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Burn Shock and Resuscitation: Many Priorities, One Goal

John Sojka, Andrew C. Krakowski and Stanislaw P. Stawicki

Abstract

Burn injuries come in a wide variety of presentations, depending on the size and depth of the thermal insult, concurrent traumatic or inhalation injury, as well as the associated physiological response of the burn victim. To minimize patient morbidity and reduce mortality, prompt recognition and tailored treatment strategies are critically important. As the percentage of total body surface area (TBSA) burned increases so do the body's physiologic response and the associated complexity of management. Understanding the pathophysiology of burn injury allows the practitioner to optimize and individualize burn patient management—a component of care critical to limiting wound progression and improving outcomes. Burn patient care starts with an accurate and thorough burn patient evaluation conducted in person by an experienced provider. For burns >10–15% TBSA, prompt initiation of fluid resuscitation greatly impacts clinical outcomes. Several formulae have been published to guide crystalloid and/or colloid fluid resuscitation in the setting of burn shock. Other important considerations include ambient temperature control, early enteral nutritional support, vitamin and mineral supplementation, assessment for inhalation injury, glycemic control, early recognition of potential complications of large volume resuscitation, potential need for cardiovascular support, and early wound excision and coverage. Burn patients often require multidisciplinary teams to manage the physical, social, and psychological effects associated with their injury. Dedicated burn centers are the ideal places for meeting the complex needs of each burn patient.

Keywords: burn injury, shock, resuscitation, traumatic injury, Parkland formula, West Penn formula, dermato-surgical considerations

1. Introduction

Burns are among the most challenging and physiologically complex injuries and can be associated with the development of early hemodynamic collapse and shock [1, 2]. Patients who have sustained significant burns are at risk of rapidly developing “burn shock” due to the simultaneous presence of local and systemic inflammatory response to injury that most closely resembles hypovolemic shock [3, 4]. While burns themselves have the potential to be the primary source of shock, the presence of large burns should not distract the vigilant provider from ruling out additional injuries during their assessment of a trauma patient [5, 6]. After addressing any immediate airway threat during the initial trauma evaluation, it is of utmost importance to promptly determine the presence of other potentially life-threatening non-burn injuries. Once other life-threatening injuries are ruled

out, the resuscitating team's focus can be directed toward managing the burn. Rapid initiation of therapy tailored to each burn patient during the initial 48 h from the time of burn injury is critical for preventing burn shock, secondary injuries, and other downstream sequelae [3]. In this chapter, we will discuss the fundamentals of burn shock, starting with pathophysiologic and mechanistic considerations and concluding with clinical management pearls.

2. Overview of mechanistic considerations

Burn management begins with a complete history and physical examination, known as the “burn patient evaluation” (BPE), which is intended to quantify and classify the thermal injury [7, 8]. Burns are typically described and classified by etiologic cause, extent of body surface area involved, and depth [9–11]. There are three broad categories of etiologies associated with burn injuries—thermal, chemical, and electrical [12–14]. Thermal mechanisms can be further broken down into flame burns, scald burns, contact burns, steam burns, or flash burns [15, 16]. This chapter focuses primarily on thermal injuries, although many of the concepts discussed herein also apply to other burn types.

The understanding of mechanistic considerations and associated tissue injury patterns is of critical importance when evaluating and treating burn victims [17, 18]. For example, thermal injury causes coagulative necrosis of the affected tissue, and the depth of injury is directly dependent on temperature and duration of exposure, which will vary widely across different types of thermal exposures and injured tissue characteristics [19, 20]. The extent of chemical-induced tissue injury will vary with substance type (acids, alkalis, or hydrocarbon-based organic solvents), concentration, and duration of exposure, but all require expedited clinical management and lavage (when appropriate) of affected areas [21–25]. Electrical injuries will vary in nature between high and low voltage exposure, and depending on exact circumstances, involved victims may be at an increased risk of presenting with cardiovascular and neurologic manifestations, as well as associated traumatic injuries from falling or violent muscle contractions [26–30].

3. Pathophysiology of burn injury

The skin plays a crucial role in maintaining physiologic homeostasis through thermal regulation, sensory reception, synthesis of vitamins and hormones, maintaining fluid/electrolyte balance, and providing barrier protection to underlying tissues [31–34]. When exposed to excessive heat, human tissues develop clinical burn injury [35]. During thermal insult, the epidermis and dermis are able to limit the direct transfer of energy to underlying tissues [19]. Various pathophysiologic derangements occur including denaturation of macromolecular structures, cell membrane dysfunction or destruction, cytokine release, arrest of local blood flow, and eventually cell/tissue death [35]. Following the initial insult, the final depth of irreversible tissue injury may increase depending on how local tissues respond to the complex microvascular and inflammatory environment in their immediate surroundings [35–38]. Morphologically, the tissue environment at the location of burn injury has three physiologically distinct zones. Based on the immediate proximity (e.g., distance or depth) from the primary burn site, these zones are the zone of coagulation, zone of stasis, and zone of hyperemia (**Figure 1**) [12, 38].

The zone of coagulation refers to the area of tissue that has been irreversibly damaged at the time of injury and has undergone coagulative necrosis [39, 40].

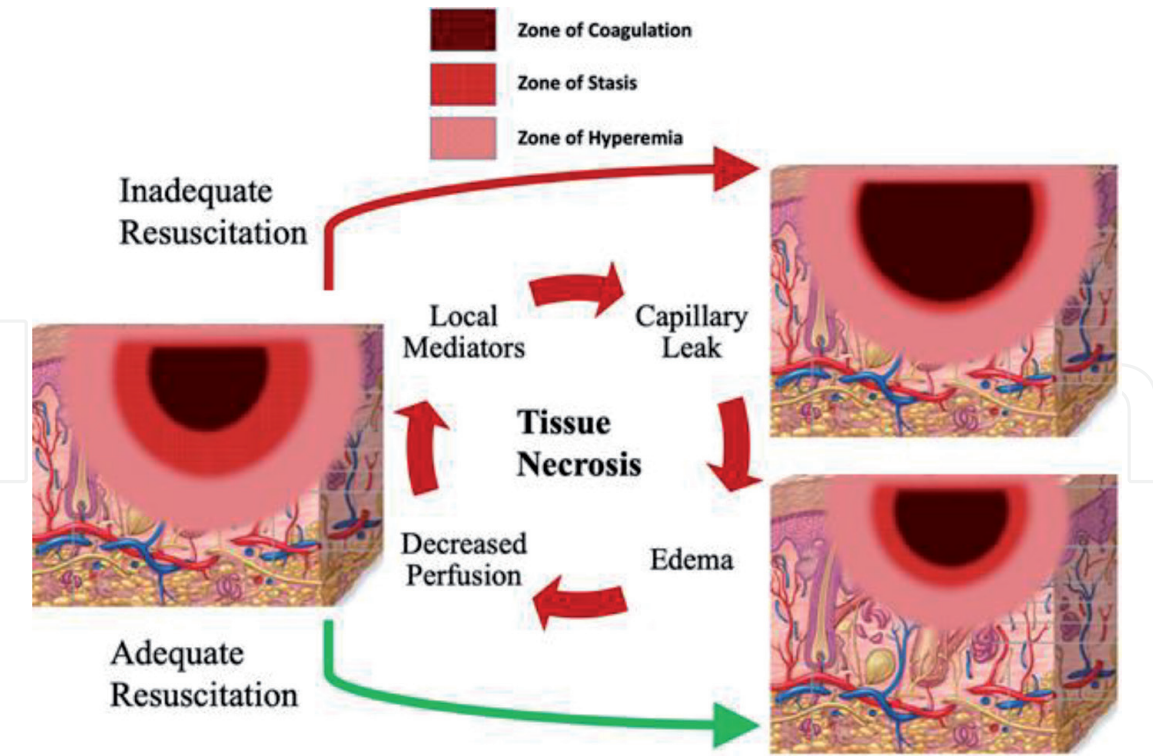


Figure 1.
This schematic displays how resuscitation interacts with the pathophysiologic changes associated with burn injury.

The zone of stasis, also known as the “watershed” region, represents the area of tissue injury that may be reversible under optimal resuscitative circumstances [40, 41]. This zone is characterized by vascular injury, capillary leakage, and high concentrations of thromboxane A_2 —a potent vasoconstrictor produced locally by platelets [1]. Catecholamines and serotonin also play an important role in modulating tissue responses within this zone [1]. The end effect is impaired tissue perfusion, and thus elevated risk of propagating the area of tissue necrosis during the initial 24–48 h following the index injury [1, 36, 42]. The zone of stasis is the area where early intervention with therapy directed at reducing vasoconstriction, optimizing perfusion, and controlling local inflammation may have the greatest effect at limiting the depth of injury. The zone of hyperemia is the most remote zone of cutaneous injury (relative to the primary burn site) where vasodilation is noted in viable tissue undergoing the healing process. This vasodilation is multifactorial and likely mediated through a combination of histamine- and kinin-related mechanisms [1, 43].

Accurate determination of burn wound depth is crucial for guiding clinical management (**Table 1**) [9, 44]. Some superficially limited burns may heal with local treatment alone, while deeper burns are more likely to require operative intervention. Although various tools are available to assist in this assessment [44–49], burn depth is usually determined during BPE through visual inspection by an experienced practitioner who then goes on to classify his or her findings in accordance to pre-established “degrees of injury severity” outlined below:

1. Superficial—commonly referred to as “first degree”—burns are generally limited to the epidermis. The burned skin is characterized by the presence of blanching erythema that tends to appear dry (without blistering) and is very tender on exam due to the proximity of sensory nerve endings. Common examples include sunburns or mild scalding from hot water [50]. Management of these burns is directed at reducing further injury, pain control, and provision of comfort measures. Within the first hour, exposing the injury to cool

Depth/ degree	Etiology	Tissue layer	Appearance	Pain	Healing time
Superficial I°	Sunlight exposure, hot liquids with low viscosity and short exposure	Epidermis only	Pink to red, moist, no blisters	Moderate–severe	3–7 days
Superficial partial IIa°	Hot liquids, chemical burns with weak acid or alkali, flash	Superficial (papillary) dermis	Blister, red, moist, intact epidermal appendages, blanching on pressure	Severe	1–3 weeks, long-term pigment changes may occur
Deep partial IIb°	Flame, chemical, electrical, hot liquids with high viscosity	Deeper layer (reticular) dermis	Dry, white, non-blanching, loss of all epidermal appendages	Minimal	3–6 weeks, with scars
Deep III°	Flame, electrical, chemical, blast, self-immolation	Full skin thickness with extension into subcutaneous tissues	Leathery, dry, white or red with visibly thrombosed vessels	No	Does not heal by primary intention, requires skin graft
IV°	Mostly prolonged flame exposure	Involves tendon, muscle, or bone	Skeletonizing of tissue, charring	No	Extensive reconstructive, limb salvage versus amputation

Table 1.
Description of clinical characteristics of burn wounds of various depths.

water or applying a cold compress can help stop the burning process and relieve pain. Topical steroids, with their vasoconstrictive effects, are often considered “first-line” treatment for acute sunburn; however, their true efficacy remains controversial [51]. Topical applications such as menthol, camphor, pramoxine, lidocaine, and diclofenac gel, if available, may be useful for reducing pain, erythema, and edema. Soothing remedies such as aloe lotion (especially when refrigerated prior to application), baking soda, and oatmeal may provide additional relief. Oral nonsteroidal anti-inflammatory drugs (NSAIDs) help provide analgesia and may assist in reducing sunburn erythema. Healing of superficial burns occurs typically over a period of 3–7 days and will not result in scar formation [50, 52]. Of note, these burns are usually not included when estimating the total body surface area (TBSA) during the BPE, mainly because burns limited to the epidermis tend not to cause significant fluid shifts or losses.

2. Moderate partial thickness burns—also referred to as “superficial second degree” injuries—by definition involve the superficial layers of the dermis [50]. Partial thickness burns are further divided into two subtypes—superficial (focus of the current paragraph) and deep (discussed in next paragraph). Superficial partial thickness burns have similar appearance to first degree

burns but will additionally appear weepy and blistered [53]. Increased exposure of dermal nerve endings for pain, touch, temperature, and pressure contributes to these burns being very painful [54, 55]. Dermal blood vessels that carry oxygen and nutrients to the skin while removing metabolic waste products are also exposed giving the wound a blanching erythematous appearance. Exposure of sweat and sebaceous glands contributes to the wound's weepy appearance and the increase in evaporative losses [56]. Hair follicles, sweat glands, and rete ridges are typically spared allowing for reepithelialization to occur over the following 1–2 weeks post injury; however, alteration in cellular milieu at the site of the injury may result in permanent skin discoloration [56–58]. Finally, the risk of scarring is increased at this injury severity level, as is the overall risk of infection.

3. Deep partial thickness burns—also known as “deep second degree burns”—extend deeper into the dermis, resulting in a wound that appears pale and mottled [59, 60]. Since not all nerve endings have been destroyed in this type of burn, there may be considerable amounts of associated pain. Coagulative necrosis of the dermis from deep partial thickness burns is considered to have extended beyond the rete ridges, thus leaving behind only hair follicles and sweat glands to contribute to reepithelialization [61]. Without the rete ridges, the healing process is significantly slower and may result in more severe scarring. Ablative fractional laser resurfacing, excision, and skin grafting can improve both the healing time and scar quality. Consequently, the boundaries of clinical management tend to become blurry when approaching deep partial thickness and full thickness burns (discussed in next paragraph).
4. Full thickness burns—also known as “third degree burns”—extend beyond the epidermal and dermal tissues and into the subcutaneous fat [62, 63]. Full thickness burns are associated with complete destruction of all nerve endings, dermal glands, and hair follicles. In addition, thermal damage to superficial veins causes thrombosis [64, 65]. As a result of the above changes, the burn area is insensate and may appear charred, brown, and leathery, or at times white and waxy. Only the wound edges have retained the necessary components for reepithelialization of the wound, which is why full thickness burns also require excision and grafting in order to heal [50, 66].
5. Fourth degree burns are defined as thermal injuries that involve tissues and structures deep to subcutaneous layer. This includes damage to muscle, tendon, or bone [67]. Patients who suffer from survivable fourth degree burns may require extensive limb-sparing efforts and reconstructive surgery to avoid amputation [67, 68].

Determining the size, or total body surface area, of a burn is the cornerstone of the BPE and provides fundamental information to guide subsequent clinical management. Properly conducted BPE also provides insight into the burn victim's physiologic state and resuscitative fluid needs, as well as general prognostic information. It is important to remember that burn injuries have the potential to quickly evolve and progress if resuscitative conditions are not optimal [69, 70]. In other words, superficial and partial thickness burns can become deep partial thickness burns, and deep partial thickness burns have the potential to become full thickness burns. Optimizing the resuscitation effort can mitigate the tissue loss by enhancing perfusion and limiting secondary injury.

4. The burn patient evaluation (BPE)

When performing the BPE, the “rule of nines” is a quick way to get an approximate estimate of burn size in the field in order to properly communicate the state of a patient over the radio to the accepting facility and initiate early goal directed therapy. When calculating TBSA of partial and full thickness burns on adults, the following body surface percentages are assigned to the corresponding anatomic regions (**Figure 2**):

- Entire head is 9%
- Neck is 1%
- Anterior trunk is 18%
- Posterior trunk is 18%
- Each upper extremity is 9%
- Each lower extremity is 18%

When compared to adults, children have disproportionately larger heads [71], thus requiring an adjusted allotment of body surface area per anatomic region (**Figure 2**). Consequently, the adjusted percentages for TBSA evaluation in a child are:

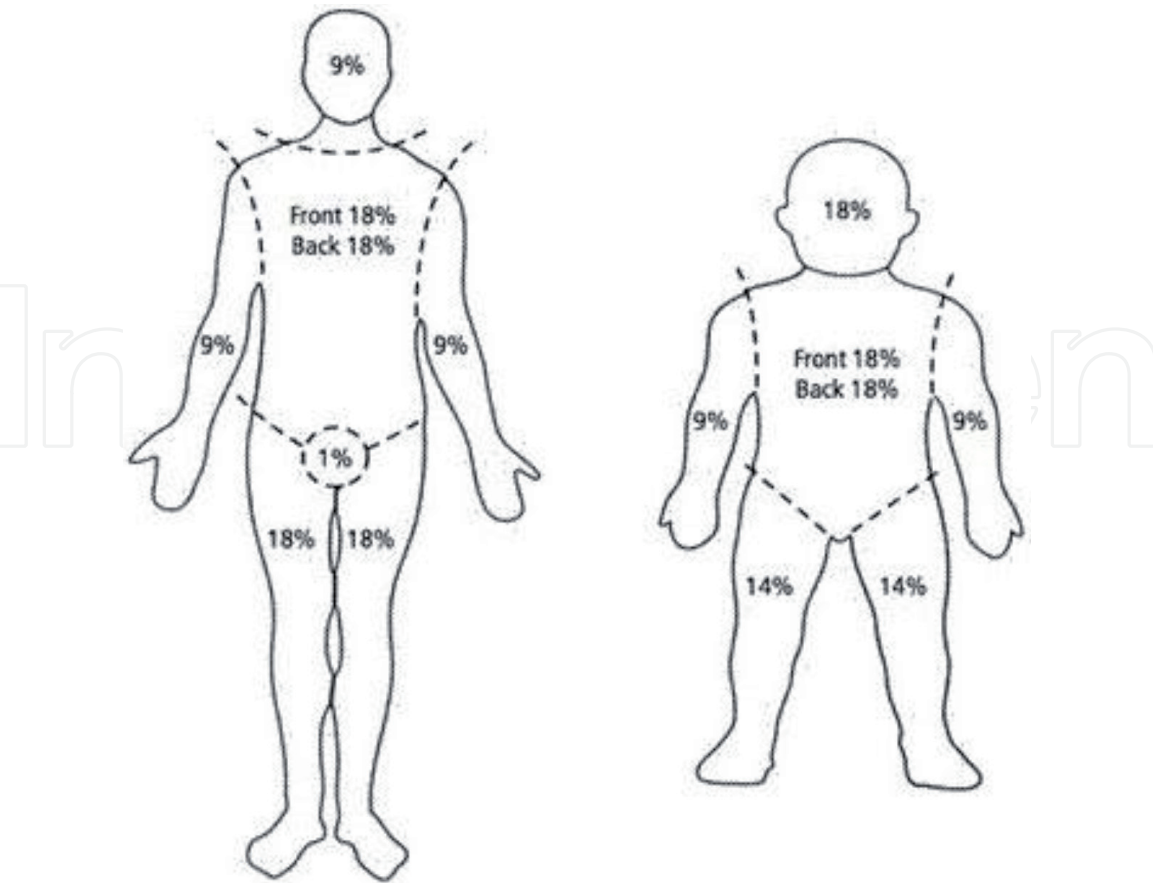


Figure 2.
(A) Left, diagram showing body surface area allocations for adult burn patients; (B) right, schematic representation of body surface area allocations for pediatric burn patients.

- Heads and neck combined are 18%
- Anterior trunk is 18%
- Posterior trunk is 18%
- Each upper extremity is 9%
- Each lower extremity is 14%

Another quick TBSA estimation technique is to use an area equal to the patient’s own palm (with extended fingers) as an equivalent of approximately 1% TBSA. This measuring standard is then applied to each burned area and is especially useful in cases of patchy injury distribution [72, 73].

During the secondary BPE, especially after full exposure is completed, a better estimation of TBSA can be obtained to more precisely direct further hemodynamic and fluid resuscitation. In the 1940s, Lund and Browder introduced a seminal paper on estimating burn size and provided a simple chart that breaks down TBSA of smaller areas of the body for different age groups [71, 74]. This method is

Area	0–1 years	1–4 years	5–9 years	10–14 years	15 years	Adult	%2°	%3°	%TBSA
Head	19	17	13	11	9	7			
Neck	2	2	2	2	2	2			
Ant trunk	13	13	13	13	13	13			
Post trunk	13	13	13	13	13	13			
R buttock	2.5	2.5	2.5	2.5	2.5	2.5			
L buttock	2.5	2.5	2.5	2.5	2.5	2.5			
Genitalia	1	1	1	1	1	1			
R arm	4	4	4	4	4	4			
L arm	4	4	4	4	4	4			
R forearm	3	3	3	3	3	3			
L forearm	3	3	3	3	3	3			
R hand	2.5	2.5	2.5	2.5	2.5	2.5			
L hand	2.5	2.5	2.5	2.5	2.5	2.5			
R thigh	5.5	6	6.5	8	8.5	9			
L thigh	5.5	6	6.5	8	8.5	9			
R leg	5	5	5.5	6	6.5	7			
L leg	5	5	5.5	6	6.5	7			
R foot	3.5	3.5	3.5	3.5	3.5	3.5			
L foot	3.5	3.5	3.5	3.5	3.5	3.5			
Total									

Table 2.
Lund and Browder’s chart for calculating %TBSA of varying age groups, with sufficient granularity to provide adequate accounting of the size and depth of the patient’s burns, categorized by anatomic area.

considered to be the most accurate and reliable method of determining TBSA, with only a few caveats. More specifically, patient populations that may not be accurately represented by Lund and Browder's chart include the morbidly obese, amputees, women with large breasts, and gravid women (**Table 2**) [71, 75].

5. Burn shock

When burns cover <10% of the TBSA, the associated inflammatory response and vascular leakage tend to remain localized within the immediate proximity of the injured tissue. However, as the TBSA approaches 15–20%, the overall quantity of cytokines released systemically into the circulatory system increases dramatically, contributing to systemic inflammatory response whereby uninjured anatomically distant body regions experience various deleterious downstream manifestations such as vasoactive changes, increased capillary permeability, and tissue edema [3, 76, 77]. In the setting of such more severe burns, abrupt fluid shifts from vasculature into the interstitial space quickly lead to clinically apparent hypovolemic shock. In the setting of severe burn injury, this type of shock is appropriately termed “burn shock” [78, 79]. The state of hypovolemic shock during the acute, or “ebb,” phase can be further exacerbated by the copresence of low cardiac output from decreased effective circulating blood volume, increased blood viscosity, and depressed cardiac contractility [77, 79, 80]. Most severely affected patients may experience multisystem organ failure (MOF) [81].

From a clinical management standpoint, the initiation of appropriate fluid resuscitation immediately upon the completion of BPE is imperative to providing (and maintaining) the necessary cardiovascular support. Every additional hour from time of injury that resuscitative fluid administration is delayed increases the risk of mortality [82]. Under resuscitation can lead to tissue hypoperfusion, acute renal injury, and death. Over-resuscitating, however, can cause increased tissue edema, compartment syndromes, acute respiratory distress syndrome (ARDS), infections (e.g., pneumonia), and MOF [83–85]. Therefore, proper resuscitation of burn patients requires individually tailored fluid administration and close monitoring in order to prevent secondary, mostly iatrogenic injuries.

Initiating appropriate intravenous fluid resuscitation requires establishing and maintaining dependable vascular access [3]. Short, large bore peripheral intravenous catheters placed through unburned skin are ideal because this approach avoids potentially thrombosed superficial veins underlying full thickness burn areas. That said, venous access through burned skin is preferred over no venous access, and in most situations may be more rapidly available than central venous access. Central venous access is reliable but comes with increased risk of complications compared to other available options such as saphenous venous cut-down or intraosseous route [86, 87]. Once adequate vascular access is established, fluid resuscitation should be initiated immediately. Optimally, a protocol-driven approach to fluid administration is preferred [88, 89].

The rate of clinical failure (defined as patient deterioration or mortality) with prompt and adequate resuscitation is relatively low (e.g., <5% even for patients with burned TBSA >85%) [90]. As a general guideline, patients who benefit the most from formula-based, calculated fluid resuscitation include adults between 15 and 50 years of age with $\geq 20\%$ TBSA involving second and third degree burns; children ≤ 15 years old and adults ≥ 50 years of age with $\geq 10\%$ TBSA involving second and third degree burns. In practice, many institutions will consider initiating resuscitative fluids when adult burn victim presents with injuries involving $\geq 15\%$ TBSA [91]. A significant body of research regarding modern fluid resuscitation protocols

demonstrates that systemic capillary leakage during the initial 24-h period after injury permits movement of large molecules into the interstitial space [92, 93]. For this reason, colloids are generally considered to provide little added benefit to crystalloid administration in the first 24 h. The topic is somewhat controversial, however, as some researchers argue that capillary permeability may begin returning to normal as early as 6–8 h after injury [90, 94, 95]. Consequently, the latter group advocates that earlier colloid addition may reduce the total amount of fluid necessary to achieve hemodynamic resuscitation and intravascular volume restoration.

5.1 The Parkland formula

The Parkland formula is among the most widely used and studied burn patient resuscitation paradigms [91, 96–98]. When originally published, this resuscitation approach advocated total crystalloid infusion of 4 mL/kg for each percent of body surface area burned [96–98]. The equation estimates the total amount of Ringer's lactate to be given in the initial 24-h post-burn period. Half of the calculated total fluid amount is to be given in the first 8 h and the remaining over the following 16 h [91, 98]. At the same time, certain limitations inherent to formula-based resuscitative approaches do exist. For example, the Parkland formula has been noted to underestimate the total volume of Ringer's lactate needed during the first 24 h in severe burns (>40% TBSA) [91, 99]. This tendency to need larger than estimated fluid volume is referred to as “fluid creep” [84, 100]. Although the exact factors responsible for this phenomenon are still being debated, one effective way of addressing it involves frequent urine output monitoring with hourly adjustments in fluid rates [84]. Goal urine output for adults is 0.5 mL/kg/h and for children ≤30 kg is 1 mL/kg/h. Some institutions have developed protocols that incorporate hourly fluid infusion rate adjustments of 10–30% depending on whether urine output is above or below goal [84]. As an example, we will consider using an hourly rate adjustment of 20% in an adult burn victim. In such scenario, if urine output decreased to <0.5 mL/kg/h, then the current fluid rate would be increased by 20%. If urine output was maintained at 0.5–1 mL/kg/h, then no rate adjustments are made. Finally, if urine output was measured to be >1 mL/kg/h, then the current fluid rate would be reduced by 20%.

5.2 The Galveston formula

Children have larger surface/volume ratios compared to adults, which translates to disproportionately higher infusion rates. The Galveston formula is designed to account for this difference, whereby during the first 24 h, patients receive fluids based on $5000 \text{ mL/m}^2 \times \% \text{TBSA} + 2000 \text{ mL/m}^2$ daily maintenance [101]. Similar to Parkland formula, half of the calculated total is given in the first 8 h and the rest over the remaining 16 h [102]. Children have lower glycogen stores than adults and consequently should have 5% dextrose added to the primary resuscitative crystalloid solution [103, 104]. As the formula indicates, children require greater amount of resuscitation fluid per kilogram than adults. Unfortunately, children also have lower physiologic reserves, which may predispose them to side effects of more aggressive fluid resuscitation approaches [105]. For example, it has been shown that the cardiac output of pediatric burn victims may not return to pre-burn levels for 24–48 h post-injury, even with complete intravascular status restoration. Furthermore, excessive secretion of antidiuretic hormone may lead to oliguria that extends beyond 48–72 h post-burn [105]. Taking the above parameters into consideration, it is recommended that urine output surveillance and fluid rate adjustments be made on a more frequent basis than adults.

5.3 Post-acute resuscitation period

Following the initial 24 h of resuscitation, both Parkland and Galveston and some derived formulae provide for a transition to reflect the changing vascular environment as hemodynamic and vascular homeostasis returns. The so-called Baxter formula—a derivation of the Parkland method—introduces a fourth “8-h period” during which plasma is given at 0.3–0.5 mL/kg/%TBSA in order to complete resuscitation [106]. The Galveston formula for pediatric patients calls for Ringer’s lactate with dextrose at a rate of $3750 \text{ mL/m}^2 \text{ burned area} + 1500 \text{ mL/m}^2 \text{ total area}$ over a 24-h period [107]. It is important to remember that these formulae, like the many other proposed paradigms, should be considered within the overall context of a multifaceted approach to manage the burn patient. Once appropriate initial resuscitation has been completed, subsequent fluid administration should be tailored to maintain post-resuscitation stability while avoiding any secondary/iatrogenic injury.

An important question arises regarding the course of action in cases where resuscitation formulae are followed appropriately yet the patient fails to meet the intended resuscitation endpoints. Such an occurrence may indicate that a secondary diagnosis (or a complication) is present, including inhalation injury, infection/sepsis, compartment syndrome, or an acute cardiovascular event (e.g., pulmonary embolism) [108]. There is no single perfect marker for determining when a patient is adequately resuscitated. Traditionally, monitoring urine output has been considered as the gold standard for ongoing assessment of resuscitative adequacy. This is because it is a convenient, practical, and inexpensive way to determine if tissues are being adequately perfused in near real-time [109]. The ability to maintain urine output of $\geq 0.5 \text{ mL/kg/h}$ in adults and older children ($>50 \text{ kg}$) may guide appropriate resuscitation in most patients, but relying on urine output alone can be both challenging and potentially misleading. For example, a recent systematic review showed that when compared to hourly urine output measurements, hemodynamic monitoring appeared to provide some degree of survival benefit, with no associated effect on renal failure [109]. At the same time, heterogeneity of data quality within that same review was problematic, and when only randomized controlled trials were examined in isolation, the mortality benefit of hemodynamic monitoring over hourly urine outputs was no longer present [109].

In practice, a patient whose cumulative fluid resuscitation approaches 250 mL/kg during the initial 24 h post-injury period should place the treating clinician on high alert for complications related to excessive or over-resuscitation [100, 108]. Careful evaluation of the patient’s extremities for signs and symptoms of compartment syndrome should be performed. In particular, burned extremities in which escharotomies may not have been indicated initially may develop the need for escharotomy as increased tissue edema underlying the burned skin further exacerbates venous flow disruption and eventually leads to compromised arterial flow [3]. The emergence of compartment syndrome may be associated with the symptoms of numbness, tingling, or pain with passive movement of the involved extremity [110]. Assessment of capillary refill as well as Doppler signals of digital arteries, palmar arches, and plantar arches of affected limbs should be performed frequently as part of clinical surveillance [50, 111]. Finally, tissue pressure measurements can be checked, and if found to be $>30\text{--}40 \text{ mmHg}$, this would also be an indication for urgent escharotomy [112, 113]. Burn care providers must remember that the determination to perform an escharotomy can (and often should) be made using clinical exam as the primary decision tool.

When performing escharotomy, areas of constrictive eschar are incised longitudinally along medial and lateral aspects of the affected body region/extremity

[114, 115]. Even after escharotomy, severely injured limbs continue to be at risk for developing compartment syndrome requiring fasciotomy [116]. Although uncommon, sudden restoration of perfusion to muscle compartments after prolonged ischemia can potentiate the swelling within an already edematous muscle tissue and cause limb-threatening compartment pressure elevations [117, 118].

Intraabdominal organs and tissues are not excluded from the widespread edema resulting from the combination of physiologic changes due to initial injury and subsequent resuscitation. Development of abdominal compartment syndrome in a burn patient undergoing massive fluid resuscitation can be difficult to identify [119, 120]. Due to high sensitivity of the renal system to increased intraabdominal pressures, decreased urine output from diminished kidney perfusion is one of the earlier signs of abdominal compartment syndrome [121–123]. Of note, in a burn patient undergoing massive fluid resuscitation, observed decrease in urine output may be erroneously interpreted as insufficient resuscitation, thus prompting the clinician to inappropriately increase fluid administration [124, 125]. One important consideration is the performance of relevant clinical cross-checks, where additional clinical variables are examined concurrently, including elevated peak airway pressures and decreased tidal volumes in mechanically ventilated patients. Patients who develop abdominal compartment syndrome will become increasingly difficult to ventilate due to increased abdominal pressures being transmitted across the diaphragms into the thoracic cavity.

When indicated, abdominal compartment pressures are fairly easy to measure. Abdominal compartment pressures are most accurately obtained in patients who are ventilated, sedated, and paralyzed (however, this is rarely the case). Placed in the supine position, the patient should be completely flat and level with the ground. Through a Foley catheter, approximately 50–100 mL of normal saline is instilled into the empty bladder, and a pressure transducer is connected to the port at the proximal end of the catheter [126, 127]. Patients with abdominal pressures approaching 30 mmHg in the setting of end organ dysfunction should be considered for decompressive laparotomy [126].

In the absence of chronic kidney disease and abdominal compartment syndrome, low urine output and depressed cardiac indices, especially in the setting of large volume fluid administration could indicate ongoing under-resuscitation and/or the presence of cardiac dysfunction. Key factors associated with the presence of clinical under-resuscitation include significant delays in initiating resuscitative fluids, underestimation of partial and full thickness burn %TBSA, or concurrent lung injury requiring mechanical ventilation [85, 88, 128]. Burn injuries have been shown to increase cardiac stress and cause myocardial dysfunction [1, 129]. Myocardial dysfunction, in turn, leads to decreased contractility and cardiac output [130]. Dedicated evaluation consisting of a clinical exam, an electrocardiogram (EKG), and bedside echocardiography may be indicated. Advanced hemodynamic monitoring may be of benefit in selected cases [99, 131, 132].

Overly aggressive intravenous fluid resuscitation has also been reported to lead to abnormal intraocular pressure elevations [84, 133]. Similar to other “compartment syndromes,” sustained intraocular pressures of ≥ 20 –30 mmHg may lead to permanent injury and vision loss [133–135]. Any unexpected or unexplained symptoms of vision changes or ocular pain should prompt a thorough reevaluation for changes in the patient’s clinical exam, fluid balance, and any other aforementioned complications.

Colloid-based resuscitation. If the patient appears to be under-resuscitated despite ongoing administration of large volumes of crystalloids, the resuscitating provider should strongly consider transitioning the resuscitative efforts to incorporate colloid-based fluid administration [83, 136]. Although there is still some

controversy regarding the optimal application and timing of various colloids during burn patient resuscitation, especially in the setting of severe burns, there is clear evidence in support of colloid use in general [83, 136, 137]. Research suggests that the use of colloids in resuscitation of severe burns (>40% TBSA or > 30% TBSA with inhalation injury) may decrease the total resuscitation volume, reduce the incidence of abdominal compartment syndrome, number of days spent on a ventilator, and potentially even mortality [138–140]. The majority of historically important formulae include some form of colloids administered at various timeframes within the first 48 h post-burn. The presence of this general theme throughout the literature corroborates the importance of colloids for resuscitation of severe burns, especially in the management of burn shock in the most severely injured population. Despite this, definitive evidence regarding the efficacy of either approach continues to be elusive.

The Parkland formula does not call for the transition to colloids prior to the first 24-h mark. If earlier administration of colloids is desired, one might consider transitioning to the Brooke Formula or West Penn formula [88, 93]. During the initial 24-h post-burn period, the Brooke Formula can be delivered as a combination of crystalloid and colloid fluids, including 1.5 mL/kg/%TBSA of Ringer's lactate plus 0.5 mL/kg/%TBSA of a colloid and 2000 mL of 5% dextrose in water [81, 141, 142]. After the first 24-h period, the formula mandates reducing the crystalloid and colloid fluid rates by 50–75% and repeating the 2000 mL of 5% dextrose in water [81, 141, 142]. The West Penn formula—first published in the early 1990s—is the most recently proposed derivation of colloid-based burn resuscitation formulae. The West Penn formula calls for Ringer's lactate at a set rate of 83 mL/h and fresh frozen plasma (FFP) at an initial rate of 75 mL/kg/36 h. The rate of FFP administration is then titrated on an hourly basis to a urine output of 0.5–1 mL/kg/h and both fluids are continued for until the 48-h mark after burn injury is reached [88, 143].

6. Ambient temperature control

Over the past several decades, major advances have been made in our understanding of the complex physiologic changes that occur as a result of severe burn injury. While burn shock, as outlined in previous sections of this chapter, is historically compartmentalized as a form of “hypovolemic shock,” we now know that “fluids alone do not cure burn shock” [143]. Consequently, there are various strategies that may be employed to help counteract or “blunt” the cascading physiologic response to burn injury. For example, even simple measures such as increasing the ambient temperature (up to 33°C) have been shown to reduce the hypermetabolic response focused on maintaining elevated body core temperatures during the acute injury phase [144].

7. Nutritional support

Delays in nutritional support can have devastating effects on patient outcomes [145]. The post-burn hypermetabolic state that begins immediately after injury can approach 200% of normal resting energy expenditure [146]. This can naturally lead to rapid depletion of energy stores, loss of muscle tissue, and further worsening of any pre-existing or acquired malnutrition. Malnutrition itself contributes to alterations in cell membrane transport, organ dysfunction, immune compromise, and delayed/abnormal wound healing [147]. Ideally, nutritional support is initiated within 6 h of injury. Due to the tremendous increase in metabolic demand, severely

burned patients are simply unable to fully meet the caloric demands on their own accord. For this reason, it is recommended that a post-pyloric feeding access be placed on admission, with prompt (preferably protocol-driven) initiation of tube feeding formulae specifically tailored to meet individual patient requirements [148, 149]. For gastric tube feeds, the choice of continuous versus bolus administration may be a secondary consideration [150]. For post-pyloric feeding, continuous administration requires the presence of intact intestinal function.

Unfortunately, the gastrointestinal tract itself is affected adversely by severe burn injury, and varied degrees of ileus may develop in the acute post-burn timeframe [151]. In the setting of complete intolerance to enteral feeding, total parenteral nutrition may be considered on highly selective basis [152]. Total parenteral nutrition is generally not recommended due to associated increases in rates of complications and mortality compared to enteral feeding, and the latter should be started as soon as the gastrointestinal dysfunction resolves [152]. A commonly used formula for calculating caloric requirements is the Curreri formula (including its variants) which calls for 25 kcal/kg/day maintenance plus additional 40 kcal/%TBSA/day [153–155].

Adequate and prompt nutritional support is critical to the overall management of burn patients, and its importance parallels the severity (e.g., %TBSA) and complexity (e.g., inhalation component) of the injury [148, 156, 157]. In addition to ensuring adequate caloric provision, it may be important to consider supplementing the patient's enteral intake with specific vitamins and minerals. For example, there has been increasing support in the literature for administration of high dose vitamin C (a.k.a., ascorbic acid) during the acute phase of burn injury [158, 159]. Cellular oxidative stress from reactive oxygen species generated immediately after burn injury appears to play a significant role in cardiovascular dysfunction of burn shock. Vitamin C is a powerful antioxidant, and it has been suggested that high dose ascorbic acid administration during the acute phase of burn shock may be protective to microvascular circulation, beneficial to cardiac output, help optimize fluid resuscitation, and may enhance wound healing [159, 160]. Other proposed components of the so-called “pharmacological” nutritional supplementation after burn injury include glutamine, arginine, n-3 (polyunsaturated) fatty acids, as well as various other vitamins and trace minerals [149, 161].

8. Special hemodynamic considerations

Patients who develop burn shock and remain hemodynamically labile despite large volume resuscitation may require additional cardiovascular support. Low cardiac output during the acute post-injury phase is a common component of early “burn shock” [162, 163] and may be more pronounced among geriatric patients [164]. In some cases, inotropic support with dobutamine may be required to maintain adequate systemic perfusion [165, 166]. Vasopressors should be avoided if possible as their vasoconstrictive properties can lead to decreased end-organ perfusion, including skin (and thus elevated risk of the propagation of primary injury or impaired healing of skin grafts) and bowel (e.g., contribution to potential bowel ischemia). This is especially applicable to patients with initial low cardiac output and early multiple organ dysfunction [167]. Patients who do require vasopressor support should undergo close hemodynamic monitoring (MAP, CVP, echocardiography, SvO₂). As the patient transitions from the “ebb phase” to the “flow phase” (typically around the 48–72 h mark) of the post-burn state, hemodynamic behavior evolves toward the hyperdynamic profile [168]. As the

hyperdynamic phase begins, cardiac output may exceed 1.5 times that of a normal baseline. Increases in cardiac output entail much greater cardiac work and overall energy expenditure. For these reasons, propranolol is highly efficacious during acute care in burn patients [169]. In fact, long-term propranolol administration initiated in the acute setting decreases cardiac work, decreases lipolysis, improves nitrogen balance, helps restore insulin sensitivity, and mitigates post-traumatic stress disorder [170–173].

9. The importance of endocrine system, including glycemic control

As part of the hypermetabolic response to burn injury, significant increases in catecholamines, glucagon, and cortisol stimulate rapid glycolysis-gluconeogenesis cycle gyrations [174]. The result is the appearance of hyperglycemia and a concurrent state of insulin resistance. The magnitude of the overall effect appears to be dependent on the severity and size of the burn injury [175]. The administration of insulin to maintain a serum glucose goal of ≤ 120 mg/dL has proven to be effective in attenuating some of the hypermetabolic changes that take place immediately after injury [176]. Insulin administration has been shown to improve muscle protein synthesis, normalize mitochondrial function, reduce oxidative stress, limit lean muscle mass loss, accelerate healing time, and improve long-term rehabilitation [176–179]. In addition to the normalization of serum glucose levels, the reduction in glycemic variability may be equally important [180, 181]. Other beneficial effects of goal-directed insulin therapy have been identified, including potential reductions in mortality, infections, sepsis, acute kidney injury, multiple organ failure, days on a ventilator, and hospital length of stay [177, 178, 182].

Although beyond the scope of the current chapter, various other endocrine system components are affected—both acutely and chronically—following burn injury [178, 183–188]. This includes the thyroid hormone metabolism [183, 184], the hypothalamic–pituitary axis [185], the renin-angiotensin system [185, 187], the reproductive system [185], among others [186]. Additional important endocrine considerations include the effects of exogenous hormone therapies, such as oxandrolone, recombinant human growth hormone, and incretin analogs [188]. Readers are referred to the primary sources listed above for further information.

10. Comment on inhalation injury

Inhalation injury requiring mechanical ventilation is associated with increased mortality and greater volume of fluid resuscitation [189–191]. Carbonaceous debris in or around the mouth, facial burns, and singed facial or nasal hair are often cited as important clues during the BPE with respect to the presence of inhalation injury [192, 193]. However, the history of closed space smoke exposure is perhaps the most important clue as to whether or not a patient might have sustained an inhalation injury. Unlike burn injuries to the skin and subdermal tissues, which are primarily thermal in nature, inhalation injury is primarily a result of chemical exposure of tracheo-bronchial and pulmonary tissues to toxic products of combustion [191, 194, 195]. Primary thermal injury to the airway is often limited to the supraglottic region [195]. Diagnosis of lung injury is graded on a standardized scale from 0 to 4 based on bronchoscopic findings of airway edema, inflammation, mucosal necrosis, tissue sloughing, and presence of soot and carbonaceous material in the airway (see **Table 3**) [195].

Inhalation injury grading scale		
Grade 0	No injury	Normal mucosa, absence of carbonaceous material
Grade 1	Mild	Minor or patchy areas of erythema, carbonaceous deposits in bronchi
Grade 2	Moderate	Moderate degree of erythema, carbonaceous deposits, bronchorrhea, with or without bronchial compromise
Grade 3	Severe	Severe inflammation with friability, copious carbonaceous deposits, bronchorrhea, bronchial obstruction
Grade 4	Massive	Mucosal sloughing, necrosis, endoluminal obliteration
Endorf and Gamelli [190].		

Table 3.
Description of inhalation injury severity grading based on bronchoscopic evaluation.

If there is any concern for inhalation injury based on the initial or subsequent BPE, patient should be placed on 100% oxygen via non-rebreather mask and undergo measurements of blood carboxyhemoglobin and cyanide levels [196, 197]. In patients with early evidence of upper airway edema or impending respiratory failure as suggested by oxygen saturations below 92% and the simultaneous presence of tachypnea with hypercapnia, intubation should be expeditious [128, 198, 199]. Ventilator management for these patients is similar to ARDS using low tidal volumes and pressure control ventilation with permissive hypercapnia (as high as PaCO₂ of 60 mmHg) [200, 201]. Additionally, sloughing of the injured pulmonary lining requires aggressive pulmonary toilet, chest physiotherapy, frequent suctioning, bronchoscopic removal of casts, and nebulizer therapy [128, 202, 203]. Various nebulizer combinations and frequencies of albuterol, heparin, acetylcysteine, hypertonic saline, and racemic epinephrine should be considered on a case by case basis depending on injury severity and clinical progression [128]. Patients should be closely monitored for development of ventilator-assisted pneumonia considering their primary injury has induced a transient immunosuppressed state—a factor that is further exacerbated by the presence of inhalation injury [204, 205]. Finally, for patients with very severe inhalation injury who continue to worsen despite maximal traditional mechanical ventilatory support, the use of high-frequency oscillatory ventilation may be indicated [206, 207].

11. Special topics and dermato-surgical considerations in burn management

11.1 Dermato-surgical considerations

When excisional burn debridement is indicated, it is recommended that it be completed within the first 24–48 h after injury [208, 209]. Early debridement can help decrease the ongoing systemic response to inflammation stemming from the persistence of devitalized tissue [210, 211]. Removal of deep partial or full-thickness burn tissue with grafting and coverage with either permanent (preferred) or temporary graft can substantially decrease the daily rate of evaporative losses [212, 213]. Institution of aggressive operative management of burns, combined with optimization of non-surgical aspects of burn care, can result in a significant decline in mortality rates. More recent developments in this particular area include the introduction of selective enzymatic debridement agent designed specifically for burn wounds [214].

11.2 Dermatologic conditions that require burn center management

Historically, the spheres of the dermatologist and the burn surgeon have failed to overlap as much as the associated anatomic and physiologic considerations might lead one to believe they should. Reasons for this lack of collegiality and collaboration have included training bias (i.e., an “elixir” versus “cold steel” approach), lack of awareness of the other’s expertise, and good old fashioned egos and turf wars. Thankfully, a new era of cooperation between these specialties has begun to emerge based on large part around the understanding that a multimodal, multidisciplinary approach may lead to more optimal clinical outcomes. The intersection of these two specialties may perhaps be best illustrated through several devastating dermatological conditions that involve the acute and extensive necrosis of cutaneous tissue, leading to catastrophic deterioration of the affected patient and a clinical picture that closely resembles a large thermal burn.

11.3 Toxic epidermal necrolysis (TEN)

TEN is a severe, life-threatening disorder (with a mortality rate approaching 40%) characterized by generalized loss of epidermis and mucosa (**Figure 3**), typically involving more than 30% of the skin [215]. A tell-tale clinical finding that is almost always present in TEN is the phenomenon in which intact superficial epidermis can, via a pushing or shearing force, be dislodged and slid over underlying layers of skin; this indicates a plane of cleavage in the skin at the epidermal-dermal junction and is referred to as Nikolsky’s sign [216]. TEN is almost always medication-induced and involves a cytotoxic T-cell reaction with apoptosis of keratinocytes mediated by Fas ligand [217]. Consequently, the first step in treatment is similar to that of a burn injury—stop the underlying causative agent (i.e., discontinue all medications that are not essential). The next step is to confirm the diagnosis through a careful medication history and skin biopsy with frozen section. The finding of full-thickness epidermal involvement distinguishes TEN from other conditions such as staphylococcal scalded skin syndrome (see



Figure 3.
Typical appearance of toxic epidermal necrolysis (TEN).

below), which may appear similar but are treated very differently. In addition to the more controversial therapeutic roles that systemic steroids, intravenous immunoglobulins, and plasmapheresis may play, the mainstay clinical TEN management is excellent “burn care,” ideally in a burn center with careful attention to pain management, electrolyte balance, topical disinfection, access to burn beds and nonadherent dressings, and prompt treatment of secondary infections. An ophthalmologic consultation is also required because of the risk of corneal erosions and scarring [218].

11.4 Staphylococcal scalded skin syndrome (SSSS)

The SSSS is typically characterized by fever and rapid onset of diffuse, painful erythema progressing to widespread formation of thin-walled, easily ruptured, fluid-filled vesicles and bullae (**Figure 4**). Newborns and small infants tend to be most susceptible, though adults may certainly be affected. Nikolsky’s sign is almost always present [216]. The clinical presentation of SSSS is the result of specific exotoxins that cleave desmoglein-1 (i.e., disrupt the connection between keratinocytes) and cause cellular detachment within the epidermis. While exotoxins are released by *S. aureus*, cultures to isolate these bacteria, however, are often negative. More helpful is a skin biopsy with frozen section that should demonstrate a very superficial epidermal split (in contrast to TEN where there is full-thickness epidermal necrosis). Differentiating SSSS from similar clinical presentations is critical because treatment typically involves the addition of medications (i.e., antibiotics) rather than the cessation of them. SSSS patients may require topical disinfection and careful placement on a burn bed covered with nonadherent sheeting. Attention to fluid replacement, pain management, electrolyte balance, and temperature and humidity control are paramount. Less urgent but just as important, the diagnosis of SSSS should prompt a search for staphylococcal “carriers” among close contacts of the affected patient. Healing is usually rapid with correct therapy and vigilant wound care [219].

11.5 Necrotizing fasciitis

Necrotizing fasciitis refers to the severe and rapid destruction of skin, subcutaneous fat, and muscle caused by bacterial infection (e.g., group A streptococci,



Figure 4.
Typical appearance of staphylococcal scalded skin syndrome (SSSS). Left—face; right—abdomen.

community-based methicillin-resistant *Staphylococcus aureus*, Gram-negative bacteria, mixed infection, etc.) [220, 221]. It is characterized by widespread dermal necrosis, vessel thrombosis, and a massive, destructive inflammatory reaction. Mortality rate without surgical involvement may approach 100%. Similar to burn wounds, surgical management of this condition may include extensive debridement and management of the associated compartment syndrome. Also similar to burns, successful treatment depends on careful fluid replacement, broad-spectrum antibiotic coverage (including for Gram-negative organisms), specialized surgical dressings, and vigilant monitoring for signs of shock [222, 223]. Eventual skin grafting and/or tissue flaps may be required to cover large soft tissue defects.

Directly relevant to the theme of the current chapter, all three of the above dermatological conditions (and many others) are subject to the same general complications and considerations, and their final prognosis is directly proportional to the extent of their skin injuries and the level of expert care they urgently receive.

12. The evolving burn scar paradigm

Irreversible scarring has long been thought to be the unavoidable, aggregated response to gross tissue injury after a severe burn. From the historical “tooth and claw” injury perspective, such a clinical endpoint made perfect sense: the inflammatory cascade would effectively help plug hemorrhage, prevent infection, and patch up the wounded enough so that they could get back into action. In the context of modern medicine, however, scarring is no longer necessarily ideal. When one considers the phenomenon of the burn survivor’s paradox—in which severely burned patients are living longer through more extreme injuries but are consequently forced to deal with the physical, psychosocial, and financial implications associated with their survival—it is clear that a disfiguring or function-limiting scar no longer confers the same advantages it did in pre-historic times. Consequently, a relatively new field of dermato-surgical medicine is evolving to address this new perspective with a focus on scar prevention, mitigation, rehabilitation, and an overall goal to reintegrate the burn survivor to “normalcy.”

Many animals (e.g., starfish, salamanders, lizards, etc.) have long been known to be able to regenerate tissue; however, it was not until relatively recently, in 2012, that researchers demonstrated the phenomenon of skin shedding and tissue regeneration in an adult mammal population, using the African spiny mouse as a model [224]. Coupling this discovery with the fact that fetal wounds heal without a scar early in human gestation and that adult humans retain the capacity to heal micro-wounds (e.g., bee stings, venipuncture, or facial rejuvenation with a fractional carbon dioxide laser, etc.) without scarring, we can now start to imagine that the door to scarless burn wound healing may not be as permanently closed to us as we once believed.

12.1 Skin copying and epidermal micrografting

Prevention of scarring might be as simple as ensuring that normal skin replaces the major wound defect [225, 226]. In essence, that is what full-thickness skin grafting seeks to accomplish, allowing the surgeon to bring in hair follicles, sweat glands, reticular dermis, subcutaneous fat, and other deep structures and relocating them to the wound bed. Unfortunately, it does so by creating another full-thickness skin wound at the donor site, a fact that limits this strategy to small wounds. Additionally, for a full-thickness graft to properly “take,” it must connect successfully to the wound bed’s underlying blood supply or the grafted tissue may die. Recently, an autologous micrografting device came to market offering to

deliver the benefits of a full-thickness skin graft without the limitations. In this technique, the proprietary device (CelluTome™ Epidermal Harvesting System, KCI, an Acelity Company, San Antonio, TX) uses suction and heat to homogeneously harvest hundreds of exceedingly small columns (700 μm diameter) of full-thickness skin without the need for anesthesia [227, 228]. The micrografts are then manually transferred directly to the recipient area. Donor sites reepithelialize within days and with little to no evidence of scarring. The recipient sites appear to demonstrate accelerated reepithelialization and seem to heal without the “fish-net” patterning associated with split-thickness skin grafts. While this novel technology is promising, long-term, prospective studies are needed to evaluate the true efficacy and clinical outcomes of this approach [227–230].

12.2 Stem cell therapy

The “holy grail” of employing stem cell therapy to improve—or even perfect!—desired wound healing after burn injury has long attracted the attention of burn surgeons. Combined gene delivery with stem cell therapy remains particularly promising. This process involves inserting a gene into recipient cells with the goal of delivering a concoction of growth factor genes at critical time points in the wound healing process [231]. This could be accomplished through any number of techniques including viral transfection, high pressure injection, liposomal vectors, naked DNA application, and it even introduces a new potential role for laser-assisted drug delivery (see below) [232]. Optimized culture conditions, preconditioning cell treatments, and the development of ideal scaffolds or matrices to optimize cell mobilization, homing, adhesion, and differentiation remain elusive but may be just over the horizon.

12.3 Cell culture autografting

In burn patients where the injuries are so extensive that donor site availability is limited or not practical, the notion of culturing human keratinocytes remains a still hopeful approach. From a general perspective, this technique is accomplished by, first, taking a small sample of the patient’s own healthy skin [233]. Next, the cells within the epidermis are separated, and the keratinocytes are grown, a process that involves providing the cells with specific nutrients. The resulting cultured skin is then applied to cover the burn wound, thus reducing the amount of healthy skin that must be removed for traditional burn wound grafting. Several companies are developing competing technologies to accomplish this goal, with one company receiving FDA approval, in 2018, for its proprietary “spray-on skin” system [234].

12.4 Laser surgery

Multiple laser and energy-based devices are now employed within the burn scar management algorithm in an effort to better “rehabilitate” the injured skin. This armamentarium includes, primarily, the vascular-specific pulsed dye laser (PDL), which helps to reduce erythema and hypertrophic scar formation, and the technique of ablative or non-ablative fractional laser resurfacing, which helps to normalize scar texture, thickness, and stiffness of the scars.

The pulsed dye laser (PDL) was the first laser to be specifically developed to treat port wine birthmarks with the principle of “selective photothermolysis” in mind [235]. First-generation PDL devices utilized a yellow light emitting at wavelength 577 nm to target oxyhemoglobin, a chromophore with absorption peaks located around 418, 542, and 577 nm. Through diffusion of heat, this laser caused selective

thermal damage of the abnormally dilated blood vessels with minimal to no collateral damage of surrounding cutaneous structures. Eventually, 585 and 595 nm wavelength PDL devices were developed to allow slightly deeper penetration through the skin (to a depth of around 1.2 mm) while still maintaining precise absorption. The development of surface cooling devices has, subsequently, afforded the use of higher energy fluences with larger spot sizes and improved treatment in darker skin surfaces. When applied to hypertrophic burn scars, PDL causes selective photothermolysis that induces coagulation necrosis of capillaries within the scar itself [236]. Because hypertrophic burn scars are characterized by pathologic neovascularization, PDL devices help to mitigate inflammation and collagen production and reduce the overall hypervascular response. From a patient perspective, PDL is also useful for helping to improve overall burn scar texture, pruritus, pain, and pliability [237].

Laser resurfacing has long been used for cosmetic indications such as treatment of fine rhytids of the eyelids and mouth, treatment of photoaging, and management of dyspigmentation. Original “fully ablative” devices, such as the carbon dioxide laser, target intracellular water as the main chromophore. Because of the abundance of water in human tissue, this process leads to non-selective and near-immediate vaporization of treated skin and a denaturation of surrounding extracellular proteins. In contrast to ablative devices, nonablative approaches induce coagulation as their primary mechanism of action without directly destroying tissue or exposing dermis to the external environment. The concept of “fractional photothermolysis” was fairly recently introduced and describes treatment of the target tissue with the generation of a precise array of evenly spaced areas of injury known as microscopic treatment zones (MTZ) [238]. Clinically, this technique results in untreated areas between the MTZs, containing significant amounts of intact epidermis and dermis available as a reservoir for a more rapid micro-healing response. With ablative fractional resurfacing (AFR) technologies, such as the fractional carbon dioxide (CO₂) and Erbium-YAG lasers, the operating surgeon may change device parameters to adjust for desired depth of treatment (to a maximum of about 3.5–4.0 mm with current devices) and accurately control the total ablated surface area within a treated area. The general rule for AFR is to decrease density (i.e., total ablated surface area) while increasing fluence (i.e., energy). How repeated pixelated thermal injuries to a burn scar could result in subjective and objective improvements is not entirely understood; however, the technique has consistently demonstrated the ability to facilitate rapid reepithelialization and a vigorous scar remodeling process while maintaining excellent safety margins [239–243]. Perhaps most notably, long-term, persistent gains in pliability, resulting in improved function and quality of life, most likely occur from a gradual process of diffuse dermal remodeling and a relative rehabilitation of dysfunctional scar tissue [244].

The varied nature of individual burn scars, the heterogeneity of burn patients, small sample sizes, a lack of treatment controls, and the cost of the devices themselves have been major limitations to research surrounding the use of lasers in the treatment of burn scars. Thankfully, several large, prospective studies are currently underway to investigate the utility of these devices, including in the pediatric population.

12.5 Laser-assisted drug delivery

The notion that certain medications or agents could be delivered topically through burn scar tissue has three potential advantages over oral administration of the same agent: directed therapy to the targeted tissue, limited systemic toxicity and side effects, and avoidance of first-pass metabolism. To this end, various chemical, biochemical, and physical strategies have attempted to enhance topical drug delivery into burn scar tissue. It is only relatively recently that AFR devices

have been utilized for this purpose [245]. In a process referred to as “laser-assisted drug delivery,” AFR devices create vertical columns of ablated tissue in the MTZs that then serve as conduits or channels for delivery of specific topical medications or agents. Pairing the delivery of topical agents temporally with AFR therapy is believed to allow for increased penetration and absorption of the applied agents, an approach that is particularly helpful in the treatment of burn scar tissue given its variable and fibrotic nature. Corticosteroids, 5-fluorouracil (5-FU), imiquimod, methotrexate, and other immunomodulators have all been used for this purpose with varying degrees of success. Overall, laser-assisted drug delivery is a promising intervention for burn scar treatment. Investigation of the optimal channel depth and channel density continues and will likely depend on each individual drug or agent’s chemical structure and the desired clinical target. Likewise, many drugs and agents have not been designed to be delivered to their target tissues in this manner, so larger prospective studies to determine safety and efficacy of this procedure will be critical.

13. Conclusion

The primary goal of clinical management of burns is to prevent the development of “burn shock.” Early classification of burns by depth and size is critical to goal-directed treatment strategies, with subsequent approaches guided by the post-injury physiological and metabolic demands. Appropriate anticipation and proactive, multimodality support of the patient, through fluid resuscitation, nutritional supplementation, and pharmacologic therapy is required for optimizing patient outcomes. Additionally, clinicians should closely monitor the patient for the development of secondary adverse events, such as infections and under- or over-resuscitation. Management of burns is complex and requires specialized facilities, teams of experienced burn surgeons, dedicated burn nurses, social workers, nutritionists, physical therapists, occupational therapists, pharmacists, respiratory interventionists, pain specialists, dermatologists, and psychologists [246, 247].

Burn center referral criteria	
1	Partial thickness burns >10% TBSA
2	Burns involving the face, hands, feet, genitalia, perineum, or major joints
3	Third degree burns in any age group
4	Electrical burns, lightning injury
5	Chemical burns
6	Inhalation injury
7	Burn injury in patients with preexisting medical disorders that could complicate management, prolong recovery, or affect mortality
8	Any patient with burns and traumatic injury wherein the burn poses the greatest risk of morbidity/ mortality. When a traumatic injury poses the greatest risk, adequate stabilization of the patient at a trauma center may be necessary prior to transport
9	Burned children in hospitals lacking the qualified personnel/equipment necessary to care for children
10	Burn injury to patients who require special social, emotional, or rehabilitative intervention

Excerpted from Guidelines for the Operation of Burn Centers (pp. 79–86), Resources for Optimal Care of the Injured Patient 2006, Committee on Trauma, American College of Surgeons.

Table 4.
Summary of burn center referral criteria; Legend: TBSA = Total body surface area.

The tremendous amount of progress in treatment of thermal injuries over the past several decades was possible because of the continuous evolution of trauma systems and burn centers, along with the development of state-of-the-art resuscitative and procedural approaches.

The critical timeline for thermal injury management occurs in the first 48 h from time of initial burn. Early burn classification should determine need for referral to a designated burn center (**Table 4**). The American Burn Association (ABA) list criteria for burn injuries that warrant referral to a designated burn center including: partial thickness burns of greater than 10% TBSA, burns involving the face, hands, feet, genitalia, or major joints, any third degree burns, electrical burns, chemical burns, inhalation injuries, burn injury to patients with significant pre-existing medical conditions, burns with additional traumatic injury, burns in children, or any burn injury to patients who may require special social, emotional, or rehabilitative assistance.

Author details

John Sojka¹, Andrew C. Krakowski² and Stanislaw P. Stawicki^{3*}

¹ Department of Surgery, St. Luke's University Health Network, University Hospital Campus, Bethlehem, Pennsylvania, USA

² Department of Dermatology, St. Luke's University Health Network, Anderson Campus, Easton, Pennsylvania, USA

³ Department of Research and Innovation, St. Luke's University Health Network, Bethlehem, Pennsylvania, USA

*Address all correspondence to: stawicki.ace@gmail.com

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