Guidelines for Burn Care Under Austere Conditions: Special Etiologies: Blast, Radiation, and Chemical Injuries

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GUIDELINES FOR BURN CARE UNDER AUSTERE CONDITIONS: BLAST INJURIES

Introduction

Recent events, such as terrorist attacks in Boston, Madrid, and London, highlight the growing threat of explosions as a cause of mass casualty disasters. Several major burn disasters around the world have been caused by accidental explosions.[1] During the recent conflicts in Iraq and Afghanistan, explosions were the primary mechanism of injury (74% in one review).[2] Furthermore, explosions were the leading cause of injury in burned combat casualties admitted to the U.S. Army Burn Center during these wars, who frequently manifested other consequences of blast injury.[3] Thus, providers responding to burn-care needs in austere environments should be familiar with the array of blast injuries which may accompany burns following an explosion.

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Rationale

Classification of Blast Injuries. Blast injuries are classified as follows:[4]

- Primary: Direct effects of blast wave on the body (eg, tympanic membrane rupture, blast lung injury, intestinal injury)
- Secondary: Penetrating trauma from fragments
- Tertiary: Blunt trauma from translation of the casualty against an object
- Quaternary: Burns and inhalation injury
- Quinary: Bacterial, chemical, radiological contamination (eg, "dirty bomb")

In any given explosion, these types of injuries overlap. Primary blast injury is more common in explosion survivors inside structures or vehicles because of blast-wave physics (see below). By far, secondary blast injury is more common. A study of 4623 explosion episodes in a Navy database identified the following injuries among U.S. service members: mild traumatic brain injury (mTBI, 10.8%), open wounds in the lower extremity (8.8%), and open wounds of the face (8.2%) to include tympanic membrane rupture. In these casualties, in whom torso body armor use was common, the extremities (41.3%) and head and neck (37.4%) were much more frequently injured than the torso (8.8%).[5] In the U.S. military's Joint Theater Trauma Registry for 2003 to 2006, Riten-our and colleagues estimated that 12% of the 4765 service members injured in explosions had primary

blast injury. Nine percent of the 4765 had tympanic membrane rupture, 3.6% had blast lung injury, and 0.1% had blast injury of the intestines. The latter two injuries were identified more frequently on autopsy: 2.3% of those killed in action had blast lung injury, and 2.0% had intestinal injury.[6]

Physics of Blast Injury. The Lovelace Foundation in Albuquerque, New Mexico, and others conducted extensive experiments on blast effects during the 1950s to 1960s, and defined the effects of overpressure and blast duration on survival. These studies concluded that mortality is 1) a function of maximum incident overpressure, and 2) an inverse function of the duration of overpressure (eg, a pressure wave of shorter duration is more lethal).[7] In the body, both *stress* and *shear* waves induce tissue damage. *Stress* refers to microscopic effects at interfaces between tissues of different densities, of which *spalling* is displacement and fragmentation of more dense into less dense tissue, and *implosion* is the opposite. *Shear* is macroscopic tissue damage which occurs as energy travels at different velocities through adjacent tissues of different densities.[8] The most striking effect of a blast wave on the body occurs in organs with air–water interfaces, which is why the tympanic membranes, lungs, and the gastrointestinal (GI) tract are vulnerable.[9] However, other interfaces in the body also affect the course taken by waves in the body, and may attenuate or focus them. For example, internal membranes within the cranium, such as the falx cerebri and the tentorium cerebelli, reflect and focus shear waves in the brain.[10]

The above concepts are dramatically impacted by the circumstances surrounding the explosion. The use of helmets and torso body armor influences the injury pattern by altering both overpressure and wave shape/duration. For example, in one study, hard body-armor plates reduced the behind-armor overpressure by a factor of more than 50. The resultant decreased risk of death from lung injury increases the likelihood of death from TBI.[11] Consistent with this point of view, a review of thoracic injuries among U.S. service members in the Joint Theater Trauma Registry suggested that blast lung constituted only 1.4% of such injuries; by contrast, pneumothorax and pulmonary contusion predominated in that database.[12] Explosions within buildings or vehicles are more lethal than explosions in the open air because structures focus and reflect blast waves, generate more secondary fragments, ignite secondary fires, and create the risk of entrapment or of structural collapse.[9] As the distance increases from the explosion, the likelihood of primary blast injury drops, and secondary blast injuries predominate.[9]

Clinical Care

Emergency Care. The immediate physiologic response to a blast wave includes a triad of bradycardia, apnea, and hypotension, which are mediated in part by the vagus nerve and specifically by pulmonary C fibers.[13] Additionally, hypotension is multifactorial, reflecting nitric oxide release by the injured lung[14] and a decrease in systemic vascular resistance lasting several hours.[15] The initiation of positive-pressure mechanical ventilation in patients with primary blast lung injury should be done with caution to avoid barotrauma, which can worsen pulmonary injury or induce arterial gas embolism (AGE).[8]

Fluid resuscitation of the patient with primary blast injury must strike a balance between over-resuscitation, which will worsen pulmonary edema, and under-resuscitation, which is poorly tolerated in animal models of blast injury accompanied by hemorrhage.[15–17] These cautionary statements about patient resuscitation in primary blast injury should not distract from the large body of evidence from the recent conflicts in Iraq and Afghanistan, which point to the importance of damage control resuscitation and damage control surgery.[18]

The work up of victims of explosions is greatly facilitated by the use of a computed tomography (CT) scanner. Faced with multiple victims with injuries from head to toe, the ability to rapidly evaluate by CT scan is invaluable.[19,20] This resource, however, is a potential bottleneck in a mass casualty scenario and may be unavailable in an austere environment.

Traumatic Brain Injury. Explosions are associated with a spectrum of traumatic brain injuries, from mild to severe. The mechanisms by which a blast wave injures the brain are complex and poorly understood.[21] As of 2007, the incidence of mTBI in service members returning from the recent wars in Iraq and Afghanistan was estimated at 19.5%. About 5% of veterans had a combination of mTBI, posttraumatic stress disorder, and depression.[22] Accordingly, all persons exposed to an explosion should undergo screening for TBI using a brief survey tool.[23] The U.S. military uses a Military Acute Concussion Evaluation tool to evaluate any service member who is dazed, confused, 'saw stars,' or had transient loss of consciousness, following an explosion, fall, motor vehicle accident, or other blow to the head. The latest version was released in 2012.[24] Eighteen of 63 combat casualties with a clinical diagnosis of mTBI and with normal CT scans had abnormal diffusion

tensor imaging (an advanced form of magnetic resonance imaging) indicating an axonal injury;[25] thus, the diagnosis of mTBI remains primarily clinical.

Otologic Injuries. Patients who are injured in explosions require otologic examination. The tympanic membrane is the most sensitive structure in the body to blast. The overpressure which causes tympanic membrane rupture in 50% of persons exposed is only 15 psi.[26] Thus, patients with tympanic membrane rupture should also be evaluated for delayed-onset lung or intestinal injury (see below). Nevertheless, rupture is not seen in all explosion casualties; rupture is affected by factors such as head position relative to the blast and by ear canal contents. Thus, the presence of an intact tympanic membrane does not exclude other blast injuries.[27,28] Eighty percent of tympanic membrane ruptures heal spontaneously; most within 3 months of injury. The surface area of rupture predicts spontaneous healing success. Healing is unlikely without surgery if the area is greater than 80%.[26]

Other findings in patients with blast injury to the ear may include hearing loss (temporary or permanent), tinnitus, otalgia, otorrhea, and bleeding from the ear. Less commonly, vertigo or gait disturbance may reflect inner ear injury, but may also point to temporal bone fracture or brain injury. In addition to otoscopy, patients should be examined for bilateral hearing acuity, for sensorineural hearing loss with a tuning fork, and for facial nerve injury.[29] Long-term follow-up, to include audiometry, should be performed for all persons exposed to explosions.[26]

Blast Lung. This is the second most common primary blast injury. "Blast lung syndrome" features dyspnea, cough, and hypoxia. The process involves alveolar-capillary disruption, intraparenchymal hemorrhage, hemo- and pneumothorax, pneumomediastinum, subcutaneous emphysema, and/or bronchopleural fistula. Blast lung injury may become manifest 6–8 hours after injury; thus, asymptomatic but at-risk patients should be observed for delayed onset of symptoms for that period of time. The chest radiograph typically shows bilateral hilar infiltrates in a "butterfly" pattern. Blast lung injury may also cause AGE, manifested, for example, by focal neurologic deficits. Physical findings of AGE may include retinal arterial air on ophthalmoscopy, tongue blanching, or livedo reticularis (lacy skin mottling). Likewise, all of these findings may be absent.[30,31]

Intestinal Injuries. These are the third most common primary blast injuries. A meta-analysis showed that the prevalence of intestinal injuries in 1040 survivors of air-blast explosions was 3%. The terminal ileum and cecum were the most commonly injured sites, but any of the other hollow organs, as well as solid viscera, can be injured. Intestinal injury appears as subserosal hemorrhage, which on histopathology is shown to be submucosal. With increased loading, immediate perforation may occur. Lesions which do not perforate at the time of injury may (in about 5% of cases) undergo necrosis and delayed perforation, most often more than the ensuing 3–5 days. In the absence of perforation, diagnosis by CT scan may be erroneous, and frequent reexamination of the patient is recommended.[32]

Eye Injuries. All explosion-injured patients should undergo an examination of the eyes. One study of 46 veterans with TBI demonstrated that 20 also had closed-eye (nonpenetrating) injuries, many of which were previously undiagnosed; 3 of these required medical or surgical intervention.[33] U.S. Army clinical practice guidelines on emergency eye care emphasize 1) documentation of eye examination to include visual acuity; 2) Wood's lamp examination of the corneas with fluorescein; 3) careful examination for globe penetration; 4) use of a metal Fox shield and avoidance of pressure or dressings to protect the patient with an open globe injury; 5) prompt specialist referral for all suspected globe injuries.[18] In the acute setting, ultrasound (performed with the lids closed and with care to *avoid pressure* on the globe) has been used for detecting injuries such as blood in the globe, vitreous foreign body, retinal detachment, or globe collapse.[34]

Extremity and Pelvic/Perineal Injuries. The extremities remain the leading site of battlefield injury, even during the recent conflicts in which explosions predominated. Wartime injuries to the extremities are particularly destructive. In comparison to civilian casualties, combat casualties have worse limb salvage rates for Gustilo-Anderson open tibia fractures grades IIIB and IIIC.[35] The blast mechanism notoriously destroys more tissue than initially may be apparent, and injects foreign material proximally along tissue planes; when in doubt, aggressive debridement and early amputation is often the best course of action. Costly and prolonged attempts at limb salvage may be ill-advised in an austere scenario. A particularly high-risk scenario is the blast victim with open pelvic fractures and/or bilateral high above-the-knee amputations. Immediate activation of a massive transfusion protocol, rapid transportation to the operating room, a multiple-team approach to surgery, damage control laparotomy with proximal vascular control, and pelvic external fixation are among the maneuvers that may be required to salvage such patients. In an austere environment, this type of care may or may not

be possible. Injuries by improvised explosive devices which use ball bearings or other small metallic projectiles may precipitate extremity compartment syndrome, with or without fractures.

Triage of Multiple Casualties. Multiple blast injuries are common in terrorist attacks, combat, and industrial accidents. Care involves an initial evaluation often supplemented with CT imaging, multiple surgical procedures, critical care, and blood-bank resources. Patients suffering blast are at risk for delayed manifestations of their injuries and therefore require monitoring over time by skilled providers. This resource set is simply not available in some austere circumstances, which mandates assignment of a skilled triage officer empowered to make difficult decisions about patient prioritization. Initial surgical care is determined by physical exam and patient stability. When imaging is not practically available, difficult decisions about diagnostic exploration of wounds and body cavities must be made based on physical findings, again supporting the need for an experienced triage officer. Blast-injured patients that are transported from the scene of injury early after the incident are at risk for delayed presentation of life-threatening injuries, particularly to the lung or bowel and should be so monitored during transport. Finally, subspecialty care is rarely available in austere settings, recommending the use of Clinical Practice Guidelines such as those promulgated by the U.S. Army Institute of Surgical Research. A particularly common example involves the eye. Subtle globe injuries are common in blast-injured patients, but specialty ophthalmologic consultation is rarely promptly available.[18]

Conclusion

The rising use of explosives as weapons of terror throughout the world means that burn providers working in austere environments or mass casualty disasters are likely to encounter patients with the spectrum of injuries described here. The multisystem response to blast injury, the complex rehabilitation needs of patients with TBI, and the large wound burden associated with blast-induced injuries of the extremities mean that the multidisciplinary burn team is well suited to take care of these types of patients.

Recommendations

- Evaluate burn patients injured in explosions for other manifestations of blast injuries.
- Inspect the tympanic membranes; understand that intact tympanic membranes do not rule out other primary blast injuries.
- Be vigilant for delayed presentation of lung and GI tract injuries.
- Screen for TBI using a tool such as the military acute concussion evaluation.
- Evaluate the eyes in all patients injured in an explosion.

GUIDELINES FOR BURN CARE UNDER AUSTERE CONDITIONS: RADIATION INJURY

Introduction

Situations in which ionizing radiation may play a role in patient care in the austere environment include nuclear reactor accidents, military grade thermonuclear detonations, and terrorist deployment of an improvised nuclear device or radiologic dispersal device. An explosive radiologic dispersal device is commonly known as a "dirty bomb." One needs to only look back to the Fukushima Daiichi nuclear reactor disaster of 2011 to be reminded of the potential for such an incident. This guideline discusses special issues which must be addressed in the care of the burn patient who has also sustained radiation injury, including acute radiation syndrome (ARS); internal contamination with radioactive materials through inhalation, ingestion, absorption through open wounds/burns, or absorption across normal skin; and external contamination.

Rationale

Austere medical care occurs when hospital resources, medical supplies, and personnel are limited or unavailable. Providing care under austere conditions may result in a deviation from the expected standard of care. When treating radiation-injured patients, limited resources should be used only for patients who have suffered survivable doses of exposure, and offer palliative care to those who are not likely to survive, if possible. Modified triage algorithms that consider the amount of exposure, in some cases as little as 2 to 6 Gy, should be used to determine survivability when resources have become scarce (Figure 1).

When radiation-injured patients overwhelm local resources, the Radiation Injury Treatment Network (RITN; *www.ritn.net*) should be alerted by calling (612)884–8276. RITN can assist with coordinating medical response to a radiation incident, and providing comprehensive evaluation and treatment for patients at participating centers around the United States. RITN centers specialize in treatment of radiation injuries and hematopoietic stem cell

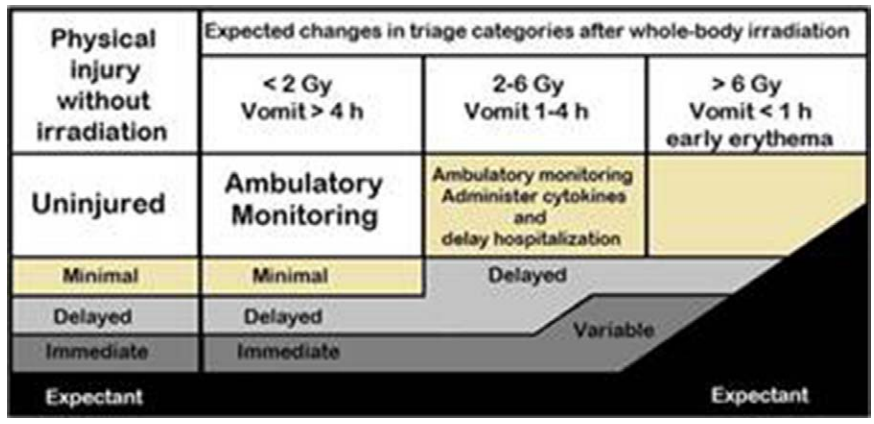

Figure 1. Expected changes in triage categories after whole-body irradiation based on injury severity. (Modified from Armed Forces Radiobiology Research Institute.)

transplantation.[36] The Radiation Emergency Assistance Center/Training Site (REAC/TS) located in Oak Ridge, Tennessee, is available 24/7 for consultation on patient management at (865)576–1005, or *http://orise.orau.gov/reacts.* When assistance is required for radiation-specific injuries, contacting REAC/TS as early as possible is imperative to ensure that time-sensitive issues have been appropriately addressed. Both RITN and REAC/TS are excellent sources for additional information on radiation injury and management.

Types of Ionizing Radiation

There are several primary types of ionizing radiation that are important considerations in disaster planning including α, β, and γ radiation. Alpha and beta radiation occur in particulate form and can become contaminants, whereas γ radiation is electromagnetic in nature and does not cause contamination. However, γ-emitting radioactive materials can become contaminants. For example, a thermonuclear explosion may release massive amounts of γ radiation in the initial blast zone and also disperse radioactive α and β particles into the atmosphere, which could then be distributed in a plume across a wide geographic area. Neutrons are also emitted when there is a criticality or a nuclear detonation, but their contribution to radiation dose is minor.

Alpha and beta particles are very small and in the event of an explosion or dispersion will be distributed as a powder or dust. Alpha radiation penetrates only a few microns, is easily shielded, and therefore does not pose a threat on normal skin. Beta particles are moderately penetrating but can be shielded by a sheet of foil. Beta radiation has the potential to cause significant burns even on normal skin. The primary threat of α and β particles is through inhalation or ingestion, where they irradiate the sensitive tissues of the eye, respiratory tract, and GI mucosa, or contaminate wounds (to include burns), which could delay or prevent wound healing. This delay or prevention of wound healing, specifically in the austere environment, will significantly complicate patient management. The presence of contamination should be determined as soon as feasible, preferably before transport or admission to a health care facility.

A common question from medical providers dealing with a contaminated patient is "is it safe for us to treat this patient?" The answer to this question is almost always "yes."[37] Contaminated patients generally pose no threat to health care workers as long as standard personal protective equipment is worn and the principles of ALARA (As Low As Reasonably Achievable) are followed. The principles of ALARA are: limit the *time* spent in the presence of radioactive materials; maximize the *distance* from radioactive materials; and maximize *shielding* from radioactive materials. Life-saving medical or surgical treatment of a casualty should not be delayed pending decontamination. Care should be taken to minimize contaminants in ambulances and health care facilities.

The presence of radiation is determined by a radiation meter (if available), such as a Geiger-Mueller meter with a pancake probe. Readings of greater than two times background in counts per minute (cpm) are considered positive for contamination. Every emergency department or receiving facility should have detection equipment available which should be checked for operational status on a regular basis. If no detection equipment is readily available, patients should be considered contaminated and appropriate responder protection and patient decontamination initiated. Patients having facial contamination with

radioactive materials should also be evaluated for the potential of internal contamination, most likely in the lung. Internal contamination may warrant lavage of the contaminated organ system (bronchoalveolar, gastric), and decorporation therapy, if the amount inhaled exceeds the annual limit on intake. Decorporation therapy is the removal of radioactive isotopes from the body using a drug specific for the radioactive contaminant.[38] Although lavage and decorporation are highly unlikely to be performed in the austere environment, it is possible to determine inhaled dose via analysis of a nasal swab with a Geiger-Mueller pancake probe.[37] Currently, there are no specific alternatives to decorporation therapy. When a patient has a burn or wound that is contaminated, potentially all secretions should be considered contaminated, and isolated and disposed of according to local policies and procedures. Access to these patients should be restricted to employees who are not pregnant and appropriately badged with a thermoluminescent dosimeter.

Radiation Burns

After a mass casualty radiation incident, both thermal and radiation burns may be seen. The incidence of radiation burns will greatly increase in those found closer to "ground zero" in the setting of a thermonuclear detonation. The differentiation of the cause of burn (thermal vs radiation) is not of great importance as the treatment of the wound is largely the same. Cutaneous radiation syndrome or local radiation injury occurs primarily when the acute local dose is at least 3 Gy, and depending on dose, development of visible skin changes is delayed by days to weeks. Sudden onset of radiation burns is seen only in very high, un-survivable doses of radiation. A radiation injury > 2 Gy in the presence of a burn > 20% TBSA worsens the triage category by one level (Figure 1). This is contingent on conventional vs crisis standards of care and normal vs poor resource availability.[39] Phases of manifest illness in cutaneous radiation syndrome with associated acute doses and timing of onset depicted in Table 1 and range from epilation to ulceration and radionecrosis.[40]

Table 1. Cutaneous radiation phases

Epilation	3 Gy	~17 days
Erythema	6 Gy	2–3 weeks*
Dry desquamation	10–15 Gy	2–3 weeks
Wet desquamation	>~20 Gy	2–3 weeks
Bullae formation (blistering)	~25 Gy	days/weeks
Ulceration/radionecrosis	>~30 Gy	days/weeks

*May have early erythema that disappears after 24–48 hours and then recurs in 2–3 weeks.

Decontamination Recommendations

Radiation burn surface area and depth are estimated using the same methods traditionally used for thermal burns. American Burn Association burn center referral criteria should be adhered to if possible.[41] The radioactively contaminated patient should be decontaminated, with special attention given to open wounds, including burns. In the austere environment, there is a strong possibility that a radiation detector may not be available, in which case wounds should be assumed contaminated. Decontamination should be gentle and sharp debridement should be avoided if at all possible because radiation-injured skin and subcutaneous tissues are exquisitely sensitive to physical trauma. In the event of embedded radioactive shrapnel, special care should be taken to limit the spread of radioactive contaminants during irrigation and debridement. This can be done with waterproof dressings and drapes. It should also be assumed that these fragments will cause uptake (internal contamination).[42]

Decontamination of the wound should include

- Determine presence of contamination if possible
- Irrigate with water or normal saline
- Scrub gently with a cloth and tepid soapy water
- Perform minor debridement if there is visible debris in the burn/wound
- Contain runoff and supplies contacting the wound (gauze, cloths) in a plastic garbage bag or similar, marked as contaminated, and disposed of accordingly[42]

Principles of radiation burn care in the field are consistent with care of thermal burns and include simple, clean dressings; topical antimicrobials (silver sulfadiazine, bacitracin); elevation of burned extremities, and traditional surgical burn intervention if resources permit.

Acute Radiation Syndrome

In caring for the radiation burn patient, the presence of ARS is highly likely and deserves mention. ARS manifests following irradiation to the total body or a significant proportion thereof. Organ systems affected include hematopoietic, GI, and neurovascular. Typically management of ARS is done in tertiary care medical centers with rapid and ample availability of blood products, intravenous (IV) fluids, antibiotics, nutritional support, and laboratory testing. Managing ARS in the austere environment will pose a considerable challenge and may involve unconventional and unproven methods because of limitations

in supplies of blood products, antibiotics, and other supplies. The whole body LD_{50} dose, even with supportive care, is 6 to 7 Gy. Patients may survive up to a 10 Gy whole body dose if they can be evacuated to a hematopoietic stem cell transplant center. Doses greater than 10 Gy are largely nonsurvivable. In the austere environment, with limited resources, nonsurvivable doses may be in the range of 2 to 6 Gy.[43] Tables 2–4 depict general guidelines for the management of ARS. The syndromes include the following.

Hematopoietic Syndrome. Seen in absorbed doses of 1 Gy or greater and requires 7 days or more to manifest, depending upon dose. The bone marrow is exquisitely sensitive to ionizing radiation, and the development of hematopoietic syndrome is the result of bone marrow hypoplasia/aplasia. Decrements in the absolute lymphocyte count will be used to corroborate the estimated whole body dose originally based on time to vomiting and predict how low the white blood cell will drop in 1 to 2 weeks during the "critical period" of neutropenia (absolute neutrophil count of less than 500/mm^3).[40] Neutropenia in the critical period can result in serious infections which may need an infectious disease consultant if available. Neutropenic patients should receive prophylactic antiviral, antimicrobial, and antifungal medications. Depending on the length of time spent in the austere environment with poor resource availability and crisis standards of care, it may not be possible to follow any of these recommendations. Blood products (platelets, packed red blood cells) will not be needed within the first few days following a radiation exposure but may be needed for physical trauma and/or thermal burns.

GI Syndrome. Seen in doses of 2 to 4 Gy or greater.[43] GI syndrome results from massive cell death throughout the epithelium of the GI tract. Nausea and vomiting are the earliest indicators of GI syndrome and can occur within 1 hour at very high doses. Patients will then develop anorexia, abdominal pain, diarrhea, hematemesis, hematochezia, fluid and electrolyte shifts, hypovolemia, and eventual renal failure and cardiovascular collapse.[5] This symptomatology will present extreme fluid and resuscitation challenges even for burn patients with a small TBSA injury. Rectal administration of medications and fluids is not recommended in patients with neutropenia as this can damage friable rectal mucosa and cause bacteremia.[44]

Neurovascular Syndrome. Seen in high-dose exposures (20–30 Gy). Neurovascular syndrome can present as cognitive and neurologic deficits, ataxia, seizures, and hypotension all from cerebral edema. Symptoms present hours to days from exposure and are generally fatal within days.[40]

Initial management in the field will probably be without knowledge of dose received, and management will be based on symptoms. A useful field dose estimator is time to vomiting (Tables 2–4), but the estimated absorbed dose using this parameter needs to be corroborated with serial complete blood counts with white blood cell differentials looking for, in particular, decrements in the absolute lymphocyte counts.[40] Beware of psychogenic vomiting, which is usually not persistent as is the vomiting that results from radiation exposure.

Conclusions

Growth Factors

Preventing profound neutropenia and subsequent infection will be critical in the healing process for the radiation-injured burn patient. Patients who

Table 2. ARS time phases and approximate whole body dose exposure 0–2 Gy

Predominant Subsyndromes	Prodromal	Latent	Manifest Illness (Critical Phase)	Recovery or Death
Primarily	Vomiting onset	Duration	Onset	Recovery
hematopoietic	>2 hr after exposure	End of prodrome	>30 d after prodrome	Expected
severity 1	Diarrhea	To days 21–35	Duration	Psych support
	None	Epilation	Dose and host dependent	Pregnancy counseling
	Headache	None	Clinical effects	
	Slight	Medical response	Fatigue, weakness	
	Level of consciousness	No hospitalization	Lethality	
	Unaffected	Optional CBC	None	
	Body temperature	Lab tests	Medical response	
	Normal		Counseling	
	Medical response			
	Outpatient unless other issue			

ARS, acute radiation syndrome; *CBC*, complete blood counts.

Table 3. ARS time phases and approximate whole body dose exposure 2–4 Gy

Predominant Subsyndromes	Prodromal	Latent	Manifest Illness (Critical Phase)	Recovery or Death
Primarily hematopoietic	Vomiting onset	Duration	Onset	Recovery
Severity 2	1–2 hr after exposure	End of prodrome	18–28 d after prodrome	Depends on GI and bone marrow recovery
Gastrointestinal	Occurs in 70–90%	To days 18–28	Duration	Surveillance for late effects
Severity 1	Diarrhea	Epilation	Weeks to months	Psychological support
	None to mild	Moderate hair loss	Clinical effects	Time to recovery
	Headache	Begins ≥15 d	Anorexia	Weeks to months
	Mild	Medical response	Fever	Death
	Level of consciousness	Hospitalization, if feasible	Malaise	Potentially avoidable with medical care
	Unaffected		Weakness	
	Body temperature		Bleeding	
	Increased		Infection	
	1–3 hr after exposure		Epilation	
	Occurs in 10–80%		Lethality	
	Medical response		Rare in low range	
	Observation in hospital		Up to 50% at higher range-die at 6–8 wk	
			Medical care can salvage many higher-range exposures	
			Medical response	
			Appropriate supportive care	

ARS, acute radiation syndrome; *GI*, gastrointestinal.

are known to have received an acute whole body dose of 2 to 3 Gy should be treated with cytokines (colony stimulating factors, or CSFs). They should be given filgrastim (granulocyte-colony stimulating factor, or G-CSF; Neupogen®, Amgen, Thousand Oaks, CA) at a dose of 5 μg/kg subcutaneous injection daily, or pegfilgrastim (Neulasta®, Amgen, Thousand Oaks, CA) 6 mg subcutaneous injection weekly as long as neutropenia persists. In infants, children, and adolescents < 45 kg, calculate the dose at 100 μg/kg. G-CSF should be available through the Strategic National Stockpile in the event of a radiation disaster.[45]

Blood Products. Patients may develop life-threatening anemia or thrombocytopenia. If this occurs and transfusion is possible, blood products should be irradiated in order to prevent transfusion associated graft vs host disease. In a medical emergency, including austere conditions, nonirradiated blood products may be given. Blood product administration should be given per AABB guidelines. Transfusion of whole blood and red blood cell products should be judicious and based on clinical findings. Typically, platelets are transfused prophylactically in the nonhemorrhagic patient for platelet counts of less than 10,000.[46] In the setting of limited resources or inability to perform platelet counts, the field provider may elect to transfuse platelets only for active bleeding. Conversely, in the presence of open wounds, or bleeding, a higher parameter may need to be considered to prevent life-threatening hemorrhage.

Infection. Patients who are known to be neutropenic should receive prophylactic broad spectrum antibiotics. A commonly accepted standard of care is a flouroquinolone, acyclovir, and an antifungal such as fluconazole. In the febrile patient, antibacterial coverage must be expanded to cover the wide array of gram-positive and gram-negative bacteria that infect neutropenic patients. Typically, this is done with a carbapenem (imipenem or meropenem) or fourth-generation cephalosporin such as cefepime.[44] In the austere environment, the clinician may have significant limits on choice of antibiotics. If this is the case, attempt to provide coverage for staphylococcus, streptococcus, and enteric gram-negative organisms from available antibiotics. More detailed topical antimicrobial coverage can be found in Guidelines for Burn Care under Austere Conditions: Wound Care. Patients with ARS are immunodeficient and efforts should be made to isolate them from infectious sources, including large crowds and dusty environments. Patients should also wear protective face masks anytime they are unable to be isolated from public areas or previously mentioned environments.

Fluid, Electrolyte, and Nutrition. In GI syndrome, large volume fluid losses from vomiting and diarrhea, complicated by anorexia, will be encountered. Patients should be given maintenance fluid

Table 4. ARS time phases and approximate whole body dose exposure 4–6 Gy

Predominant Subsyndromes	Prodromal	Latent	Manifest Illness (Critical Phase)	Recovery or Death
Hematopoietic	Vomiting onset	Duration	Onset	Recovery
Severity 3	<1 hr after exposure	End of prodrome	8–18 d after prodrome	Will require aggressive supportive care
Gastrointestinal	Occurs in 100%	To days 8–18	Duration	Surveillance for late effects
Severity 2	Diarrhea	Epilation	Weeks to months	Psychological support
Neurovascular	Mild at low end, moderate at high end of dose	Moderate to complete hair loss	Clinical effects	Time to recovery
Severity 1	Onset 3–8 hr after exposure	Medical response	Anorexia	Months to years
	10% in high end of dose	Hospitalization, if feasible	Fever	
	Headache		Malaise	
	Moderate		Weakness	
	Onset: 4–24 hr after exposure		Bleeding	
	Occurs in 50%		Infection	
	Level of consciousness		Epilation: hair lost by days 11–21	
	Unaffected		Nausea, emesis	
	Body temperature		Lethality	
	Increased		20–70% die at 4–8 wk	
	1–2 hr after exposure		Medical response	
	Occurs in 80–100%		Aggressive supportive care	
	Medical response			
	Treatment in specialized hospital if feasible			

Adapted from Diagnosis and Treatment of Radiation Injuries. IAEA Safety Reports Series No. 2. Vienna 1998.[42]

requirements plus compensation for fluid losses with normal saline or Lactated Ringer's IV. Oral replacement may not be possible due to the injured GI mucosa. Severe electrolyte imbalance may also be seen and should be monitored for if possible. Antiemetics should be given if indicated; most effective would be odansetron or other 5HT3 antagonist. Effective alternatives include lorazepam, promethazine, prochlorperazine, diphenhydramine, scopolamine, and dronabinol. Any of these agents can be used in addition to odansetron for breakthrough nausea. Nutritional support is not critical early on; however, over time (days to weeks) may be required in order for proper healing of burns and other trauma to occur. Patients with GI syndrome are not likely to do well with enteral feedings until healing of the gut tissue takes place, which will be evident by resolution of nausea, vomiting, and diarrhea. Therefore, if nutrition is required, a parenteral formula should be used if available.

In the austere environment when standard of care is replaced by crisis standard of care, it may not be appropriate to give critical supplies (growth factors, blood products, antibiotics, IV fluids) to patients who have absorbed doses of radiation that will require intensive resources in order to survive. Patients may need to be triaged as expectant in order to direct medical supplies and material to patients with a greater chance of survival. It must also be remembered that austere conditions will most likely be temporary, and the expected duration of austere conditions will have to be considered in use of medical supplies. Clinical reassessment and repeat triage are critical, as resource scarcity worsens or improves.[47] This guideline is in no way a comprehensive reference for management of the patient who has been irradiated in the austere environment. This document is intended to be the catalyst for future research. Comprehensive guidance on diagnosis and treatment for health care providers of irradiated patients can be found at the U.S. Department of Health and Human Services, Radiation Emergency Medical Management website, *http://www.remm.nlm.gov/*.

Recommendations

- Irradiated patients will likely need decontamination verified by a handheld radiation detector (Geiger-Muller meter) if possible.
- Traumatic injuries are the number one priority in an irradiated patient.
- In the austere setting, the triage category may be significantly worsened in an irradiated patient.
- Radiation burns will present as delayed onset, and should be treated as a thermal burn.

- Burn surgical intervention should be accomplished sooner, rather than later, because of the impaired wound healing and neutropenia of ARS.
- Development of ARS is dose dependent. Irradiated patients may develop ARS and will require intensive management of hematologic, infectious disease, and fluid/electrolyte issues.

GUIDELINES FOR BURN CARE UNDER AUSTERE CONDITIONS: TOXIC INDUSTRIAL CHEMICALS

Introduction

Burn providers in an austere environment may encounter a variety of chemical injuries. Some of these are caused by accidental exposure to toxic industrial chemicals (TICs), some by the employment of chemical warfare agents, and some by the use of TICs as improvised chemical weapons. In this section, the diagnosis and treatment of inhalation injury and burns caused by the most common chemicals will be discussed. Other chemical agents which could be encountered, such as nerve agents, are outside the scope of this review; more information is available from the Centers for Disease Control at *http://www.bt.cdc.gov/agent/agentlistchem.asp*, from the Agency for Toxic Substances & Disease Registry (ATSDR) at *http://www.atsdr.cdc.gov/MMG/index.asp*, and in the *Textbook of Military Medicine* at *http://www.bordeninstitute.army.mil/cwbw/default.htm*.

Inhalation injury is a common route of exposure for TICs related to burn injury. In general, the treatment of acute lung injury secondary to TICs is similar to that for smoke inhalation injury. Treatment is supportive and includes 1) airway management, 2) lung-protective ventilation, 3) pulmonary toilet, and 4) avoidance of volume overload or excessively rapid fluid infusion that might worsen pulmonary edema. Close monitoring for the development of acute lung injury and ventilator-associated pneumonia is required for all patients requiring mechanical ventilation related to inhaled TICs. A specific drug treatment or antidote for TICs is likely to work best immediately after injury. Finally, these patients should be transferred to a center with expertise in inhalation injury, if feasible.

Pathophysiology and Clinical Care

Chlorine (Cl_2). This gas is used abundantly in industry and is a common cause of industrial and transportation accidents.[48] Chlorine was one of the first chemical weapons deployed during World War I (WWI). In Iraq in 2006–2007, chlorine was used as a component of improvised explosive devices by insurgents to attack both civilian and military/political targets.[49] According to some models, release of a large quantity of chlorine in an urban area could cause numerous deaths.[50] Long-term health effects include reactive airway disease, dermal burns, and posttraumatic stress disorder.[51] Chlorine dissolves in water to form hydrochloric (HCl) and hypochlorous (HOCl) acids; all three species participate in pathogenicity. Inhalation of chlorine causes both small airway and alveolar injuries.[52]

Proposed treatments include inhaled (nebulized) or IV corticosteroids, nebulized sodium bicarbonate in water (eg, 3.75–4.2%), and nebulized β agonists.[53–56] Nebulized sodium bicarbonate has not shown clear benefit in existing reports. Chlorine rapidly depletes levels of endogenous antioxidants (ascorbate, glutathione, and urate) in the airways.[57] Recent research has focused on antioxidant strategies, to include IV and aerosolized delivery of ascorbic acid and deferoxamine.[58,59]

Phosgene ($COCl_2$). Phosgene has a characteristic new-mown hay smell. It is used commercially in the production of plastics, drugs, pesticides, isocyanates, and polyurethane.[60] It is also released during structural fires and welding near or combustion of chlorinated hydrocarbons. It was the most lethal chemical agent used during WWI. The classic presentation is that of delayed-onset pulmonary edema; the casualty may be seen and discharged, only to come back in 6 to 12 hours with lethal edema triggered by exertion. Patients may be hypovolemic due to rapid loss of plasma volume into the lungs.

Consider IV corticosteroids if the patient presents soon after exposure; administer bronchodilators.[61,62] The pathophysiology of phosgene inhalation injury includes oxidative stress and influx of neutrophils into the lung. Proposed new treatments focus on these mechanisms and include *N*-acetylcysteine, ibuprofen, aminophylline, isoproterenol, and colchicine, but none have been proved effective in humans.[63,64]

Hydrogen Sulfide (H_2S). This gas has a "rotten eggs" smell. It is commonly experienced in the petroleum, natural gas, animal husbandry and waste management industries and has been called "dung lung."[65,66] It enters the bloodstream via the lungs, binds to cytochrome c oxidase, and (like cyanide) prevents oxygen use by the cells. An additional proposed mechanism of action (at high doses) involves the formation of reactive oxygen species.[67,68] H_2S is metabolized to thiosulfate; it also binds to hemoglobin to

form sulfhemoglobin.[68] "Knockdown" is a sudden loss of consciousness and cessation of breathing due to the effect of H_2S on brainstem mitochondria.[69] Other effects are seizures and myocardial ischemia. Its direct toxic effect on the lungs causes pulmonary edema. A direct effect on the cornea causes keratoconjunctivitis ("gas eye"). Treat the patient with supportive care, to include IV fluids, oxygen, and, if obtunded, mechanical ventilation. After initial resuscitation, patients who were unconscious for a prolonged period may manifest brain anoxia, acute lung injury, and/or multiorgan failure.

Antidotes have been used but without clear evidence of benefit. Consider IV sodium nitrite (as for cyanide poisoning). IV nitrites can produce hypotension and low levels of methemoglobinemia.[70] The cyanide antidote hydroxocobalamin has also been used.[71,72] Some authors have proposed hyperbaric oxygen.[73]

Anhydrous Ammonia (NH_3). Ammonia is commonly used in the fertilizer, refrigeration, food processing, petroleum, and explosives industries.[74] It has a strong odor, which is an effective warning sign for exposure. White and colleagues[75] described the treatment of five casualties who were injured during a battle in which a container of ammonia was struck by a projectile and exploded. Ammonia is transported in liquid form at subzero temperatures. It reacts quickly on release to form NH_4, ammonium hydroxide, a strong base, which is water soluble. Thus, it causes alkali skin and eye burns, as well as frostbite.[76] It may also cause rapid, severe tracheobronchial or pulmonary inflammation and obstruction if inhaled, followed by pulmonary edema.

Provide supportive care with intubation and ventilation and decontaminate the patients. Inhaled corticosteroids were not effective in animal models, suggesting the directly destructive mechanism of this chemical.[77] Copiously irrigate patients with skin and ocular involvement, as for any alkali injury.[78]

Mustard Agent (HD). Although mustard agents are not considered traditional TICs, their effects cause extensive dermal burns and their exposure occurs in combat or austere environments in countries that maintain these chemicals. Two types of mustard agent have been used as weapons. One, nitrogen mustard, was also used as a chemotherapeutic agent. The other, sulfur mustard (HD), has only been used as a weapon. Although HD was developed during the latter portion of WWI, it caused more casualties than all the other agents combined.[79] Traces of HD and other chemical weapons are still occasionally encountered in places where munitions were dumped following WWI.[80] HD was used by Iraq against Iran during the Iran–Iraq War of 1980–1988.[81] HD is troublesome for the following reasons: 1) it is relatively easy to make and is stockpiled in various third world countries, to include some which are currently experiencing civil war; 2) symptoms are delayed 2 to 24 hours after exposure; 3) it is persistent in the environment, placing medical personnel and others at risk of cross-contamination; 4) it generates incapacitated casualties without causing a high death rate, thus posing logistical challenges; and 5) there is no specific antidote.[82,83]

HD predominantly affects moist areas of the body (eyes, airways, axilla, groin). HD quickly cyclizes in tissue and alkylates cell components (DNA and proteins). This DNA damage causes cell death, as well as mutations which affect the health of survivors for years to come.[38] Other mechanisms include release of reactive oxygen species, depletion of glutathione, generation of reactive nitrogen species by iNOS, and production of proinflammatory cytokines like tumor necrosis factor α.[84–87] HD is radiomimetic, meaning that it predominantly affects rapidly dividing cells in the GI tract and marrow. Basal keratinocytes are particularly vulnerable to HD, which is why skin injuries feature dermal–epidermal separation (similar histologically to toxic epidermal necrolysis syndrome).[82] Wound healing, compared to thermal injuries of similar depth, is greatly prolonged.

Because HD is a persistent chemical warfare agent, the first principal in management is to protect caregivers and patients through sound protection measures and effective casualty decontamination.[88] A treatment plan for mustard agent casualties was developed by the U.S. Army Burn Center in preparation for Operation Iraqi Freedom, which assumed that all U.S. forces injured with HD would be decontaminated in the field, then evacuated to the Burn Center in San Antonio, Texas.[89] Triage of mustard casualties uses the following indicators of high-dose exposure: 1) rapid onset of pulmonary symptoms, that is, within 2 to 6 hours; 2) ≥25% TBSA cutaneous injury (not just erythema); 3) heavy vomiting within 24 hours of exposure; or 4) a lymphocyte drop of ≥ 50% within 24 hours of exposure. Treatment includes airway support, close monitoring of those with lung injuries for pneumonia, ophthalmology evaluation, atropine and antiemetics for vomiting, cutaneous management based on depth of injury, and granulocyte-colony-stimulating factor (GCSF) for those with decreased lymphocyte counts. Lymphopenia is an early marker for impending pancytopenia; the main effect of GCSF is to prevent the neutropenia.[90,91]

Hydrogen Fluoride. Hydrogen fluoride and the aqueous form, hydrofluoric acid, are common chemicals in the gasoline, glassware, and semiconductor industries. Chemical suppressants with fluorinated hydrocarbons may produce HF used and could produce toxicity in a confined-space, long-exposure duration.[92,93] HF dissolves in the epithelial lining to create hydrofluoric acid.[94] Low doses cause pulmonary irritation, and large doses can cause bronchial and pulmonary parenchymal destruction. Systemic toxicity may develop and result in hypocalcemia, hyperkalemia, and sudden cardiac death. Pulmonary complications are treated supportively. Systemic toxicity is treated with IV calcium, and local burns due to hydrofluoric acid are treated with topical calcium.[95] Nebulized calcium has been used for treatment of hydrogen fluoride inhalation injury.[96]

Others. Hydrogen chloride gas is produced by the pyrolysis of polyvinyl chloride, a plastic used for pipes.[96] It is an occupational hazard for firefighters.[97] Pulmonary toxicity can develop and is treated supportively. Isocyanates, such as methylisocyanate, can be produced during pyrolysis of chemicals and polymers.[98] Toluene diisocyanate (TDI) and diphenyl methane diisocyanate (MDI) are also produced from polymer plants during a fire. Isocyanates produce pulmonary toxicity (Figure 2).

Conclusion

Any of the chemical agents discussed in the manuscript may be encountered by burn care providers working in austere, mass casualty, or battlefield environments. Incorporation of agents like chlorine into improvised explosive devices indicates the willingness of terrorists to use TICs as agents of opportunity. Thoroughly decontaminate casualties and avoid secondary contamination of providers and medical facilities. Employ the same principles of care as for burns and smoke inhalation injury caused by conventional means. Finally, know the specific antidotes or treatments available for many of these TICs. The burn-care team is uniquely qualified to care for casualties with TIC-related injuries.

Recommendations

- Be prepared to perform decontamination of chemical casualties in the deployed environment
- To avoid spread of toxic chemicals, decontaminate casualties outside of the hospital

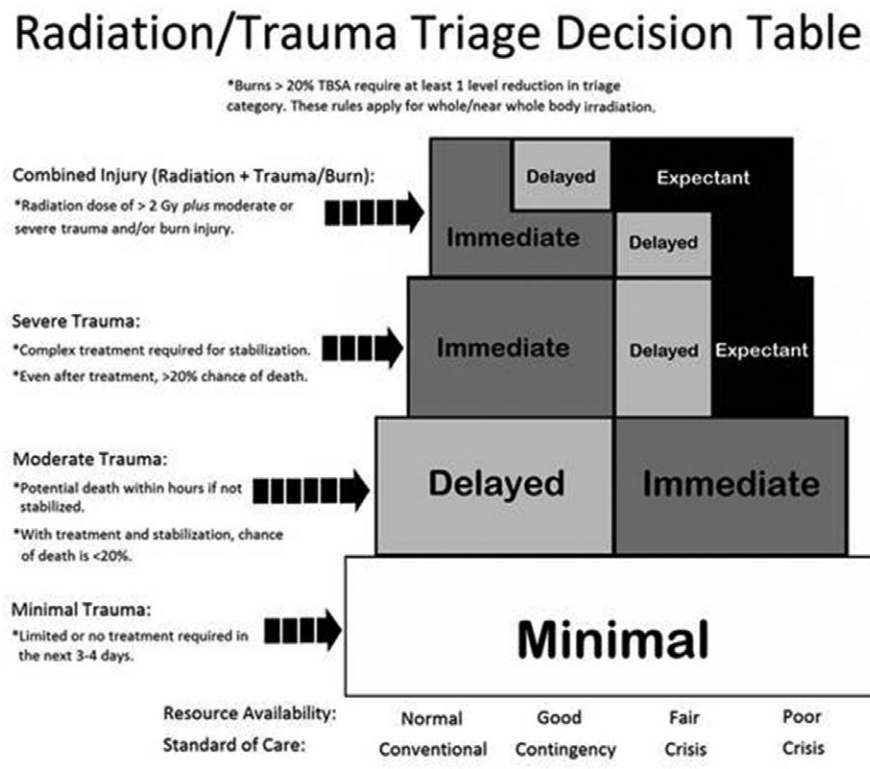

Figure 2. Triage category for combined injury and trauma based on injury severity. (Modified from Radiation Emergency Medical Management—Triage Tools.[99])

- Consider specific therapies based on identification of the chemical, for example:
  - o Chlorine: antioxidants
  - o Phosgene: early IV corticosteroids; observation for delayed onset pulmonary edema
  - o Hydrogen sulfide: hydroxocobalamin or nitrites
  - o Ammonia: copious prolonged decontamination
  - o Mustard agent: monitor lymphocyte count; GCSF for lymphopenia
  - o Hydrogen fluoride: calcium

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