the last four decades. This collective review is presented in two parts. Discussion: The following components are included in Part I: 1) search and treat life-threatening trauma; 2) conduct a thorough history; 3) examine the wound using aseptic technique; 4) anesthetize the wound before cleansing; 5) hair removal, skin disinfection, hemostasis, surgical debridement, and mechanical cleansing; 6) antibiotics, drains, and open wound management. Conclusion: On the basis of these comprehensive research studies, we have noted a marked reduction in the incidence of wound infection in traumatic wounds. © 2009 Elsevier Inc.

Keywords—trauma wound repair; life-threatening trauma; aseptic technique; local anesthesia; hair removal; antibiotics; open wound management

INTRODUCTION

We have written this report about our comprehensive research program involving studies of the biology of traumatic wound repair. Our investigations of the mechanism of wound injury, soil infection-potentiating factors, dynamic and static tensions, and the microflora of the skin have led to these factors becoming important predictors of the outcome of wound repair. In this collective review, we will provide an overview of these advances in traumatic wound repair.

SEARCH AND TREAT LIFE-THREATENING TRAUMA

The proper evaluation of the patient hinges on an expeditious but comprehensive assessment. This initial as-
erssment can be divided into primary and secondary surveys. The primary survey deals with the diagnosis and treatment of life-threatening conditions that produce death within minutes unless treatment is initiated. These life-threatening issues must take precedence over any wound repair concerns. External bleeding almost always can be controlled by direct pressure over the site of bleeding (1). Bleeding of an injured extremity that is refractory to direct pressure will stop after inflation of a sphygmomanometer placed proximal to the bleeding site. After elevating the injured extremity for 1 min, the cuff is inflated to the lowest pressure that will arrest the bleeding. This measured level of inflation pressure can be maintained for at least 2 h without injury to the underlying vessels and nerves. Once the patient’s condition has stabilized, a careful head-to-toe examination of the patient, searching for other injuries, must follow.

CONDUCT A THOROUGH WOUND HISTORY

Before inspecting the wound, the Emergency Physician (EP) must carefully question the victim regarding the timing and mechanism of injury. The time in which the accident occurred has considerable influence on wound management decisions. A delay in treatment lasting longer than 6 h often is associated with a proliferation of bacteria to a level (10^6 bacteria or greater per gram of tissue) that may result in the development of infection (2). Exposure of the wound for this length of time has other side effects that limit the therapeutic efficacy of antibiotics. The vessels within the open wound exhibit increased vascular permeability with extravasation of blood proteins into the wound. By 3 h, this developing coagulum is of sufficient magnitude to surround the bacteria and protect them from contact with either systemic or topical antibiotics (3). This inflammatory exudate on the surface of the wound provides an explanation for the resistance of the open wound to delayed antibiotic treatment. Consequently, antibiotics are administered intravenously to patients who have obviously contaminated wounds.

Clinically, one of the most important consequences of any wounding process is that the divided edges of the wound are more susceptible to infection than the unwounded tissue. The magnitude of this enfeebled resistance varies with the mechanism of injury. Some soft tissue injuries are due to cuts by either a piece of glass or the metal edge of a knife (4). In such cases, shear forces of equal magnitude are applied to this tissue in opposite directions in two adjacent parallel planes separated by a small distance, and result in a linear laceration. The amount of tissue volume contacted by sharp devices is extremely small, and, consequently, very little total energy (< 100 joules) is required to produce tissue failure. The resultant wound exhibits considerable resistance to the development of infection, with the infective dose being 10^6 bacteria per gram of tissue or greater. This remarkable resistance to bacterial infection has been identified in all soft tissues tested (e.g., tongue, fat, muscle, skin) (2).

Occasionally, the soft tissue wound is due to a collision of two bodies, with the mechanism of injury being compression or tension rather than shear forces. A soft tissue wound resulting from an automobile accident is a case in point. Such wounds usually can be easily recognized by their characteristic appearance, a stellate laceration with abrasions of the skin adjacent to the wound (4). The energy requirement for tissue failure as a result of these forces is considerably greater than for shear forces, because the energy results in demonstrable damage to the wound edges, which is associated with a reduction in blood flow and an increased susceptibility to infection (10^4 bacteria per gram of tissue) (1).

A collision between a missile and the human body represents a considerably higher level of energy absorption per unit volume of tissue than that encountered in an automobile accident. As tissues are struck by a missile, a combination of shear, tensile, and compressive forces interact to produce a relatively predictable amount of destruction (4). At speeds up to 300 M/s, the “low-velocity” projectile penetrates the target, making a deep, narrow tract. In such injuries, the tissue damage is confined to the immediate pathway of the bullet. When a high-velocity projectile (> 2000 M/s) strikes the human body, considerably more energy is absorbed by the body than with low-velocity missiles. The magnitude of this resultant tissue injury is extensive and difficult to ascertain until 4 or more days after the injury.

The environs in which the injury occurred may be predictive of the number of pathogens in the wound. Lacerations inside or in contact with the oral cavity are usually heavily contaminated with facultative species and obligate anaerobes. Within the oral cavity, the largest numbers of organisms are encountered in the gingival crevices and in plaque on the teeth. The debris removed from the crevices and the plaque on the teeth are composed primarily of bacteria in the range of 10^{11} per gram wet weight, a number that is far greater than infective doses of bacteria (> 10^6 bacteria per gram of tissue) for most soft tissue wounds. This potential source of heavy contamination accounts for the reported high infection rate of wounds resulting from human and animal bites (5,6). Feces also contain an abundant microflora occurring in a concentration of 10^{11} per gram of passed feces. Approximately 20–30% of the net weight of stool is a solid mass of bacteria, nearly all anaerobes. Wounds contracted by human or animal fecal contaminants run a high risk of infection despite therapeutic intervention.
The likelihood of non-viable foreign bodies being in wounds also can be predicted by a careful history. In missile injuries, clothing and missile fragments are encountered in the wounded tissue. Soil and dirt frequently are found in lacerations resulting from industrial or farming accidents. Although it has been widely recognized for centuries that severe bacterial infection often develops in wounds containing dirt and soil, there has been little knowledge until recently of the role of components of soil in this infection process.

Interdisciplinary research in this area has clarified the role of soil in the development of infection. Specific infection-potentiating factors have been identified in the soil, which include its organic components as well as its inorganic clay fractions. For wounds contaminated by these fractions, only 100 bacteria are necessary to elicit infection (7). Their ability to enhance the incidence of infection seems to be related to their damage to host defenses. In the presence of these fractions, leukocytes are not able to ingest and kill bacteria (8). This deleterious effect on white blood cell function is a result of a direct interaction between the highly charged soil particles and white blood cells. Soil infection-potentiating fractions also have considerable influence on non-specific humoral factors. Exposure of fresh serum to these fractions eliminates its bactericidal activity. As expected, these particles, which are highly charged species, react chemically with amphoteric and basic antibiotics, limiting their activity in contaminated wounds (9).

The concentration of these fractions in soil can be correlated with their location. Environmental conditions in swamps, bogs, and marshes encourage the production of soil with as much as 98% organic infection-potentiating fractions. The major inorganic infection-potentiating particles are the clay fractions, which reside in heaviest concentration in the subsoil rather than in topsoil. Consequently, traumatic soft tissue injuries occurring in swamps or excavations run a high risk of being contaminated by these fractions, which predispose the wound to serious infection.

A corollary to these observations is that some soil contaminants, such as sand grains, are relatively innocuous. This fraction, which has a large particle size and a low level of chemical reactivity, exerts considerably less damage on tissue defenses than do the other infection-potentiating fractions. Surprisingly, the black dirt on the surface of highways also seems to have minimal chemical reactivity.

**EXAMINE THE WOUND USING ASEPTIC TECHNIQUES**

The EP must wear powder-free latex-free gloves that comply with the comprehensive performance requirements of the National Fire Protection Association (NFPA). Glove selection for emergency medical care has become an especially important clinical consideration after the development of the latex allergy epidemic (10). As of March 1999, the total number of latex allergic reactions associated with exposure to gloves containing natural rubber latex (NRL) reported by the Food and Drug Administration (FDA) was 2330, including 21 deaths. NRL is a substance composed of hundreds of complex proteins from the rubber tree, *Hevea brasiliensis*, including enzymes involved in biosynthesis as well as lipids, nucleotides, and co-factors. Glove manufacturers use chemicals such as accelerators and antioxidants to change the durability, stretch, and thermal stability of NRL (11). Two to three percent of the final glove product is natural protein. Investigations have isolated and identified the rubber elongation factor, designated as Hev b1, in this natural protein as the major allergen causing the NRL allergy (12). NRL allergy was first reported in North America in 1989 (13). The increased frequency of NRL allergies has been attributed to many factors, from changes in the manufacturing process to an increase in the quantity of gloves produced at a reduced cost. These manufactured gloves were found to contain higher levels of the NRL proteins, which increased health care workers’ exposure to NRL (14).

Reported reactions to latex include contact urticaria, rhinitis, asthma, and anaphylactic shock, and the development of reactions to latex exposure has been linked to people’s production of IgE antibodies to natural latex after repeated exposure to the substance. Once formed, this IgE antibody will induce an anaphylactic response stimulated by the latex antigen (15–24). Some individuals may tolerate an unknown amount of exposure before reacting, but continual exposure will eventually progress to anaphylaxis. Before anaphylaxis, certain general symptoms are observed, such as erythema, excessive tearing, chemosis, sore throat, hoarseness, allergic rhinoconjunctivitis, urticaria, or facial edema (19,20).

In addition, powder has been shown to be a vector for latex allergy. Currently, cornstarch is the lubricant found on many surgical and examination gloves used by health care workers. Most health care personnel have an unfounded confidence in cornstarch and mistakenly believe it is safe. Experimental and clinical studies have confirmed that cornstarch causes toxic reactions in every tissue in the body (21). These cornstarch particles also serve as an agent for exposure and sensitization to latex protein during donning procedures (22,23). Therefore, powdered latex gloves present a twofold threat via contact with openings in the skin as well as respiratory inhalation of aeroallergens (24). The National Institute for Occupational Safety and Health has recognized this link and the danger that the continued use of these powdered gloves presents to workers (25). A safety
report alert released in June 1997 entitled, Preventing Allergic Reactions to Natural Rubber Latex in the Workplace, alerted the public, employers, and safety and health officials to this increase in allergic reactions to latex, particularly among health care workers.

Consequently, there is an urgent need for a safe alternative to NRL emergency medical gloves. One attractive alternative to NRL had been nitrile, a copolymer of butadiene and acrylonitrile. This NRL-free product has been used extensively by glove manufacturers because nitrile gloves are extremely durable and extensible and permit the user to maintain excellent tactile discrimination. Because the patient often is not aware of having a latex sensitivity, our emergency medical personnel wear non-NRL, nitrile gloves (Intercept Elite Nitrile Gloves; FirstLine, LLC, Buelton, CA) to avoid eliciting an allergic reaction (26). These gloves comply with the stringent codes and standards established by the NFPA (27).

The testing procedures for NFPA approval for emergency medical gloves include well-defined conditioning procedures. After room temperature conditioning, the liquid type integrity test, biopenetration test, ultimate tensile strength, elongation and modulus test, puncture resistance test, and dexterity test are performed. Even though the nitrile examination gloves are thinner than the latex examination gloves, they exhibit a greater puncture resistance (27). Because the NFPA realizes the unique work conditions in emergency medical care, it has designed three special conditioning tests to evaluate glove performance that include accelerated heat aging, exposure to isopropanol, and flexural fatigue. It is important to emphasize that the glove hole leakage rate for emergency medical examination gloves is only 1%, compared to 4% for the hospital examination gloves approved by the FDA. Concerned about the dangers of NRL gloves with cornstarch, Legacy Healthcare System banned the use of cornstarch glove products in all of its hospitals in Oregon and Washington in 2001.

During closure of the traumatic wound, emergency personnel must wear sterile powder-free surgical gloves designed to protect them and their patients against transmissible deadly blood-borne viral infections. The FDA has set compliance policy guides for manufacturers of surgical gloves. The FDA allows surgeons’ gloves whose leakage defect rates do not exceed 2.5% acceptable quality level to be used in surgical wound closure. The implications of this policy are potentially enormous to EPs and their patients. This unacceptable risk to personnel and patients could be significantly reduced by the use of double surgical gloves. Because double-gloves are also accessible to needle puncture, a double-glove hole indication system was developed to detect surgical needle hole puncture (28). Molnlycke Health Care (Norcross, GA) has devised a powder-free NRL and nitrile double-
require no adjustment after repeated use. The loupes are designed to be coaxial to the EP’s line of sight and to conform to the interpupillary distance at a specific working distance. The individual’s refraction is incorporated into the loup’s oculars and the surrounding spectacle. Loupes with a 2.5× magnification incorporated into the spectacle are available with either the Galilean lens system (surgical telescope standard field) or the Keplerian system (surgical telescope expanded field). We prefer the Keplerian loupes, even though they are slightly heavier and longer than the Galilean loupes. This additional weight is not uncomfortable. The maximum field of view of the Keplerian telescope is 4.4 inches, allowing visualization of the entire laceration. Construction of knots with instruments can be easily visualized in this expanded field of view. The Keplerian lens system also provided a brighter and clearer peripheral image than the Galilean lens system (31).

Important considerations in the management of a wound are its location, configuration, biomechanical properties, and endogenous microflora. The level of endogenous bacteria (> 10^5) in the hairy scalp, axilla, foreskin, nails, mouth, perineum, and vagina is sufficient to be a potential source of infection. In the remaining skin regions, the microflora (10^2, 10^3) usually are sparse and not a possible source of infection. The unique biomechanical properties of the skin at the site of wounding also must be carefully evaluated (4).

Skin is an elastic membrane that is stretched across a bony framework by static skin tensions. Clinical evidence of these tensions is the retraction of the edges of traumatic lacerations, allowing visualization of the underlying tissue. The magnitude of pre-existing static tensions varies among individuals, at different sites in the same individual, and in different directions in many sites. Large differences in the magnitude of static skin tensions are readily apparent in various anatomic sites within the same person. The skin in one region may be relatively taut; in others it is lax. In a human volunteer, the estimated static skin tension of the arm skin subjected to high tension exhibits marked retraction of the skin edges and heals with wide scars. In contrast, wounds with minimal separation of their edges, being subjected to low static tensions, heal with fine, narrow scars.

When treating patients with gaping wounds with marked retraction of their edges, it is best to warn the patient that this wound may heal with a widened scar, necessitating revisional surgery 12 or more months after the injury. Because simple excision and closure of the widened, healed scar seldom gives a gratifying result, in contrast, W- and Z-plasties often result in a narrow scar, being subjected to lower tensions per length of wound perimeter than a straight scar. These scar revisions are best performed by plastic surgeons.

Dynamic forces have an important influence on static skin tensions. The dynamic tensions are caused by a combination of forces that are associated with joint movement, mimetic muscle activity, or gravity. The impact of these forces on the linear wound can be estimated by conducting rather simple measurements. Mark points A and B at the ends of the laceration and then points C and D, which are perpendicular and equidistant between points A and B. Measure first the distances between points A and B and then C and D before and after flexing the underlying joints or contracting the mimetic muscles of the face. If the distances between points A and B change considerably while C and D remain relatively stationary, the wound often will heal with an unattractive wide scar. If the reverse is true, the wound usually will heal with a narrow, imperceptible scar. The clinical significance of the dynamic changing skin tensions on the healing of scars can be best appreciated in wounds over joints. Scars in the direction of the transverse axis of the joint are imperceptible as compared to the hypertrophic scars that develop along its longitudinal axis. At a later date (> 12 months), the directional orientation of the scar can be altered by a W- or Z-plasty so that it follows more closely the direction of the lowest dynamic skin tensions.

**ANESTHETIZE THE WOUND BEFORE CLEANSING**

Patients with traumatic soft tissue injuries often complain of pain, which usually is localized to the site of the injury. Immobilization of the injured site reduces the discomfort. Cleansing of bacteria, soil, and other debris from traumatic injuries as well as surgical debridement cannot be accomplished without adequate analgesia, from either local anesthetization or procedural sedation. The patient’s natural response to cleansing of a non-anesthetized wound is withdrawal, making cleansing difficult. Many of the principles of pain management for children are identical to those used for adults (32).

Lidocaine hydrochloride (1%) is routinely used as the local anesthetic agent. Loss of sensation occurs within 5 min and lasts an average of 97–156 min. This agent does not damage local defenses, invite infection, or exhibit any demonstrable antibacterial activity that would limit the recovery of organisms from infected wounds. The amount of lidocaine administered should be limited to 4.5 mg/kg and not exceed 300 mg (30 mL of a 1% solution). When the duration of anesthesia must be prolonged, bupivacaine rather than lidocaine should be used because its duration for anesthesia is nearly four times longer than that of lidocaine (33). Vasoconstrictors, such as epinephrine, should not be used as adjuncts to anes-
thet agents injected directly into the wound. These agents exert deleterious effects on tissue defenses and potentiate the development of infection (34).

Treatment of the majority of lacerations may be performed under infiltration anesthesia using a no. 27 needle. The subcutaneous branches of the sensory nerves to the wound are anesthetized by the injection of 1% lidocaine into intact skin at the periphery of the wound. Injections by inserting the needle through the cut edge of the wound may be less painful.

Regional nerve block is a valuable clinical tool that can be safely mastered when the nerve is superficial in its anatomic location. Its clinical value becomes especially apparent when anesthetizing lacerations of the palm of the hand or the sole of the foot. Infiltration of a local anesthetic agent into this exquisitely sensitive skin is often deemed unbearable. Fortunately, the nerve supply of these anatomic regions is very susceptible to regional nerve block through more proximal skin, which has a considerably higher threshold to pain than skin of the palm or sole.

**HAIR REMOVAL, SKIN DISINFECTION, HEMOSTASIS, SURGICAL DEBRIDEMENT, AND MECHANICAL CLEANSING**

Hair is a source of wound contamination, and removal of hair prevents hair from becoming entangled in suture and the wound during closure. Hair removal can be minimized by clipping with scissors around the wound edges or by applying lubricant or ointments, such as bacitracin, to keep hair out of the wound edges. Eyebrows should never be removed as part of wound preparation. They provide an important landmark for the precise reapproximation of the divided tissue. Misalignment of the wound edges in an eyebrow may be exceedingly difficult to correct at a later date.

The infection rate in surgical wounds after razor preparation of the skin is significantly greater than that after hair removal by electric clippers (35). This increased incidence of infection after razor preparation is probably related to the trauma inflicted by the razor. Wounded hair follicles provide access to and substrate for bacteria. Surgical electric clippers cut hair close to the skin surface without nicking the skin. We use a surgical clipper with a disposable clipper blade assembly (Allegiance Healthcare Corporation, McGaw Park, IL) to remove extensive amounts of hair from the skin around the wound. Clipping hair immediately before wound repair has been associated with a lower risk of surgical site infection than shaving (36). The vast majority of ED lacerations, however, require no hair removal. Using sterile lubricant or bacitracin ointment to keep hair from entering the wound is often enough.

Disinfection of the skin around the wound by antiseptic agents should be initiated without contacting the wound itself. Two groups of antiseptic agents, containing either an iodophor or chlorhexidine, exhibit activity against a broad spectrum of organisms and suppress bacterial proliferation. The superiority of one antiseptic agent over another has not been shown. Although these agents can reduce the bacterial concentration on intact skin, they seem to damage the wound defenses and invite the development of infection within the wound itself (37). Consequently, inadvertent spillage of these agents into the wound should be avoided.

During any wounding process, blood vessels will be divided, resulting in bleeding into the wound. The magnitude of blood loss is directly related to the size of the divided vessels. Fortunately, most bleeding can be stopped by applying direct pressure to saline-soaked lint-free sponges placed within the wound. Rubbing or abrading the wound must be avoided, because this dislodges thrombi and may cause further bleeding. Bleeding from cut ends of large vessels whose diameter is over 2 mm can be stopped with a suture ligature of non-reactive synthetic absorbable braided suture materials. The divided end of the vessel should be isolated over a short length and clamped with a small curved hemostat. This technique is preferred over clamping the retracted vessel along with the contiguous bloodstained tissue. In the latter case, the amount of strangulated tissue is about five times greater than with the vessel-isolating technique.

Occasionally, as with a patient with a bleeding diathesis, primary wound closure cannot be accomplished due to persistent bleeding. In such cases, the wound should be packed with gauze sponges and elevated, if the anatomic site of the wound allows. The wound then should be reexamined within a few hours to determine if hemostasis is now sufficient to allow primary closure. Before closure, any residual hematoma should be evacuated from the wound because it can serve as a culture medium for bacteria.

Debridement removes tissue heavily contaminated by soil infection-potentiating fractions and bacteria, and excises devitalized tissues that impair the wound’s ability to resist infection. The capacity of devitalized fat, muscle, and skin to enhance bacterial infection is comparable (38). However, as little tissue as possible should be debrided. Devitalized soft tissue enhances infection by acting as an anaerobic culture medium promoting bacterial growth, and by inhibiting phagocytosis. Identification of the exact limits of devitalized tissue in wounds remains a challenging problem, especially in muscle. Viability of muscle can be determined by the “4C” guidelines (color, consistency, contraction, circulation).
Non-viable muscle is identified by its dark color, its mushy consistency, its failure to contract when pinched with forceps, and the absence of brisk bleeding from its cut surface. If delayed primary closure is considered, these clinical indicators of muscle viability are most accurate when the wound is examined 4–5 days after the initial wound repair.

The viability of skin is considerably easier to judge than that of muscle. At 24 h after injury, a sharp line of demarcation is often apparent between the devitalized and viable skin. For fresh skin wounds in which this demarcation is not precise, as little tissue as possible should be removed. In some anatomic sites, like the trunk, debridement is best accomplished by more complete excision of the skin and deep tissues. The soft tissues are usually free of specialized tissues such as nerves or tendons. In these regions, heavily contaminated wounds with serpiginous defects can be converted into clean wounds by more generous tissue excisions. The adequacy of debridement may be monitored either by forcibly packing the wound with gauze or by coloring the wound surface with a vital dye. Complete excision of the wound, back to a margin of normal tissue, is judged by dissecting in a plane that does not expose the gauze or the blue dye.

When a heavily contaminated wound contains specialized tissues, such as nerves or tendons, consultation is recommended. A specific exception to the general principle of removing all devitalized tissue is made in treating specialized tissues that perform important physical functions, regardless of their viability. Tissues like dura, fascia, and tendon may survive as free grafts without living cells if immediately covered by healthy pedicle flaps. Cells from the wound may then invade the graft as part of the healing process. If these tissues can be rendered clean, they should be left in the wound.

After debridement, the selection of wound closure technique is dependent on the level of wound contamination and the amount of residual devitalized tissue. In wounds contacted by gross pus or feces, an infective dose of bacteria often remains on the wound surface despite the most aggressive wound cleaning. Infection can be minimized by utilizing delayed primary closure of the wound before granulation tissue forms: 5–7 days. If the wound is not clean at this time, a further delay in closure is warranted, and the wound can be closed secondarily; after granulation tissue is formed. If the wound is still not clean, it should not be closed, but allowed to heal by tertiary intent. As the wound heals, it gains increased resistance to infection, permitting closure on or after the fourth post-wounding day without subsequent infection. For high-energy depositor missile injuries, tissue injury is extensive and difficult to ascertain accurately soon after injury. In these cases, the wound should be explored in the operating room to remove devitalized tissue and foreign bodies, to rule out damage to vessels and nerves, and to relieve increased compartmental pressure that may follow edema or slow bleeding into a fascia-enclosed muscle compartment. Open wound management is the method of choice with delayed primary or secondary closure.

Traumatic wounds resulting from impact injuries usually contain devitalized tissue that is easily recognized. Debridement, cleansing, and antibiotic treatment usually convert these wounds into clean wounds that are amenable to primary closure. Debridement of skin and underlying tissue leaves a significant soft tissue defect that resists reapproximation. As a result of strong static skin tensions on the edges of the debrided wound, repair is accomplished with a wide scar. In general, extensive wound debridement is best performed in an operating room with adequate lighting and surgical instruments.

Mechanical forces are employed to rid the wound of bacteria and other particulate matter that is retained on the wound surface by adhesive forces. The techniques used are irrigation and scrubbing. Low-pressure irrigation can be used for clean wounds, and high-pressure irrigation should be reserved for dirty or heavily contaminated wounds. High-pressure irrigation is defined as 7 psi (pounds per square inch) and low-pressure as 0.5 psi (39).

The magnitude of the hydraulic forces is a function of the relative velocities and the configuration of the particle. When subjected to the same irrigating stream, particles with a smaller frontal surface area experience less force than particles with a similar configuration, but with a greater surface area. Consequently, it takes significantly smaller hydraulic pressures to rid the wound of large foreign bodies than it does to remove small particles and bacteria.

The level of hydraulic forces experienced by the particle is also increased considerably as the velocity of the irrigating stream is raised. The simplest and most practical methods of increasing the velocity are to increase the pressure within the irrigating syringe, and to reduce the internal diameter of the needle or catheter. The pressure experienced by a wound surface from fluid delivered from a 19-gauge needle and 35-mL syringe is 7 psi. In contrast, the pressure encountered by a surface irrigated by a bulb syringe is only 0.5 psi. The bacterial removal efficiency of the irrigating stream is proportional to the pressure experienced by the wound surface. High-pressure irrigation with a 35-mL syringe attached to a 19-gauge needle operated manually by one hand effectively decreases the level of bacterial contamination (40). The cleansing effect of the bulb syringe irrigation is negligible because the wound bacterial concentration is not significantly affected by this low-pressure irrigation sys-
tion of bacteria into soft-tissue wounds. However, the irrigation fluid disseminates into the interstices of the wound, predominantly in a lateral direction. This lateral spread occurs within the loose areolar tissue, contributing to the development of post-operative edema. Consequently, high-pressure irrigation may make the wound more susceptible to infection, so this technique should be reserved for contaminated wounds. Contaminated wounds will benefit from irrigation, but should not be closed primarily.

The occupational risk to the EP of exposure to bloodborne viruses by virtue of accidental splashing of the irrigant is another potential complication. Several techniques, such as cupping the double gloved hand around the wound and irrigating through the space between the thumb and index finger, are recommended to reduce splatter. Recently, a cuplike device was marketed to prevent splatter while allowing irrigation with appropriate pressures. Another solution to splashing is to position the tip of the needle perpendicular to and in contact with the wound surface. The intimate contact of the needles with the wound diminishes splashing and ensures that the maximum wound irrigation force is used to decontaminate the wound.

Although scrubbing is an effective means of removing bacteria from wounds, tissue trauma inflicted by scrubbing impairs the wound’s ability to resist infection and allows residual bacteria to elicit an inflammatory response (41). Sponges with a low porosity are more abrasive and exert more damage to the wound than sponges with a higher porosity. We have found that the addition of a non-toxic surfactant, poloxamer 188 (Shur-Clens®, ConvaTec Professional Surfaces, Skillman NJ), to a fine-pore-size sponge, minimizes the tissue damage it inflicts while maintaining the bacterial removal efficiency of mechanical cleansing (42). Shur-Clens® is so innocuous that it does not irritate the patient’s conjunctiva. This wound cleanser does not alter the wound’s resistance to infection and healing, or the cellular components of blood. However, it exhibits no antibacterial activity. Exposure of the wound to either Hibiclens™ (Mölnlycke Health Care US, LLC; Norcross, GA) or Betadine® (Purdue Products L.P., Stamford, CT) surgical scrub solution has been shown to damage tissue defenses, and cause pain or irritation to tissues.

Embedded foreign debris should be removed as soon as possible. Removal of embedded foreign particles requires either local or regional anesthesia. A natural-fiber scrub brush soaked in saline or Shur-Clens® removes the embedded debris from most wounds. When the embedded particles remain in the wound despite wound cleansing in the ED, the patient should be transferred to the operating room to remove the particles.

ANTIBIOTICS, DRAINS, AND OPEN WOUND MANAGEMENT

The relative success of antibiotic therapy in the prevention of infection in wounds is influenced by the time of administration, the concentration of bacteria in the wound, the presence of soil infection-potentiating factors, and the mechanism of injury. In laboratory and clinical studies, antibiotic therapy is significantly more effective when the drug is administered immediately. Delay in antibiotic treatment diminishes its therapeutic merit. When there is an unavoidable delay in administering these drugs, the length of time during which the wound is left open becomes significant. Exposure causes a sequence of events that substantially limits the therapeutic value of antibiotics.

When any wound is left open, its vessels exhibit a marked increase in vascular permeability. Fluids from the intravascular space extravasate and fill the wound crater (2). This exudate is rich in a wide variety of proteins, including fibrinogen. Once outside the vessels, much of the protein exudate is reabsorbed and partly polymerizes to form fibrin. This resulting fibrinous coagulum surrounds the bacteria and protects them from contact with the antibiotic. The cause of this exaggerated inflammatory response in the open wound has not been defined. However, it may be related to environmental conditions. The temperature of the ED is usually consid-
erably below the systemic body temperature, encouraging loss of heat from the wound. In addition, evaporation of fluid from the wound surface results in further heat loss and cooling of the tissues. A consequence of fluid heat loss from the wound is desiccation. Warming the treatment room or covering the wound with wet sponges should reduce these environmental effects. Paradoxically, the fibrinous wound coagulum, which limits the effectiveness of antibiotics, may be a crucial positive factor in the host’s defense against infection. The coagulum may serve as a plug in the open mouths of lymphatics, preventing dissemination of bacteria. Occlusion of lymphatics by the coagulum then becomes an obstacle to the invasion of bacteria and, in part, accounts for the resistance of an open wound to systemic sepsis. This surface coagulum may be disrupted by mechanical forces. Gentle scrubbing of the surface of the wound with a gauze sponge disturbs the fibrinous cover and allows an antibiotic to gain intimate contact with the bacteria. Consequently, the therapeutic effectiveness of antibiotics is measurably enhanced by this treatment.

Antibiotics must be administered to patients with wounds in which the magnitude of tissue injury is extensive and difficult to ascertain accurately soon after injury. In such cases, open wound management is the method of choice, with subsequent additional debridement as dictated by the appearance of the wound. Antibiotic therapy is an adjunct to debridement, rather than a replacement. In all missile injuries, adequate blood levels of penicillin or an antibiotic (cephalasporin) with a similar spectrum of activity should be established as soon as possible after wounding to prevent streptococcal bacteremia. Streptolysin produced by the virulent streptococcal species breaks down the fibrin that has been deposited in the body in an attempt to wall off collections of bacterial pathogens (43).

Drainage evacuates potentially harmful collections of certain fluids, such as pus and blood, from wounds. In instances in which no definite localized fluid exists, drainage is prophylactic and its potentially harmful effects become more important. Drains act as retrograde conduits through which skin contaminants gain entrance into the wound. Placement of drains within experimental wounds exposed to subinfective inoculations of bacteria greatly enhances the rate of infection compared with undrained controls (44). In our experiments, both Silastic and Penrose drains dramatically increased the infection rate of soft tissue wounds. The rate of infection when the drain is brought out through the wound is similar to the rate when the drain lies entirely within the wound, suggesting a deleterious effect from the drain per se.

The timing of the closure is critical. A decision must be made as to whether the closure should be immediate or delayed. Immediate closure should be reserved for traumatic wounds that have not been contacted by feces, saliva, purulent exudate, or soil infection-potentiating fractions. Immediate approximation of the skin edges of this group of wounds should be accompanied by an extremely low infection rate (< 5%, regardless of the closure technique employed). Open-wound management with delayed primary closure is recommended for wounds that exhibit a high risk for infection after primary closure. The fundamental bases for delayed primary closure were the experiences of military surgeons who learned repeatedly over the centuries that immediate closure of battle wounds frequently results in infection (45). These wounds are best left open until delayed primary closure can be undertaken 4 days after traumatic injury. All wounds resulting from missile injuries, regardless of their appearance, are candidates for delayed primary closure. In these cases, the wound should be explored to remove foreign bodies, to rule out the presence of damage to specialized structures (e.g., vessels, nerves), and to relieve increased compartmental pressure that may follow edema or slow bleeding into a fascia-enclosed muscle compartment. The removal of devitalized tissue is advisable, but in practice is difficult, as its definition is unclear. Wounds contacted by feces, saliva, purulent exudates, or soil infection-potentiating fractions are also candidates for open wound management. Because a delay in wound care that lasts longer than 6 h in compromised tissue is associated with an increased risk for infection, open-wound management is also an option.

The rationale for delayed primary closure is that the healing open wound will gain resistance to infection and permit an uncomplicated closure. The reparative process of open wounds associated with this developing resistance to infection in the open wound undergoing primary closure is associated with accelerated skin healing. In addition, Johnson and co-workers showed that secondary closure of the subcutaneous tissue and skin results in stronger fascial strength than that encountered after primary closure (46).

Although the type of open-wound management must be individualized for each wound, aseptic technique is mandatory. For an infected wound filled with purulent discharge, the major objective is to remove the inflammatory exudate that will interfere with wound repair. Packing the wound with sterile gauze is a reliable method of absorbing the purulent exudate from the crevices of the wound. Periodic dressing changes are usually necessary every 4–6 h until a granulating wound bed becomes evident. The presence of residual necrotic tissue, foreign bodies, or soil infection-potentiating fractions demands additional meticulous debrideaments as dictated by the appearance of the wound. This reinspection of the wound with debridement must be continued until the wound is free of devitalized tissue and foreign
bodies. Management of wounds heavily contaminated by bacteria is accomplished by packing the wound with sterile, dry, fine-meshed gauze that is then covered by a sterile dressing. This wound should not be disturbed for the first 4 days after the initial cleansing operation, unless the patient develops an unexpected fever. Unnecessary inspection during this period increases the risk of contamination and subsequent infection. On or after the fourth day, the wound margins can be approximated with minimum risk of infection. The selection of the technique for delayed primary closure will be based on the same considerations as used in primary closure. If percutaneous sutures are selected for wound closure, they can be passed through the wound edges at the end of the initial procedure and left untied until the time of delayed primary closure. This step spares the patient the additional administration of a local or general anesthetic agent that is required for sutureal closure. The occasional wound that is destined to develop infection after delayed closure can be identified with quantitative microbiology. When the bacterial count of the tissue is lower than $10^5$ organisms/g of tissue, delayed closure can be accomplished without infection (46). After wound cleansing, the physical integrity and function of the injured tissue must be restored. The technique of wound closure selected depends on the type of wound. Primary closure can be accomplished with clean wounds without tissue loss.

CONCLUSIONS

Our investigations of the mechanism of wound injury, soil infection-potentiating factors, dynamic and static tensions have become important predictors of the outcome of wound repair. In Part I of this collective review, we have highlighted the first six steps that are necessary to achieve trauma wound repair with the lowest incidence of wound infection.

The first step is the proper evaluation of the patient using an expeditious but comprehensive assessment. These life-threatening issues must take precedence over any wound repair concerns. External bleeding almost always can be controlled by direct pressure over the site of bleeding.

Before inspecting the wound, the EP must carefully question the patient regarding the timing and mechanism of injury. The time in which the accident occurred has considerable influence on wound management decisions. It is essential that the EP continually examine the wound using aseptic techniques. The EP must wear powder-free latex-free gloves. Sterile, powder-free surgical gloves should be used during wound management. Although not commonly used, magnifying lenses should be considered to enhance the EP’s visualization of the wound.

Cleansing bacteria, soil, and other debris from traumatic wounds, as well as surgical debridement, cannot be accomplished without adequate analgesia, from either local anesthesia or procedural sedation. Lidocaine hydrochloride (1%) is routinely used as a local anesthetic. Regional nerve block is a valuable clinical tool that can be safely mastered when the nerve is superficial in its anatomic location.

Hair removal with electric clippers before wound repair has been associated with a lower risk of surgical infection than shaving. Bleeding from cut ends of large vessels whose diameter is $>2$ mm can be stopped with a suture ligature of non-reactant synthetic absorbable braided suture materials. Debridement removes tissue heavily contaminated by soil infection-potentiating fractions and bacteria, and excises devitalized tissues that impair the wound’s ability to resist infection. Identification of the exact limits of devitalized tissue in wounds can be challenging, especially in muscle. However, the viability of muscle can be determined by the “4C” guidelines (color, consistency, contraction, circulation). If delayed primary closure is considered, these clinical indicators of muscle viability are more accurate when the wound is examined 4–5 days after the initial wound repair. Mechanical forces are applied to rid the wound of bacteria and other particulate matter that are retained on the wound surface by adhesive forces. The two techniques used are high-pressure irrigation and scrubbing with a non-toxic surfactant.

The relative success of antibiotic treatment in the prevention of infection in wounds is influenced by the time of administration, the concentration of bacteria in the wound, the presence of soil infection-potentiating fractions, and the mechanism of injury. Antibiotics must be administered to patients with wounds in which the magnitude of tissue injury is extensive and difficult to ascertain accurately soon after injury. In such cases, open wound management is the method of choice, with subsequent additional debridement as dictated by the appearance of the wound. Drainage evacuates potentially harmful collections of fluids, such as pus and blood, from wounds. In instances in which no definite localized fluid exists, drainage is prophylactic and its potentially harmful effects become more important.

REFERENCES
