Burn injury is a leading cause of life-threatening trauma worldwide, affecting more than 450,000 Americans each year, and is associated with an average mortality rate of 0.8%. Patients with an increased risk of death from burn injuries include elderly patients and patients with large burns or inhalation injury. Providing optimal care for patients with major burn injuries requires the coordinated effort of multidisciplinary teams in which anesthesia providers play a critical role. Anesthetic management for burn surgery can be technically challenging because of difficult airway management and vascular access, as well as cognitively demanding because of dramatic pathophysiologic changes that compromise hemodynamic stability and alter patient response to many anesthetic agents.

The following article reviews the literature related to the pathophysiology and clinical management of major burn injuries and highlights the key concepts relevant to the delivery of safe and efficacious anesthesia for these patients.

Keywords: Burn management, burn shock, burn surgery, inhalation injury, major burn surgery.

Burns are among the most devastating injuries encountered in medicine and are a leading cause of life-threatening trauma worldwide. According to the Centers for Disease Control and Prevention, someone in the United States dies in a fire every 175 minutes and is injured every 31 minutes. Groups with an increased risk for fire-related injury and death include children under 5 and adults more than 65 years of age, poorer Americans, and those living in rural areas or in substandard housing.

The American Burn Association estimates that more than 450,000 burn-injured patients seek medical treatment in the United States each year, resulting in 45,000 hospitalizations and 4,000 deaths. The risk of death from burn injury increases with advancing age, increasing burn size, and the presence of inhalation injury. Up to 30% of burn injuries sustained each year are considered major burn injuries, characterized by burns to over 20% of total body surface area (TBSA) in adults, more than 10% TBSA in children and elderly patients, or full-thickness burns to >5% TBSA (Tables 1 and 2). Burns involving the face, airway, or genitalia are also classified as major burn injuries regardless of the percentage of TBSA affected.

Dramatic improvement in patient outcomes over the past 3 decades has been attributed to advancements in the understanding of major burn injury pathophysiology, improved burn shock management, early aggressive surgical intervention, and the development of specialized burn treatment centers. Yet providing optimal care to patients with major burn injuries remains challenging. Anesthetic management is complicated by physiologic derangements due to massive destruction of tissues that affect virtually all organ systems and alter patient response to anesthetic agents. Providing safe and effective anesthesia for burn surgery requires a fundamental understanding of the pathophysiological consequences of major burn injury as well as a familiarity with aspects of assessment, resuscitation, and pharmacotherapy that are unique to this patient population.

Pathophysiology of Major Burn Injury: A Brief Review for Anesthesia Providers

- **Burn Injury.** Major burns cause massive tissue destruction and activation of an inflammatory response that leads to dramatic systemwide physiologic derangements. Burn injury pathophysiology evolves in 2 distinct phases, a burn shock phase followed by a hypermetabolic phase, both of which have an impact on anesthetic management by altering patient hemodynamics (Table 3).

Acute burn injury results in an area of necrosis surrounded by ischemic tissues that may potentially become viable if adequate perfusion is restored. Within minutes to hours of injury, burned tissues release inflammatory and vasoactive mediators including histamine, prostaglandins, kinins, thromboxane, and nitric oxide that increase capillary permeability and cause localized burn wound edema. Subsequent reperfusion of ischemic tissues produces reactive oxygen species, toxic cell metabolites that cause further cellular membrane dysfunction and propagation of the immune response.

- **Burn Shock.** In addition to the local effects of burn injury, major burns cause the release of circulating mediators such as tumor necrosis factor and interleukins.
that result in a systemic inflammatory response syndrome.12-14 Within 6 to 8 hours of injury, increased microvascular permeability, vasodilatation, vascular stasis, decreased cardiac contractility, and reduced cardiac output result in massive edema formation in both injured and noninjured tissues. A massive leak of fluid and electrolytes from the intravascular space into the interstitial space, combined with fluid losses through drainage and evaporation from burn wounds, further impairs tissue perfusion. Rapid and effective intravascular volume replacement is critical to the prevention of burn shock, a combination of distributive, hypovolemic, and cardiogenic shock, in which plasma volume is insufficient to maintain preload or cardiac output and tissue hypoperfusion ensues. Failure to adequately replace intravascular volume can lead to significant organ injury from systemic inflammatory responses and multiorgan dysfunction. In the event that fluid resuscitation is successful, a pronounced hypermetabolic response develops over several days to weeks.13-16

- Hypermetabolic Phase. The hypermetabolic response to burns is more severe and sustained than any other form of trauma.15 A massive surge in catecholamines and corticosteroids, 10 to 50 times greater than nonburned plasma levels, drives the hypermetabolic response causing increased myocardial oxygen consumption and cardiac work. Persistent tachycardia, systemic hypertension, increased muscle protein degradation, insulin resistance,
elevated core temperature, and liver dysfunction are characteristic of this hyperdynamic phase of burn injury. Cardiac output and heart rate increase up to 150% above nonburned patient values and may remain elevated for up to 2 years postburn. Hyperventilation occurs during the hypermetabolic phase and persists until wound closure. Elevated metabolic rates also compensate for the large amounts of heat and water (up to 4,000 mL per m² burn area per day) lost through disrupted tissues. Proteins and amino acids are mobilized to meet immense metabolic demands and energy requirements, resulting in significant loss of lean body mass that further impairs immune function and wound healing.

The severity of the hyperdynamic, hypercatabolic response is related to TBSA burned and the duration of time patients are exposed to elevated levels of catecholamines and stress hormones. Left untreated, hypermetabolism leads to physiologic exhaustion and death. Strategies used to ameliorate the hypermetabolic response include early surgical intervention, maintenance of a warm environment, nutritional support to replenish catabolic losses, and pharmacological agents such as insulin and β-antagonists. Early excision and grafting of burn eschar attenuates the hypermetabolic response by preventing further net protein loss, catabolism, and the development of sepsis. Warming the environment to a neutral temperature (28-33°C) has been shown to reduce the magnitude of the hypermetabolic response.

Anesthesia for Burn Surgery

Preoperative assessment of patients with major burn injuries should include routine features of preoperative evaluation with particular attention to airway management, pulmonary status, and the distribution and severity of burn wounds. The patient’s current physiologic status should be thoroughly evaluated by considering vasopressor requirements, ventilator settings, pulmonary compliance, adequacy of resuscitation (ie, volume status and urine output), and derangements in laboratory study values, particularly acid-base disturbances. Table 4 provides a succinct list of preoperative concerns to guide the preoperative evaluation of patients with major burn injuries.

Burn wound severity is quantified according to TBSA burned (see Table 1) and wound depth (see Table 2) and is used in the initial management period to direct fluid resuscitation and surgical intervention.

Table 3. Pathophysiologic Changes During Early and Late Phases of Major Burn Injury

<table>
<thead>
<tr>
<th>Early phase</th>
<th>Late phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiovascular</td>
<td>Hypovolemia, ↓ cardiac output, ↑ SVR</td>
</tr>
<tr>
<td>Pulmonary</td>
<td>Airway obstruction and edema, pulmonary edema, Carbon monoxide poisoning</td>
</tr>
<tr>
<td>Renal</td>
<td>↓ Glomerular filtration rate, myoglobinuria</td>
</tr>
<tr>
<td>Endocrine and metabolic</td>
<td>↑ Metabolic rate, ↑ core body temperature, ↑ muscle catabolism</td>
</tr>
<tr>
<td>Hepatic</td>
<td>↓ Perfusion</td>
</tr>
<tr>
<td>Hematologic</td>
<td>Hemoconcentration, hemolysis, thrombocytopenia</td>
</tr>
<tr>
<td>Gastrointestinal</td>
<td>↓ Perfusion with mucosal damage</td>
</tr>
<tr>
<td>Neurologic</td>
<td>↑ Cerebral edema, ↑ intracranial pressure</td>
</tr>
</tbody>
</table>

Anesthesia for Burn Surgery

Immediate airway assessment is always the first priority because of the potential for massive airway edema that can result in acute obstruction and death. The key features of airway assessment in major burn injury patients include preexisting airway abnormality, current airway injury (ie, inhalation injury), and signs of airway obstruction. Inhalation injury is the most frequent cause of death in burn patients in the United States, occurring in 10% to 25% of burn injured patients and increasing mortality by up to 25%. Clinical manifestations of an inhalation injury may be delayed up to several hours postexposure, but a history of entrapment in a closed space, facial burns, symptoms of respiratory distress, and the presence of carbonaceous sputum increase the likelihood that an inhalation injury has occurred. Because of the significant impact that inhala-
Inhalation injury has on mortality and morbidity, prompt intubation is warranted in the presence of these findings.8,19,20

• Inhalation Injury. Clinical manifestations of inhalation injury depend on the chemical composition and particulate size of inhaled smoke, the duration of exposure, and the patient’s tidal volume during inhalation.19 Smoke inhalation injury results in 3 types of injury including thermal injury mostly restricted to the upper airway, chemical irritation of the respiratory tract, and systemic toxicity due to the absorption of toxic gases such as carbon monoxide.

Because of the heat dissipating properties of the oropharynx and nasopharynx, thermal injury is primarily restricted to airway structures above the vocal cords, unless steam is inhaled.19,20 Heat destroys the epithelial layer, denatures proteins, and activates the complement cascade leading to the release of histamine and nitric oxide and the formation of xanthine oxidase, which ultimately result in the production of reactive oxygen species and reactive nitrogen species. Reactive oxygen species and reactive nitrogen species both cause increased endothelium permeability that results in edema formation. Immediate injury may result in erythema, ulceration, and edema; however, clinical symptoms such as dyspnea and stridor may not develop until the edema significantly decreases airway diameter. The aggressive fluid administration necessary to treat burn shock associated with major burn injuries further exacerbates edema formation and may result in more rapid progression of airway obstruction.

Chemical injury from incomplete products of combustion (eg, aldehydes and oxides of sulfur and nitrogen, hydrochloric acid and carbon monoxide) is the primary cause for damage to the tracheobronchial area and lung parenchyma.19,20 Destruction of bronchial epithelium results in mucosal edema and sloughing, impaired mucociliary clearance, interstitial edema, inactivation of surfactant, and the formation of endobronchial casts, which can lead to partial or complete airway obstruction. Pulmonary compliance may be decreased up to 50% within the first 24 hours after injury causing acute microatelectasis and ventilation perfusion mismatch.

Fiberoptic bronchoscopy is the current gold standard for diagnosis and evaluation of inhalation injury and may be used to visualize and assess mucosal erythema, ulceration, and necrosis from the level of the posterior pharynx to 4 or 5 generations of bronchi.20,21 Chest radiographs may show signs of diffuse atelectasis, pulmonary edema, or bronchopneumonia but tend to underestimate injury in the immediate postburn period when signs of damage are primarily confined to the conducting airways.

• Carbon Monoxide Poisoning. Carbon monoxide poisoning should be suspected in patients with inhalation injuries and is diagnosed by elevated carboxyhemoglobin (COHb) levels.22 Clinical presentation of acute carbon monoxide poisoning is variable, but the severity of observed symptoms generally correlates with COHb level (Table 5). A COHb level greater than 30% requires a high concentration of inspired oxygen to quickly reduce COHb half-life because carbon monoxide binds to hemoglobin, myoglobin, and cytochromes with an affinity 200 times stronger than that of oxygen, and elimination of COHb is dependent on alveolar oxygen pressure rather than alveolar ventilation. The COHb half-life can be reduced from 4 hours with room air to 60 to 90 minutes with the administration of 100% inspired oxygen.

• Ventilatory Concerns and Settings. Alterations in pulmonary physiology accompany all major burn injuries even in the absence of inhalation injury.21 Circulating mediators cause hypoxemia and increase lung vascular permeability and pulmonary vascular resistance, which

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Table 4. Specific Concerns for Preoperative Evaluation of the Patient With Major Burn Injuries9

- Patient age, preburn and current body weight, body habitus, and preexisting comorbidities (including conditions that increase risk of infection)
- Airway assessment, current management (intubated/nonintubated), and extent of compromise (ventilator mode and settings)
- Extent of injuries (percentage of total body surface area burned): burn depth and distribution, inhalation injury and associated injuries (eg, fractures)
- Mechanism of injury (flame, explosion, chemical, electrical, scald) and time elapsed since injury
- Vascular access and adequacy of resuscitation (current fluid requirements, urine output)
- Surgical plan (patient positioning, estimate of areas to be excised, and donor sites to harvest) and previous anesthetic records

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Figure 1. Wallace Rule-of-Nines Method for the Assessment of Total Body Surface Area (TBSA) Burned
(Reprinted with permission from BMJ Publishing Group Ltd.18)
Figure 2. Lund-Browder Chart for the Assessment of Total Body Surface Area Burned

Abbreviations: Ant, anterior; Post, posterior; PTL, partial thickness loss; FTL, full thickness loss.

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are characteristic of acute lung injury (ALI) and acute respiratory distress syndrome (ARDS). Pulmonary derangements predispose patients to reactive airway disease, laryngospasm, bronchospasm, ventilation-perfusion mismatch, marked decrease in pulmonary compliance, pneumonia, and ultimately pulmonary failure. Treatment modalities include tracheal intubation with administration of supplemental oxygen and mechanical ventilation, bronchodilators, and frequent suctioning of copious and tenacious airway secretions. Even though existing randomized control trials have not demonstrated significant survival advantage over LTV, these modalities may provide rescue therapy in patients with refractory hypoxemia. High-frequency oscillation ventilation, high frequency percussive ventilation, and airway pressure release ventilation employ low tidal volumes and high mean airway pressures or PEEP to improve oxygenation and recruit alveoli, respectively. Ultimately it will be at the discretion of the anesthesia provider to adjust ventilation according to individual patient parameters.

**Mechanical Ventilation Strategies.** Goals of ventilation in patients with inhalation injury include maintenance of adequate blood oxygenation and elimination of carbon dioxide to prevent respiratory acidosis and decrease the work of breathing. Many strategies have been used in an attempt to optimize ventilation in these patients, yet the ideal ventilatory mode remains elusive and ventilation remains challenging. Conventional low-tidal volume ventilation (LTV) has been shown to improve patient survival in patients with ALI/ARDS and currently represents the standard of care, although studies using the LTV strategy have typically excluded patients with inhalation injury. The lung protective LTV protocol developed by the ARDS Network includes a target tidal volume of 6 mL/kg predicted body weight (with a range of 4-8 mL/kg depending on plateau pressure and pH), plateau pressure ≤ 30 cm H2O, FiO2 as low as possible to maintain PaO2 ≥ 90 mm Hg and permissive hypercapnia up to pH 7.2.

Alternative modes of ventilation and adjunctive therapies such as inhaled nitric oxide and increased levels of positive end-expiratory pressure (PEEP) are also currently used in patients with inhalation injury. Even though existing randomized control trials have not demonstrated significant survival advantage over LTV, these modalities may provide rescue therapy in patients with refractory hypoxemia. High-frequency oscillation ventilation, high frequency percussive ventilation, and airway pressure release ventilation employ low tidal volumes and high mean airway pressures or PEEP to improve oxygenation and recruit alveoli, respectively. Ultimately it will be at the discretion of the anesthesia provider to adjust ventilation according to individual patient parameters.

**Cardiovascular Issues and Fluid Resuscitation.** Patients undergoing anesthesia for burn surgery require judicious fluid administration to maintain intravascular volume and global tissue perfusion in the setting of hypovolemia, systemic inflammation, and extravascular fluid shifts. To facilitate resuscitation, a minimum of 2 large-caliber peripheral intravenous catheters should be placed, preferably through unburned tissue. Evidence-based literature has yet to identify the ideal type of fluid or regimen for resuscitation of burned patients. Modern fluid resuscitation is typically governed by treatment center preference and guided by a handful of formulas that estimate initial fluid requirements based on burn severity and body weight (Table 6). Fluid formulas provide a starting point for resuscitation and are particularly useful to providers who do not routinely care for burn injured patients. The Parkland Formula is the most widely used resuscitation formula in the world, though only the initial 24-hour crystalloid portion tends to be followed closely. Proposed more than 30 years ago, these guidelines are easy to calculate and use isotonic crystalloid solutions that are readily available and relatively inexpensive. According to the formula, patients receive 4 mL/kg per percentage of TBSA burned of lactated Ringer’s solution within the first 24 hours after burn injury, with half of that volume administered within the first 8 hours.

**Table 5. Symptoms of Acute Carbon Monoxide Toxicity Based on Blood Carboxyhemoglobin (COHb) Level**

<table>
<thead>
<tr>
<th>COHb (%)</th>
<th>Symptom</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10</td>
<td>Usually asymptomatic, may have headache</td>
</tr>
<tr>
<td>&gt; 20</td>
<td>Headache, dizziness, confusion, visual disturbances, dyspnea, and nausea</td>
</tr>
<tr>
<td>&gt; 40</td>
<td>Coma and seizures due to cerebral edema</td>
</tr>
<tr>
<td>&gt; 60</td>
<td>Cardiopulmonary dysfunction and death</td>
</tr>
</tbody>
</table>

**Table 6. Fluid Resuscitation Formulas Commonly Used in the United States**

<table>
<thead>
<tr>
<th>Formula</th>
<th>Fluid in 1st 24 h</th>
<th>Crystalloid in 2nd 24 h</th>
<th>Colloid in 2nd 24 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parkland</td>
<td>LR, 4 mL/kg per % TBSA</td>
<td>20%-60% estimated plasma volume</td>
<td>Titrated to UO of 30 mL/h</td>
</tr>
<tr>
<td>Evans</td>
<td>NS, 1 mL/kg per % TBSA</td>
<td>50% of 1st 24-h volume and D5W, 2L</td>
<td>50% of 1st 24-h volume</td>
</tr>
<tr>
<td>Slater</td>
<td>LR, 2 L and FFP, 75 mL/kg</td>
<td>50% of 1st 24-h volume</td>
<td>50% of 1st 24-h volume</td>
</tr>
<tr>
<td>Brooke</td>
<td>LR, 1.5 mL/kg per % TBSA</td>
<td>Colloid, 0.5 mL/kg per % TBSA and D5W, 2 L</td>
<td>50% of 1st 24-h volume</td>
</tr>
<tr>
<td>Brookel</td>
<td>LR, 2 mL/kg per % TBSA</td>
<td>0.45% NS titrated to UO</td>
<td>1 U FFP per liter 0.45% NS and D5W as needed for hypoglycemia</td>
</tr>
<tr>
<td>Modified Brooke (Cleveland)</td>
<td>LR, 4 mL/kg per % TBSA and NaHCO3, 50 mEq</td>
<td>50% of 1st 24-h volume</td>
<td>50% of 1st 24-h volume</td>
</tr>
</tbody>
</table>

Abbreviations: UO, urine output; LR, lactated Ringer’s solution; FFP, fresh frozen plasma; NS, normal saline; D5W, dextrose 5% (5 g dextrose/100 mL water).
Initial assessment of burn severity tends to be inaccurate even when performed by experienced clinicians, emphasizing the need for continuous assessment of clinical end points to ensure that patients are neither underresuscitated nor overresuscitated. Actual fluid rates should be continuously adjusted to maintain urine output of 0.5 to 1.0 mL/kg/h in adults and 1.0 to 1.5 mL/kg/h in children. Patients who tend to require more fluid than predicted by formulas include children and patients with inhalation injuries or additional traumas.

Isotonic crystalloids have traditionally been the fluid of choice for resuscitation of major burn injury patients, particularly during the initial 24-hour postburn period when capillary permeability is maximal. The use of colloids (e.g., albumin, hydroxyethyl starch preparations) for volume replacement remains controversial despite theoretical benefits over crystalloids including replenishment of plasma proteins and greater longevity in the intravascular space. Colloids have been found to reduce overall fluid requirements and improve patient hemodynamic stability when compared to crystalloids, even within the initial 24-hour postburn period, yet an increase in patient survival has not been demonstrated, and their use in many US treatment centers remains limited. In a recent review of modern resuscitation strategies, Tricklebank reports the successful use of other unique preparations that combine crystalloid with albumin or plasma to decrease fluid requirements and avoid adverse effects associated with overresuscitation such as abdominal compartment syndrome. Because virtually all fluids have potential for both benefit and detriment, the best resuscitation protocol will ultimately provide a combination of fluids with properties best suited for an individual patient’s unique physiologic needs.

- Hematology. The combined effects of burn injury and fluid resuscitation during the acute phase results in anemia and thrombocytopenia. Red blood cells are lost through heat-induced damage and bleeding burn wounds, particularly during excision procedures where brisk bleeding demonstrates adequate tissue viability. Activation of clotting factors in the burn wound itself induces a hypercoagulable state that further compromises hematologic stability and increases the risk for venous thrombosis, pulmonary embolism, and less commonly, disseminated intravascular coagulation.

Blood loss during burn surgery is most closely related to the amount of burn area excised. Blood conserving strategies include early excision and wound closure and the use of tourniquets, albumin, cell saver, hemorrhagic agents (e.g., fibrin sealant), and epinephrine soaked dressings. Currently accepted guidelines support blood transfusion when hemoglobin decreases below 6 g/dL, but rarely when hemoglobin is 10 g/dL or greater. In a recent review of US burn center blood transfusion practices for patients with major burn injuries, Palmieri et al report a mean hemoglobin transfusion threshold of 8.1 g/dL that is influenced by TBSA and patient weight. Restricted blood transfusion protocols are associated with reduced mortality and rates of infection in adults and children with major burns.

- Renal and Hepatic Effects. Patients with major burn injuries are susceptible to acute renal failure (ARF) due to the combined effects of hypovolemia and increased levels of catecholamines, angiotensin, vasopressin, and aldosterone, which cause systemic vasoconstriction and can lead to renal insufficiency. In a retrospective study examining the incidence of ARF in patients with major burn injuries, Kim et al found that the risk of ARF and death increase with increasing burn size. Factors that lower the incidence of ARF include appropriate fluid resuscitation that is adjusted to urine output, early wound excision, and the prevention of sepsis. Liver damage may result from hypovolemia-related hypoperfusion during the initial stages of burn injury, and subsequently from sepsis, drug toxicity, or blood transfusion.

- Temperature Regulation. Patients with major burn injuries are at great risk for perioperative heat loss due to loss of skin barriers. Aggressive efforts to minimize heat loss during burn surgery are required to prevent hypothermia and exacerbation of the hypermetabolic response. Maintaining ambient temperatures between 28°C and 33°C increases patient survival due to a reduction in metabolic rate and muscle and protein catabolism. Heat conserving strategies include placing the patient on warming blankets or other insulated surfaces, covering the patient with plastic or forced-air blankets, and using warming fluids and blood products. Core temperature may be continuously monitored through either a temperature sensing bladder catheter or an esophageal probe to ensure adequacy of warming measures.

### Anesthetic Techniques for Burn Surgery

The ideal anesthetic technique for burn surgery has yet to be described. With the exception of succinylcholine, virtually all anesthetic agents have been used safely in patients with major burn injuries. Selection of specific agents ultimately depends on airway status, patient pathophysiology and provider preference (Table 7). Abnormal drug effects result from burn mediated changes to organ systems that control the distribution, transformation, and excretion of drugs and from changes to receptor populations. In general, drug pharmacokinetics undergo a biphasic response that corresponds to the burn shock and hypermetabolic phases of burn injury.

During the initial burn shock phase, decreased circulating blood volume, cardiac output and tissue perfusion lead to reductions in renal and hepatic blood flow, which prolongs the rate of drug distribution and onset of clinical effects. Lower doses of agents are typically required because of prolonged duration of action and slower rates...
of renal clearance. During the subsequent hypermetabolic phase, high blood flow to the liver and kidneys, decreased plasma albumin, and an increased level of α1-acid-glycoprotein result in altered protein binding and increased renal clearance. Anesthetic requirements are generally increased including minimum alveolar concentration for volatile anesthetics, and the duration of action is decreased requiring frequent redosing of agents.

- **Induction.** Balanced general anesthesia consisting of an opioid, muscle relaxant, and volatile agent is the most common anesthetic technique used for burn excision and grafting.\(^8,10\) Propofol and thiopental have been successfully used for induction, though they should be carefully titrated to minimize dose dependent cardiac and respiratory depression.\(^10,11\) Etomidate is an effective induction agent because of its stable hemodynamic profile and is considered a good choice for burned patients who may not tolerate changes in heart rate or cardiac output. However, the use of etomidate in septic patients is controversial because of adrenocortical suppression following a single bolus dose and likewise may not be the best choice of induction agent for immunocompromised burn patients.\(^32\)

Ketamine offers many advantages for induction and maintenance of anesthesia for burn-injured patients and is routinely used for burn-related procedures.\(^8,10,11,33\) Ketamine may be particularly useful for the induction of hypovolemic patients due to sympathomimetic effects that cause dose-dependent increases in arterial blood pressure and heart rate.\(^34\) Increased systemic vascular resistance may be advantageous during burn surgery, as it reduces heat and blood loss from burned skin compared with vasodilation caused by virtually all other anesthetic agents. Ketamine offers additional benefits of airway reflex preservation, dissociative anesthesia, and potent analgesia. Minimal increases in heart rate observed after ketamine is administered to hypermetabolic patients may result from preexisting elevated levels of catecholamines that result in a decrease in the number of receptors and a down-regulation of receptor affinity.\(^10\) Because ketamine increases cerebral blood flow and systemic blood pressure, it should be avoided in patients with closed head or penetrating eye injuries. Unpleasant emergence delirium associated with ketamine may be mitigated by administration of benzodiazepines or dexmedetomidine.\(^10,33\)

- **Intubation.** All patients with face, neck, and upper chest burns are considered potential difficult airways due to facial and airway edema that may distort the normal anatomy and/or limit neck and mandibular mobility.\(^8-11,21\) Mask ventilation after anesthetic induction may be challenging and intubation by direct laryngoscopy may be virtually impossible. Fiberoptic intubation in the awake and spontaneously breathing adult patient may be the safest and most efficacious option for patients with a suspected difficult airway and can be facilitated with topical anesthesia and sedation.\(^21\) Pediatric patients require deep sedation for fiberoptic intubation, which can be facilitated by inhalation induction with a volatile anesthetic or intravenous ketamine, 1 to 2 mg/kg.\(^11\)

Cuffed endotracheal tubes (ETTs) are the standard of care for burn-injured adults and recent evidence suggests they may also be advantageous in infants and children undergoing burn surgery.\(^11,35\) In a recent retrospective review of pediatric patient outcomes following intubation for burn surgery at a Washington burn center, Dorsey et al\(^35\) found modern low-pressure, high-volume cuffed ETTs were not associated with increased incidence of postextubation stridor but were instead associated with reduced rates of clinically significant air leak and immediate reintubation when compared with uncuffed ETTs. Cuffed ETTs may be particularly useful in pediatric patients with major burn injuries who require high ventilatory pressures due to decreased lung compliance associated with inhalation injury and/or large volume fluid resuscitation.

- **Maintenance.** Volatile anesthetics are routinely used during maintenance of adult patients and for induction and maintenance of pediatric patients.\(^8-11\)
Dose-dependent vasodilation and cardiac depression may limit volatile anesthetics as sole agents and nitrous oxide, which has the least effect on cardiovascular and respiratory function, and may be the most useful of the volatile agents as a component of a balanced anesthetic technique. Volatile anesthetics may be particularly effective in patients with inhalation injuries because of their bronchodilatory effects.\textsuperscript{10} A total intravenous anesthetic technique should be considered in patients managed with nonconventional ventilators such as high-frequency oscillatory ventilation to avoid interruption in lung-protective benefits. Anesthetic agents including fentanyl, sufentanil, propofol, ketamine, and midazolam may be used as continuous infusions to provide anesthesia for surgical procedures.

One of the most striking altered drug responses seen in burned patients is the response to neuromuscular blocking agents.\textsuperscript{31} Burn injury causes proliferation of extrafungal nicotinic acetylcholine receptors leading to increased resistance to nondepolarizing muscle relaxants and increased sensitivity to depolarizing muscle relaxants (ie, succinylcholine). Administration of succinylcholine greater than 24 hours postburn injury may result in a potentially lethal hyperkalemic response similar to that seen in patients with degenerative neurological disorders.\textsuperscript{10} The release of massive amounts of potassium from muscle cells increases with increasing dose, TBSA burned, and the amount of time elapsed since burn injury. The response may persist for up to 18 months after burn injury, during which time succinylcholine should be avoided. Resistance to nondepolarizing muscle relaxants may develop within a week of burn injury and persist for up to a year and is proportional to TBSA burned. Burn patients may require a 2- to 5-fold greater dose and serum concentration of nondepolarizing muscle relaxant than nonburned patients.\textsuperscript{31,36,37} Rocuronium in large doses up to 1.2 mg/kg has been used effectively to facilitate rapid-sequence induction in patients with major burn injuries, but it should be used with caution in patients at risk for difficult intubation because of the prolonged duration of action associated with large doses.\textsuperscript{38} Resistance has not been found to prolong recovery times or have an impact on efficacy of reversal agents.\textsuperscript{31}

- **Adjuvants.** Insulin and \(\beta\)-adrenergic antagonists have been used to reverse mediators of the hypermetabolic response and may be useful for anesthetic management of patients in the hyperdynamic phase of burn injury.\textsuperscript{13-17} Insulin therapy has been found to reduce mortality and morbidity in critically ill patients. Proposed mechanisms for its anabolic effects include increased uptake of amino acids and glucose into tissues, regulation of proteolysis, and initiation of protein translation.\textsuperscript{16} Beta-antagonist therapy ameliorates the effects of circulating catecholamines and blocks \(\beta\)-adrenergic stimulation, leading to reductions in cardiac work, tachycardia, metabolic rate, and thermogenesis. Propranolol, titrated to a 15% to 20% reduction in heart rate (0.5-4 mg/kg/d), has been found to decrease cardiac work and improve oxygen delivery to myocardial tissue and to decrease resting energy requirements, muscle catabolism, and fatty liver infiltration.\textsuperscript{16}

- **Postanesthetic Considerations and Pain Management.** Postanesthetic considerations for patients with major burn injuries include the decision to extubate and provision of adequate postoperative analgesia. Many burned patients will remain intubated after surgery because of a need for mechanical ventilation, continued airway protection, or pulmonary rehabilitation.\textsuperscript{8,10} If the patient is to be extubated, a smooth emergence is imperative to maintain integrity of freshly placed grafts and may be facilitated with adequate analgesia and gradual emergence in an intensive care unit.

Burn injuries are intensely painful due to direct tissue injury and inflammation-mediated hyperalgesia.\textsuperscript{33,39} Initial and ongoing painful stimulation of nerve endings by inflammatory mediators (such as bradykinin and histamine) and neurotransmitters (such as glutamate and substance \(P\)) affect both peripheral and central pain mechanisms and contribute to the development of chronic pain syndromes.\textsuperscript{39} Although burn pain is well recognized and has been well described, it remains poorly managed.\textsuperscript{33,39} Intraoperative pain assessment is often confounded by the physiologic manifestations of burn injury including hypertension and persistent tachycardia. Adequate analgesia and sedation are required to avoid adverse physiological and psychological outcomes. Pain-induced tachycardia and increased myocardial oxygen consumption contribute to stress-induced hypermetabolism and increased susceptibility to acute stress disorder and posttraumatic stress disorder.\textsuperscript{39}

Multimodal techniques for the treatment of pain and anxiety have proven successful in burn patient management.\textsuperscript{8,11,33,39} Opioids, titrated to response, remain the mainstay of therapy during the initial phase of burn injury and prolonged, continued administration often leads to tolerance in burn patients. Benzodiazepines, propofol, ketamine, and dexmedetomidine have been found to significantly reduce pain and anxiety during burn procedures and may be helpful in ameliorating opioid tolerance.\textsuperscript{33,39} Regional anesthesia and peripheral nerve blockade have also been used successfully in burn surgery, and further studies are warranted to determine the full potential of these techniques.\textsuperscript{40,41}

**Summary**

As an expert in airway management, intraoperative hemodynamic control, and postoperative pain management, the knowledgeable anesthesia provider is a valuable member of the multidisciplinary burn care team. Patients with major burn injuries often present in varying states of physiologic compromise, yet surgery and thus anesthesia
must not be delayed because wound excision and closure are critical for patient survival. Safe and effective anesthetic management involves careful consideration of the systemwide pathophysiologic changes that result from the large-scale destruction of tissues and the hemodynamic consequences of massive fluid shifts and a profound inflammatory response. Alterations in patient response to anesthetic agents vary with phase of burn injury and may persist for months to years, which has an impact on anesthetic management long after the initial injury. Providing anesthesia for burn surgery is challenging yet rewarding, as it facilitates recovery from some of the most devastating injuries seen in medicine.

REFERENCES

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