



THE EFFECT OF BLAST-RELATED BURN INJURIES FROM PROLONGED FIELD CARE TO REHABILITATION AND RESILIENCE

A REVIEW of the Scientific Literature

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Preface

This report is intended to facilitate the Ninth Department of Defense International State-of-the-Science Meeting (SoSM) on Blast Injury Research. The SoSM series was established in 2009 under the authority of the U.S. Department of Defense (DoD) Executive Agent for Blast Injury Research. Its purpose has been to identify knowledge gaps in blast injury research; ensure that DoD medical research programs address existing gaps; foster collaboration between scientists, clinicians, and engineers in blast injury–related fields; promote information sharing on the latest research; and identify immediate, short-term, and long-term actions to prevent, mitigate, and treat blast injuries. The ninth SoSM topic was “Mitigating the Impact of Blast-Related Burns from Prolonged Field Care to Rehabilitation and Resilience.”

A foundational part of each SoSM consensus process is a comprehensive background literature review. This review provides an overview of the literature and delivers a series of recommendations for future medical research relating to burns, emphasizing prolonged field care and rehabilitation research and recommendations. This work may be of interest to senior military and medical leaders, DoD policymakers, military and veterans research portfolio managers, and healthy and injured military service members and their families.

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Summary

The U.S. Army Medical Research and Development Command and the U.S. Department of Defense (DoD) Blast Injury Research Coordinating Office (BIRCO) sponsored the Ninth U.S. Department of Defense International State-of-the-Science Meeting (SoSM) for Blast Injury Research to identify what is known and what is not known regarding key blast injury–related topics and emerging issues. The topic of the SoSM was “The Impact of Blast-Related Burn Injuries from Prolonged Field Care to Rehabilitation and Resilience.” To inform the SoSM and the associated work group and recommendation process, the BIRCO requested that the RAND Corporation’s National Defense Research Institute conduct a comprehensive literature review on burn injury following blast injury.

We developed four main literature review objectives:

1. Describe the epidemiology and outcomes of blast-related burn injury.
2. Review the evidence on prevention and acute management of blast-related burn injuries.
3. Review the evidence on prolonged field care and blast-related burn injuries.
4. Review the evidence and innovations about chronic care of blast-related burn injuries.

To complete this review of articles from 2008 to 2019, we defined key research questions about blast-related and military-relevant burns; identified articles meeting a defined set of inclusion criteria in the peer-reviewed scientific literature and the DoD grey literature; docu-

mented and coded key article features; and synthesized and analyzed the abstracted data. Article findings were synthesized using the continuum of health research, from foundational research to health services research, as defined in the National Research Action Plan (NRAP), outlined by DoD and the U.S. Department of Veterans Affairs. Articles written in a language other than English were excluded, as were articles that were not in the public domain (e.g., classified, For Official Use Only).

Results of the Literature Review

Overall, we identified articles about blast-related burn injuries published between 2008 and 2019. Among identified articles, basic and applied clinical research had roughly equal representation. In the body of the report, we further summarize the studies on the biophysiological mechanisms of blast-related burn injuries and complications, the incidence and prevalence of burn injuries, and aspects of acute and long-term burn care.

Synthesis of Evidence and Preliminary Recommendations

This report concludes with four key preliminary recommendations based on the results of our literature review and synthesis of the evidence.

Recommendation 1: Invest in Research Areas Where the Epidemiology Indicates a Greater Need for Improvement in Clinical Care and Service Delivery

The epidemiological literature provides a direct indication of the most frequent comorbidities, sequelae, and causes of mortality associated with burn-related injury. Therefore, it would be valuable to map these findings onto the existing treatment research portfolio to identify areas that are understudied and underinvested. By way of example, burns are the most common type of noncombat pediatric civilian injury presented at combat support hospitals in Iraq and Afghanistan (Arul

et al., 2012), yet we found only case studies addressing this population. Studies addressing prevention and treatment of infection, as well as inhalation injury, are necessary to better address burn injury, a leading cause of fatality among military service members. Studies along these lines would be particularly valuable in the prolonged field care setting, where access to antiseptics and other resources is restricted.

Prevention efforts likewise require additional research. Overall, additional research measuring the relative value of investments in prevention versus treatment could have significant value and generate cost savings. There is limited research on prevention of blast-related burns, including only a small set of informational campaigns that could be implemented in a military context. Additionally, research testing the current application of diagnostic and severity assessment tools in military contexts would be valuable. The only study that we identified in this space concluded that existing methods for measuring total body surface area (TBSA) produce highly variable results and that TBSA determination can be important for determining care plans (Martin, Lundy, and Rickard, 2014).

Recommendation 2: Review How Guidelines Are Developed, How Often They Are Updated, and How the Guidelines Integrate New Evidence

We found a significant number of systematic literature reviews pertaining to blast-related burn injuries. However, the synthesis of these into a systematic and routinely updated set of guidelines appears to be lacking. We recommend reviewing burn-injury care guidelines at regular intervals to account for evolving best practices and innovations.

Recommendation 3: Expand Training on, and Test New Models of, Prolonged Field Care for Blast-Related Burn Injuries

Few studies have addressed prolonged field care. The evolving nature of adversaries' capabilities, military operations, and weaponry suggests that prolonged field care capabilities are essential for managing severe blast-related burns. The literature has outlined several areas requiring further research, including the impact of training clinicians in forward treatment of blast-related burns on outcomes (Parkhouse, 2009; Studer

et al., 2015); improved training in fluid resuscitation and pain management; and the design and subsequent dissemination of forward burn kits. Limited research on BiobraneTM and similar wound-management products shows promise in a prolonged field care setting, but studies have been small and should be expanded. Finally, studies yielding direct applications—such as investigations finding that silver-nylon dressing is uniquely portable and easy to use and has key antimicrobial properties (Barillo, Pozza, and Margaret-Brandt, 2014; Studer et al., 2015)—might serve as guideposts for standard setting.

Recommendation 4: Develop Enhanced Care Coordination and Triage Strategies for Civilian Burn Patients Receiving Care in Military Treatment Facilities

There is limited research on triage algorithms and systematic emergency-treatment guidelines for civilian burn patients receiving burn care at military treatment facilities (MTFs) in combat areas. International humanitarian law requires providing emergency medical support for civilians, including children, who are injured in conflicts. Providing forward treatment for civilians with noncombat burn injuries at field hospitals can have a significant resource and logistical impact on facility operations, including bed space, operating room supplies, and nursing time, and pediatric admissions to MTFs for intensive care can require a disproportionate share of resources (Jeevaratnam and Pandya, 2014). Furthermore, the availability of surgery to treat burn injuries and technology to perform skin grafting is uncommon in local civilian treatment facilities in combat areas, which creates difficulty in planning discharge and follow-up care for civilian burn patients who need significant aftercare. While there are extensive protocols for evacuating military members who sustain serious burn injuries to higher-level facilities, civilian patients are faced with fewer opportunities for comprehensive emergency burn care and effective aftercare delivered locally. This increases the likelihood of poor outcomes, and civilian patients must compete for significant time and resources from local MTFs. Emergency department triage algorithms used in civilian mass casualty incidents involving burns could be modified and tested for the military setting.

Acknowledgments

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Abbreviations

ACS	abdominal compartment syndrome
AKI	acute kidney injury
ALARACT	All Army Activity
AMA	American Medical Association
BIRCO	Blast Injury Research Coordinating Office
BRG	Burn Resuscitation Guidelines
BWI	burn wound infection
CBRNE	chemical, biological, radiological, nuclear, or explosive
CEA	cultured epidermal autograft
CINAHL	Cumulative Index of Nursing and Allied Health Literature
CRRT	continuous renal replacement therapy
DASH	disabilities of the arm, shoulder, and hand
DoD	U.S. Department of Defense
DTIC	Defense Technical Information Center
ECMO	extracorporeal membrane oxygenation
ED	emergency department
HO	heterotopic ossification
ICU	intensive care unit
IED	improvised explosive device
ISS	injury severity score

IT	information technology
IV-PCA	intravenous patient-controlled analgesia
LAD	limited-access dressing
MBC	mass burn casualty
MRSA	methicillin-resistant <i>Staphylococcus aureus</i>
mTBI	mild traumatic brain injury
MTF	military treatment facility
NATO	North Atlantic Treaty Organization
NPWT	negative-pressure wound therapy
NRAP	National Research Action Plan
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
PTSD	posttraumatic stress disorder
PWD	platform wound device
QOL	quality of life
SoSM	State-of-the-Science Meeting
START	Simple Triage and Rapid Treatment
TBI	traumatic brain injury
TBSA	total body surface area
THAM	tris(hydroxymethyl)aminomethane
USAISR	U.S. Army Institute of Surgical Research
VR	virtual reality

Background and Purpose

Blasts are complex events that can lead to multiple types of injuries through various mechanisms. Researchers tend to classify blast injuries into four (sometimes five) categories: primary injuries, caused by interactions between the blast wave and the body; secondary injuries, caused by debris carried by the blast; tertiary injuries, caused by physical displacement as a result of the pressure from the blast; and quaternary injuries, caused by secondary consequences of the blast, including thermal burns (Singh et al., 2016). Burn-relevant quinary effects include infections of burn wounds and bacterial, chemical, and radiological contamination (Cancio et al., 2017; Popivanov et al., 2014).

Burns are one of the most difficult types of injury for which to care. This is because the skin is an essential organ that supports fluid balance and thermoregulation and defends against microorganisms that can cause severe, life-threatening infections. Once the skin is burned, it can no longer perform these functions well. In addition, burns cause a severe inflammatory and hypermetabolic state that can lead to multiple organ failure. Blast-related burns, in particular, are associated with infection, mortality, disability, mental illness, and discharge from the military.

Compared with civilians, deployed service members are twice as likely to suffer a burn injury. Approximately 5–20 percent of combat-related casualties during Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF) included severe burns (Nuu-tila et al., 2019; Wolf et al., 2006), and burns constitute 10 percent of all combat-related injuries to the head and neck regions (Johnson

et al., 2015). In recent conflicts in Iraq and Afghanistan, improvised explosive devices (IEDs) accounted for as much as 87 percent of all burns (Lairet, Bebart, et al., 2012a). IED-related burns are at elevated risk of infection because they are often contaminated with dirt and debris (Murray, 2008). This is consistent with research that shows that burn injuries resulting from military operations are clinically different from burn injuries sustained by civilians, given that service members are more likely to die of infection and gastrointestinal complications (Gomez et al., 2009). Infection control is essential for burn management because pathogens to which service members are exposed in current combat operations are increasingly resistant to antibiotics (Barillo, Pozza, and Margaret-Brandt, 2014). However, immediate evacuation might not always be possible. In these cases, burn injuries might have to be managed in a prolonged field care environment, which presents challenges unique to military populations.

Purpose of the Review

This literature review was used to support the expert panelists of the Ninth U.S. Department of Defense (DoD) International State-of-the-Science Meeting (SoSM) for Blast Injury Research. This comprehensive review provides background information and preliminary recommendations to support and inform the expert panelists as they facilitate working groups and develop final recommendations. The topic of the meeting and literature review is “The Impact of Blast-Related Burn Injuries from Prolonged Field Care to Rehabilitation and Resilience.”

Generally, this review focuses on research pertaining to blast-related burn injuries. However, during the screening process, we also retained non-blast-burn articles if they had clear military relevance. This review summarizes the results of available studies across all levels of blast mechanisms, from primary to quinary. As noted earlier, *primary blast injuries* involve tissue damage that occurs as a direct result of the shock of the overpressure wave colliding with the body. *Secondary blast injuries* are those produced by fragments from an exploding device or secondary projectiles from the environment (e.g., debris,

vehicle fragments). *Tertiary blast injuries* result from blast-related displacement of body parts that strike other objects, causing a variety of injury types (e.g., blunt, avulsion, crush). *Quaternary* and *quinary injuries* result from other explosive products or the clinical consequences of environmental contaminants (e.g., biologicals, radiation, released fuels), respectively.

Defining *Blast-Related Burn Injury*

Before proceeding to the literature review, and in collaboration with the planning committee, we discussed the terms *blast-related* and *blast-related burn injury*, which is used in the review. The Blast Injury Research Coordinating Office (BIRCO) defines *blast-related injuries* as “a complex type of physical trauma resulting from direct and/or indirect exposure to an explosion” (BIRCO, 2019). These explosions may be from an IED, a mortar, a gas explosion, or an equivalent. This literature review focuses on blast-related burn injury resulting from all degrees of burn, including first- through fourth-degree and inhalation burns.

Organization of This Report

In Chapter Two, we discuss the methodology underlying the literature review. In Chapters Three through Seven, we discuss the findings from the literature review. In Chapter Eight, we provide an overarching discussion of the results and our suggested preliminary recommendations.

The report also contains two appendixes: Appendix A contains a list of planning committee members, and Appendix B contains a list of search terms and results.

Review Methodology

The RAND team conducted a six-step process to execute this literature review: (1) select a planning committee, (2) define key research objectives, (3) identify publications, (4) screen publications for inclusion, (5) carry out data abstraction, and (6) complete data analysis. We discuss the six steps in more detail in the following sections.

Select a Planning Committee

Drawing on nominations from the BIRCO and leading experts in the field, we selected 11 individuals to form a planning committee that represented a diversity of settings, educational backgrounds, and administrative, research, and clinical foci. The planning committee reviewed selection terms and provided additional terms. (See Appendix A for a list of the planning committee members.)

Define Key Research Objectives

In reviewing the literature, we focused on findings from translational research relating to burn prevention, the continuum of burn wound care, and post-injury rehabilitation for service members. The following aims were of particular interest:

1. Describe the epidemiology and outcomes of blast-related burn injuries.

2. Review the evidence on prevention and acute management of blast-related burn injuries.
3. Review the evidence on prolonged field care and blast-related burn injuries.
4. Review the evidence and innovations about chronic care of blast-related burn injuries.

Identify Publications

We took the following steps to develop search terms to identify publications: (1) identified potential search terms from previous SoSM literature reviews, including terms specifically relevant to blast-related burn injury; (2) performed a preliminary PubMed literature search using these terms, using the results to improve the search strategy; and (3) had the planning committee review the search terms and recommend adjustments and additional terms. Table 2.1 summarizes the final search terms for three domains: (1) Blast Terms and Mechanism of Injury, (2) Burn Terms, and (3) Exclusion Considerations. The exact search strategies used for each literature database, along with the number of results returned, are presented in Appendix B.

Peer-reviewed literature that described blast-related burn injury, prevention, and treatment was searched using the following databases: PubMed, Web of Science, Cumulative Index of Nursing and Allied Health Literature (CINAHL), PsycINFO, and IEEE. DoD grey literature was searched from the Defense Technical Information Center (DTIC). All databases were searched from calendar years 2008 through 2019 (inclusive). This 12-year time horizon was selected for consistency with previous SoSM literature-review search strategies.

Screen Publications for Inclusion

After identifying publications using the search procedures described in the previous section, we inspected titles, abstracts, and report summaries to determine whether to include publications in further analysis.

Table 2.1
Search Terms

Domain 1: Blast Terms and Mechanism of Injury	Domain 2: Burn Terms	Domain 3: Exclusion Considerations
blast*	burn OR burns	Leukemia* OR
bomb*	graft*	Leukaemia* carcinoma
combust*	transplant*	lymphoma*
deflagrat*	"autologous	neoplasm*
explos* OR explod*	keratinocytes"	myelodysplastic
implos* OR implode*	thermal injur*	myelodysplasia*
"mine field" OR "mine fields"	inhalation injur*	"sun burn"
grenade*	"flame retardant"	sunburn
IED*	"tear gas" OR "tear gases"	burnout
incendiary	Parkland formula*	biomass
landmine* OR "land mine" OR "land mines"	Baxter formula*	greenhouse
minefield* OR "mine field" OR "mine fields"		methane
overpressure		archaeol*
"pressure differential" OR "pressure differentials"		renewable
military		e-cigarette
combat		neutron
		twister
		CREST
		transplant
		"tear gas"
		"energy elasticity"

NOTE: * indicates a variety of words that include a given stem; for example, *explos** refers to *explosion*, *explosions*, *explosive*, and so on.

Articles were determined to meet inclusion criteria if they were written in English, addressed burn injuries, either had blast exposure as a source of the burn injury or were of direct military relevance, and addressed one of the research questions of interest. Articles also must have been publicly available, so for DTIC documents, we used only those assigned as "Distribution A: Approved for public release: distribution unlimited."

We included articles that fell into one of the following categories: observational study, trial or experiment, case study or case series, meta-analysis, literature review, or simulation study. Studies with both domestic and international authors and populations were included. In many instances, blast exposure was not the sole source of burn injury but was included as one of several exposures addressed. In instances in which comorbid conditions were discussed, such as traumatic brain injury (TBI), we coded the study as "polytrauma."

Articles did not need to report original data to meet inclusion criteria; commentaries and narrative reviews were also included. *Commentaries* were defined as peer-reviewed scientific clarifications or expanded discussions relating to a recently published article, almost always from the same journal as the original research. We differentiated commentaries from *editorials*, which we defined as opinion pieces, viewpoints, sounding boards, or positions and announcements from a journal's editors. We included peer-reviewed literature reviews of all types—including brief reviews, scoping reviews, narrative reviews, systematic reviews, and meta-analyses.

For situations in which it was unclear from the title and abstract alone whether the article met inclusion criteria, the full text was obtained and reviewed to determine whether the article was eligible for full data abstraction. Records that were scored as meeting all inclusion criteria were eligible for data abstraction.

Carry Out Data Abstraction

For each article that met inclusion criteria, we abstracted the following content: title, authors, publication year, publication journal, sample size and unit of analysis (where applicable), National Research Action Plan (NRAP) category or categories (DoD, U.S. Department of Veterans Affairs, U.S. Department of Health and Human Services, and U.S. Department of Education, 2013), subject type (e.g., human, animal simulation), study design, period of follow-up (where applicable), study population (active duty or reserve, veteran, civilian), total body surface area (TBSA) percentage, type and cause of burn (e.g., fire, chemical), whether the study addressed polytrauma, whether the study addressed prolonged field care, and findings.

Complete Data Analysis

Content analysis was done in three phases: preparation, organization, and integration. During the preparation phase of concept formation,

the research team reviewed abstracted findings, drawing from prior knowledge to conceptually group studies into categories based on NRAP categories. The database of article features developed during data abstraction was used to characterize the features of the studies; examples include the studies conforming to each NRAP category, the study design classification, and the study population (i.e., civilian versus active-duty military or veterans). This report provides key findings by NRAP category.

Foundational and Etiological Research Results

In this chapter, we discuss the physical and biological aspects of blast burns and the mechanisms of burn injury, including inhalation burns. We focus on the NRAP categories of foundational and etiological research.

Blast-Related Burns

Blast injuries are caused by an explosion event, which rapidly converts liquid or solid explosive material into gas (Shuker, 2010; Singh et al., 2016; Wilkerson and Lemon, 2016; Wolf et al., 2009). The heat and gas produced by an explosion form a blast wave that travels away from the source of the explosion at a supersonic rate. This wave creates areas of extreme pressure on its outer edge, known as the *overpressure* of the blast. The void created by the overpressure is known as the *underpressure*. The intensity of the blast is characterized by the overpressure and is affected by the environment: In open spaces, the blast pressure will dissipate fairly rapidly, but in closed environments, the explosive force of the blast can be maintained (Wolf et al., 2009).

Different aspects of the environment may influence the severity of blast burns. For example, in a review of facial burns, Shuker noted that burns related to blasts are more severe in closed settings, where the blast wave is less likely to dissipate (Shuker, 2010). Antanovskii and Remennikov, 2010, drew similar conclusions after developing a mathematical model and conducting a live, controlled experiment of a bus explosion. They varied the window strength and the size of the

explosion to predict pressure and passenger survival. They found that weaker windows increased the chance of survival for individuals on the bus but also increased the risk of casualties from flying debris outside the bus. Shuker, 2010, noted multiple mechanisms of injury, including thermal energy released by the initial explosion and sands or other material activated by blast winds, and secondary sources of injury, such as car fires or inhalation of burned materials. Shuker also noted compounding issues, such as the reduction in atmospheric oxygen because of fire and the additional damage that secondary fires and heat can cause to open wounds (Shuker, 2010).

Blast-related flash and flame burns to the face are particularly common in cases in which the victim is close to the blast site (Shuker, 2010). Flash and flame burns occur because of direct or indirect exposure of a patient to a flame source. These burns can cause damage to facial skin, the eyelids, and the lips, as well as the burning of facial hair. Although flame burns tend to cause deeper tissue damage than flash burns because of their longer duration—and flash burns may go undiagnosed initially—flash burns are often associated with damage to the airway and respiratory regions, which can be life-threatening. According to one study, while secondary, tertiary, and quaternary blast injuries involving the airway can be managed with standard methods, primary blast injuries to the lungs are unique (Maung and Kaplan, 2014). In such cases, the propagation of the blast wave can lead to the collapse of the lung, pulmonary embolism, air embolism, or bleeding in the brain.

In many cases, blast-related burns occur simultaneously with other penetrating injuries or traumatic amputations. For example, in one case study of an explosion at a fireworks factory, postmortem examination of the victim revealed superficial to deep tissue burns alongside multiple puncture wounds and lacerations (Nagesh et al., 2010). Complications of this injury included acute respiratory distress syndrome and a breakdown in liver and renal functions, leading to multiple organ failure. In another case study of a presumed suicide by acetylene explosion, the authors found evidence of a multistage injury: They deemed the victim to have survived the trauma from the initial blast event but to have died from resulting burns (Kashiwagi et al., 2009).

According to a review article on facial injuries, airway injuries from blasts can have many causes, including inhalation of smoke, gases, dust, sand, and other debris (Shuker, 2010). In addition, the nature of the injury will vary with the material being inhaled (Shuker, 2010). Inhalation injuries can be classified into three categories: upper-airway thermal injuries, lower-airway injuries caused by chemical irritants, and metabolic asphyxiation, which impedes oxygen delivery and consumption at the tissue level (Chatzivasiloglou et al., 2016). Larger, water-soluble particles tend to cause upper-airway injuries, while smaller particles result in damage to tissue and lungs. In a case study of an inhalation injury caused by a grenade explosion, the compounds Sudan I and potassium chlorate oxidizer resulted in orange-pigmented sputum (Chatzivasiloglou et al., 2016). The authors noted that the variety of smoke inhalation injuries and their symptoms is one reason for limited diagnostic criteria for treating these injuries (Chatzivasiloglou et al., 2016).

Burn-Related Infections and Other Complications

Three articles examined the foundational science and etiology of burn-related infections. In a review article, Dallo and Weitao, 2010, examined the causes and features of multidrug-resistant *Acinetobacter baumannii*, a common bacterial infection following battle injuries, including burns. The authors noted that the bacterial species may form a biofilm in response to antimicrobial treatment and is responsible for several types of opportunistic illnesses, some of which can be fatal. A second study, Hauck et al., 2012, described a related bacterial source—*A. calcoaceticus*-*A. baumannii*—and multidrug-resistant clones thereof, which are responsible for a large proportion of nosocomial infections. Hauck and colleagues analyzed two CRISPR-Cas systems to help define clonal complexes and traced them to their source, finding that these systems might provide important cues for understanding bacterial evolution. A third study, Hospenthal et al., 2011, identified a recently discovered species of bacteria, *Saksenaea erythrospora*, on the deceased body of a 26-year-old male injured in combat in

Iraq, raising questions about the prevalence of this bacteria within the region. The authors discussed the properties of *Saksenaea erythrospora* in detail.

Several other types of complications were noted in the literature. Blast-related burns and, particularly, penetrating trauma resulting from blast mechanisms, can lead to massive blood loss and anemia. Given concern that anemic patients may suffer poorer clinical outcomes during aeromedical evacuation, Hamilton et al., 2015, examined whether burn victims with lower hemoglobin levels experienced more complications, such as renal failure, than patients with normal hemoglobin levels. In a retrospective analysis of patients evacuated by U.S. Air Force Critical Care Air Transport Teams, Hamilton and colleagues found no statistical difference in mortality, complications, or clinical outcomes between anemic and nonanemic groups. In a case study, researchers examined the complication of abnormal hemoglobin production (methemoglobinemia) in the victim of a tugboat explosion with 61-percent TBSA burns (Jiwani, Beberta, and Cancio, 2018).

In a review article, one researcher examined the potential complication of cyanide toxicity in victims of fire burns (Barillo, 2009). Barillo noted observational and experimental evidence that atmospheric cyanide increases during fires but observed that evidence of cyanide toxicity in victims of fire is significantly weaker and not supported or refuted by any large-scale or experimental studies. In another study, Enlow and Mayfield, 2013, the researchers evaluated the composition of potentially hazardous particles and chemicals in burnt composite material. They noted that the materials that they were investigating were similar to composite materials used in protective equipment worn by U.S. Air Force firefighters. The investigators identified several compounds, such as carbon-fiber fragments, that can cause lung injury after burning.

Nuclear detonations are a special case of burn-inducing blasts and carry their own potential complications. A North Atlantic Treaty Organization (NATO) subject-matter meeting detailed severity definitions and injury profiles for whole-body radiation dose, as well as blast and thermal exposure, to achieve a consensus profile endorsed by NATO members (Burr et al., 2009).

An understanding of the biological mechanisms leading to morbidity and mortality following burn exposure has been derived in part from animal studies. A retrospective analysis of combat casualty records from the DoD Trauma Registry found an association between elevated mean arterial pressure (hypertension) and mortality, but only when the sample was limited to burn victims (Davidson et al., 2018). The authors hypothesized that hypertension in burn victims could be predictive of other life-threatening physiologic changes, such as increases in renin and adrenal gland hypertrophy (Davidson et al., 2018).

Epidemiology Results

Developing an understanding of the incidence, distribution, magnitude, and determinants of blast-related burn injuries is integral to forming a comprehensive approach to avert and mitigate the damage caused by such events. Epidemiological insights can be used to develop strategies to prevent blast-related burn injuries, help guide treatment and long-term management of injuries that have occurred, and learn about the downstream impacts and comorbidities associated with burn injuries. In this chapter, we focus on the measurement of burn incidence in relation to the populations at risk—that is, military personnel and civilians who incur blast-related burn injuries in combat environments. We report on articles in the epidemiology NRAP classification.

Incidence and Prevalence of Burn Injuries

Incidence rate and *prevalence* are measures used to express the frequency and pervasiveness of a condition within a population. Together, they serve as indicators of a population's health status with respect to a portfolio of health conditions and diseases. It is estimated that approximately 5–20 percent of combat-related casualties during the first ten years of OIF and OEF involved severe burns (Breederveld and Tuinebreijer, 2009; Wolf et al., 2006); this is consistent with a variety of estimates from other recent conflict settings, such as Mali (Akpoto et al., 2015), Nigeria (Amaefule et al., 2019; Dabkana et al., 2015), and Israel and Palestine (Mosleh et al., 2018).

Although blast-related burn injuries affect service personnel and civilians, the incidence, demographics, and treatment of civilian blast-related burn injuries differ from those of blast injuries that occur in military settings. Researchers conducted a six-year retrospective record review of civilian patients with blast-related burns and compared findings with those from a military cohort. Compared with blast-burn injuries sustained in a military environment, blast-burn injuries were generally uncommon in civilian settings, where burn injuries were of lower severity and could be managed without referral to a burn unit (Patel, Tan, and Dziewulski, 2016). Breederveld and Tuinebreijer, 2009, concluded that military burn victims were more likely to suffer from facial and hand burns, have a higher chance of suffering an inhalation lesion, incur more injuries associated with the burn, and have significantly longer transportation times to treatment facilities. Gomez et al., 2009, describes a retrospective review of autopsy reports from patients with burn injuries treated at the U.S. Army Institute of Surgical Research (USAISR) Burn Center in San Antonio, Texas; the researchers found that military operation burn victims died more frequently of infection and gastrointestinal complications, while noncombat-related burn victims were more likely to die from cardiac arrest and renal failure. The authors suggest that the difference might reflect demographic differences between the two groups, such as younger age, higher injury severity, and more-delayed treatment among patients injured during a military operation.

Page et al., 2017, describes a retrospective review of UK armed forces personnel who were evacuated for combat and accidental burn injuries between 2008 and 2013. Significantly fewer combat burn injuries occurred in the 2008–2013 period than in the period between 2001 and 2008, while the number of accidental noncombat injuries remained constant. The authors attributed the decrease in combat burn injuries to a relative decrease in military intensity after 2008 and suggested a need to provide additional education to prevent accidental burn injuries.

Several studies examined the notably high rate of facial injuries among military burn patients and its connection to prolonged transport and delayed intervention. According to Johnson and colleagues,

2015, burns constitute 10 percent of all combat-related injuries to the head and neck regions. Breederveld and Tuinebreijer, 2009, notes that protective military equipment, such as body armor, helmets, and durable clothing, often leaves the face and hands exposed to potential thermal injury. The study also notes that, during the 2003–2005 operation in Iraq, 80 percent of military patients who were evacuated to the USAISR for severe burn injuries had suffered hand burns, while 77 percent had suffered facial burns. Transportation time for burn patients stationed in Iraq and Afghanistan can be at least three to four days, while emergency and intermediate treatment often fail to punctually address the inhalation injuries commonly associated with facial injuries (Breederveld and Tuinebreijer, 2009). Researchers performed a study to characterize the epidemiology of airway management in maxillofacial trauma and noted that 51.4 percent of cases of severe maxillofacial injury treated at military treatment facilities (MTFs) in Iraq and Afghanistan between 2004 and 2010 required intubation on initial presentation (Keller, Han, Galarneau, and Brigger, 2015). They also noted a significant relationship between the presence of head and neck burn injury and airway inhalation injury ($p < 0.0001$). Chan et al., 2012, comprehensively characterizes combat injuries to the craniomaxillofacial region sustained during OIF and OEF; the researchers found that most facial burns associated with craniomaxillofacial injuries are present in multiple anatomic locations on the face and neck regions, which highlights the unique challenges associated with treating such injuries.

Multiple studies specifically examined noncombat burn injuries among children in Iran, Iraq, Afghanistan, and Syria who were treated as part of humanitarian care provided by the U.S. military (Edwards et al., 2014; Karimi et al., 2012; Kuvandik, Ucar, and Karakus, 2018; Wilson et al., 2013) and U.S. military partners (Arul et al., 2012). In a case review of trauma admissions to a U.S. combat support hospital in Afghanistan, burns represented the most common noncombat injury among pediatric patients and required the most operative procedures (Arul et al., 2012). In a study on the epidemiology of pediatric medical care provided during ten years of U.S. military operations in Iraq and Afghanistan (2001–2011), Borgman et al., 2012, estimated that

burns were the mechanism of injury for 13 percent of pediatric trauma patients, with more burns occurring in OIF than in OEF. Mathieu and colleagues, 2015, studied pediatric wartime extremity injuries treated at Kabul International Airport Combat Support Hospital between 2009 and 2013. Their retrospective review of database records indicated that 25 percent of noncombat-related injuries among children were the result of burns.

Burn Injury and Disease Patterns

Prevalence and Characteristics of Burn Injuries—Adults

Among the studies that involved civilians, there were multiple factors associated with burn-injury frequency, higher burn severity, and mortality. In an epidemiological study to examine the characteristics and determinants of burn injuries among patients admitted to a Baghdad burn hospital, Lami and Al Naser, 2019, determined that young adult males, children, and low-educated patients represented the majority of admitted civilian and military burn patients. Approximately 13 percent of patients in the study died, primarily because of multiple organ failure, septicemia, and shock. Likewise, Lundy and colleagues, 2010, performed a descriptive analysis of intensive care unit (ICU) patients at a combat support hospital in Baghdad and found that U.S. military personnel suffered significantly more explosion injuries and burns than Iraqi military and noncoalition military counterparts. In Kabul, Afghanistan (2007–2008), Padovese and colleagues, 2010, observed that the median age of presentation among burn victims was 19 years, there were slightly more female victims than male victims exposed, and the mean TBSA burned was 36.5 percent, thus resulting in a mortality rate of 28 percent. By comparison, a similar retrospective study on burn injuries at a burn unit of a military hospital in Bahrain found that men were more likely to be affected by burn injuries than women (Louri et al., 2018). Men between 21 and 30 years old and between 51 and 60 years old represented the majority of patients in the ICU, while children aged one to ten constituted the majority of patients in the burn ward. Both studies found that flame and scald burns were

the most common causes of burn across age groups. A fourth study reviewing the epidemiology of burn patients at a military hospital in Rabat, Morocco ($n = 294$), found that a large preponderance of burns (94 percent) were thermal, 4 percent were electrical, and 2 percent were chemical and that a majority (70 percent) of patients were ages 20–59 (Elkafssaoui et al., 2011). Likewise, Goodarzi and colleagues, 2014, examined burn injuries at a hospital in Iran ($n = 836$) and found that burn victims were more common among young adults (aged 20–30) than among other age groups and that flammables and gas explosions were the most common source, with a mortality rate of 22 percent.

Studies have also compared the prevalence and distribution of burn injuries at medical centers in the United States, such as the USAISR Burn Center. Renz and colleagues, 2008, reviewed medical records at this facility from 2003 to 2007 across 540 casualties admitted after long-range transport; they found that the mean burn size was 17 percent TBSA, with a mean severity score of 12.2, ± 13.7 . Although frequency and distribution of injuries have evolved over time and across settings, evidence also indicates that burn injuries have been and will continue to be a persistent threat over time (Nam et al., 2014).

Prevalence and Characteristics of Burn Injuries—Children and Adolescents

Researchers conducted a retrospective cohort study on pediatric patients to learn about factors associated with mortality among patients with isolated burn injury. In this pediatric cohort, mortality increased disproportionately with burn severity, and many pediatric patients needed resource-intensive long-term care (Borgman, Matos, and Spinella, 2015). Another retrospective database review of pediatric war-time admissions to U.S. military combat support hospitals determined that although burn injuries accounted for approximately 13 percent of pediatric admissions to the hospital, burns were the cause of death in over 27 percent of those who died (Creamer et al., 2009). Edwards and colleagues, 2012, examined pediatric records entered in the Joint Theater Trauma Registry between 2002 and 2010 and found that, among children of all age groups, burns from an explosive device that resulted in injuries are independently predictive of mortality.

Buyukbese Sarsu and Budeyri, 2018, provided further specificity on injury sources; the authors studied Turkish and Syrian children and found that mortalities associated with burns were caused predominately by fire and ballistic injuries that resulted in third-degree burns. This pattern was similar to that of a retrospective study of burn injuries among 62 Nigerian children; 52 percent of injuries were flame burns (Oludiran and Umebese, 2009). Among children younger than three, scalds were responsible for 70 percent of cases.

Prevalence of Posttraumatic Stress Disorder Among Burn Patients

Several studies examined the relationship between burns and posttraumatic stress disorder (PTSD). Gaylord, Holcomb, and Zolezzi, 2009, examined the clinical records of patients admitted to a military burn center to compare the rate of PTSD among military personnel with that of civilians treated at the same facility. The researchers found that the incidence of PTSD in burned combat service members did not significantly differ from that of civilians in the same burn unit, suggesting that PTSD is associated with the burn injury itself, not the environment in which the burn occurred. An earlier study by Gaylord and colleagues, 2008, reviewed PTSD and mild traumatic brain injury (mTBI) assessments from 76 burned service members and documented those who had both PTSD and mTBI (18 percent), those who screened positive for PTSD but not mTBI (13 percent), those who screened positive for mTBI but not PTSD (23 percent), and those who did not screen positive for either PTSD or mTBI (46 percent). The researchers noted that symptom presentation for PTSD and mTBI can be clinically similar and recommended further screening for PTSD and TBI, given the high rate of comorbidity of these conditions among burned service members. Mora and colleagues, 2009, also compared subgroups of populations with and without burn- and blast-related exposure and found that burn patients who were IED-wounded with primary blast injuries and mTBI had a higher prevalence of PTSD, compared with all other groups.

A subset of research studies examined development of PTSD following blast-related burn exposure. For example, Su, 2018, examined the prevalence of PTSD and depressive symptoms among civilian burn

survivors in the aftermath of a mass casualty event and found that theory-derived cognitive variables, such as negative appraisal of symptoms and disorganized memory, predicted post-burn PTSD symptoms in this sample more accurately than burn-related variables and risk factors collected from a meta-analysis. In a subsequent study, Su and colleagues, 2020, found that half of survivors (52 percent) observed experienced significant posttraumatic growth over a two-year period following blast exposure. In a retrospective study with 49 service members, McGhee and colleagues, 2011, found that self-reported early acute pain scores later predicted PTSD symptom levels but that pain scores were not associated with injury severity. In an earlier study, McGhee and colleagues, 2009, examined the relationship between propranolol prescription and PTSD incidence following burn injury. The research team found that the prevalence of PTSD was 32 percent in those receiving the medicine, compared with 27 percent in those not receiving it—a nonsignificant difference.

Prevalence of Infection Among Burn Patients

Another concern with burn injuries is infection and the presence of bacteria, particularly multidrug-resistant organisms (Ressner et al., 2008). Gomez and colleagues, 2009, examined cause of death from burn injuries, reviewing autopsy reports performed for 74 of 100 patients admitted to USAISR with burns from 2004 to 2007 who subsequently died. About half were burned in combat operations (OIF or OEF), and the other half were burned under noncombat circumstances. Combat-related burn casualties were clinically distinct from noncombat-related burn casualties: Those dying from combat-related burn injuries were more likely to die from infection than those dying from noncombat-related burn injuries. Infection was the leading overall cause of death (61 percent), followed by a pulmonary complications (55 percent). The most common organisms among those who died from infection were *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, and fungi. Keen and colleagues, 2010a, published multiple studies on drug-resistant bacteria isolates in military burn patients. In one study, they performed a retrospective records review of bacteria identification and antibiotic susceptibility records for patients treated at the USAISR Burn Center ICU

to examine how bacteriology changes during extended hospitalizations and how this is influenced by burn severity. They found that initial bacteriology in evacuated patients with combat-related burn injuries was significantly different from patients who sustained noncombat-related burn injuries. Furthermore, the type of pathogens identified in patients varied with the level of TBSA burn (TBSA percentage).

Keen and colleagues, 2010b, also examined the prevalence of multidrug-resistant isolates at the USAISR Burn Center and found that isolates are associated with higher TBSA and longer hospital stays. Lin and colleagues, 2018, similarly looked at the prevalence of various isolates, focusing on bloodstream infection. *Acinetobacter baumannii* (21 percent), *Ralstonia pickettii* (19 percent), and *Chryseobacterium meningosepticum* (14 percent) were the most common pathogens. Miranda and colleagues, 2008, examined the prevalence of microorganisms at a burns unit and ICU at a regional center in the United States. The five most prevalent organisms cultured in this setting were *Staphylococcus* (23.9 percent), *Acinetobacter* (21.2 percent), methicillin-resistant *Staphylococcus aureus* (MRSA) (20.8 percent), *Pseudomonas* (9.7 percent), and *Enterococcus* (5.2 percent). *Acinetobacter baumannii* was significantly more prevalent in military inpatients than in civilian inpatients. Mitchell and colleagues, 2014, studied the characteristics of a less prevalent but relatively lethal bacterium: *mucormycosis*. They found that the incidence of mucormycosis was 4.9 per 1,000 admissions, resulting in 11 military deaths and one civilian death. Overall mortality was 92 percent among the population studied.

Tang and colleagues, 2018, performed a retrospective observational study of recurrent and polymicrobial bloodstream infections with resistant strains in patients who experienced severe burns during an industrial disaster in eastern China. Findings indicated that bloodstream infections were very common in severe burn patients, with gram-negative organisms and *Candida* as the leading causes. The researchers emphasized the importance of preventive catheter-care bundles for severe burn patients using central venous catheters. Aurora and colleagues, 2019, studied recurrent bacteremia infection in military burn victims admitted to the USAISR Burn Center and found that recurrent bacteremia increases mortality in this population. Large

burn size, third-degree burns, increased injury severity, perineal burns, and mechanical ventilator usage were independent factors predictive of recurrent bacteremia and increased mortality. Clemens and colleagues, 2017, likewise found that perineal burns were associated with a fivefold increased incidence of bacteremia and mortality and that burns to the genitalia, perineum, and buttocks more generally are associated with increased likelihood of mortality. Burn injury to reproductive organs is also associated with impaired fertility among survivors (Covington, 2016), which may result in psychological sequelae.

Prevalence and Characteristics of Burn Injuries from Mass Casualty Events

The epidemiology of burns in mass casualty events and terrorist attacks provides an additional source of knowledge on the manifestation and distribution of blast-related burn injuries in settings ranging from Europe (Turégano-Fuentes et al., 2008) and the Middle East (Paydar et al., 2012) to Africa (Van Kooij et al., 2011) and South Asia (Tekade et al., 2017; Yu et al., 2016). For example, Paydar and colleagues, 2012, wrote an overview of the events of a mosque bombing in Shiraz, Iran, outlining the average age of patients (26 years), sex breakdown (67 percent male and 23 percent female), and most-prevalent causes of hospital admission). Following a similar schema, Peleg and colleagues, 2008, examined the distribution of health conditions and injuries among 2,228 patients who survived terrorist events in the Israeli-Palestinian conflict. The authors further compared mean hospital stay length and outcomes among individuals with burn injuries with those of individuals without burn injuries, as well as with comparison groups in non-terrorism-related contexts. The researchers found that mean hospital length was 18.5 days among individuals in the terrorism-related burn group, compared with 11.1 days among individuals in the non-terrorism-related burn group, and that the terrorism-related burn group had higher mortality rates than all other groups.

Konwinski, Singh, and Soto, 2015, discussed common features of 2013 Boston Marathon bombing victims with lower-extremity injuries, finding that a majority (70 percent) retained shrapnel and 16 percent had soft-tissue lacerations without retained shrapnel. By contrast,

Dant and colleagues, 2016—looking across 18 case studies based on 432 bombings that resulted in 6,554 casualties—found that areas typically injured involve the upper body (e.g., head and neck), extremities, and soft tissue and that glass shattering was a frequent source of injury. In an analysis of suicide bombers in Sri Lanka, Ruwanpura and colleagues, 2008, found an absence of shrapnel injuries and, more commonly, the presence of a cyanide capsule in the neck. Evidence from these three studies indicates that forms of terrorist attacks and mass casualty events differ by setting and result in differential injury profiles, pointing to the need for epidemiological studies to understand local patterns and inform preparation of the health care system in the event of a future occurrence. Along these lines, in an attempt to synthesize a pattern of injuries and trauma among victims of terrorist attacks in divergent settings, Rozenfeld and colleagues, 2016, devised a conceptual schema of terrorist explosion events according to five categories: explosions inside buildings, explosions near buildings, explosions inside buses, explosions near buses, and explosions in an open space. The authors showed that this new taxonomy better distinguished expected types of resultant trauma, including burn injury, thus allowing for more-appropriate emergency response preparation.

Prevalence of Alternative Burn-Injury Profiles in Military and Nonmilitary Settings

Other, rarer manifestations and complications associated with blast exposure are also described in the literature—e.g., acute compartment syndrome of the thigh. Masini and colleagues, 2013, report on a cohort of individuals with this syndrome, noting—among other findings—that overall mortality was 23 percent and burns were associated with elevated mortality rates. Another study by Markell and colleagues, 2009, describes the frequency and characteristics of abdominal catastrophes. They found abdominal catastrophe present in 2.8 percent of individuals admitted to the USAISR Burn Center between 2003 and 2008. Associated mortality was 78 percent. In a third article, Pavelites and colleagues, 2011, describe a case series of six deaths related to uncommon causes of medical burns, including chemical ingestion, and detail the characteristics of associated burn injuries.

Another category of studies consists of those that inspect the operation of burn pits—a common way to get rid of waste at military sites in Iraq and Afghanistan—and, in particular, the characterization of health outcomes occurring as a function of repeated exposure to smoke and heat generated by burn pits. In one retrospective cohort study, the Armed Forces Surveillance Center compared those deployed to U.S. Central Command locations with those who were not and found similar incident rates for a wide variety of outcomes (e.g., cardiovascular diseases, respiratory diseases) (Armed Forces Health Surveillance Center, Naval Health Research Center, and U.S. Army Public Health Command [Provisional], 2010). In a second retrospective cohort study, Abraham and colleagues, 2014, examined personnel deployed to locations with burn pits (Iraq) and locations without burn pits (Kuwait) and compared these individuals with U.S.-based personnel. They found that deployed personnel had elevated levels of respiratory symptoms and asthma compared with those in the United States, but that this was not related to deployment at locations with burn pits.

A final subset of studies focused on types of blast-related burn exposures that are largely unrelated to military settings but that nevertheless might have lessons that are relevant in the military context. Related studies have chronicled the epidemiology of burn injuries from pressurized aerosol cans (Langbart and Vandervord, 2011), electrical equipment (Mashreky et al., 2011; Olaitan, Oseni, and Olakulehin, 2011), and fireworks in settings ranging from the United States (Sandvall et al., 2017; Stahlman and Taubman, 2018) to Iran (Shams Vahdati, Hemmate Gadim, and Mazouchian, 2016; Tavakoli et al., 2011; Vaghardoost et al., 2013). Among these, Stahlman and Taubman, 2018, found that 302 firework-related injuries were reported from 2008 to 2017 and that incidence of injury was higher among those who were U.S. Army members, those in enlisted rank, and those in combat-specific occupations. Burn was the most common form of injury resulting from fireworks (57.0 percent). Burn disasters in shooting ranges is another topic that emerged and likewise might be preventable with educational interventions (Uygun, Öksüz, and Yüksel, 2008).

Outcomes and Functional Status Among Burn Patients

The short- and long-term health outcomes for patients who have sustained burn injuries vary depending on burn severity and comorbidities associated with the burn injury. Rizzo and colleagues, 2019, performed a retrospective review of medical records collected between 2008 and 2019 to compare the characteristics, outcomes, and functional status of military burn patients with a civilian cohort treated at the same burn center (USAISR Burn Center) over the same period. They determined that military burn patients tended to be younger than civilian patients, had a higher incidence of flame-induced and inhalation burns, and exhibited higher mean TBSA burned (TBSA percentage) and lower overall mortality. In addition to the mode of injury and the environment in which it occurred, the physical characteristics of the individual can affect burn-injury outcomes. Jia, Tynelius, and Rasmussen, 2016, performed a cohort study on the dose-response relationship between body mass index (BMI) in civilian young adults and the risk of mortality from unintentional injuries and found that underweight subjects had a higher risk of mortality in cases of unintentional burn injury.

Three studies examined the relationship between burn injuries and likelihood of return to military duty. Researchers performed a retrospective study of factors associated with military burn injuries that predict failure to return to work. Factors that are most strongly associated with failure to return to duty include length of hospitalization for burn injury, TBSA, and presence of inhalation injury (Chapman, Richard, Hedman, Chisholm, et al., 2008). In a retrospective study to determine the rate at which service members return to duty after upper-extremity amputations, Kift and colleagues, 2017, found that patients who sustained burn injuries were more likely to remain on active duty postamputation than were patients with a similar amputation type but without concomitant burn injuries (65 percent compared with 40 percent). Lesho, 2011, published a broader analysis examining the various medical conditions observed among a surgically augmented brigade medical company during the 2007 Iraq surge. Burns were among the most common forms of trauma observed. Of all patients treated, 95 percent of patients returned to duty, 2.5 percent were admitted, 2 percent were evacuated, and less than 1 percent died.

Mercado and colleagues, 2008, studied the relationship between mTBI and cognitive functioning among OIF and OEF service members with explosion injuries who were admitted to a burn unit. Through a retrospective review of clinical evaluations, the researchers concluded that an mTBI diagnosis did not predict cognitive dysfunction among this cohort of trauma patients, as measured by the Repeatable Battery for the Assessment of Neuropsychological Status; this was further confirmed in a report by Cooper and colleagues, 2010. Escolas and colleagues, 2017, hypothesized a link between burns and suicide and conducted a postdischarge cause-of-death analysis for combat-related military burn patients. They found no indication of suicide as a cause of death for discharged patients, concluding that combat burn injury did not appear to increase risk of death by suicide among recovering burn patients.

Prevention, Screening, and Diagnostic Research Results

In this chapter, we explore the NRAP prevention, screening, and diagnostic research categories.

Burn-Prevention Technologies

Several papers have observed a relationship between the development and use of protective materials in combat and changes in the distribution of burn injuries. Epidemiological studies of combat-related and noncombat-related burn injuries have identified the hands and face as the most commonly burned body parts in recent conflicts (Kauvar and Baer, 2009). This injury pattern has been linked to the use of protective clothing, which nearly fully protects the body and limbs but leaves the hands and face exposed (Roeder and Schulman, 2010). The observed decline in the depth and severity of burn injuries sustained on the body has also been attributed to the use of fire protective clothing (Foster, Moledina, and Jeffery, 2011).

Studies have highlighted the unique challenges associated with designing thermal protective clothing for military personnel. Service members, particularly those who are expected to operate on the ground in a combat setting, have different garment requirements from, for example, firefighters, whose clothing can be nearly fully flame resistant for short periods (Hull et al., 2012). For example, service members must maintain mobility in very hot settings for long periods of time

and might not be able to accommodate potential cooling technologies, such as a water-cooled vest (Hull et al., 2012). Champion, Holcomb, and Young, 2009, note that clothing will need to balance protection and combat efficiency.

One study in our review presented new evidence on the design of protective materials for use by service members in combat. Hull and colleagues, 2012, performed a series of experiments and mathematical simulations to test the flash and flame protection of fabrics that could be used in an undershirt in conjunction with the Army Combat Uniform. Among seven samples evaluated, the best-performing fabric sample—in terms of air permeability, thermal protective performance rating, and time to second-degree burn—was composed of 94 percent m-aramid, 5 percent p-aramid, and 1 percent static dissipative fiber. An important finding from this paper was that a fabric sample composed of 82 percent polyester and 18 percent elastane melted at high heats, despite protection from direct flame exposures. The authors caution that polyester might not be safe for use in military garments.

In addition to materials worn by service members, innovation in equipment and facilities can improve fire safety, given the extreme heat that can be created by a blast event (Imran et al., 2017; Zheng et al., 2019). One study, for example, discusses the use of silicone rubber fire-safety cables, which harden and maintain their thermal protection in the event of a fire (Bacher, 2010). Another study discusses renewed research efforts to develop fire-resistant fuel that can be feasibly deployed to the battlefield (Westbrook et al., 2014). A fire-resistant fuel composed of diesel fuel, water, and an emulsifier was successfully developed in the 1980s but was never deployed on a large scale for both technical and logistical reasons; the fuel mixture required water of a purity that was difficult to obtain in the battlefield, among other factors. The authors argue that a key challenge in more recent efforts to develop fire-resistant fuel is the Army's single-fuel policy, which requires the use of jet-propulsion fuel 8 for ground vehicles. This fuel has a low flashpoint, raising the technical requirements of any fire-resistant mixture.

Burn-Prevention Education Strategies

An important resource for studies concerned with burn prevention and blasts in a military context is the clinical trials program within the USAISR Burn Center, which is the only DoD burn center that is verified by the American Burn Association and that contains records of all Iraq or Afghanistan service members evacuated because of a burn injury (Baer et al., 2009). A limitation of the USAISR data—and therefore of the studies that use the data—is that they underestimate the true incidence of burn injuries because they capture only burns resulting in medical evacuation (Kauvar, Wade, and Baer, 2009). Another limitation is that, at least to date, most studies using this database are retrospective, and identifying appropriate controls for comparison is often challenging. However, these databases can be used to identify potential candidates for randomized interventions.

We found two studies about informational interventions targeting service members, both of which use the USAISR database. The first was a retrospective study of the effectiveness of an All Army Activity (ALARACT) message, distributed to Army leaders, that emphasized the importance of wearing fire-resistant-rated hand gear (e.g., Nomex or Kevlar) (Hedman et al., 2008). The message was distributed in December 2005, and the authors compared a variety of outcomes derived from USAISR records 17 months before (August 2004–December 2005) and 17 months after (January 2006–May 2007) the message to assess its effectiveness. Although the incidence and severity of hand injuries were unchanged following the intervention, the ratio of hand injury to TBSA was statistically significantly lower (36 percent pre-ALARACT; 25 percent post-ALARACT), possibly reflecting greater awareness of the risk of hand injury. Extending from these studies, similar research in civilian settings has shown that burn-prevention media campaigns can successfully improve knowledge and alter behavior, although such campaigns might need to be reintroduced at routine intervals to have a sustained effect (Muller et al., 2013).

In addition to limitations in the research design, Muller and colleagues attribute the study's mixed results to challenges inherent in deploying educational interventions in a military setting. To be effec-

tive, an ALARACT message must be distributed to all units in theater, which is complicated by unit mobilization. Furthermore, such factors as heat and individual preferences may reduce compliance. Finally, service members must perceive available protective technology, such as fire-resistant gloves, to be effective for an informational intervention to modify behavior.

Another retrospective study sought to evaluate the effectiveness of a memorandum designed to reduce noncombat burns from burning waste (Kauvar and Baer, 2009). The memorandum was created by physicians, nurses, and other clinical staff affiliated with the USAISR Burn Center and highlighted safe methods of waste disposal, including wearing gloves and protective clothing. The incidence of waste-burning injuries fell from 1.67 admissions per month prior to the intervention to 0.33 per month afterward. This difference was statistically significant. Limitations of the study include the relatively small sample size (20 waste-related burns were identified in the pre-intervention period, compared with four in the post-intervention period) and the absence of a control group or randomized study design.

An additional study sought to classify electricity-related burn injuries according to voltage, shock current available, fault current available, power, energy, and waveform—ultimately as a way to establish standardized safety protocols and educate those in the workplace about potential hazards (Gordon, Carr, and Graham, 2017).

Diagnostic Tools

Assessing the nature and severity of burn injuries is a critical step in burn treatment, but such an assessment can be complicated by several conditions specific to blast-related injuries. One survey of soft-tissue facial injuries from blasts, for example, argues that the presence of airway trauma, which can be easily overlooked in a clinical setting, is a more important indicator of mortality risk than traditional measures of injury severity (Shuker, 2010). Diagnosis also might require making inferences about the nature of the blast event. In a review of best practices following nuclear explosions, Wolbarst and colleagues, 2010, note

that physicians often will need to make preliminary diagnostic decisions using estimates of the radiation dose received by patients, which will require some knowledge of the blast event or educated guesses based on clinical symptoms. Laboratory, clinical, and other diagnostic tools for assessing burn injuries and co-occurring complications have been evaluated in the literature. Another study found that monitoring of procalcitonin (PCT) and NT-proBNP levels significantly improves diagnosis of catheter-related bloodstream infection, for which severe burn patients are at significant risk (Zhou et al., 2018).

Laboratory Testing

The difficulty of accurately measuring burn-injury risk using clinical techniques in forward-deployed settings has led researchers to look for biomarkers that can reliably and accurately predict injury severity (Janak et al., 2017). If accurate, these measures could facilitate early treatment decisions, such as triage and evacuation.

To date, several promising biomarkers have been identified. In a study testing the association between five urinary biomarkers and two clinical measures of injury severity—having a high injury severity score (ISS) and having a blast mechanism of injury (as opposed to a gunshot wound)—Janak and colleagues, 2017, found that, among injured military personnel in their sample, four of the five biomarkers were significantly higher in severe injuries, and all were higher in blast injuries. These associations did not hold in a comparable civilian cohort, although the authors point out that the civilian analysis was likely underpowered (22 observations, compared with 80 in the military cohort).

Other researchers have attempted to identify biomarkers in burn victims. In a prospective study of patients with severe burn injuries, Yang and colleagues, 2014, found concentrations of serum creatinine and plasma and urine neutrophil gelatinase–associated lipocalin to be associated with early acute kidney injury (AKI) and early mortality. In a study of an aluminum dust explosion in China, blood platelet concentrations collected from severely burned victims in the five days following the injury were significantly lower in patients who developed AKI and higher in patients who experienced successful resuscitation

(Shou et al., 2017). A retrospective analysis of 24 patients admitted to a burn unit with either sepsis or septic shock following a water park explosion in Taiwan found significantly higher serum procalcitonin levels among patients with septic shock, while measurements of the other potential biomarkers were not significantly different between the two groups (Wu et al., 2017). Janak et al., 2017, the study conducted among 80 service members and 22 civilians, reported that urinary biomarkers were associated with both severity and mechanism of injury.

Clinical Medical Assessments

Total Body Surface Area

TBSA is a key diagnostic tool in burn assessment and management. As an indication of the importance of TBSA in the treatment of burns, a retrospective study of records at the USAISR Burn Center found a roughly linear relationship between TBSA and the number of acute operations performed. The same relationship did not hold for reconstructive operations (e.g., skin grafting). In the study sample, the number of such procedures declined after TBSA of 40 percent, which the authors attribute to multiple factors, including the difficulty of finding donor tissue for patients with large burns (Chan et al., 2015).

TBSA also has been associated with clinical outcomes. One study of a major mass casualty event, for example, found that initial TBSA diagnosis was a statistically significant predictor of infection (Kao et al., 2018). Earlier research has found that morbidity and mortality are significantly increased in burn injuries with TBSA greater than 40 percent and that the inflammation process affects the whole body in injuries with TBSA greater than 20 percent (Rylah and Smith, 2015).

There are several methods for measuring TBSA. The clinical assessment method considered to be most accurate is the Lund-Browder chart, which was developed in the 1940s and divides the body into several age-adjusted regions; the clinician assesses the extent of burn within each (Lund and Browder, 1944; Martin, Lundy, and Rickard, 2014). Alternatives, including the “rule of nines” and serial halving, have been developed for use in settings in which the Lund-Browder method is infeasible, including forward-deployed environments (Rylah and Smith, 2015). These methods involve roughly parti-

tioning the body into regions to bound the extent of the burn and are considered to be sufficiently accurate for early assessment and triage, but not for treatment at Role 3 facilities or full medical treatment facilities (Martin, Lundy, and Rickard, 2014).

Given the clinical importance of TBSA assessments, researchers have examined variation in their accuracy across methods and examiners. One study compared TBSA estimates of two cohorts: military health personnel who had not been trained in burn assessment but who had access to a Lund-Browder chart, and trained burn specialists (Martin, Lundy, and Rickard, 2014). Each group's estimates were compared with estimates performed by two expert reviewers. The untrained cohort tended to underestimate TBSA relative to the expert reviewers (mean of 52.53 percent compared with 64.5 percent). In contrast, the trained cohort's estimates were not statistically different from the benchmark but exhibited a large range (from 48 percent to 85 percent), suggesting a wide variation in TBSA estimates even among trained clinicians.

Injury Severity Score

Another commonly used measure of injury severity in both burn research and clinical settings is the ISS. This score, which is not specific to burns and is meant to capture the extent of polytrauma in a trauma victim, is calculated by partitioning the body into six regions, calculating the severity of injury in each region, and then adding scores across regions (Baker et al., 1974).

The ISS and other measures of burn and injury severity—including the Modified Baux Index (Stern and Waisbren, 1979) and the Abbreviated Burn Severity Score Index (Tobiasen, Hiebert, and Edlich, 1982)—are frequently used to predict mortality from burn injury (Janak et al., 2018). Janak and colleagues, 2018, identified a potential flaw in research that uses the ISS alongside other measures of burn severity when estimating the relationship between mortality and burn injury. Because the ISS inherently overlaps with traditional measures of burn severity, such as TBSA and the presence of an inhalation injury, using it as a control variable in multivariate analyses might mask the independent effects of other measures. In a retrospective

review of records from the USAISR, Janak and colleagues, 2018, find that adjusting for the ISS attenuates the independent effect of TBSA on mortality risk by 20 percent.

Clinical Mental Health Assessments

Posttraumatic Stress Disorder and Traumatic Brain Injury Assessments

Burn victims are at an elevated risk for developing PTSD and mTBI (McGhee et al., 2011). As a result, researchers have investigated the use of diagnostic tools to screen for these conditions—for example, by using the Military Acute Concussion Evaluation tool to screen for mTBI in clinical settings (Cancio et al., 2017). This tool guides the clinician through a brief questionnaire covering concussion and symptom screens (e.g., “Was there loss of consciousness?”) and cognitive and neurological exams (e.g., concentration, pupil response, speech fluency) (Defense and Veterans Brain Injury Center, 2018). One takeaway from this work is that clinical assessments of symptoms (e.g., subjective cognitive impairment, pain, fatigue) are not necessarily associated with standard measures of burn severity. In a retrospective study of service members with burn injuries and a PTSD screen recorded in the Joint Theater Trauma Registry, McGhee et al., 2011, tested the association between early acute pain scores and PTSD diagnosis. Although the authors did not find a statistical relationship between pain severity categories and standard measures of injury severity (TBSA and ISS), they did find statistical differences in PTSD risk between the mild and severe pain groups. Similarly, Mercado and colleagues, 2008, found no relationship between mTBI and cognitive function in a sample of service members with burn injuries, but they did find an association between mTBI and psychiatric comorbidity (as measured by the Repeatable Battery for the Assessment of Neuropsychological Status).

Prediction Studies

Two studies examined prediction of outcomes in burn patients. The first was a retrospective study of burn patients using a U.S. registry (Chan et al., 2015). The authors found that higher TBSA, higher ISS, longer ICU length of stay, and allograft use were all associated with

higher acute operative burden and that the presence of upper-extremity burns was a significant determinant of reconstruction following discharge. In another study, Kao and colleagues, 2018, examined predictors of two complications, AKI and burn wound infection (BWI), among burn patients at a hospital in Taiwan following a mass casualty explosion. They found that being male was a predictor of AKI and that initial TBSA was a predictor of BWI.

Treatment and Follow-Up Care Results

In this chapter, we explore the NRAP treatment and follow-up care categories.

Acute Care

Fluid Resuscitation and Management

Vascular damage, which is very common after a severe burn injury, reduces fluid circulation and can result in immunological compromise and organ dysfunction (Pitt et al., 1987). Therefore, fluid resuscitation is critical in the 24 hours after major burns because fluid transfusion can prevent early shock and improve myocardial function after a burn injury (Ran et al., 2010). It is important to replace fluids through intravenous fluid resuscitation when TBSA is greater than 20 percent, according to the American Burn Association Practice Guidelines (Pham, Cancio, and Gibran, 2008). However, resuscitation with an excessive fluid volume also is a serious issue and can result in such complications as pulmonary edema or abdominal compartment syndrome (ACS) (Lamb et al., 2010).

There are several formulas to calculate the volume of fluid needed for resuscitation. Two of the most popular fluid resuscitation formulas in the United States are the Parkland formula (Baxter, 1981) and the modified Brooke formula (Warden, 1992), both of which use the patient's weight and TBSA. Chung and colleagues compared 24-hour volumes of fluid between groups of military casualties with less than 20 percent TBSA who received initial fluid volumes based on either

the Parkland formula or the modified Brooke formula. They found that, on average, the modified Brooke formula resulted in significantly fewer 24-hour volumes without resulting in higher morbidity or mortality (Chung et al., 2009). An alternate formula used widely for burn patients in China is the Third Military Medical University (TMMU) protocol, which also uses TBSA and weight and is a feasible option for resuscitation for burn patients (Luo et al., 2009). More recently, a simplified “rule of ten” formula was developed that involves estimating TBSA to the nearest ten and multiplying it by ten for adult patients weighing 40–80 kg (Chung et al., 2010). Simulation studies using randomly defined values of patient weights and TBSA found that the value calculated using the rule of ten fell between the values calculated by the Parkland formula and the modified Brooke formula 88 percent of the time (Chung et al., 2010). This simplified approach might be beneficial in combat scenarios, where prehospital care must be administered in difficult conditions. Apart from weight and TBSA, other factors, such as drug use, may influence the volume of fluids needed. However, Juern, Peltier, and Twomey, 2008, found that, contrary to prior studies, methamphetamine-positive burn patients did not have higher fluid requirements than methamphetamine-negative matched controls.

Use of formulas to calculate the volume of fluid needed for resuscitation in burn patients is inconsistent. Chung, Salinas, and Renz, 2011, evaluated which, if any, formulas were used by providers at USAISR Burn Center to calculate patients’ initial fluid-resuscitation rates during the prehospital burn-resuscitation stage. They found that only 21 percent of patients received an initial fluid rate consistent with existing formulas, possibly because of their complexities. In a descriptive retrospective study of prehospital care of burn patients with less than 20 percent TBSA in a combat zone, Lairet, Lairet, et al., 2012, found that more than half (58 percent) of patients did not receive any fluid resuscitation during prehospital care and that those who did received fluid volumes far exceeding recommendations, pointing to the need for education among military responders. In another study by Ennis and colleagues, 2008, a burn center that received casualties from the conflicts in Iraq and Afghanistan implemented Burn Resuscitation Guidelines (BRG) that included fluid requirements. After implementa-

tion of the BRG, more patients received guideline-concordant care. In addition, mortality and rates of ACS decreased.

Mechanical Ventilation and Intubation

Burn patients, particularly with severe trauma, may require acute respiratory care. Factors known to affect mortality include the presence of an inhalation injury, tracheostomy, and the use of an endotracheal intubation (Zengin et al., 2015). Among burned military casualties in OIF and OEF, an estimated one-third (32.6 percent) had acute respiratory distress syndrome (Belenkiy et al., 2014); this figure is similar to that of burn casualties in civilian settings (Waters et al., 2015). In a review article of inhalation burn treatment, Maung and Kaplan, 2014, note that special considerations are needed for inhalation injury because of direct chemical damage to small airways, complicated by excessive blood flow to poorly ventilated lung segments. Mechanical ventilation might be appropriate for these patients, but there is controversy about the ideal techniques.

Shuker, 2010, provides a review of specific considerations for blast facial burns. He notes that blast waves, hot air, and smoke inhalation may cause swelling of the mouth, nose, pharynx, and larynx, which can restrict respiratory airflow, possibly necessitating endotracheal intubation. Although this is generally a straightforward procedure, Shuker notes that, in cases where intubation is challenging, cricothyroidotomy or tracheostomy should be used. Elsewhere, Shuker, 2015, discusses unique complexities associated with thermal shell-fragment craniofacial soft-tissue injury.

Topical Treatments

Topical treatments have been used for many decades to treat burns; in fact, Soviet scientists made significant contributions to developing topical treatments for burns during World War II because of the prevalence of burn injuries (Sokolov et al., 2017). In this section, we review several more-recent articles that discuss the use of topical treatments for burn therapy.

In a case series of 13 burn victims exposed to a mustard gas attack, Kilic and colleagues, 2018, found that antihistamine was useful

in relieving itching from the burn and noted the utility of a topical antiseptic applied to skin lesions to prevent infection. Another article discussed the complexities of care for patients with white phosphorous burns and reported the positive effects of mafenide acetate and flaminol forte to prevent infection (Aviv et al., 2017).

Three other articles specifically looked at topical treatments for eye injuries. Schultz, 2012, described initial steps in developing a topical therapy to prevent vision impairment because of corneal burns caused by explosions during combat operations. In initial trials of the topical therapy, in which small interfering RNAs were applied to burned *ex vivo* rabbit corneas, the treatment reduced levels of collagen and scarring (Schultz, 2012). In a review of eye injuries, Scott, 2011, recommended topical antibiotics for epithelial defects and conjunctivitis resulting from thermal injuries and recommended topical lubricants to mitigate the effects of corneal exposure. In the case of chemical burns, he recommended irrigation of the affected eye with Ringer's lactate solution immediately after injury.

Surgical Wound Care

Wound Debridement

Wound debridement is often the first step in surgical wound care and involves cleaning dead and contaminated tissue from the burn site (Saldanha et al., 2018). Shuker, 2010, provided a review of specific considerations for debridement of facial blast burns. He noted that facial blast injuries require more-aggressive debridement than other types of burn injuries and recommended the use of a pressured saline-solution jet to clean the affected area.

Wong and colleagues, 2019, presented a case series of five burn patients undergoing a novel use of the diathermy scratch pad, a cheap and effective tool for surgical debridement and dermabrasion prior to skin grafting. Four of the patients healed without further intervention, while one required a secondary skin graft because of infection.

Skin Grafting

Skin grafting is the process of taking healthy skin tissue and grafting it onto the affected area. Skin can be *autografted*, meaning that it is taken from a healthy donor site on the same individual's body, and can be partial or full thickness. Skin also can be *allografted*, which means that it is taken from an individual of the same species—either a cadaver or a living donor. Several studies discuss novel techniques and special considerations involved with skin grafting in burn patients.

A case study by Ibrahim and colleagues, 2012, described the successful use of reverse tissue expansion in an autograft surgery. In this case, the technique allowed for autograft with limited donor site availability. In a case series, Lundy and colleagues, 2011, described the allograft treatment of two Iraqi child burn victims who had TBSAs that were too high for autograft. In both cases, donations from their fathers allowed for temporary wound closure.

Matsumura, Harunari, and Ikeda, 2016, described their experience using cultured epidermal autograft (CEA). At the time of the study, CEA was not approved in clinical practice but was used as an experimental treatment in seven patients with blast burns following a mass casualty explosion (Matsumura, Harunari, and Ikeda, 2016). The epithelialization of each CEA site was successful for six of the seven patients at two to four weeks following injury, with the seventh patient's autograft being complicated by a MRSA infection.

Li and colleagues, 2019, reviewed cell sheet technology, which uses seed cells to regenerate skin tissue and which has the advantage of not requiring scaffolds, unlike other regenerative techniques. Two additional articles discussed the role of regenerative medicine in the context of skin grafting and tissue repair. Another study evaluated the regenerative properties of acellular fish skin as a conformal cover for severe burn wounds on the battlefield. The researchers found that this form of covering has unique biomechanical properties that make it an ideal option (Magnusson et al., 2017).

Flap Surgery

Flap surgery is another common surgical technique used on burn patients. It is similar to skin grafting but involves moving tissue to an

area with an intact blood supply (as opposed to a graft, which relies on growth of new blood vessels). Flap surgery can be *local*, meaning that a piece of nearby tissue is rotated to cover the affected area without being disconnected from its blood supply, or *free*, meaning that the tissue comes from a different part of the patient and the blood vessels on the free flap are reconnected through vascular surgery. Several studies have discussed flap surgery as it pertains to burn patients (Satteson et al., 2018).

Bakhach and colleagues described a case series of 14 civilians with blast-burn injuries who underwent early free-flap reconstruction (Bakhach et al., 2017). The authors noted that free-flap surgery was necessary in these cases because of the lack of available local donor sites (Bakhach et al., 2017). Igde and colleagues, 2019, discussed the specific challenges of late-term reconstruction in a case study of a blast-burn patient in Syria. The patient, who had received care for his facial burns previously, presented 18 months after initial injury, unable to close his eyes. The successful application of a frontal muscle flap restored function to his eyelids.

Nasal reconstruction also presents challenges because of the limited availability of local flaps. Yen and colleagues, 2018, described a case series in which six patients underwent free-flap surgery for nasal reconstruction. Sources of free flaps included the forearm, thigh, and sural artery, and the nasal frameworks were constructed using costal or conchal cartilage. Other unique treatment challenges of facial burns noted in the literature include prolonged transport to a burn center, delayed initial intervention, and difficulty finding color-matched donor skin (Johnson et al., 2015).

In some cases, an *island* flap is used, meaning that the flap is not applied to adjacent tissue. In a retrospective review of electrical burn patients at a military hospital, Xue and colleagues, 2008, examined the use of *island myocutaneous flaps* (flaps that contain both muscle and skin). In the 23 patients examined, three flap surgeries were performed within seven days of injury, 16 were performed eight days to six weeks post-injury, and four were used in secondary reconstructions (over six weeks), with all patients reaching complete recovery.

Synthetic Wound Dressings

Wound dressings also can be made of synthetic material, although they are typically intended to be used on a temporary basis. Several articles explored their use in burn patients.

Austin and colleagues, 2015, conducted a retrospective cohort study of patients with upper-extremity excised burn wounds to compare operative time and operating room costs between Biobrane (a synthetic nylon dressing) and cadaveric allografts. They found that Biobrane was more time-efficient and cost-effective than cadaveric allograft and carried a similar complication rate.

Three studies examined the use of silver-nylon dressing for burn wounds. Barillo, Pozza, and Margaret-Brandt, 2014, conducted a literature review on the uses of silver-nylon dressing for military burn wound dressing and noted its advantages for use in challenging or remote environments. They noted that its ease of use and antimicrobial properties made it ideal for use until transfer to a more advanced medical facility was possible. In a retrospective case-control study of the efficacy of a silver-nylon dressing on combat-related burn injuries, Aurora and colleagues, 2018, found that, compared with topical antimicrobial agents, silver-nylon dressing had lower infection rates and similar rates of burn-related complications. Pozza, Matthew, and Lunardi, 2014, described a case series of two service members with combat-related burns in Afghanistan who received silver-nylon dressings. The dressings helped prevent infection prior to transfer to a more advanced facility.

Negative-Pressure Wound Therapy

Negative-pressure wound therapy (NPWT) is a technique used in burn care that applies a sealed wound dressing and a vacuum pump. Vacuum wound devices are perhaps some of the most innovative devices available and have changed the face of acute and chronic wound care (Danks and Lairet, 2010). Jeffery, 2009, described three cases that used gauze-based NPWT during skin grafting. The author noted the importance of conducting thorough wound debridement prior to NPWT, drying the skin to maintain a good seal, and applying adhesive around the skin adjacent to the wound.

Another article discussed the use of limited-access dressing (LAD), a special case of NPWT. *LAD* is a moist wound dressing with negative pressure that does not require frequent changing and allows limited access for pathogens. In a case series that detailed burns from a mass casualty tanker explosion in India, LAD efficiently prevented infection, despite limited additional resources (Kumar, 2013).

Other Topics in Surgical Wound Care

Five studies examined other topics related to surgical wound care. For example, in a literature review, Kowal-Vern and Orkin, 2016, examined the effects of antithrombin to reduce blood loss during eschar excision. The authors found evidence supporting the use of antithrombin, but they pointed to a lack of human studies on recombinant antithrombin specifically and called for large-scale clinical trials. Mansilla and colleagues, 2015, described the first case of using bone marrow mesenchymal stem cells to treat a severe blast-burn patient and observed rapid wound regeneration and healing of the autograft donor site. Similarly, Funderburgh, 2016, detailed the potential benefits of stem cell-based therapy for corneal burns and discussed efforts to develop a therapeutic device to promote this therapy. De Buys Roessingh and colleagues, 2013, described ways to integrate cellular therapies to aid in repairing damaged tissues more rapidly, specifically focusing on the treatment of burns and trauma. Albrecht and colleagues, 2018, conducted a controlled trial that tested the ability of timolol (a beta-adrenergic receptor antagonist) to improve epidermal wound closure on samples of irradiation-burned *ex vivo* human skin cultures. The results indicated that a beta-adrenergic receptor antagonist, such as timolol, could be useful in burn treatment of combined burn and radiation injury.

Maintenance Care

Treatment of Complications and Comorbidities

Burn injuries are complex, often involve multiple body systems, and can result in significant complications and comorbidities. Several

researchers have examined the treatment of complications and comorbidities among burn patients.

Chung and colleagues, 2008, examined the use of continuous renal replacement therapy (CRRT), more commonly known as *dialysis*, on outcomes in severely burned service members with AKI. The authors prospectively enrolled patients in a single military burn ICU and compared them with a historical control group treated before CRRT became available at the facility. They found that early and aggressive CRRT intervention in severely burned individuals improved hemodynamic stability and lowered 28-day mortality compared with patients in a closely matched control cohort.

In another study, Lu, Tandang-Silvas, et al., 2018, examined the complication of *heterotopic ossification* (HO), an extraskeletal formation of bone that may develop from blast injuries or severe burns because of the disruption of the bone morphogenetic protein (BMP) signaling pathway. The authors first conducted a computer simulation to identify compounds, from a large digital library, that could inhibit HO. They found a family of compounds with terminal hydrogen-bonding acceptor groups and then tested these compounds in vitro, confirming the hypothesized properties. The tests suggested that these compounds could be used in a prophylactic drug to prevent HO in burn and blast patients.

Metabolic acidosis (the excessive production of acid) is another common complication following burn injuries. The alkalizing agent tris(hydroxymethyl)aminomethane (THAM) is a potential treatment for this complication. Naylor and colleagues, 2018, completed a retrospective review of pediatric casualties in Afghanistan and Iraq receiving THAM. The authors did not draw conclusions about efficacy given the observational nature and small number of patients who received THAM, but they noted that THAM was administered infrequently and to more-severely injured patients.

Parkhouse, 2009, in a review of the treatment of military burn casualties, notes that the common complication of stress ulceration in burn patients has decreased with the expanded use of antacids and gastric acid prophyllaxis among patients with major burns.

Severe blast-burn patients often have respiratory complications. Hsu and colleagues, 2017, presented a case series in which extracorporeal membrane oxygenation (ECMO) was used for six very severely injured blast-burn patients (TBSA greater than 50 percent). The patients received ECMO 14–63 hours following injury. Five of the patients died, and causes of death included multiple organ failure, septic shock, and cardiogenic shock.

ACS can occur in burn patients, even without abdominal injury. In the case of an injured U.S. service member in Afghanistan who was burned in an explosion, researchers believed that systemic inflammatory response syndrome—combined with aggressive fluid resuscitation—was partly to blame for the patient's ACS (Lamb et al., 2010). In some cases, treatment can lead to additional complications. Kennedy, Goldie, and Nickerson, 2011, documented a novel case in which a partial-thickness burn progressed to a full-thickness injury after the administration of *cardioversion* (electric shocks to the heart).

Scarring

Petro, 2015, conducted a retrospective study of examples of modern military treatments focusing on scar manipulation techniques. Contracture scars provide natural wound closure following burns but can impair mobility and function when they form over joints (Kim et al., 2012). Kim and colleagues conducted a retrospective analysis of treatment of contracture scars in a civilian population in India, the majority of whom sustained burns from kerosene stove blasts. They noted that patients undergoing delayed reconstruction—typically full-thickness skin grafts—tended to have worse outcomes than those who received comprehensive initial therapy. Scarring in burn patients was also examined in two case studies; researchers found that custom-designed pressure garments and face masks improved the appearance of scars by encouraging a flattened growth pattern of collagen fibers (Bassetto et al., 2015; Harris et al., 2008).

Pain Management

Patients with severe burns require effective pain management, both for the burns themselves and for the painful processes of wound debride-

ment and surgery. The amount of pain medication needed varies based on the severity of the injury. A retrospective analysis of intravenous patient-controlled analgesia (IV-PCA) use in burn patients following a mass casualty explosion in Taiwan found that TBSA and higher pain scores were associated with higher use of IV-PCA morphine (Lin et al., 2019).

The use of ketamine for pain treatment in burn patients was examined in two studies. Through a retrospective chart review, McGhee and colleagues, 2008, identified 241 burn patients with TBSA greater than 20 percent. The authors found that rates of PTSD, as measured by the PTSD Checklist–Military, were lower among patients who received perioperative ketamine for pain management than among those who did not, despite the ketamine group having more-severe injuries and more-intensive surgical treatments. In a subsequent larger study, in which similar methods were used to study 289 service members with burn injuries, McGhee and colleagues, 2014, found no difference in PTSD rates in ketamine and no-ketamine groups.

Several researchers have examined the use of immersive virtual reality (VR) during wound care as a method to control pain, in combination with traditional pharmacological treatment. Hoffman, 2014, discusses the advantages of allowing patients to use VR to escape their pain, showcasing results from controlled studies demonstrating large reductions in the amount of pain patients experience during both wound care and physical therapy as a result of VR sessions. Functional MRI brain scans have shown significant reductions in pain-related brain activity during VR, comparable to the amount of pain reduction from a moderate dose of hydromorphone. Maani and colleagues conducted two case series of two service members that described the technology and illustrated its potential to control pain in burn patients during treatment (Maani et al., 2008; Maani, Hoffman, Fowler, et al., 2011). In a subsequent study, 12 U.S. service members with blast burns received half their severe burn wound-cleaning procedure while in an immersive VR experience and half with usual care. During the VR experience, they rated their pain as lower, reported care to be less unpleasant, and spent less time thinking about their pain (Maani, Hoffman, Morrow, et al., 2011). VR also was examined by Soltani and

colleagues, 2018, during physical therapy exercises of patients hospitalized for burn care. In a randomized trial of 39 patients, individuals who used VR reported lower pain ratings and less time spent thinking about pain and rated their physical therapy experience more positively, compared with the control group.

Infection Control and Management

Because of the nature of burn injuries and treatment, infection is a very common complication (Brown Baer et al., 2012). Five studies examined treatment of infection or related conditions in burn patients. In a case series of three servicemen with blast-burn injuries, Lewandowski and colleagues, 2013, found that diluted Dakin's solution combined with NPWT successfully treated opportunistic fungal infections. Rose and colleagues, 2014, examined the use of *bacteriophages*, viruses with the ability to lyse bacteria, as an alternative treatment for multidrug-resistant bacterial infections in burn patients. In an initial, exploratory trial, they tested bacteriophages on nine burn patients with multidrug-resistant bacterial infections. Although the small sample size did not allow for tests of efficacy, the study served as a proof of concept and prompted recommendations for future use, including the application of a gel or dressing instead of a spray to prevent runoff of the solution from the wound. Similarly, Lu, Dai, et al., 2018, examined bactericidal properties of oregano oil against multidrug-resistant isolates, finding significant antibacterial activity against 11 isolates—including *Acinetobacter baumannii*—in vitro and in a mouse burn model. An additional case study described a novel use of methylene blue, a drug with multiple medical uses, to successfully treat *septic cardiomyopathy* (heart disease stemming from an infection) in a burn patient (Schlesinger and Burger, 2016). Lastly, Shao and colleagues, 2018, found that burn patients at risk for infection observed more-rapid and more-complete healing when tangential excision was implemented earlier rather than later.

Long-Term Care

Three articles discussed long-term care among burn patients in the areas of nutritional support, physiotherapy, and involvement of families in recovery. First, in a review article, Parkhouse, 2009, examined best practices with regard to nutritional support of burn patients. He noted that burn patients have significantly higher calorie requirements, increasing with TBSA, and that supplemental tube feeding is recommended as early as can be tolerated, with carbohydrates being especially important. Second, a case series of ten patients with blast-burn injuries to the hand discussed postoperative therapy for patients. Physiotherapy in a rehabilitation center, at-home exercises, hand massage, and elevation all were used to reduce inflammation (Pistré and Rezouk, 2013). Third, Degeneffe, Tucker, and Griffin, 2015, discussed involving families in the recovery process. The article focused on service members—many of whom suffered severe burns—who had been injured by IEDs. Some challenges noted by families included learning to care for the injured family member at home, developing relationships with the family member's treatment team, and finding time to adequately care for the family member.

Although limited research has been conducted to explain the quality of life (QOL) among burn survivors during posthospitalization rehabilitation, Yoder, McFall, and Glaser, 2017, conducted a longitudinal study to examine QOL among 131 burn survivors (both civilians and military personnel). The team concluded that expectations about individual ability to rehabilitate differ significantly between military and civilian patients and that there is much room for interventions to improve QOL.

Military Policy and Health Services Research Results

In this chapter, we examine how military health policies, evidence-based practices, and systems-based approaches affect the risks and outcomes of blast-related burn injuries, and we focus on the NRAP military policy and health services research categories. Services research helps establish targets and identify key points of reference to better understand the best practices and cost-effectiveness of various techniques in preventing and treating blast-burn injuries. This knowledge can improve efficiency in delivering treatment services, improve treatment adherence and effectiveness, and improve access to services in critical settings.

Resources and Cost

Data on the distribution of costs of treating burn patients in the aftermath of a combat blast event or civilian mass casualty explosion disaster can provide key information for improving cost-effectiveness and efficiency in resource management in future incidents. Mathews and colleagues, 2017, performed a retrospective analysis of patient expense records to investigate the economic effects of treating civilian blast-related burn injuries in the aftermath of a mass casualty event in Taiwan. A minority of patients in the cohort experienced TBSA greater than or equal to 50 percent, but they consumed nearly 64 percent of the total cohort expenses. Inpatient ward fees, therapeutic treatment

fees, and medication fees were the biggest cost drivers. In an analysis of the same civilian disaster in Taiwan, Kao and colleagues, 2018, examined the cost of treating individual patients and estimated the cost of care by percentage of TBSA burns. They report that each patient costs an average of \$1,035 per TBSA percentage, with an average total cost of \$50,415. Jeevaratnam and Pandya, 2014, performed a case analysis of casualties treated for burns at a UK MTF and noted that the treatment of civilians with noncombat burns had a significant logistical impact on facility operations and placed a strain on nursing time, dressing resources, and bed space.

Treatment of pediatric patients can require a disproportionate share of resources in intensive care and hospital bed-days. Arul and colleagues, 2012, performed a case review of pediatric admissions at Camp Bastion, Afghanistan, over a four-month period in which blast-burn cases were the most common type of battle-related injury and burns were the most common cause of nonbattle-related injury admissions. Care for pediatric burn patients used significant services and was associated with more operative procedures and longer average length of stay than care for other, nonburn-related trauma patients (six days versus two days).

Mathews and colleagues, 2017, assessed the costs of treating burn patients after an explosion disaster. Their retrospective analysis of patient expense records found that inpatient ward fees were the largest expense (30 percent), followed by therapeutic treatment fees (22 percent) and medication fees (11 percent). Patients with TBSA greater than or equal to 50 percent tend to have higher inpatient expenses. A study by Dallas and colleagues, 2013, simulated the potential health system response in the event of a mass casualty scenario—specifically, the consequences of a nuclear exchange between Israel and Iran—and concluded that burn patients would require “enormous resources to treat.”

Health Care Delivery Research

Mass Casualty Burn Events

Multiple studies discussed the coordination of initial emergency-response efforts following a civilian mass casualty blast event. Albanese and colleagues, 2014, described the establishment of clinical guidelines for emergency department (ED) staff responding to mass casualty incidents involving chemical, biological, radiological, nuclear, or explosive (CBRNE) devices by using the DISASTER mnemonic (detect, incident command system, security and safety, assessment, support, triage and treatment, evacuation, and recovery) to assign specific job actions or tasks to emergency responders. In an analysis of emergency-response efforts to a 2017 chemical factory explosion, Kondo and colleagues, 2019, discussed the unique risks of CBRNE incidents to the health of first responders and highlighted the need for specialized training to ensure that emergency responders have the knowledge to protect themselves from harm while managing the decontamination and triage of patients. Kearns and colleagues, 2014, reviewed another aspect of burn disaster-response planning for critically injured patients, focusing on transportation resources, such as ground-based ambulances, private and hospital-based specialty care ambulances, aeromedical services, and military or federal resources available in all states. The authors discussed the importance of developing a transportation annex to coordinate intrafacility, intrastate, and interstate resources.

Several studies have been conducted about a mass casualty burn incident commonly known as the Formosa Fun Coast explosion because it occurred at the Formosa Fun Coast water park in New Taipei, Taiwan. Yeong and colleagues, 2018, describe a local health system response to the incident that proved markedly successful, involving precise triage, traffic control, facility expansion, staff recruitment, and clear-cut treatment strategies for severely burned patients. Ng and colleagues, 2018, retrospectively analyzed data from patients sent to a local hospital, developing a triage system specifically for mass casualty burn incidents. The triage system uses consciousness, breathing, and burn size as the modifiers, so, although this particular algorithm might raise excessive immediate attention, thereby increasing the

potential of exhausting resources, the study adds to the triage system knowledge base. In addition, Kuo and colleagues, 2018, conducted a study addressing the question of whether victims of this incident were sent to the appropriate hospitals, given their injuries. Their findings suggest that systemic preplanning should be considered to maximize the function of preliminary hospitals in burn care.

Kim and colleagues, 2013, performed an assessment of the early reconstructive surgery response at a hospital in Boston, Massachusetts, following the 2013 Boston Marathon bombings. The researchers identified several factors that allowed for efficient early diagnosis and treatment of patients' injuries, including interdisciplinary daily rounds and protected operating room block time. Little and colleagues, 2012, performed a comparative case study to identify the hospital ED interventions, developed during the Bali bombings of 2012, that were effective for reducing ED length of stay and mortality. These practices included holding ED disaster-response planning and training, implementing early Code Brown notification, providing regular hospital-wide use of short message service to communicate with ED staff, controlling public and media access to the ED, providing early panendoscopy to determine intubation needs, and putting senior clinical decisionmakers in all areas of the ED during the response. The use of technology and early communication to organize tertiary services and emergency surgery also is a critical element during emergency response following a chemical plant explosion (O'Neill et al., 2012).

Transportation, Triage, and Multidisciplinary Collaboration

Blast injuries incorporate multiple injury mechanisms, including penetrating fragmentary injury, blunt-force trauma, flash burn, and overpressure wave damage, thus making them exceedingly complex to treat (Valerio et al., 2014). Management of the individual patient requires a multidisciplinary team, and wartime bombings also require expertise in triage (Luks, 2010; Rowley-Conwy, 2013). Although the speed and precision of transporting patients from the battlefield to burn centers has improved in recent decades (primarily because combat operations in Iraq and Afghanistan have caused an increase in burn patients, which, in turn, has forced technological advancements), there is still a

need for further improvements in this domain (Schmidt and Mann-Salinas, 2014).

The importance of multidisciplinary and multiorganizational collaboration in triage and transportation of military or civilian burn patients has been discussed in several studies. Barillo and colleagues, 2010, presented a case study in which six military burn patients were transferred over 7,000 mi, from Guam to San Antonio, Texas. The transfer was made possible by the creation of a temporary burn ICU midway, at Tripler Army Medical Center in Hawaii. The researchers described the transportable burn ICU as an efficient response to a sudden need for additional ICU beds. The study also highlighted the importance of medical cross-training in effectively managing complex patients. Ng and colleagues, 2018, discussed the advantages of a mass burn casualty (MBC) hospital ED triage algorithm compared with two other triage algorithms—Simple Triage and Rapid Treatment (START) and the Taiwan Triage and Acuity Scale—following an explosion in Taiwan. The researchers also discussed future adjustments to the MBC triage algorithm and criteria to accommodate other potential disasters.

Breederveld and Tuinebreijer, 2009, described emergency treatment guidelines during prolonged triage and transportation of combat burn casualties in Iraq and Afghanistan. They noted that, because transportation of burn patients can take three to four days and patients may be treated in three to four different medical facilities, the initial treatment of burn casualties should focus on emergency management and temporary and intermediate treatment. This includes evaluating the need for escharotomy, fasciotomy, or laparotomy; compartment syndrome; abdominal hypertension; or ACS.

Prehospital casualty triage algorithms are used widely but might have significant limitations that affect their effectiveness in triaging severe or unusual injury types that involve prolonged transport, such as combat blast and burn injuries and injuries from mass casualty situations. These algorithmic deficiencies can lead to *undertriage*, which occurs when minor or moderate casualties are more complex than initially triaged. Neal, Barbera, and Harrald, 2010, developed the “-PLUS” (i.e., penetrating trauma, labor/pregnant casualties, uncon-

ventional casualties, and smoke and other inhalations) Prehospital Casualty Triage algorithm to supplement common existing triage algorithms, such as START. The authors note that further research and field assessment are needed.

Options for civilian burn-injury intervention are limited, compared with the generally well-structured care and transportation regimens for military burn victims in wartime. An estimated 70 percent of all prehospital transport of civilian patients is done by the lay public, and 93 percent of civilian patients receive basic first aid, in the field or during transport, that is administered by untrained individuals, such as relatives or friends (Atiyeh and Hayek, 2010). While military burn patients are evacuated to Levels IV and V treatment facilities for definitive and long-term care, civilian patients receive care at Level III military facilities, which often are underequipped for this type of care.

Sufficient Predeployment Training

Training for medical personnel must contribute to better outcomes and decreased mortality rates. Several studies have discussed what skills are most necessary to provide high-quality care to service members with burn injury, how that training might be more consistently accessed prior to deployment, and how individuals might help cover shortages of specific personnel.

Bonnet and colleagues, 2012, evaluated the activity of visceral surgeons to compare the skills and qualifications required in a deployed setting and a civilian setting. As expected, nontrauma-related emergencies and elective surgeries required the same skills as those required in civilian practice, although war-related injuries and nonwar-related trauma emergencies were significantly more challenging. The study concluded that a visceral surgeon in a Role 3 MTF should master a variety of skills and expertise to be able to treat many different types of patient injuries, particularly thoracic and vascular wounds.

Surgeons are not the only ones who must be competent in many areas. Finnegan and colleagues, 2015, studied British military nurses—specifically, the impact and effectiveness of the predeployment educational preparation and clinical placement provided for nurses. One important finding was that clinical exposure was lacking, meaning

that nurses were not routinely exposed to levels of trauma often seen in wartime. Military medical personnel must be educated in many different areas, which means that they must be placed in clinical settings where they can use these skills and be exposed to sufficient trauma levels before being deployed.

If medical personnel were trained more broadly and received proper exposure predeployment, then shortages of specific personnel would not be as adversely felt as they are now. Bush and colleagues, 2009, recognized a shortage of active-duty vascular surgeons in the military, so they studied a base of volunteers that have been called on previously to supplement the surgeon shortage. Because there is a limited number of military surgeons, civilian volunteers play an important role in providing care.

Additionally, the stress impact to medical providers of caring for combat burn patients is seldom explored. A qualitative survey study by Peterson and colleagues, 2019, used results from the Military Healthcare Stressor Scale to compare the impact of combat-related stressors and medical-specific health care stressors, such as exposure to patients with severe burns, on 1,138 military medical personnel deployed to Iraq between 2004 and 2011. Although 18 percent of military medical personnel reported experiencing significant impact from combat exposure, 67 percent reported experiencing significant impact from medical-specific stressors, suggesting that medical stressors are substantially more impactful than combat exposure on medical personnel. The researchers conclude that 5–10 percent of deployed medical personnel might be at risk for clinically significant levels of PTSD.

Strategies to Increase Implementation of Practice Guidelines

Several studies examined the effectiveness of, and user compliance with, burn-resuscitation guidelines and use of burn-flow sheets and formulas to calculate the fluid-resuscitation rate in the prehospital stage. Chung, Salinas, and Renz, 2011, examined which, if any, formula the providers were using to calculate patients' initial fluid-resuscitation rate during the prehospital stage; they concluded that prehospital providers were not using a formula to determine the initial fluid rate, likely because the formulas were too complex. Caldwell and colleagues, 2017, con-

ducted an evaluation of the USAISR burn flow sheet for en route care documentation of burned combat casualties and found that, although the majority of providers initiated a burn flow sheet, common misuse included missing data and miscalculations. Use of the burn flow sheet was associated with a decline in ACS but no change in mortality. To streamline practices, the researchers recommended simplifying recommendations and instituting additional built-in prompts and automated decision-support tools. Ennis and colleagues, 2008, performed a prospective evaluation of burn-resuscitation guidelines for severely burned military casualties. They found that implementing the burn-resuscitation guidelines and system-wide standardization improved outcomes for severely burned patients.

Chapman, Richard, Hedman, Renz, et al., 2008, evaluated the use of the American Medical Association (AMA) impairment guides and the disabilities of the arm, shoulder, and hand (DASH) questionnaire on OIF and OEF combat casualties recovering from hand burns. Results indicated that both instruments can provide comprehensive assessment of disability and impairment and could be used to monitor changes in health status over time and that both were able to discriminate between casualties returned to duty and casualties not returned to duty. The computer-calculated AMA impairment scores can be used reliably to detect change in impairment and function, while the DASH questionnaire should be used to detect change in disability in patients recovering from hand burn injury.

Kao and colleagues, 2018, examined ICU resource management during a mass casualty event and concluded that treatment guided by evidence-based outcome predictors can improve mortality outcomes in burn injuries. These factors include adequate communication around logistics and capacity, accuracy of triage and management, ensuring adequate fluid resuscitation, and early debridement and skin grafting to prevent burn wound infections.

Access to Care

Pediatric trauma care in a military field hospital is often disproportionately resource-intensive and has a significant effect on the morale of medical personnel in the treatment unit (Arul et al., 2012). Inwald and

colleagues, 2014, performed a retrospective review of pediatric patients admitted to a deployed intensive therapy unit in a British military field hospital in Afghanistan that admits both adults and children to assess how the unit copes with the specific challenges of treating critically injured children. Only 14 percent of total admissions over a one-year period were pediatric patients, approximately half of whom had sustained blast-related injuries. Of the 16 patients with predicted mortality greater than 50 percent, seven survived; these children typically would be characterized as “unexpected survivors.” There was a single documented death of a patient with an ISS of less than 50 percent, and there were no documented deaths in patients with severity scores below 16. Although comparisons were not made to the adult patients in the unit, the researchers concluded that, given appropriate support, it is possible to provide adequate intensive care to children in a deployed military intensive therapy unit.

Health information technology (IT) is an increasingly vital component of care in many contexts in health care delivery, including in burn-injury treatment and rehabilitation. These innovations improve patients’ access to accurate, more-efficient care. Nemeth and colleagues, 2016, evaluated an initiative to develop an ecologically valid IT system for use in a military burn ICU. Through a qualitative process, the researchers distilled the essential factors in the treatment environment that affect clinician decisions and patient outcomes, ultimately developing 39 requirements for a prototype IT system meant to support clinician workflow, increase staff efficiency, and improve patient care quality. In an earlier study, Yoder, McFall, and Cancio, 2012, evaluated the utility and acceptance of using a videophone to collect QOL data from burn patients for 18 months after they were discharged from the USAISR Burn Center. Users gave the experience an overall mean score of 61.84 out of a possible total score of 85, indicating that most of the 25 participants were generally satisfied with the videophone. Some users reported dropped calls or intermittent inconsistent video or audio, which can be improved as technology advances. Using remote technology to report longitudinal QOL data can improve access to long-term rehabilitation programs for those who sustain serious burn injuries.

Prolonged Field Care

In many cases, the best course of action for a burn patient is evacuation from combat operations. However, this is not always possible. Furthermore, plans must be made for future military engagements where evacuation might become more difficult. In this section, we discuss how decisions are made to evacuate a service member, care that is currently provided in a prolonged field care setting, and areas that need improvement to provide more-effective prolonged field care.

First, we present the general military field care concept as it applies to forward theater care for burn patients, touching only briefly on acute care. (See Chapter Six for more on acute care.) This concept-level look provides a sense of how field care is intended to play out for burn patients in a prolonged, far-forward field setting. We then address the challenge of infection control, the role of technology, and the gaps in current research.

General Military Field Care Concept

The continuum of care in the military extends from the point of wounding in the combat zone (Levels I–III) through caring for the service member outside a combat zone (Levels IV and V). These levels of care are defined in Table 7.1.

In the acute phase of care (Level I), all life-threatening conditions, such as an obstructed airway or a hemorrhage, must be addressed first. Research shows that hemorrhage control is one of the most consistent interventions performed in this acute phase of care (Lairet, Bebart, et al., 2012). A full survey of the patient must be conducted to evaluate injuries. Then, all garments must be removed fully, and clean water should be used to irrigate wounds quickly. As discussed in Chapter Six of this report, fluid resuscitation is critical in the acute phase of care (Parkhouse, 2009). For this reason, TBSA must be calculated, and vascular access must be established. In fact, vascular access has been shown to be one of the most common lifesaving interventions performed at this stage (Lairet, Bebart, et al., 2012). However, research shows that the administration of fluid management is inconsistent in the military at this stage of care (Lairet, Lairet, et al., 2012) and that hypoten-

Table 7.1
Levels of Burn Care in the Combat Field

Level of Care	Description of Care
I	<ul style="list-style-type: none"> Care provided as close to time of injury as possible Immediate stabilization and evacuation to aid station
IIa*	<ul style="list-style-type: none"> Short-term maintenance Resuscitation
IIb*	<ul style="list-style-type: none"> Short-term maintenance Resuscitation Acute, lifesaving surgical care Army: surgical care provided by forward surgical team Navy or Marines: surgical care provided by forward resuscitative surgical team Air Force: surgical care provided by mobile field surgical teams
III	<ul style="list-style-type: none"> Care provided at combat support hospital (Army), Air Force theater hospital (Air Force), or hospital ship (Navy) Offer variety of resuscitative and surgical care, staffed by specialists equivalent to well-staffed community hospital
IV	<ul style="list-style-type: none"> More-definitive surgical care provided outside a combat zone Provided currently at Landstuhl Regional Medical Center in Germany
V	<ul style="list-style-type: none"> Rehabilitative and tertiary care Provided at various military and U.S. Department of Veterans Affairs medical facilities around the United States

NOTE: *Typically, there will be IIa or IIb care, depending on availability. A service member will not go to both an IIa and an IIb aid facility.

sive resuscitation is one of the least common lifesaving interventions performed in the acute phase of care. Research also shows that endotracheal intubation and chest needle decompression are inconsistently performed in the acute phase of care (Laird, Bebar, et al., 2012).

Literature also suggests that hypothermia management is critical at this stage. Then, the wounds must be bandaged. Research findings demonstrate that, for less than 20 percent TBSA, wet dressing should be used. For more than 20 percent TBSA, dry bandages should be used. When there are evacuation challenges, care might have to be provided in this setting for an extended period of time. There is burn-care telecommunication available through the USAISR Burn Center (Studer et al., 2015). Researchers and clinicians also have suggested that providers might consider carrying dedicated burn kits at

aid stations and evacuation vehicles because burns require a significant number of bandages. There are both acute burn kits and prolonged field care burn kits (Studer et al., 2015).

Because burns are dynamic and can greatly affect organs in the first days after an injury, providers should be prepared for the deterioration of the patient after the initial four hours. Research shows that intubation should be considered for any patient with more than 20 percent TBSA, and urine output should be monitored through catheterization so that appropriate fluids can be administered to the patient. This care may be provided at a Level II, III, or IV care facility, depending on availability of evacuation. However, research shows that this type of monitoring will be required fairly quickly and therefore might need to be provided in a prolonged field care environment. Pain management also will be required, and Studer and colleagues, 2015, recommend that at least two peripheral IV lines be established before edema sets in.

Studer and colleagues, 2015, argue that if evacuation to a burn center will be delayed more than 12 hours, providers should consider performing initial wound debridement. Keller, Han, Galarneau, and Gaball, 2015, postulate that surgeons dealing with maxillofacial fractures, coupled with burns in theater, should receive training in managing these face and neck burns. Early debridement, coupled with appropriate wound coverage, has been shown to reduce mortality; however, this process is resource-heavy and is currently not available in most prolonged field care settings (Parkhouse, 2009). Prolonged field care also might be complicated by competing resources: Level III facilities often must care for civilian burn victims from the surrounding population, in addition to service members (Jeevaratnam and Pandya, 2014).

Because of rapid evacuations, as of 2013, just two service members from NATO nations participating in the war in Afghanistan had surgery in theater (Jeevaratnam and Pandya, 2014). However, Studer and colleagues, 2015, suggest that it might be possible to at least begin this process in a prolonged field care setting to prevent infection. They suggest that clinicians remove blisters using gauze and scrub brushes soaked in surgical antiseptic, as well as surgical scissors, to excise wounds. In-theater surgery especially would require adequate wound care to manage infection.

Infection

As previously discussed, infection control and prevention are critical to burn care, especially because research shows that pathogens to which service members are exposed in current combat operations are increasingly resistant to antibiotics. This care begins in the field and might need to be managed for more than 48 hours in a prolonged field care setting. First, thorough cleaning and bandaging of burns are required; in addition to flushing out the wound, this includes topical antimicrobial therapy (Barillo, Pozza, and Margaret-Brandt, 2014). Parkhouse, 2009, demonstrated that if surgery is performed to excise wounds, antibiotics must be administered as soon as possible; antibiotics given three to four hours after surgery were shown to be ineffective. Research shows that appropriate bandaging to avoid infection is also critical. USAISR recommends mafenide dressing during the day (because these dressings can be painful) and silver sulfide at night. However, recent advancements in bandaging show promise to replace this infection-management protocol (Austin et al., 2015; Nuutila et al., 2019; Studer et al., 2015).

Technologies

Newer silver-impregnated dressings are ideal for prolonged field care (Barillo, Pozza, and Margaret-Brandt, 2014). They can be left in place for seven days without being changed and can be rewetted to be used again (Studer et al., 2015). Another possibility for wound care when surgical debridement is not possible is Biobrane. Researchers report that “BiobraneTM may serve as a triage and transport option for severe burns in the military and mass casualty settings” (Austin et al., 2015).

A second example, akin to Biobrane, is a platform wound device (PWD), developed by Applied Tissue Technologies LLC, which provides a sterile, transparent polyurethane enclosure. It can be applied immediately after injury and topically delivers analgesics and antibiotics to the wound area.

PWDs with negative-pressure treatment also has been explored for use in a prolonged field care environment for head and facial burns. Authors using a pig model found that the PWD and negative-pressure

treatment reduced erythema and edema and encouraged tissue formation compared with controls (Nuutila et al., 2019).

Discussion and Preliminary Recommendations

In this review of blast-related burn-injury research from 2008 through 2019, we identified 3,863 unique sources, of which 239 met our review criteria for inclusion. Eleven additional sources were identified that either were seminal articles or provided context for interpreting the literature. Included studies were categorized as basic (foundational, etiologic, and descriptive epidemiological) and applied (clinical, health services, and policy) research areas. A majority of the basic research consisted of epidemiological studies, while applied research addressed a full spectrum of relevant topics: injury prevention, screening and assessment, treatment and follow-up, health services, and military policy.

Epidemiological research suggests that, although the prevalence of blast-related burn injuries is lower than that of some other combat-related injuries (e.g., TBI), these injuries are nevertheless a common feature of serious combat injury and present a level of complexity that merits greater research attention from both clinical and operational perspectives. Severe burns accounted for about 5–20 percent of combat-related casualties during OIF and OEF (Nuutila et al., 2019; Wolf et al., 2006), including about 10 percent of combat-related injuries to the head and neck (Johnson et al., 2015). Among those evacuated from theater, about one-third did not return to duty, depending on TBSA and inhalation injury (Chapman, Richard, Hedman, Chisholm, et al., 2008). Infection is perhaps the most common and serious blast-burn complication and cause of death, and it is potentially more common after combat blast-related burns than noncombat-related burns.

Foundational and etiologic research primarily addressed the physics of blast injury and the biophysiological mechanisms of blast-related burn injuries and ensuing complications. Several studies discussed mathematical models and controlled blast experiments to predict burn-injury severity under a variety of conditions (Antanovskii and Remennikov, 2010; Shuker, 2010). Shorter distance from the blast and enclosed (versus open) spaces resulted in increased burn-injury severity. Other factors, such as type of explosive materials and individual-level risk factors, were discussed less often and might represent an important area for future research.

Etiologic studies of the relationship between blast-related burns and co-occurring blast-related injuries, including penetrating wounds, infection, anemia, and hypertension, have identified various mechanisms by which these injuries can complicate treatment and subsequent outcomes. Future research should address the biophysical relationships between blast burns and co-occurring injuries and polytrauma type and severity. Additional research should focus on the mechanisms behind and clinical complications of blast-burn exposure, as described in the Chapters Four and Six of this report.

Most treatment research on blast-related burns addressed acute care, early surgical wound care, and longer-term maintenance care. There were fewer studies addressing follow-up care (research addressing the length and durability of treatment, long-term consequences of treatment, rehabilitation, and relapse prevention). Efforts to improve the quality of care for burns are underresearched. Several studies have outlined innovations related to pain management and reduced risk of infection, both of which are areas that require further study.

In terms of prevention and screening, we identified relatively few research projects that were concerned with developing new material and devices to prevent blast-related burns among service members. Multiple authors noted the difficulty of preventing injuries in combat situations while maintaining the flexibility and efficiency necessary for service members to perform their duties. The results of informational interventions to prevent burn injuries have been mixed (Hedman et al., 2008; Kauvar et al., 2009). Lastly, we inspected articles that assessed effectiveness of diagnostic and severity assessment tools in military con-

texts. We found evidence that existing methods for measuring TBSA, for example, produce highly variable results (Martin, Lundy, and Rickard, 2014). The impact on clinical outcomes is unclear and should be assessed. Other studies of follow-up care included studies relating to nutritional support, physiotherapy, and family involvement in recovery after burn injury. More research is needed that addresses the long-term needs of patients with blast-related burns.

Finally, despite the limited body of research on military policy and health services, articles from this category provided various insights, which were primarily concerned with cost, care-coordination efforts and guidelines, and flow charts developed to aid in care delivery. In terms of costs, the research indicated that inpatient ward fees, therapeutic treatment fees, and medication fees were the biggest cost drivers. With regard to care coordination, authors emphasized the importance of multidisciplinary and multiorganizational collaboration in triage and transportation of military or civilian burn patients. Finally, studies in which researchers examined the effectiveness of, and user compliance with, burn-resuscitation guidelines and use of burn flow sheets had mixed results. However, system-wide standardization was shown to improve outcomes for severely burned patients.

An unique aspect of health service delivery for burns incurred in the military context involves the potential need for prolonged field care. Following a reduction of troops and combat missions in the theaters of Iraq and Afghanistan, U.S. military forces—and special operations forces, in particular—have expanded their scope and mission into more remote and rugged terrain, where U.S. air superiority might prove elusive. Capacity for rapid military medical evacuation in this scenario will be severely restricted. In addition, military personnel exposed to burn injuries are at heightened risk of infection and complications. Therefore, strategic thinking and specific planning are necessary to develop, practice, and refine potential strategies to care for burns in prolonged field care settings.

We note that, in a prolonged field care setting, a burn injury might need to be managed for more than 48 hours. Studies emphasized that early debridement, coupled with appropriate wound coverage, has been shown to reduce mortality (Parkhouse, 2009). Research

also shows that appropriate bandaging to avoid infection is critical, and newer uses of silver-impregnated dressings are ideal for prolonged field care (Barillo, Pozza, and Margaret-Brandt, 2014). Another possibility for wound care when surgical debridement is not possible is Biobrane, which would be used to replace allograft as a skin substitute prior to surgery and during the healing process (Austin et al., 2015). Finally, PWDs and negative-pressure treatment have shown promise for head and facial burns in a prolonged field care environment (Nuutila et al., 2019).

Limitations

In this literature review, we did not assess the quality of the scientific research completed. We are reluctant to assess the quality of this wide scope of burn literature—spanning all aspects of blast burns, from the physics of blasts to triage of burn patients—without greater collaborative involvement of appropriate subject-matter experts. This literature review is not a substitute for expert interpretation and review of research quality.

Preliminary Recommendations

Drawing on our review of the relevant literature, we offer four preliminary recommendations to (1) support the expert panelists as they facilitate the working groups at the SoSM and develop recommendations and to (2) advance our understanding and improve the outcomes after blast-related burn injuries.

Recommendation 1: Invest in Research Areas Where the Epidemiology Indicates a Greater Need for Improvement in Clinical Care and Service Delivery

The epidemiological literature provides a direct indication of the most frequent comorbidities, sequelae, and causes of mortality associated with burn-related injury. Therefore, it would be valuable to map these

findings onto the existing treatment research portfolio to identify areas that are understudied and underinvested. By way of example, burns are the most common type of noncombat pediatric civilian injury at combat support hospitals in Iraq and Afghanistan (Arul et al., 2012), yet we found only case studies addressing this population. Studies addressing prevention and treatment of infection, as well as inhalation injury, are necessary to better address a primary cause of mortality among military blast-related burn injuries. Studies along these lines would be particularly valuable in the prolonged field care setting, where access to antiseptics and other resources is restricted.

Prevention efforts require additional research. Overall, additional research measuring the relative value of investments in prevention versus treatment could have significant value and generate cost savings. There is limited research on prevention of blast-related burns, including only a small set of informational campaigns that could be implemented in a military context. Additionally, research testing the current application of diagnostic and severity assessment tools in military contexts would be valuable. The only study that we identified in this space concluded that existing methods for measuring TBSA produce highly variable results and that TBSA determination can be important for determining care plans (Martin, Lundy, and Rickard, 2014).

Recommendation 2: Review How Guidelines Are Developed, How Often They Are Updated, and How the Guidelines Integrate New Evidence

We found a significant number of literature reviews pertaining to blast-related burn injuries. However, to our knowledge, the synthesis of these into a routinely updated set of guidelines appears to be lacking. Inspecting the pace at which novel evidence has entered into the literature—slightly more than 20 articles per year—we recommend reviewing guidelines every couple of years with new evidence and innovations to inform best practices.

Recommendation 3: Expand Training on, and Test New Models of, Prolonged Field Care for Blast-Related Burn Injuries

Few studies have addressed prolonged field care. Given shifts in potential adversaries and their capabilities and the evolving nature of military operations and weaponry, prolonged field care capabilities are essential for managing severe blast-related burns. The literature has outlined several areas requiring further research, including the impact of training clinicians in the forward treatment of blast-related burns on outcomes (Parkhouse, 2009; Studer et al., 2015); improved training on fluid and pain management; and the design and dissemination of forward burn kits. Limited research on Biobrane and similar platform wound devices shows promise in a prolonged field care setting, but studies have been small and should be expanded. Finally, studies yielding direct applications—such as investigations finding that silver-nylon dressing is uniquely portable and easy-to-use and has key antimicrobial properties (Barillo, Pozza, and Margaret-Brandt, 2014; Studer et al., 2015)—might serve as guideposts for standard setting.

Recommendation 4: Develop Enhanced Care Coordination and Triage Strategies for Civilian Burn Patients Receiving Care in Military Treatment Facilities

There is limited research on triage algorithms and systematic emergency-treatment guidelines for civilian burn patients receiving care at MTFs in combat areas. International humanitarian law requires providing emergency medical support for civilians, including children, who are injured in conflicts. Providing forward treatment for civilians with noncombat burn injuries at field hospitals can have a significant resource and logistical impact on facility operations, including bed space, operating room supplies, and nursing time, and pediatric admissions to MTFs for intensive care can require a disproportionate share of resources (Jeevaratnam and Pandya, 2014). In a study on patients admitted to a British MTF in Afghanistan, burns were the most common cause of nonbattle injury among admitted pediatric patients and were associated with a significantly longer length of stay than other trauma injuries (six days versus two days) (Arul et al., 2012). Furthermore, the availability of surgery to treat burn injuries

and technology to perform skin grafting is uncommon in local civilian treatment facilities in combat areas, which creates difficulty in planning discharge and follow-up care for civilian burn patients who need significant aftercare. While there are extensive protocols for evacuating military members who sustain serious burn injuries to Level IV and Level V facilities, civilian patients face fewer opportunities for comprehensive, systematic emergency burn care and effective aftercare delivered locally. This increases the likelihood of morbidity and mortality, and civilian patients must compete for significant time and resources from local MTFs. Researchers have developed ED triage algorithms for use in civilian mass casualty incidents, such as factory explosions, that involve burns; these algorithms might be used to coordinate and triage civilian patients treated at military facilities in combat areas, thus emphasizing the critical window within the first four hours of injury.

Ninth SoSM Discussion Questions

The summaries, findings, and preliminary recommendations presented in this report informed the Ninth SoSM, which occurred in March 2020. This literature review raised awareness surrounding the current state of the science regarding blast injury. Continued discussions at the Ninth SoSM included the following:

1. What are the most promising preventive interventions and surgical restoration and reconstruction advances for patients with blast-related burn injuries? What research is needed to understand the effectiveness and limitations of these measures? What outcomes should be studied?
2. What skills, capabilities, and equipment will be needed in the future for prolonged field care for blast-related burns?
3. What are the most promising rehabilitative innovations for patients with long-term effects of blast-related burn injuries? What research is needed to understand the effectiveness and limitations of these innovations? What outcomes are most important to assess?

4. What are the most important research, technological, and policy opportunities, and what gaps must be addressed regarding blast-related burn injuries?

Planning Committee Members

This meeting was made possible because of the guidance, planning, and insights of the members of the Ninth SoSM Planning Committee:

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Search Terms and Results

PubMed

2008–Present

English Language

Blast[tiab] OR blasts[tiab] OR bomb[tiab] OR bombs[tiab]
OR bombing[tiab] OR bombings[tiab] OR combust[tiab] OR
combustion[tiab] OR deflagration[tiab] OR deflagrate[tiab]
OR explosion[tiab] OR explosions[tiab] OR explosive[tiab] OR
explosives[tiab] OR explode[tiab] OR exploded[tiab] OR exploding[tiab]
OR “Explosions”[Mesh] OR “mine field”[tiab] OR “mine fields”[tiab]
OR grenade[tiab] OR grenades[tiab] OR IED[tiab] OR IEDs[tiab] OR
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OR imploded[tiab] OR imploding[tiab] OR incendiary[tiab] OR
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“land mines”[tiab] OR “mine field”[tiab] OR “mine fields”[tiab]
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overpressured[tiab] OR overpressures[tiab] OR overpressuring[tiab]
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overpressurising[tiab] OR overpressurization[tiab] OR
overpressurize[tiab] OR overpressurized[tiab] OR overpressurizing[tiab]
OR pressure differential*[tiab] OR military[tiab] OR combat[tiab]

AND

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OR transplants[tiab] OR transplantation[tiab] OR “autologous

keratinocytes"[tiab] OR thermal injur*[tiab] OR cultured epithelial autograft*[tiab] OR inhalation injur*[tiab] OR "flame retardant"[tiab] OR "tear gas"[tiab] OR "tear gases"[tiab] OR Parkland formula*[tiab] OR Baxter formula*[tiab]

NOT

Leukemia*[tiab] OR Leukaemia*[tiab] OR carcinoma[tiab] OR lymphoma*[tiab] OR neoplasm*[tiab] OR myelodysplastic[tiab] OR myelodysplasia*[tiab] OR "sun burn"[tiab] OR sunburn[tiab] OR burnout[tiab]

AND

(humans[mh] OR inprocess[sb] OR publisher[sb] OR pubmednotmedline [sb])

Results: 1523

PsyInfo

2008–Present

English Language; Academic Journals

TI (blast OR blasts OR bomb OR bombs OR bombing OR bombings OR combust OR combustion OR deflagration OR deflagrate OR explosion OR explosions OR explosive OR explosives OR explode OR exploded OR exploding OR "mine field" OR "mine fields" OR grenade OR grenades OR IED or IEDs OR implosion OR implosions OR implode OR implodes OR imploded OR imploding OR incendiary OR landmine OR landmines OR "land mine" OR "land mines" OR "mine field" OR "mine fields" OR minefield OR minefields OR overpressure OR overpressured OR overpressures OR overpressuring OR overpressurisation OR overpressurised OR overpressurising OR overpressurization OR overpressurize OR overpressurized OR overpressurizing OR pressure differential*) OR AB (blast OR blasts OR bomb OR bombs OR bombing OR bombings OR combust OR combustion OR deflagration OR deflagrate OR explosion OR explosions OR explosive OR explosives OR explode OR exploded OR exploding OR "mine field" OR "mine fields" OR grenade OR grenades OR IED or IEDs OR implosion OR implosions OR implode OR implodes OR

imploded OR imploding OR Incendiary OR landmine OR landmines OR “land mine” OR “land mines” OR “mine field” OR “mine fields” OR minefield OR minefields OR overpressure OR overpressured OR overpressures OR overpressuring OR overpressurisation OR overpressurised OR overpressurising OR overpressurization OR overpressurize OR overpressurized OR overpressurizing OR pressure differential*)

AND

TI (burn OR burns OR graft* OR transplant OR transplants OR transplantation OR “autologous keratinocytes” OR thermal injur* OR cultured epithelial autograft* OR inhalation injur* OR “flame retardant” OR “tear gas” OR “tear gases” OR Parkland formula* OR Baxter formula*) OR AB (burn OR burns OR graft* OR transplant OR transplants OR transplantation OR “autologous keratinocytes” OR thermal injur* OR cultured epithelial autograft* OR inhalation injur* OR “flame retardant” OR “tear gas” OR “tear gases” OR Parkland formula* OR Baxter formula*)

NOT

TI (Leukemia* OR Leukaemia* OR carcinoma OR lymphoma* OR neoplasm* OR myelodysplastic OR myelodysplasia* OR “sun burn” OR sunburn OR burnout) OR AB (Leukemia* OR Leukaemia* OR carcinoma OR lymphoma* OR neoplasm* OR myelodysplastic OR myelodysplasia* OR “sun burn” OR sunburn OR burnout)

Results: 42 – duplicates = 31

CINAHL

2008–Present

English Language; Academic Journals; Exclude MEDLINE

TI (blast OR blasts OR bomb OR bombs OR bombing OR bombings OR combust OR combustion OR deflagration OR deflagrate OR explosion OR explosions OR explosive OR explosives OR explode OR exploded OR exploding OR “mine field” OR “mine fields” OR grenade OR grenades OR IED or IEDs OR implosion OR implosions OR implode OR implodes OR imploded OR imploding OR incendiary OR landmine OR landmines OR “land mine” OR “land mines”

OR “mine field” OR “mine fields” OR minefield OR minefields OR overpressure OR overpressured OR overpressures OR overpressuring OR overpressurisation OR overpressurised OR overpressurising OR overpressurization OR overpressurize OR overpressurized OR overpressurizing OR pressure differential*) OR AB (blast OR blasts OR bomb OR bombs OR bombing OR bombings OR combust OR combustion OR deflagration OR deflagrate OR explosion OR explosions OR explosive OR explosives OR explode OR exploded OR exploding OR “mine field” OR “mine fields” OR grenade OR grenades OR IED or IEDs OR implosion OR implosions OR implode OR implodes OR imploded OR imploding OR Incendiary OR landmine OR landmines OR “land mine” OR “land mines” OR “mine field” OR “mine fields” OR minefield OR minefields OR overpressure OR overpressured OR overpressures OR overpressuring OR overpressurisation OR overpressurised OR overpressurising OR overpressurization OR overpressurize OR overpressurized OR overpressurizing OR pressure differential*)

AND

TI (burn OR burns OR graft* OR transplant OR transplants OR transplantation OR “autologous keratinocytes” OR thermal injur* OR cultured epithelial autograft* OR inhalation injur* OR “flame retardant” OR “tear gas” OR “tear gases” OR Parkland formula* OR Baxter formula*) OR AB (burn OR burns OR graft* OR transplant OR transplants OR transplantation OR “autologous keratinocytes” OR thermal injur* OR cultured epithelial autograft* OR inhalation injur* OR “flame retardant” OR “tear gas” OR “tear gases” OR Parkland formula* OR Baxter formula*)

NOT

TI (Leukemia* OR Leukaemia* OR carcinoma OR lymphoma* OR neoplasm* OR myelodysplastic OR myelodysplasia* OR “sun burn” OR sunburn OR burnout) OR AB (Leukemia* OR Leukaemia* OR carcinoma OR lymphoma* OR neoplasm* OR myelodysplastic OR myelodysplasia* OR “sun burn” OR sunburn OR burnout)

Results: 65 – duplicates = 36

Web of Science

2008–Present (Social Citation Index/Arts & Humanities Index)

English Language

(TS=(blast OR blasts OR bomb OR bombs OR bombing OR bombings OR combust OR combustion OR deflagration OR deflagrate OR explosion OR explosions OR explosive OR explosives OR explode OR exploded OR exploding OR “mine field” OR “mine fields” OR grenade OR grenades OR IED or IEDs OR implosion OR implosions OR implode OR implodes OR imploded OR imploding OR incendiary OR landmine OR landmines OR “land mine” OR “land mines” OR “mine field” OR “mine fields” OR minefield OR minefields OR overpressure OR overpressured OR overpressures OR overpressuring OR overpressurisation OR overpressurised OR overpressurising OR overpressurization OR overpressurize OR overpressurized OR overpressurizing OR “pressure differential” OR “Pressure differentials”)

AND

TS=(burn OR burns OR graft* OR transplant OR transplants OR transplantation OR “autologous keratinocytes” OR “thermal injury” OR “thermal injuries” OR “cultured epithelial autograft” OR “cultured epithelial autografts” OR “inhalation injury” OR “inhalation injuries” OR “flame retardant” OR “tear gas” OR “tear gases” OR “Parkland formula” OR “parkland formulas” OR “Baxter formula” OR “Baxter formulas”)

NOT

TS=(Leukemia* OR Leukaemia* OR carcinoma OR lymphoma* OR neoplasm* OR myelodysplastic OR myelodysplasia* OR “sun burn” OR sunburn OR burnout))

2014–Present (Conference Proceedings—Science/Conference Proceedings—Social Science & Humanities)

English Language

(TS=(blast OR blasts OR bomb OR bombs OR bombing OR bombings OR combust OR combustion OR deflagration OR deflagrate OR explosion OR explosions OR explosive OR explosives OR explode OR exploded OR exploding OR “mine field” OR “mine fields” OR gre-

nade OR grenades OR IED or IEDs OR implosion OR implosions OR implode OR implodes OR imploded OR imploding OR incendiary OR landmine OR landmines OR “land mine” OR “land mines” OR “mine field” OR “mine fields” OR minefield OR minefields OR overpressure OR overpressured OR overpressures OR overpressuring OR overpressurisation OR overpressurised OR overpressurising OR overpressurization OR overpressurize OR overpressurized OR overpressurizing OR “pressure differential” OR “Pressure differentials”)

AND

TS=(burn OR burns OR graft* OR transplant OR transplants OR transplantation OR “autologous keratinocytes” OR “thermal injury” OR “thermal injuries” OR “cultured epithelial autograft” OR “cultured epithelial autografts” OR “inhalation injury” OR “inhalation injuries” OR “flame retardant” OR “tear gas” OR “tear gases” OR “Parkland formula” OR “parkland formulas” OR “Baxter formula” OR “Baxter formulas”)

NOT

TS=(Leukemia* OR Leukaemia* OR carcinoma OR lymphoma* OR neoplasm* OR myelodysplastic OR myelodysplasia* OR “sun burn” OR sunburn OR burnout))

Total: 1808 – duplicates = 1755

IEEE

2008–Present

English

Search Run April 10, 2019

((((((((((((Abstract:blast) OR Abstract:bomb) OR Abstract:explode) OR Abstract:explosion) OR Abstract:explosive) OR Abstract:implode) OR Abstract:implosion) OR Abstract:combust) OR Abstract:deflagrate) OR Abstract:deflagration) OR Abstract:overpressure) refined by:Publisher:IEEE; Year:2008-2019)) AND (((((((((((((Abstract:burn) OR Abstract:graft) OR Abstract:thermal injur*) OR Abstract:transplant) OR Abstract:inhalation injur*) OR Abstract:autologous keratinocytes) OR Abstract:flame retardant) OR Abstract:tear gas*) OR

Abstract:parkland formula*) OR Abstract:baxter formula*) refined by:Publisher:IEEE; Year:2008-2019)

OR

((((((((((((Abstract:blast) OR Abstract:bomb) OR Abstract:explode) OR Abstract:explosion) OR Abstract:explosive) OR Abstract:implode) OR Abstract:implosion) OR Abstract:combust) OR Abstract:deflagrate) OR Abstract:deflagration) OR Abstract:overpressure) refined by:Publisher:IEEE; Year:2008-2019)) AND (((((((((((Document Title:thermal injur*) OR Document Title:burn) OR Document Title:graft) OR Document Title:transplant) OR Document Title:inhalation injur*) OR Document Title:autologous keratinocytes) OR Document Title:flame retardant) OR Document Title:tear gas*) OR Document Title:parkland formula*) OR Document Title:baxter formula*) refined by:Publisher:IEEE; Year:2008-2019)

OR

((((((((((((Document Title:blast) OR Document Title:bomb) OR Document Title:explode) OR Document Title:explosion) OR Document Title:explosive) OR Document Title:implode) OR Document Title:implosion) OR Document Title:combust) OR Document Title:deflagrate) OR Document Title:deflagration) OR Document Title:overpressure) refined by:Publisher:IEEE; Year:2008-2019)) AND (((((((((((Abstract:burn) OR Abstract:graft) OR Abstract:thermal injur*) OR Abstract:transplant) OR Abstract:inhalation injur*) OR Abstract:autologous keratinocytes) OR Abstract:flame retardant) OR Abstract:tear gas*) OR Abstract:parkland formula*) OR Abstract:baxter formula*) refined by:Publisher:IEEE; Year:2008-2019)

OR

((((((((((((Document Title:blast) OR Document Title:bomb) OR Document Title:explode) OR Document Title:explosion) OR Document Title:explosive) OR Document Title:implode) OR Document Title:implosion) OR Document Title:combust) OR Document Title:deflagrate) OR Document Title:deflagration) OR Document Title:overpressure) refined by:Publisher:IEEE; Year:2008-2019)) AND (((((((((((Document Title:thermal injur*) OR Document Title:burn) OR Document Title:graft) OR Document Title:transplant) OR Document Title:inhalation injur*) OR Document Title:autologous keratinocytes)

OR Document Title:flame retardant) OR Document Title:tear gas*)
OR Document Title:parkland formula*) OR Document Title:baxter
formula*) refined by:Publisher:IEEE;)

**Results: 103 – duplicates = 78 – (removed citations that contained
any of the NOT terms) = 76**

DTIC

2008–Present

Documents; Projects

Search Run April 5, 2019

Subject (blast OR blasts OR bomb OR bombs OR bombing OR bomb-
ings OR combust OR combustion OR deflagration OR deflagrate OR
explosion OR explosions OR explosive OR explosives OR explode OR
exploded OR exploding OR “mine field” OR “mine fields” OR gre-
nade OR grenades OR IED or IEDs OR implosion OR implosions
OR implode OR implodes OR imploded OR imploding OR incendi-
ary OR landmine OR landmines OR “land mine” OR “land mines”
OR minefield OR minefields OR overpressure OR overpressured OR
overpressures OR overpressuring OR overpressurisation OR overpres-
surised OR overpressurising OR overpressurization OR overpressurize
OR overpressurized OR overpressurizing OR “pressure differential*”
OR fire OR fires)

AND

Subject (burn OR burns OR graft* OR transplant OR transplants OR
transplantation OR “autologous keratinocytes” OR “thermal injur*”
OR “cultured epithelial autograft*” OR “inhalation injur*” OR “flame
retardant” OR “tear gas” OR “tear gases” OR “Parkland formula*” OR
“Baxter formula*”)

NOT

Subject (Leukemia* OR Leukaemia* OR carcinoma OR lymphoma*
OR neoplasm* OR myelodysplastic OR myelodysplasia* OR “sun
burn” OR sunburn OR burnout)

OR

Title (blast OR blasts OR bomb OR bombs OR bombing OR bombings OR combust OR combustion OR deflagration OR deflagrate OR explosion OR explosions OR explosive OR explosives OR explode OR exploded OR exploding OR “mine field” OR “mine fields” OR grenade OR grenades OR IED or IEDs OR implosion OR implosions OR implode OR implodes OR imploded OR imploding OR incendiary OR landmine OR landmines OR “land mine” OR “land mines” OR minefield OR minefields OR overpressure OR overpressured OR overpressures OR overpressuring OR overpressurisation OR overpressurised OR overpressurising OR overpressurization OR overpressurize OR overpressurized OR overpressurizing OR “pressure differential*” OR fire OR fires)

AND

Subject (burn OR burns OR graft* OR transplant OR transplants OR transplantation OR “autologous keratinocytes” OR “thermal injur*” OR “cultured epithelial autograft*” OR “inhalation injur*” OR “flame retardant” OR “tear gas” OR “tear gases” OR “Parkland formula*” OR “Baxter formula*”)

NOT

Subject (Leukemia* OR Leukaemia* OR carcinoma OR lymphoma* OR neoplasm* OR myelodysplastic OR myelodysplasia* OR “sun burn” OR sunburn OR burnout)

Results: 444 – duplicates = 442

Total: 3863

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