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# Thermal and Electrical Injuries

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Modern burn care has been characterized by substantial increases in survival and improvements in functional outcomes for burn patients over the past 30 years. Twenty-first century optimal burn care consists of a specialized treatment scheme that incorporates early surgical wound closure, critical care management, and rehabilitation efforts. The success of burn treatment as a multidisciplinary model has fostered the organization of burn centers as regional resources for severely injured patients, including individuals with large open wounds.

The review in this article and the Burn Care Guidelines published by the American Burn Association both illustrate the need for Class I evidence to support standards of burn care [1]. In many cases, our practices are based on years of Class II evidence from small clinical trials. Multicenter research collaborations, such as the National Institutes of Health–funded genomics project "Inflammation and the Host Response" (http://www.gluegrant.org), have begun to codify standards of practice that should pave the way for improved future multicenter clinical trials [2,3].

## Acute burn care

### *Burn wound management*

Early eschar excision for massive burn injuries has had the greatest impact on burn patient survival by reducing the incidence of wound sepsis, hypercatabolism, numbers of operations, and hospital lengths of stay [4–6]. Wounds that take longer than 3 weeks to epithelialize typically heal with excessive scarring and contractures that produce aesthetic and functional impairment. Clinicians must be able to anticipate the healing potential of

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a fresh wound to weigh the relative risks and benefits of excision and grafting of the burn wound. An accurate estimation of burn depth is paramount to proper wound management. An experienced burn provider usually can identify shallow or full-thickness wounds based on clinical grounds alone. Intermediate dermal injury (''indeterminate'' burn) poses the greatest challenge. Unfortunately, several studies indicate that initial evaluation even by an experienced surgeon may be only 50% to 70% accurate as to whether an indeterminate dermal burn will heal within 3 weeks [7–9].

Investigators have searched for an objective adjunct to clinical judgment so that patients with indeterminate burns with poor healing potential also may benefit from early excision. Various techniques attempt to quantify physical changes associated with skin injury, such as the presence of denatured collagen, wound edema, and an altered blood flow pattern [10–13]. The most recent development in this field is noncontact laser Doppler imaging, which records the reflectance shift of moving red blood cells in the dermal capillary plexus to provide a color perfusion map of the wound [14]. Theoretically, reduced dermal blood flow portends a low likelihood of healing and could prompt a clinician to operate sooner. This technique is well tolerated by patients and avoids the artifact of pressure on the wound with the scanning device held at a distance. Noncontact laser Doppler imaging examinations can be repeated serially over the first several days after burn as wound bed perfusion evolves throughout the resuscitation phase. Indeterminate dermal burns may become progressively deeper several days after injury (a process termed ''wound conversion'') as healing potential is affected by perfusion, edema, and infection [15]. Wound conversion, however, is minimized when a patient receives adequate fluid resuscitation and proper wound management [16]. Although promising, noncontact laser Doppler imaging has not yet demonstrated consistent reproducibility and has been no more reliable than experienced burn surgeons [17–19]. It has not been incorporated into the mainstream of burn care.

Although full-thickness and deep dermal burns are best excised within the first week after injury, more superficial wounds may be treated with topical agents until they heal or have demonstrated that they will not heal within 3 weeks. An ideal dressing should be comfortable for the patient, easy to apply and remove, conform to the wound, be relatively cheap, and require infrequent changes. Biologically, it must provide a moist wound environment, limit growth of micro-organisms with good eschar penetration, have no or minimal systemic effect, and débride devitalized tissue as needed. Currently, such universal dressing does not exist; however, not all wounds require these features. Small shallow burns, for example, do not require dressings with antimicrobial activity. Greasy gauze is appropriate for shallow dermal burns. A recently marketed ointment containing β-glucan (Glucan-Pro, Brennan Medical, St Paul, Minnesota), a carbohydrate derived from oat, may be appropriate for shallow wounds because it is soothing and mitigates itching. β-glucan may have an immunomodulatory effect by

stimulating macrophage activity [20,21]. β-glucan is also available as a dressing (Glucan II, Brennan Medical, St Paul, Minnesota) and is a favored dressing for donor sites at many centers across the United States [22,23].

Biologic dressings may enhance partial-thickness injury healing. Their proposed benefits stem from infrequent dressing reapplication, improved patient comfort, and topical administration of growth factors. A growing list of biologic dressings has been approved by the US Food and Drug Administration, with several more undergoing clinical trial. In larger burns in which cost is a limiting factor and outpatient therapy is not feasible, human cadaver skin and porcine skin remain good choices for temporary biologic dressings. Table 1 lists frequently used biologic and nonbiologic dressings for burn wounds.

Antibiotic activity becomes more relevant in dressings for deeper wounds, because they are more prone to infection. The most common

Table 1
Commonly used dressings for burn wounds, skin grafts, and donor sites

| Dressings | Category | Examples | Appropriate indications |
|---|---|---|---|
| Nonbiologic | | | |
| | Petrolatum | Xeroform, Xeroflo, Adaptic, Aquaphor gauze | Partial-thickness burns, skin grafts, donor sites |
| | Silver | Acticoat, Acticoat-7, Aquacel-Ag, Silvasorb | Partial-thickness burns, skin grafts, donor sites |
| | Polyurethane | OpSite, Tegaderm | Partial-thickness burns, donor sites |
| | Foam | Lyofoam | Partial-thickness burns |
| | Silicone | Mepitel | Partial-thickness burns, skin grafts, donor sites |
| | Negative pressure therapy | Wound VAC system | Skin grafts |
| Biosynthetic and biologic | Oat | Glucan II | Partial-thickness burns, skin grafts, donor sites |
| | Collagen and fibroblasts | Transcyte, Apligraf | Partial-thickness burns |
| | Collagen, fibroblasts, and keratinocytes | OrCel | Partial-thickness burns |
| | Allograft (cadaver) | Fresh or cryopreserved | Partial-thickness burns |
| | Xenograft | Porcine skin, porcine intestinal submucosa (Oasis) | Partial-thickness burns |

topical antimicrobial agent for deeper dermal burns is silver sulfadiazine (Thermazine, King Pharmaceuticals, Bristol, Tennessee). Silver is effective against a broad spectrum of gram-positive and gram-negative organisms, including most types of *Staphylococcus aureus* and *Pseudomonas aeruginosa* [24]. It has been incorporated in commercially available dressings, such as Acticoat (Smith and Nephew, Largo, Florida) and Aquacel-Ag (ConvaTec, Princeton, New Jersey) [25,26]. Both products can be used to cover partial-thickness burns, meshed skin grafts, and donor sites.

Ideally, when a burn wound is excised, the wound bed should be replaced with full-thickness autograft skin; unfortunately, full-thickness skin availability is limited by the number and size of full-thickness donor sites that can be primarily closed [27]. Whenever possible, split-thickness sheet grafts should be applied as sheet grafts to maximize function and aesthetics [28]. The standard practice of expanded meshed split-thickness skin autograft achieves wound closure over larger areas, but its disadvantages include fragile wound beds, suboptimal appearance, reduced pliability, and scarring. In patients with large burns, serial harvesting (''recropping'') of donor sites may be necessary with larger body surface injuries; one must wait for donor sites to heal, and subsequent skin grafts are thinner and of lesser quality. In the meantime, fresh or cryopreserved cadaver (allograft) skin can be used as a temporary biologic dressing over the excised burn wound bed. Taken together, the current process of partial-thickness autografting for large burns yields suboptimal results for burn wounds covered with widely expanded skin grafts and the reharvested donor sites. The recognition of current limitations has created an impetus for research on commercially available skin substitutes.

There are two general classifications of skin substitutes: cultured epidermal grafts and dermal substitutes. Several caveats exist regarding use of skin substitutes for permanent wound coverage. Cultured epithelial autografts have limited use as a stand-alone replacement because they provide a thin and fragile sheet of keratinocytes that frequently sheer and offer little durability [29–31]. Although epithelial allografts may be suitable as biologic dressings, they cannot be used as skin substitutes because they are ultimately rejected by the recipient's immune system. The dermis determines optimal engraftment and graft durability. In vitro autologous dermal regeneration has not been achieved with current available technology. Providing a dermal layer for wounds requires an exogenous matrix template. Integra (Integra LifeSciences Corp., Plainsboro, New Jersey) is a dermal replacement template comprised of an inner matrix layer of bovine collagen and shark glycosaminoglycan, adhered to a silicone outer layer [32–34]. The inner layer forms a scaffold for in situ dermal regeneration while the outer layer contains water vapors and provides a physical barrier to the outside environment. After approximately 2 weeks, the neodermis is sufficiently vascularized to accept a thin partial-thickness autograft (0.06 in thick) [35]. Although Integra is relatively fragile and susceptible to infection,

sufficient longitudinal experience in several centers suggests that consistently good results with this product are possible [32,36–38]. An acellular cryopreserved cadaver dermis (AlloDerm, LifeCell Corporation, Branchburg, New Jersey) also has been marketed as a dermal replacement, but clinical endorsement for this product as an acute burn wound replacement remains limited [39,40]. Boyce and colleagues [41] reported on a promising new approach of maturing the epidermal-dermal skin substitute in vitro by culturing autologous keratinocytes on a collagen matrix. The composite skin replacement is applied to the wound 2 to 3 weeks after harvesting autologous skin; in the meantime, the wound bed can be prepared with another layer of dermal substitute. If successful, this strategy could reduce the problem of shearing seen with application of cultured cells directly onto a wound bed and increase the elasticity, pliability, and function of the wound bed.

*Fluid resuscitation*

Judicious fluid resuscitation is one the greatest challenges in the care of acutely burned victims. Burn injuries over more than 20% of surface area result in increased capillary permeability and edema in burned and nonburned tissues. Vasoactive mediators from injured skin, such as histamine, prostaglandins, and oxygen-free radicals, mediate a massive capillary leak syndrome that typically lasts for 24 hours after injury [42]. Burn shock is characterized by persistent hypovolemia that demands continuous intravenous fluid rate modification over the first 24 to 48 hours of hospitalization. Several formulas developed over the past 50 years to estimate patient fluid needs have been based on body weight and burn surface area. Each formula differs on the amount and type of crystalloid and the necessity for colloid infusion during resuscitation. The most widely used formula in adults is the Parkland (or Baxter) formula [43], which calls for the infusion of 4 mL/kg/% total body surface area (TBSA) burn lactated Ringer's solution for 24 hours. Half of the volume should be administered over the first 8 hours and the other half during the next 16 hours. Throughout this period, the clinician must continuously re-evaluate patient response to resuscitation and titrate the fluids to achieve a mean arterial pressure of more than 60 mm Hg and urine output of more than 30 mL/h. In children, low glycogen stores and maintenance fluid needs should be addressed by augmenting the resuscitation fluid with an isotonic maintenance solution that contains dextrose. Controversy persists among burn specialists over the use and timing of colloids. Animal studies suggest that capillary permeability is maximal within the first 8 to 12 hours and may be exacerbated by colloid administration [42,44]. Centers that routinely use colloids generally administer them later in the resuscitation phase.

Deep burns, inhalation injury, comorbid illnesses, associated injuries, and delay in resuscitation are recognized to increase fluid requirements [45]. Formulas only serve as initial guidelines, and maintenance of urine

output (0.5 mL/kg/h in adults and 1 mL/kg/h in children) is the best surrogate marker of adequate end-organ perfusion. Not satisfied with crude reliance on urine output, many investigators have sought to improve goal-directed therapy during resuscitation. Despite the appeal of invasive hemodynamic monitoring and the natural desire to augment oxygen delivery, a well-designed prospective randomized trial failed to show any advantages to preload-driven resuscitation [46]. Patients who were given preload-driven resuscitation had equally low central filling pressures and intrathoracic blood volumes compared with patients on the Parkland formula. The authors concluded that the additional fluid volume (60% over initial calculations) administered to the ''preload'' group leaked out of the intravascular space and contributed to peripheral edema.

Although Dr. Baxter repeatedly stressed that most patients could be resuscitated with 3.7 to 4.3 mL/kg/% TBSA burn, recent reports describe average resuscitation volumes significantly exceeding predicted needs, as high as 8 mL/kg/% TBSA [47,48]. This phenomenon has been termed ''fluid creep.'' Proposed explanations for this discrepancy include not reducing fluid rates when urine outputs exceed 0.5 mL/kg/h, relying on invasive monitors to guide resuscitation, and administering larger doses of opioids to control burn pain (termed ''opioid creep'') [49]. It may be possible that the nature of burn injuries and inhalation injuries has evolved; patients who have been in methamphetamine explosions may exemplify this evolution, because they typically require large resuscitation volumes [50]. Whether higher fluid administration correlates with improved survival is unclear. Compared with the mid-twentieth century, acute renal failure, a common sequela of underresuscitation, is uncommon when resuscitation is initiated early and death because of failed resuscitation is even rarer. Excessive volume resuscitation generates its own complications. Edema may become severe enough in unburned extremities that escharotomies and, occasionally, fasciotomies become necessary [51]. Lung tissue edema may lead to acute respiratory failure [52]. Gut and mesenteric edema manifests as intra-abdominal hypertension; fascial release may be required to treat abdominal compartment syndrome [53,54]. Edema also may become symptomatic in the orbits, as evidenced by elevated intraocular pressures and need for lateral canthotomies [55].

Several strategies to mitigate ''fluid creep'' are currently being investigated. For instance, hourly urine output measurements have been criticized because hourly intervals are arbitrarily chosen for convenience. A recent animal study suggested that an automated closed-loop system that adjusts fluid administration to continuous urine output measurement may decrease fluctuations based on human interventions [56]. Such systems could be adapted with additional inputs, such as blood pressure or base deficit measurements, to guide resuscitation needs. Considerable interest also exists in antioxidant therapy, because membrane lipid peroxidation and oxygen-free radicals are major components of burn shock physiology [57]. Animal and

clinical studies suggest that antioxidants reduce fluid requirements and burn wound edema during resuscitation [58,59]. Early administration of tocopherol and ascorbate in critically ill surgical trauma patients also shortens the duration of mechanical ventilation and decreases the incidence of multiorgan failure [60]. Antioxidant therapy as an adjunct to burn resuscitation mandates large-scale multicenter prospective validation before it should be accepted as standard of care. Another interesting strategy is plasma exchange, which theoretically removes inflammatory mediators circulating in the systemic circulation. Although Warden and colleagues [61] described the use of plasma exchange to salvage patients who were failing resuscitation more than 20 years ago, confirmatory studies to explain its salutary mechanisms or clinical benefits are still lacking.

*Inhalation injury and intensive care management*

Airway burn injuries can be divided into two types: upper airway thermal injury and lower airway chemical injury. Carbon monoxide poisoning is more accurately categorized as a systemic intoxication with the lung as a portal of entry. Clinicians often group all three into ''inhalation injury'' because all three insults may coexist, for example, in a patient who has been in a closed-space fire. The diagnosis of an upper airway burn can be made readily by assessment of hoarseness or stridor and examination of the posterior pharynx for edema or mucosal slough. Injuries to the lower airways can be diagnosed by direct visualization (fiberoptic bronchoscopy), suggestion of a ventilation/perfusion mismatch (xenon scan), or radiographic evidence of small airway inflammation and obstruction (CT scan) [62–64]. Xenon scanning is mostly of historical interest, and additional information obtained via CT scan is of questionable clinical value. The transport of patients to the radiology suite with ongoing resuscitation is cumbersome and at times hazardous. Although bronchoscopy confirms a clinical diagnosis of inhalation injury, it rarely alters clinical management.

The diagnosis of carbon monoxide poisoning can be measured easily with a serum carboxyhemoglobin level. Administration of 100% oxygen reduces the half-life of carboxyhemoglobin from 4 hours (on 21% $O_2$) to approximately 45 minutes. In practice, many patients with carbon monoxide poisoning have normalized values upon arrival to the burn center. Proponents of hyperbaric oxygen (HBO) therapy have argued that hyperbaric chamber treatment lessens long-term neurologic sequelae, even with normal pretreatment carbon monoxide levels. Two prospective randomized trials of HBO therapy have yielded conflicting results [65,66]. Scheinkestel and colleagues [65] described sequential chamber treatments over 3 to 6 days, with hyperbaric-treated individuals performing worse on neuropsychological testing compared with normobaric treatment. Conversely, Weaver and colleagues [66] used a treatment algorithm consisting of three HBO treatments within 24 hours of enrollment and reported that cognitive

impairments were less frequent at 6 weeks in the HBO group and persisted at 1-year follow-up. The first study specifically excluded burn patients, whereas the second report apparently did not include major burn injuries, as evidenced by few being patients hospitalized (14%) or requiring mechanical ventilation (8%). The presence of a major burn requires careful fluid resuscitation, whereas mechanical ventilation imposes an additional logistical challenge for patients placed in HBO chambers. In our own experience, severely burned victims with concomitant carbon monoxide poisoning experience high complication rates when HBO therapy is attempted [67]. HBO treatment for carbon monoxide poisoning in patients probably should be limited to patients with burn injuries smaller than 15% TBSA.

Patients with lower airway inhalation injury are at risk for developing acute respiratory distress syndrome because of direct airway injury coupled with increased volume resuscitation requirements. Although an optimal ventilation strategy for inhalation injury remains to be defined, many burn centers have adopted the use of lower tidal volumes and reduced airway plateau pressures to treat acute respiratory distress syndrome based on compelling data from the Acute Respiratory Distress Syndrome Network group [68]. Although ''prophylactic'' use of a lung protective ventilation strategy in inhalation injury is an appealing concept, previous efforts have failed to show clinical benefits in patients at risk for acute respiratory distress syndrome [69]. For the small number of patients who oxygenate poorly on conventional settings, high-frequency oscillatory ventilation can improve oxygenation dramatically while acute respiratory distress syndrome resolves [70,71]. Several pharmacologic means to minimize airway narrowing, prevent airway obstruction, and improve clearance of debris have been shown to have variable success in animal models of lower airway inhalation injury. These strategies include mucus fragmentation (N-acetylcysteine), bronchodilation (β2 agonists, nitric oxide), clot dissolution (antithrombins, tissue plasminogen activator, and heparin), flow turbulence reduction (partial liquid ventilation), and inhibition of inflammation (steroidal and nonsteroidal anti-inflammatory agents) [72–77]. Widespread adoption of any of these agents awaits confirmation with level I evidence.

Prolonged mechanical ventilation often complicates the care of large burns, with or without inhalation injury. The debate over tracheostomy compared with translaryngeal intubation remains unresolved, because there are no prospective studies with appropriate side-by-side comparison [78–81]. For any benefit of tracheostomy to be realized, this procedure should be performed early in the patient's course. Predictors of successful ventilator weaning are often inaccurate, however, and tracheostomy can be a morbid procedure. Outcome comparison is also difficult because all patients with tracheostomy are cross-over from the translaryngeal intubation, and an accurate assessment of long-term tracheal complications can be made only by fiberoptic laryngoscopy on all patients studied. It is likely that individual burn centers will remain entrenched either on the conservative or aggressive

side of the tracheostomy debate. Given the absence of Class I evidence, recommendations for airway management must include options rather than standards of clinical care.

*Anemia*

Hospitalized burn victims become anemic because of hemodilution, relative bone marrow suppression, and frequent laboratory draws. Early eschar excision, currently widely accepted as a standard of burn care in North America, traditionally has been associated with significant operative blood loss [82]. Blood transfusion is a life-saving treatment in some circumstances but has potential drawbacks, such as viral transmission, transfusion reactions, and immunosuppressive effects. ''Passenger'' leukocytes present in transfused packed red blood cell units are critical components of immune modulation [83]. Transfusion of leukocyte-depleted blood reduces the incidence of infection in postoperative cardiac and noncardiac surgery patients [84,85]; however, the validity of this approach in the injured patient remains to be established. In a multicenter retrospective study on blood use in burn centers, Palmieri and colleagues [86] reported that patients with burns over 20% received on average 14 units of packed red blood cells over the course of their hospitalization, and they suggested that transfusion requirements independently increased the risk of infections and mortality. Methods developed to reduce intraoperative blood loss include use of tourniquets, compression wrappings and elevation for extremities, application of hemostatic agents and epinephrine-soaked pads to excised wounds, and subcutaneous infusion of dilute epinephrine under the eschar and donor sites [82,87]. With accumulating data underscoring the safety of relative anemia (hemoglobin of 7 g/dL) in critically ill patients [88,89], burn centers are gradually accepting lower steady-state hemoglobin levels outside the operating room. The current trend is to adopt a restrictive transfusion policy based on individual patients' demonstrated needs.

The necessity for prophylaxis of deep venous thromboses and pulmonary emboli in burn patients remains unresolved. Although thromboembolic disease was historically viewed as a rare occurrence in burn patients, recent reports document a varying incidence of deep venous thromboses/pulmonary emboli in this patient population proportional to the frequency of duplex ultrasound examinations, whether performed as a serial screening tool or selectively based on symptomatology [90–92]. Compression devices are of unproven value, and their application is poorly tolerated in individuals with lower extremity open wounds. Administration of heparin and related compounds must be weighed against their side-effects. Most notably, heparin-induced thrombocytopenia has emerged as a recognized complication in the burn unit [93,94]. Heparin-induced thrombocytopenia is a severe prothrombotic state that is associated with dreaded complications, such as digit necrosis, limb loss, and even death. The efficacy of alternative

anticoagulation agents, such as low molecular weight heparin compounds and pentasaccharides, has not yet been evaluated. Large-scale prospective studies are needed before we are able to define the indications and the most efficacious agents for deep venous thromboses/pulmonary emboli prophylaxis in burn patients.

*Modulation of post-burn hypermetabolism*

Burn injuries over more than 25% TBSA are associated with a hypermetabolic state that develops over the first 5 days and persists until the wounds are completely healed. Sometimes it lasts up to a year after injury [95]. Protein catabolism is a particularly deleterious feature of this response: the loss of lean body mass is a barrier to rehabilitation for all patients and retards normal growth in burned children. Early surgical wound excision and skin grafting remains the most expeditious way to reduce the inflammatory burden posed by the wound. Routine care in the burn intensive care unit also should include specific daily management strategies to manage hypermetabolism. Maintenance of warm ambient temperatures (33°C) partially reduces the obligatory heat loss created by fever [96]. Nutritional supplementation must be instituted early in the patient's course, ideally during the resuscitation phase and before ileus develops. Enteral feedings initially can be based on estimated needs and subsequently adjusted by indirect calorimetry. The prevention, prompt diagnosis, and treatment of infections represent a daily challenge in burn patients. Control of infection also significantly reduces energy expenditure over a patient's hospitalization. Hyperglycemia is another marker of severe metabolic derangement and has been associated with worse outcomes in burn patients [97,98]. Two recent prospective, randomized evaluations by Van den Berghe and colleagues [99,100] have established that maintenance of euglycemia via continuous insulin infusion is desirable in critically ill patients because it decreases the incidence of infections and reduces mortality.

During the recovery phase, a rehabilitation program that includes exercise against resistance builds not only lean body mass but also muscle strength [101,102]. Pharmacologic agents that help preserve and restore lean body mass represent adjuncts in modulating post-burn hypermetabolism. Recombinant growth hormone (administered over 1 year) prospectively evaluated in a double-blind trial in children with severe burns suggested that children on growth hormone gained more lean body mass, height, and bone-mineral content than control subjects [103]. The benefits of growth hormone are not applicable to adults, because hyperglycemia is a common side effect in this group [104]. Oxandrolone, a testosterone analog, is an anabolic steroid with reduced virilizing potential [105,106]. A prospective trial of oxandrolone in children demonstrated improvement in net protein balance after 1 week of administration [107]. In a recently completed randomized, placebo-controlled trial, adults who received oxandrolone had

reduced lengths of hospital stay compared with patients on placebo [108]. Although many factors potentially impact length of stay, the study suggests a benefit to oxandrolone. Propranolol, a nonselective beta-blocker, reduces tachycardia, energy expenditure, and substrate cycling and prevents fatty infiltration of the liver [95,109]. In a randomized study of 25 children, Herndon and colleagues [110] demonstrated that propranolol attenuated the effect of hypermetabolism by reversing muscle protein catabolism. Beta-blockade also constitutes an attractive strategy for adults in which tachycardia is undesirable and less well tolerated in patients with pre-existing heart disease. Ongoing trials are indicated to evaluate the efficacy and safety of propranolol in adults.

*Electrical injuries*

Electrical burns represent a minority of admissions at major burn units but often cause severe morbidity beyond obvious skin injuries. In particular, high-voltage injuries (arbitrarily defined as $>1000$ V) may lead to temporary dysrhythmias in survivors, be associated with major blunt trauma, and cause deep tissue destruction. Other deficits may manifest themselves in a delayed fashion: two commonly described long-term sequelae are peripheral motor or sensory neuropathy and the appearance of cataracts [111,112]. Most patients with electrical burns are young men injured at work (eg, construction workers, electricians, and linemen). Injury and disability in this demographic group result in major loss of wages and significant medical costs [113,114]. No Class I evidence exists to support standardized management of electrical burns. Available guidelines recommend 24-hour telemetry monitoring for all patients with high-voltage injuries and for patients with low-voltage injuries who have an abnormal initial EKG [115]. Some data, however, suggest that monitoring high-voltage injuries with an initial normal EKG may be superfluous [116]. Deep electrical injuries generate rhabdomyolysis and myoglobinuria. In this setting, fluid resuscitation should be titrated to maintain a urine output of 100 mL/h until the urine clinically appears clear. Acute renal failure from myoglobinuria is rare unless resuscitation is delayed. Several methods have been proposed to enhance renal clearance of myoglobin, including alkalinization of urine and osmotic diuresis with mannitol [117]. These adjunct measures are of unproven value and represent individual centers' practices and will remain so until prospective evidence validates their benefit over simple isotonic crystalloid resuscitation.

Early fasciotomy or surgical débridement of necrotic muscle may be warranted when severe acidosis and myoglobinuria do not rapidly improve with aggressive resuscitation; management in a burn center in which these injuries can be monitored closely by a burn surgeon is optimal. Although most limbs can be salvaged with early diagnosis of compartment syndrome and compartment fasciotomies, major débridement and early amputation

occasionally may be necessary [118]. Although routine fasciotomy has been advocated, a review of national trends in management of patients with electrical burns supports selective decompression [119]. Mann and colleagues [113] reported that most patients with high-voltage injuries (70%) did not require emergent operation and no amputations were required in patients who were monitored. Monitoring consists of serial clinical assessments of tissue perfusion and peripheral nerve function in at-risk extremities. The use of technetium scan has not gained wide acceptance for it is overly sensitive in detecting deep tissue damage [120]. Fibrosis is the end of result of limited deep-tissue necrosis, whereas overly aggressive débridement may introduce infection and increase the risk of amputation.

## Rehabilitation and reconstruction

With an increasing number of survivors of major burn injuries, successful re-entry into society becomes the next major challenge. A coordinated burn center program that includes surgeons, physiatrists, pediatricians, occupational and physical therapists, vocational rehabilitation specialists, and psychologists is essential to successful rehabilitation. Perhaps because of their resilience and adaptive ability, children recover well even after major burn injury. Sheridan and colleagues [121] reported that most children treated at Shriners Burn Institute (Boston) who survived massive burns ($\geq$70% TBSA) became productive members of society. In their series however, 20% of patients had physical scores below norm; indicating that this subgroup had persistent sequelae. In adults, an important benchmark may be return to work. There is little information reported in the literature on this subject, however. A recent two-center review reported that median time off work approximated 12 weeks, and 90% of patients had regained employment by 2 years [122]. It is noteworthy that only 37% of patients returned to their preinjury job without accommodations. Several factors contributed to this finding: burn size, location of burns, and psychiatric history. A related but seldom reported outcome is impairment. Standard methods to calculate physical impairment are not widely used in burn care because they require either tedious calculations (whole person impairment rating) or initial investment in costly equipment ($27,000 for the Dexter Evaluation system) [123,124]. Psychological assessment is another important component of impairment rating. Efforts are underway in this arena to develop tools that are appropriate gauges of the quality of life in burn survivors. The ongoing multicenter collaborative Burn Injury Rehabilitation Model System Program funded by the National Institute of Disability and Rehabilitation Research has increased awareness among burn providers and patients about burn survivor needs; despite progress since its inception, much more can be done to improve our patients' return to function.

Reconstructive surgery is essential to the rehabilitation process because it helps restore function and body image. The problems of hypertrophic

scarring and contracture remain enormous challenges for reconstructive burn surgeons. Hypertrophic scars may develop in healed burn areas, grafted sites, and even donor sites. Commonly used preventive strategies aimed at reducing raised scars include pressure therapy, topical silicone gel application, and massage [125–127]. Well-designed prospective studies to support use of these modalities are lacking. Patients with large burns can expect to undergo several scar revisions over their lifetime, because each procedure results in small incremental gains in function and appearance. Current understanding of the pathophysiology of hypertrophic scarring unfortunately remains limited, because many previous studies have studied mature scars and not scars in evolution. A standard animal model for hypertrophic scarring does not yet exist. Recent laboratory efforts have focused on the female red Duroc pig as multiple laboratories attempt to validate similarities in skin healing between this model and humans [128–130].

## Access to burn care

The success of modern burn care, characterized by improved survival rates and return to preinjury function, is closely associated with the development of specialized burn centers. The burn center is not just "an area of the hospital" but a system of care that includes a specialized infrastructure, highly trained providers, and treatment algorithms that serve the unique needs of the burn victim. The burn center must be equipped to deliver all aspects of burn care, from initial management and acute surgical wound coverage, through rehabilitation and long-term reconstruction. Akin to other areas of medicine in which a relationship between volume and outcome has been established, the same appears true for burn centers. This process has driven regionalization of burn care in the past two decades, with many low-volume centers closing and seriously injured patients being referred to regional burn centers for definitive care. The American Burn Association has participated actively in this transformation by generating criteria for burn center referral (Box 1). The American Burn Association in association with the American College of Surgeons also has established a burn center verification program for approximately two decades. So far, 43 of the 139 listed burn centers in the United States have been certified by this process, and it is likely that they will continue to serve as centers of excellence for the foreseeable future.

Specialized burn care has created a demand for highly trained providers, including surgeons, nurses, therapists, psychologists, pharmacists, and rehabilitation physiatrists to form a multidisciplinary care team. The ranks of burn surgeons are usually filled with individuals having completed training in general surgery or plastic surgery. Their scope of practice, however, also includes components of pediatric and surgical critical care. Surgeons interested in burn care often seek additional training through burn fellowships. Whereas these individuals only number five to seven per year,

**Box 1. American Burn Association burn unit referral criteria**

1. Partial thickness burns >10% TBSA
2. Burns that involve the hands, face, feet, genitalia, perineum, or major joints
3. Third-degree (full-thickness) burns in any age group
4. Electrical burns, including lightning injury
5. Chemical burns
6. Inhalation injury
7. Burn injury in patients with pre-existing medical disorder that could complicate management or recovery or affect mortality
8. Patients with concomitant burn and trauma in which the burn injury poses the greatest risk of morbidity or mortality
9. Burned children in hospitals without qualified personnel or equipment for the care of children
10. Burn injury in patients who require special social, emotional, or long-term rehabilitative intervention

*Adapted from* the American Burn Association. Burn unit referral criteria. Available at http://www.ameriburn.org. Accessed June 30, 2006.

many fellowship positions remained unfilled. A similar situation exists for other burn team specialists. Experienced burn therapists are in short supply because proficiency requires many months of on-the-job training, and advertised positions may stay unfilled for indefinite periods of time. Whether this reality will result in a workforce shortage or create additional impetus for regionalization remains an unanswered question.

The large-scale use of air transport for burn patients started during the Vietnam War, during which field burn casualties were flown to the Brooke Army Medical Center in San Antonio, TX. Since that time, transport of burn patients has become more sophisticated, especially with the addition of respirators that were not available in the Vietnam Era. Successful transfer/transport over large distances requires good communication and coordination between referring and receiving facilities and highly trained personnel in the prehospital phase of care. Although our regional burn center covers an area one-fourth the land mass of the United States, outcomes for long-distance transfer patients are equivalent to that of patients directly admitted to the burn center [131].

Regionalization of care also creates two additional challenges: (1) proper patient triage and (2) coordination of transport, sometimes over great distances. It has been long recognized that referring physicians often under- or overestimate burn surface area, which leads to inappropriate initial care, increased morbidity and mortality, and unnecessary use of air transport

systems. Initial burn triage appears well suited for televideoconference consultation because most injuries can be assessed rapidly by an experienced provider at a remote location. Several burn centers in the United States and abroad have gained experiences with the application of telemedicine to initial burn treatment and patient follow-up [132–134]. Its reported advantages include improved access to tertiary care in rural and medically underserved areas, cost savings with fewer air transports for minor burns, increased patient satisfaction thanks to reduced travel expenses, and more time spent with providers. Cost savings are mainly felt on the patient side, whereas the use of videoconference technology represents a major expenditure for health care systems because of investments in infrastructure, maintenance costs, and communication expenses. Others have reported on the use of e-mail, including pictures for patient data communication [135]. This method has the added benefit of minimal technologic investment. So far, regulations have lagged behind technology with many unresolved issues such as patient confidentiality, licensure and credentialing, malpractice liability for providers, and reimbursement agreements that could offset the cost of telemedicine. Clearly, this area represents a most exciting development in burn care and likely will mature over the next few years.

## Burn disaster planning

Mass disasters caused by explosions or structure fires typically result in a large number of burn casualties. The Rhode Island Station nightclub fire on February 20, 2003 resulted in 100 deaths and 215 injured patients, more than 50 of them with serious burns [136]. The terrorist attacks on September 11, 2001 were so lethal that the number of injured survivors was actually small. Still, one third of injured patients in New York City needed treatment for severe burns [137]. One could imagine that had the World Trade Center towers not collapsed, the number of burn casualties would have been much higher. The optimal care for burn victims follows a sequence of rapid and proper field triage, followed by intensive care management, burn excision and wound coverage procedures, and finally rehabilitation. For all these reasons, early access to specialized burn care is of paramount importance.

The triage of casualties at the scene naturally involves the activation of state and local response systems. To augment local capacities, the federal government can deploy disaster medical assistance teams to the scene. Burn specialty teams are specialized disaster medical assistance teams that consist of burn-experienced personnel to provide assistance needed in the initial care of burn victims. Four regional burn specialty teams are currently available for federal deployment. Burn specialty teams were deployed after the World Trade Center attack on September 11 and to support local resources after the Rhode Island nightclub fire. The last layer of this tiered response system involves military support to civil authority via activation of US Army special

medical augmentation response teams. Two burn-specialized special medical augmentation response teams are currently based in San Antonio, TX, but so far have never been used for US civilian mass casualties. Because special medical augmentation response teams possess long-range air evacuation capabilities, they could become invaluable in the secondary triage and transfer of victims outside the disaster area.

Recognizing that casualty numbers exceeding 50% of maximum capacity (surge capacity) would quickly exhaust resources of local burn centers, the American Burn Association has advocated for a triage system unique to mass casualty burn events [138]. Primary triage is handled according to state and local activation plans, with burn patients triaged to a burn center within 24 hours of injury. Secondary triage is the coordinated transfer of patients from one burn center to a verified burn center after surge capacity is reached. In the event that casualties overwhelm local and national resources, patients would be triaged according to a survival probability grid that prioritizes treatment for patients with the highest likelihood of survival.

## Burn research

A central tenet of any burn center should be its commitment to education and research. The physiologic challenge caused by burn injury may be greater than any other type of insult on the human body. It is a model that lends itself to study and can be replicated in the laboratory. In 2006, the official publication of the American Burn Association was renamed the *Journal of Burn Care and Research*. This change underscores the need for additional research to validate current practices and test unanswered questions in our field. In the clinical arena, several projects are worthy of mention because they embrace the concept of economy of scale to patient-oriented research. First, the organization of the National Burn Repository has created a large patient database accessible for research. Second, many centers across the United States have organized into a burn multicenter trial group. Their efforts have resulted in noteworthy publications on transfusion practices [85], toxic epidermal necrolysis syndrome treatment [107], and validation of oxandrolone as anabolic agent [86,108,139]. ''Inflammation and the Host Response to Injury'' is a major National Institute of Health–funded multicenter program that includes trauma and burn patients. This ambitious translational project aims to correlate genomic and proteomic responses to physiologic perturbations observed at the bedside. Finally, the burn injury model system is a multi-institutional project funded by the National Institute of Disability and Rehabilitation Research (http://bms-dcc.uchsc.edu) to evaluate longitudinal outcomes after major burns. Optimally, current efforts in bench research, translational science, and outcome analyses will generate the necessary Class I evidence to create standards in burn care for the next generation.

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