Injuries From Explosions: Physics, Biophysics, Pathology, and Required Research Focus

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Background: Explosions cause more complex and multiple forms of damage than any other wounding agent, are the leading cause of death on the battlefield, and are often used by terrorists. Because explosion-related injuries are infrequently seen in civilian practice, a broader base of knowledge is needed in the medical community to address acute needs of patients with explosion-related injuries and to broaden mitigation-focused research efforts. The objective of this review is to provide insight into the complexities of explosion-related injury to help more precisely target research efforts to the most pressing areas of need in primary prevention, mitigation, and consequence management.

Methods: An understanding of the physics and biological consequences of explosions together with data on the nature or severity of contemporary combat injuries provide an empiric basis for a comprehensive and balanced portfolio of explosion-related research. Cited works were identified using MeSH terms as directed by subtopic. Uncited information was drawn from the authors' surgical experience in Iraq, analysis of current combat trauma databases, and explosion-related research.

Results: Data from Iraq and Afghanistan confirm that survivable injuries from explosions are dominated by penetrating fragment wounds, substantiating longstanding and well-known blast physics mechanisms. Keeping this factual basis in mind will allow for appropriate vectoring of funds to increase understanding of this military and public health problem; address specific research and training needs; and improve mitigation strategies, tactics, and techniques for vehicles and personal protective equipment.

Conclusions: A comprehensive approach to injury from explosions should include not only primary prevention, but also injury mitigation and consequence management. Recalibration of medical research focus will improve management of injuries from explosions, with profound implications in both civilian and military healthcare systems.

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In Iraq and Afghanistan, ~25,000 US and Coalition forces and ~100,000 Iraqis have been injured or killed by explosive devices. Explosion-related injuries and deaths are also becoming part of civilian life. The National Counterterrorism Center reported that in 2007, ~14,000 terrorist attacks occurred throughout the world, resulting in >44,000 injuries and >22,000 deaths, a 20% to 30% increase over 2006.[1,2] Fueled largely by the war in Iraq, this dramatically increased morbidity and mortality is in part attributed to the targeting of groups of people by suicide bombers on foot (the number who did not use a vehicle rose by 90% in 2007).[2] Other trends include coordination of attacks to inflict maximum damage (e.g., secondary attacks on first responders),[2] use of chemicals in improvised explosive devices (IEDs),[2] and a substantial increase in suicide bomb attacks (more than twice in 2007 than in the highest previous year: 2005).[3] Although a large proportion of these incidents occur in areas of conflict, hundreds of criminal bombing incidents occur in the United States every year (with an average of 205 injured or killed per year in the past 3 years for which data are available [2004–2006]).[4] In response to this ubiquitous and growing problem, a national strategy is needed to broaden the focus of research funded by federal dollars earmarked for explosion-related injury research. The focus of this research should be based on well-described explosion physics and epidemiology of injury. In addition, a public health model of primary, secondary, and tertiary blast injury prevention would have widespread value in both military and civilian settings.

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All authors had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

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Table 1 DoD Nomenclature for Blast Injury Categories After Explosions[6,8,9,15]

Category	Definition	Typical Injuries
Primary	Produced by contact of blast shockwave with body Stress and shear waves occur in tissues Waves reinforced and reflected at tissue density interfaces Gas-filled organs (lungs, ears, etc.) at particular risk	Tympanic membrane rupture Blast lung Eye injuries Concussion
Secondary	Ballistic wounds produced by primary fragments (pieces of exploding weapon) and secondary fragments (environmental fragments, e.g., glass) Threat of fragment injury extends further than that from blast wave	Penetrating injuries Traumatic amputations Lacerations Concussion
Tertiary	Blast wave propels individuals onto surfaces/objects or objects onto individuals, causing whole body translocation Crush injuries caused by structural damage and building collapse	Blunt injuries Crush syndrome Compartment syndrome Concussion
Quaternary	Other explosion-related injuries, illnesses, or disease	Burns Toxic gas and other inhalation injury Injury from environmental contamination
Quinary	Injuries resulting from specific additives such as bacteria and radiation ("dirty bombs")	

Explosive devices cause injury by multiple mechanisms, some of which are exceedingly complex. Unlike the well-described kinetic energy coupling of car crashes and bullet injuries, explosive mechanisms and their interactions with human tissue are inadequately characterized for use in state-of-the-art modeling to complement experimental studies. Further, because the entire array of explosion-related injuries is often referred to en masse as "blast injuries," major confusion has arisen as to what constitutes a blast injury. Does the definition include just the overpressure injury or does it encompass all mechanisms of blast injury and explosion-related trauma? This lack of clear definition and communication has resulted in an overestimate of the biological consequences of primary blast overpressure and underestimation of multimechanistic and projectile fragment injury in both the lay and scientific literature.[5] This confusion has resulted in miscommunication about research priorities and appropriateness of strategies for injury mitigation and consequence management, even as the incidence of injuries from explosions increases in insurgent warfare and global terrorism.

The purpose of this review is to provide insights into the complexities of explosion-related injury that may be used to improve preventive measures and patient care, and more precisely target research efforts to address the most pressing areas of need. Cited works were identified using MeSH terms (explosion, blast, terrorism, etc.) as directed by subtopic. Uncited information is drawn from the authors' experiences as a surgeon in Iraq (J.H.), analysts of current combat trauma databases (J.H. and H.C.), and participants in multidisciplinary engineering-medical teams involved in explosion-related research (L.Y. and H.C.).

CATEGORIES OF EXPLOSION-RELATED INJURY

Injuries from explosions are generally classified as primary, secondary, tertiary, quaternary, and quinary after the injury taxonomy described in Department of Defense (DoD) Directive 6025.21E[6] (Table 1). Detonation of an explosive device sets off a chain of interactions in the objects and people in its path.[7] The shock front of the blast wave quickly dissipates and is followed by the blast wind, which propels fragments to create multiple penetrating injuries. Although these are termed secondary injuries, fragments are usually the predominant wounding agent.[8] The blast wind also propels large objects into people or people onto hard surfaces (whole or partial body translocation), creating blunt or tertiary injuries; this category of injury also includes crush injuries caused by structural collapse.[9] Heat, flames, gas, and smoke generated during explosions cause quaternary injuries that include burns, inhalation injury, and asphyxiation.[9] Quinary injuries are produced when bacteria or radiation are added to the explosive device and released on detonation.

BLAST BIOPHYSICS

If an individual is close enough to the point of detonation, the initial blast wave increases pressure in the body, causing stress and shear, particularly in gas-filled organs such as the ears, lungs, and (rarely) bowels. The risk and severity of injuries (from temporary shift of hearing threshold through tympanic rupture and lung injury to dismemberment and death) increase across a range of high explosives from 5 lb to 2,000 lb (2–907 kg) of TNT equivalent (the approximate weights for a pipe bomb and car bomb, respectively). The most common form of primary blast injury is tympanic mem-

Table 2 Short-Duration Primary Blast Overpressure Effects on Unprotected Persons[13,18]

Pressure (psi)	Effect
2	Auditory shift
5	Possible eardrum rupture
15	50% chance of eardrum rupture
30–40	Slight chance of lung injury
80	50% chance of lung injury
100–120	Slight chance of death
130–180	50% chance of death
200–250	Probable death

psi, pounds per square inch.

brane rupture,[10,11] which is often the only significant overpressure injury experienced and can occur at pressures as low as 5 pounds per square inch (psi). Pulmonary injuries including pneumothorax, air embolism, interstitial and subcutaneous emphysema, and pneuomediastinum may occur at pressures of 40 psi and higher.[12] Approximate short-duration pressure effects are given in Table 2.[13]

Although open-space explosions predominate in all armed conflicts, including the current global war on terrorism, it is critical to note that explosive effects are substantially different in closed spaces, where blast waves deflect, ricochet, and coalesce. Enclosure magnifies their destructive power and generates large numbers of secondary fragments through the breakup of structures and vehicles. Bombings in enclosed spaces increase the likelihood of building collapse as the blast wave breaks windows, forces exterior walls outward, and pushes floors upward, causing the roof and interior walls to collapse.[7] Enclosed-space explosions are associated with higher rates of injury and death than open-air explosions. In the 1995 Oklahoma City bombing of the Murrah Federal Building, 5% of those in the uncollapsed section of the building died and 18% of the survivors were hospitalized; in the collapsed portion of the building, however, 87% died and 82% of the survivors were hospitalized.[14] In a 1996 Israeli study, open-air bombings were associated with almost 8% mortality, whereas closed-space bus bombings were associated with 49% mortality.[10]

Laboratory research in blast biophysics underscores the primary problem with the commonly-held definition of blast, i.e., it does not include the fragment injury that accompanies almost every explosion in real-world conflict. A recent example is an extensive review of primary blast overpressure injuries from >50 experimental studies in animals.[15] In this review, primary blast lung injury does not occur when animals are >20 m from a 100-kg TNT explosion. However, fragment injury would cause immediate death or extensive injury at such close proximity to the epicenter of the explosion. In two recent laboratory studies,[16,17] animals had to be subjected to blast waves with high mean peak overpressures (17–24 psi) to generate a discernable primary blast injury. In a real-world explosion, these pressures would require very close proximity (10–20 m), resulting in almost certain death

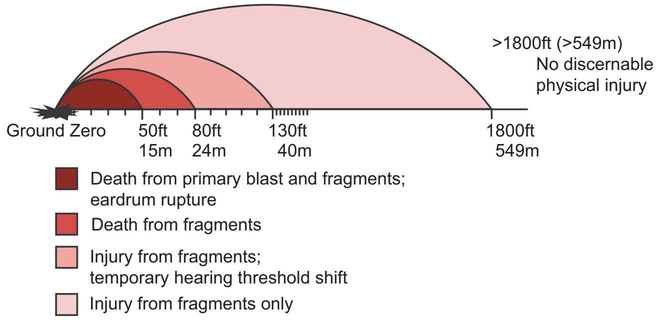

Fig. 1. *Morbidity and mortality as a function of distance from open-space detonation of a 155-mm (220 lb, ~100 kg) shell. Distances are in proportion from ground zero to 130 feet (40 m). The interval between 130 feet (40 m) and 1,800 feet (549 m), however, is too large to allow proportional spacing.*

from fragment injury. These idealized laboratory experiments of primary blast overpressure are important, but must be placed within the context of real-world explosions, in which fragment injury almost always occurs and dominates.

Primary blast injuries are more likely to be a component of multimechanistic injury when the explosion occurs in an enclosed space because the blast wave is reflected by and bounces off surfaces, thus compounding and enhancing the destructive potential of the pressure waves.[18] Immediate death from pulmonary barotrauma (blast lung) occurs more often in enclosed-space than in open-air bombings.[19–21] Most (95%) of all explosions in Iraq and Afghanistan, however, occur in open spaces,[22] and most injuries and deaths are from fragments.[8]

Because the safe standoff distance for fragments exceeds that for blast overpressure by a factor of 100, in a free-field environment, one is unlikely to be affected by blast overpressure within ranges that usually result in potentially survivable fragment injury (Fig. 1).

Figure 2 shows the radius at which the environment created by common artillery and mortar rounds reaches 2 psi (the threshold for temporary hearing loss from overpressure effect) compared with the radius of propagation of casing fragments. Fragment throw distance (the basis for safe standoff distance) and blast overpressure are both a function of casing material thickness and net explosive weight. However, in a free-field environment, where there are no structures to block the propagation of casing fragments, the dominant injury mechanism from a cased weapon is always fragment penetration.

The greatest diagnostic challenges for clinicians at all levels of care in the aftermath of explosions are the large numbers of casualties and multiple penetrating injuries.[8,23] Conventional explosive weapons are designed to maximize the number and velocity of casing fragments (Fig. 3). With initial velocities of many thousands of feet per second, the fragment throw for a 155-mm (220 lb/100 kg) shell could well exceed 1,800 feet (~549 m), whereas the lethal radius of the blast overpressure is less than 3% of this distance (~50

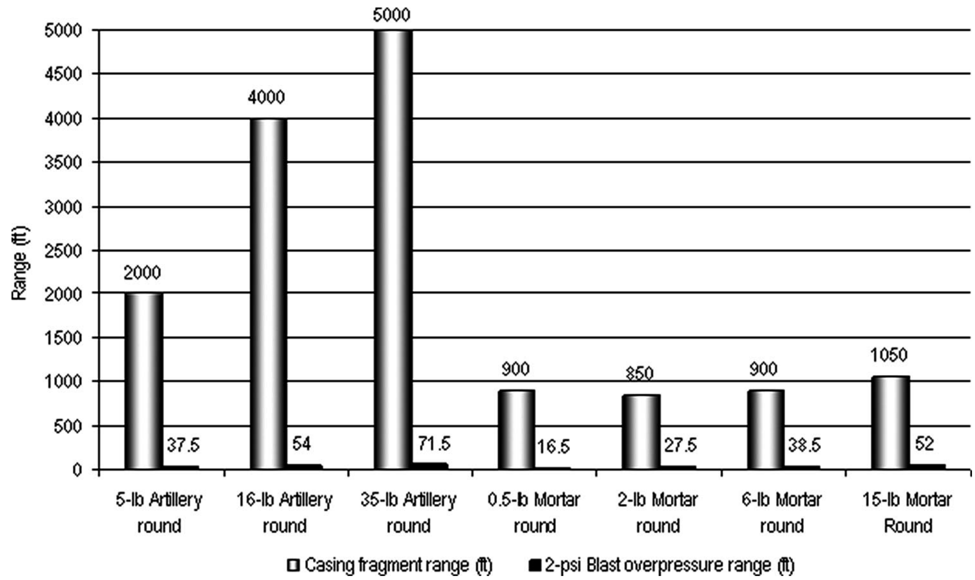

Fig. 2. *Range of fragment throw and blast overpressure effect.*

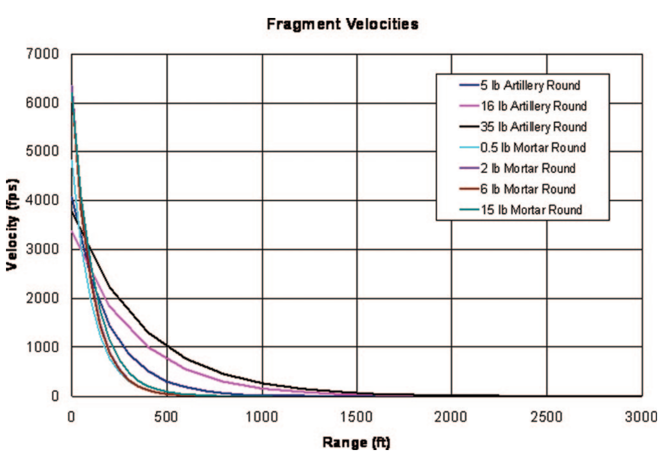

Fig. 3. *Typical fragment velocities from artillery and mortar rounds.*

feet, ~15 m; Fig. 1). Both military and terrorist weapons developers design weapons to maximize fragmentation injury so as to significantly increase the damage radius of a free-field explosive. Regardless of whether they are created from shattered munitions casing, flying debris, or embedded objects that terrorists often pack into homemade bombs, fragments exponentially increase the range and lethality of explosives and are the primary cause of explosion-related injury.[8,24] This point was reinforced in a study of 44 mass-casualty terrorist bombings reported in the literature between 1966 and 2002, in which secondary blast injury was the most common category of injury.[25] In general, if a person is close enough to an open-air explosion to be injured by blast overpressure, he or she is killed by fragments. This fact was further corroborated in a recent autopsy study by Kelly et al.,[26] wherein Operations Iraqi Freedom and Enduring Freedom decedents close to the epicenter of an explosion had "total body disruption," i.e., nonsurvivable injuries.

IMPROVISED EXPLOSIVE DEVICES

Explosive weapons used by insurgents and terrorists are predominantly IEDs, a term encompassing the plethora of weaponized explosive materials (often built around artillery and mortar rounds) that are deployed to achieve tactical objectives. IEDs are the weapon of choice for terrorists, and are designed to cause "gross disruption and disintegration of the body."[27] They include bare charges, booby traps, car and truck bombs, and large culvert bombs directed at vehicles.

In contrast to conventional military ordnance, in which the projected primary fragments are created by the breakup of the casing surrounding the explosive, IEDs generate fragments of shell casing as well as metal objects such as nails, nuts and bolts, or ball bearings packed inside or around the explosive mixture. Precise timing and location are also used to maximize the numbers of injured and dead[28] (e.g., during morning rush hour on a London Tube, in a crowded restaurant in Tel Aviv, on buses, in military convoys, in lines of police force recruits in Iraq).[28]

In the current conflicts in Iraq and Afghanistan, roadside and under-carriage IEDs are frequently used to target vehicles. In their 2008 study of injuries from roadside IEDs, Ramasamy et al.[29] classified IEDs as (1) explosive-formed projectiles, (2) conventional explosive devices formed from munitions, and (3) suicide or vehicle-borne devices. In their subset of patients (100 casualties who were killed in action or admitted to a British field hospital in southeastern Iraq in 2006), only 2 (3.7%) of the 53 IED-related casualties had significant primary blast injury.[29] These results led the authors to conclude that "the blast component of these devices is not a significant factor in injury causation."

Most explosives used against vehicles detonate outside the vehicle, although a shaped charge munition can enter a vehicle and then explode. When a detonation occurs close to

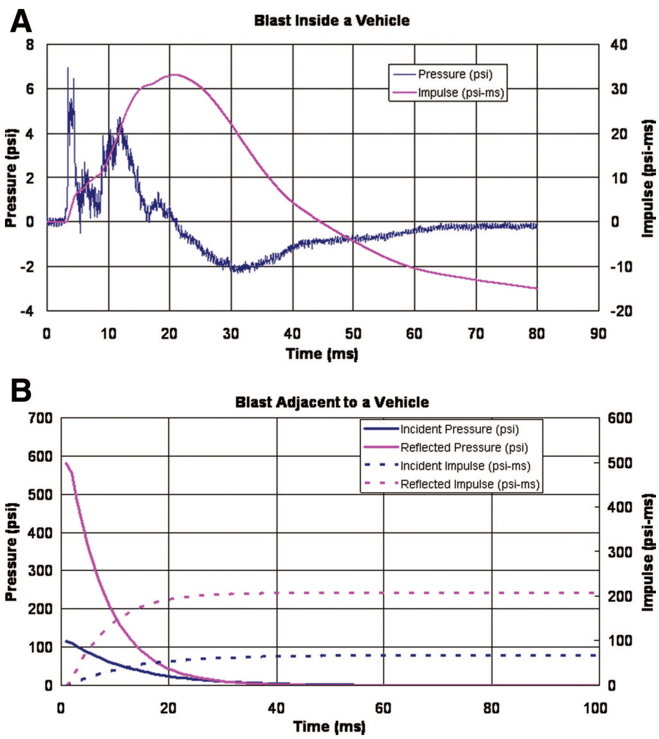

Fig. 4. *Blast overpressure inside and adjacent to a vehicle located 10 feet (3 m) from a 38.75-lb (17 kg) bare charge of C-4 explosive.* A, *1-degree blast overpressure inside vehicle.* B, *1-degree blast overpressure adjacent to vehicle.*

but outside a vehicle, the resulting blast wave diffracts around; reflects off; and, to a much lesser extent, transmits into the interior of the vehicle. The momentum imparted to the vehicle causes acceleration and displacement of both vehicle and occupants, frequently resulting in blunt injury. Because only a small portion of the blast wave is transferred into the vehicle, the risk of blast overpressure injuries to its occupants is substantially reduced relative to personnel in the free field. Test data illustrating this point are provided in Figure 4, with blast overpressure impulse measurements taken from inside an armored vehicle located 10 feet (3 m) from a 38.75 lb (17 kg) bare charge of C-4 explosive. The peak incident overpressure outside the vehicle is 28 times that inside the vehicle and the impulse (the integral of pressure and time) is three times that inside the vehicle. From an injury perspective, those inside the vehicle would be at some risk of eardrum rupture and well below the threshold for lung injury, but individuals standing outside and adjacent to the vehicle (but protected from fragment injury) would have a ~50% risk of death from primary blast injury such as blast lung.

Further, because seatbelts are only intermittently available and infrequently used and airbags are not available in military vehicles, vehicle displacement (with or without flipping or rollover) caused by the overpressure loading can result in significant standard blunt injury to the occupants, often with concussion or blunt traumatic brain injuries (TBIs) of various degrees. These blunt injuries are similar to those seen in civilian motor vehicle crash occupants before the advent of crashworthiness standards. Data from the Joint Theater Trauma Registry (JTTR), a database of injured combatants from Iraq and Afghanistan who did not die at the scene, document that most TBIs on the battlefield are associated with explosions, and 97% are classified as minor concussions. Of casualties with documented head injuries, 44% had no recorded evidence of anatomic intracranial injury, although there was often a brief, transient loss of consciousness or concussion. Prevention of blunt head injury or standard concussion is a major concern, especially in light of recent research establishing a connection between mild TBI and posttraumatic stress disorder (PTSD).[30,31] This has reignited research interest in mitigation strategies as simple as improving padding inside the current combat helmets.

Vehicle-borne IEDs (VBIEDs) are commonly used by insurgents and terrorists. Although the structure of the vehicle contains and thus reduces the blast overpressure effects to the intended victims, VBIEDs typically produce increased injury from secondary fragments. VBIEDs range widely in destructive power and in how much explosive they can hold.

CONTEMPORARY INSURGENCY WAR DATA

The JTTR data provide a fresh and empirical perspective on combat-related injury from explosive devices. Of the US military personnel in the database who were injured in an explosion between 2004 and 2006, most had injuries caused by an IED.[22] The incidence of primary blast injury in this patient population was 12.2%, of which 75% were tympanic membrane ruptures. Blast overpressure was the cause of death in only 1.5%[22] (echoing the 3.7% rate in British forces described

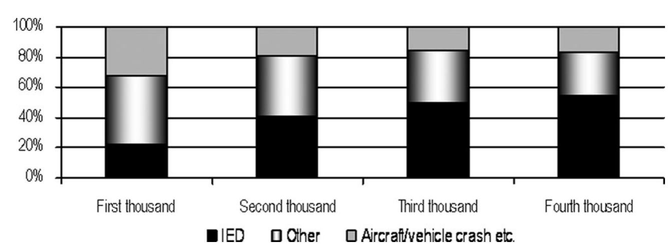

Fig. 5. *Cause of death in Iraq from injury, by thousands killed.*[32]

Table 3 **Comparison of Explosion-Related Injuries in Iraq: March 2003 to December 2004 vs. January 2005 to October 2006**[28]

	2003–2004	2005–2006	*p*
No. patients (N)	2588	1935	
ISS (average)	8.5 ± 9.8	10.6 ± 10.2	<0.0001
Primary blast injury (%)	11.5	14.5	<0.01
Tympanic membrane rupture (%)	8.7	10.3	NS
Blast lung (%)	3.1	4.6	<0.01
Intestinal blast (%)	0.1	0.1	NS
Mortality (%)	1.4	1.5	NS

ISS, injury severity score; NS, not significant.

Table 4 Blast Injury Research Shortfalls

Injury Category	Insult	Injury	Mechanism of Injury	Models		Injury Criteria
				Physical	Numerical	
Extremity trauma	Primary blast	Amputation	Known	None	None	None
	Conventional primary fragments	Penetration	Known	√	Limited	√
	Unconventional primary fragments	Penetration	Known	√	None	None
	Structural debris	Penetration	Known	√	None	None
		Blunt trauma	Known	*†	None	Very limited*
		Crush	Known	*	None	Very limited
Head and thorax trauma	Blast traumatic brain injury	Unknown	Unknown	None	None	None
	Concussion	Known	Known	?	?	√
	Conventional primary fragments	Penetration	Known	√	Limited	√
	Unconventional primary fragments	Penetration	Known	√	None	None
	Structural debris	Penetration	Known	√	None	None
		Blunt trauma	Known	*†	None	Very limited*
		Crush	Known	*	None	Very limited
Blast lung injury	Blast wave	Bradycardia, apnea, hypotension, pneumothorax	Known	PPE*	Limited	Limited
Primary blast injury to ear	Blast wave	Tympanic membrane rupture	Known	*	Limited	Injury criteria and models exist but there is concern about their accuracy

* Not validated.
† No material properties.
PPE, personal protective equipment.

earlier[29]) and which included those killed in action, i.e., before medical treatment facility care. Recent data from the US DoD show the increasing use of IEDs accompanied by declining use of other types of wounding agents (Fig. 5).[32] A recent case series comparison of forward resuscitative surgical units in Iraq between earlier and later phases of the war describes the transition to insurgency warfare and its attendant increase in injuries per patient (1.6 vs. 2.4), increase in casualties with fragment wounds (48% vs. 61%) and decrease in gunshot wounds (43% vs. 33%).[33] Despite increasing injury severity in the later phase, mortality was unchanged (Table 3).[33]

DISCUSSION

Explosions produce the ultimate polytrauma causing an astonishing variety of injuries by multiple mechanisms in multiple body regions[9,34–36] that range from concussion and minor lacerations to traumatic amputations, from crush syndrome to ocular injuries, to death from blunt or penetrating injury or both. There is no other wounding agent so effective at inflicting such a diverse constellation of injuries.

Primary blast overpressure injuries are relatively uncommon in both surviving casualties and as a cause of death on the battlefield. In contrast, fragments are propelled over a far greater radius and, combined with tertiary blast injury and other mechanisms, make up most explosion-related injuries. Thus, although the term "blast injury" has gained acceptance as a general descriptor of injuries from explosions, use of this term disguises the fact that most injuries, particularly in those with any associated chance of survival, are caused by multiple mechanisms, predominantly by penetrating fragments, not by blast overpressure.

DoD Response to Medical Consequences of Explosions

Force health protection, which includes provision of care to the injured, is a key responsibility of the DoD. Research in support of force health protection is a militarily-unique portfolio rarely addressed elsewhere. As the global war on terrorism developed, the DoD spent ~$35 million per year on research to improve combat casualty care. However, other than addressing hemorrhage control for explosion-related fragment injury, few of these research dollars were directed toward understanding the complexities and nuances of injuries caused by explosive devices.

A 2001 to 2003 research gap analysis funded by the Technical Support Working Group emphasized the need for explosion-related biomedical and engineering research (Table 4) and identified several roadblocks to success at a community-wide consensus workshop in June 2004 (Table 5) that are still relevant today. In June 2005, DoD Directive 2000.19 established the Joint Improvised Explosive Device Defeat Organization to "focus all Department of Defense actions in support of combat commanders and their respective joint task force efforts to defeat

Table 5 Roadblocks to Success Identified at Community-Wide Consensus Workshop, June 2004

Category	Specific Barrier
Standardization	Lack of test and modeling standards inhibits utility of test data and models
Knowledge management	No vehicle for technical interchange, no information repository
Epidemiology and test data	Limited access to epidemiological and test data
	Additional data needed to identify and understand injury mechanisms
Injury mechanisms	Enhanced novel explosives (ENE) injury mechanism
	Mechanism of injury for various body regions
	Effect of PPE on blast injury mechanism
Physical models	No scaling factors for human and animal models; multi-insult surrogates
Numerical models	No validated numerical models
	No high-rate material properties
	Serious multidisciplinary research collaboration required
Injury criteria	No validated injury criteria
	No injury severity as function of scaled distance
Incapacitation and performance	Inability to measure incapacitation, engineering data, synergistic human effects, quantitative performance, or to predict blunt impact trauma effects over time

improvised explosive devices as a weapon of strategic influence." In 2006, DoD Directive 6025.21E[6] was issued and the Secretary of the Army designated the US Army Medical Research and Materiel Command as the executive agent to coordinate and ensure the comprehensive nature of this medical research initiative. However, their discretionary capability has been hampered by Congressional earmarking of how the dollars should be spent.

Data Collection and Analysis

As the wars in Iraq and Afghanistan continue, analyses of combat injuries use increasingly larger and representative datasets.[37] These data have been scrutinized by multidisciplinary teams that can ultimately complete the picture of pathophysiological phenomenology including psychosocial sequelae and rehabilitative needs. A searchable database of anatomic surface wound entry points and underlying organ injury severity is now available. This can provide actionable information to helmet and body armor designers to further increase the effectiveness of personal protective equipment (PPE), thus allowing for mission-specific, anthropomorphically-sensitive tradeoffs between weight and mobility.[38] Examination of this full spectrum of wounding and sequelae through to rehabilitation continues to refine our knowledge of the scope and nature of the problem and the research needed to optimally protect combatants, and diagnose and treat those who sustain injuries from explosions.[39] A body of quality empirical data from the war is an essential prerequisite for deploying available research and development resources to optimize force-protection capabilities and future civilian needs.

Congressionally Mandated Research Focus on Primary Blast

Funding for combat injury research has been building since FY07. Early in Operations Iraqi Freedom and Enduring Freedom, analyses by the Defense and Veterans Brain Injury Center on data from patients at Walter Reed Army Medical Center up to several months postinjury identified symptomatologies related to mild or moderate TBI that was hypothesized to be related to exposure (especially repeated exposure) to explosions and blast overpressure.[40,41] Superficial plausibility for this hypothesis was further fueled by the fact that improved PPE and treatment strategies converged to create a larger number of patients surviving injuries caused by explosive devices and increased concern about possible long-term effects of mild TBI caused by blast overpressure.[30] However, despite the diagnostic ambiguities, and similar to shell shock during World War I, mild TBI has been heralded as the "signature injury" of the current conflict in Iraq.[31] Congressionally mandated research on TBI and psychologic consequences of combat has mobilized academia and industry to search for biomarkers or other schema to discriminate this important diagnosis from the PTSD that occurs in 20% to 30% of patients (both military and civilian) after serious injury.[42] The disproportionate emphasis on primary blast overpressure accurately reflects neither current knowledge of open-space explosions and physics of blast injury, nor the fragment/multimechanistic injuries that predominantly affect casualties of explosions.

TBI gained a sufficiently high profile for the US Congress to add $150 million in research funding to the 2007 DoD supplemental appropriation earmarked for TBI and another $150 million for PTSD. Together, these supplemental appropriations amounted to about five times that being spent on all other combat casualty care research. While addressing critically important areas of research, this resulted in an overemphasis on certain areas of research that did not fully integrate and incorporate state-of-the art knowledge of mechanism of injury and epidemiology. The DoD has recently taken steps to rebalance and diversify the range of research initiatives and is intensifying a broad effort to address contemporary combat injury as documented by epidemiologic data.

The FY08 supplemental appropriation earmarked >$270 million for a broad Combat Casualty Care Research agenda, plus another $70 million for TBI. Other significant recent

Congressional earmarks for research and development to benefit combat casualties include (1) a $61 million FY09 appropriation for research on orthopedic and soft-tissue injuries (which account for ~85% of combat injuries) and (2) an $80 million earmark to seed two multi-institutional research programs in regenerative medicine. In addition, private funds have been mobilized to support the Intrepid National Armed Forces Rehabilitation Center to improve prostheses for and rehabilitation of amputees. This diversified effort will yield important advances in both military and civilian trauma care.

Remaining Research Needs

The data from Iraq and Afghanistan serve to emphasize the discordance, discussed earlier, between the experimental environment using laboratory animals to assess the effects of blast overpressure with the realities of combat where the blast overpressure is primarily designed to propel fragments that can cause death from hemorrhage. It is essential that laboratory experimentation, clinical epidemiologic data from the conflict, and computer modeling be synchronized and brought into coordination to be responsive, not only to the realities of combat but also to the limitations of each of these three fields in solving the problems related to improved mitigation and care of combat injuries.

More than ever before, the military and defense industries are increasing their understanding of the physics, epidemiologic data, and resources needed to advance the prevention, mitigation, and treatment of explosion-induced combat injuries. A multidisciplinary approach that involves physicists, engineers, physiologists, doctors, nurses, and medics is also essential to making the needed advancements. Although much federal funding has been allocated and great strides are anticipated in TBI and PTSD, the overall focus of explosion-related research, based on the biomedical physics and epidemiology of the resulting wounds, needs to be broadened. If this occurs, the goals of improved survivability and mitigation of injuries that result from explosive blasts may be reached.

Vehicle Design

A major area requiring innovation is improvement in the design of light tactical vehicles for better survivability in an explosion environment. Fielding of the Mine Resistant Ambush Protected (MRAP) armored personnel carrier was seen as a means of improving survivability whereas the Joint Light Tactical Vehicle is developed as a much-needed replacement for the High Mobility Multipurpose Wheeled Vehicle (HMMWV). IED explosions targeting vehicle-borne combatants have a particularly complex sequence of injury-causing mechanisms for the vehicle occupants. Considerable additional work is needed to better characterize the response of vehicles to explosions, understand the implications of vehicle response on occupant survival, and design cost-effective vehicle and occupant countermeasures. Improved tactical combat vehicle design must incorporate not only civilian crashworthiness criteria but also blastworthiness criteria based on a sound scientific foundation of the physics and bioeffects of explosive devices, all placed within a tactically relevant environment.

Personal Protective Equipment

PPE is designed to reduce the risk of penetrating injury from fragments to active combatants and has undergone significant improvements during the current war. Its effectiveness is clearly demonstrated in the change in distribution of injuries in contemporary conflicts, with reductions in lethal chest injuries and increased survivors with significant multiple limb and craniofacial trauma from fragments.[43,44] However, little improvement has been provided for concussion protection from blunt injury. Fusion of clinical data with data on tactical environments and on dismounted versus mounted actions will yield information that will make it possible for PPE designers and manufacturers to create anthropomorphically-sensitive and mission-specific PPE.

Survivability Inside Buildings

Terrorist attacks in urban and combat environments are increasing in frequency and are likely to continue in the future. IEDs are widely considered to be the weapon of choice for the next domestic terrorist event in the United States. Development of technologies for improving survivability inside buildings impacted by explosions will become increasingly important to both civilians and military personnel. Current blast physics models are weak when it comes to understanding and predicting the complex propagation of blast waves through a building, debris fields created by damage to structures, and the impact of all mechanisms of injury on humans. Improved prediction tools will support accurate medical planning and resource management and enable physical security personnel to identify and address vulnerable areas within urban terrains.

Availability of Real-Time Data

Huge strides have been taken to make real-time data available to operational commands. It is critical that operational and epidemiologic data be fused to provide real-time data that can be queried to identify statistically significant and actionable information. This would facilitate recognition of trends in theater that could inform the design of prevention and mitigation strategies and guide development of technologies, tactics, training, and procedures for improved combat casualty care.

Increased Knowledge and Understanding of Explosion-Related Injuries

With the many incidents of bombing and use of explosive devices in many locations in the world, it is incumbent on both military and civilian healthcare systems to gain an understanding of how injuries are caused by explosive devices and for researchers to respond to the substantial gaps in our knowledge in this field—to the benefit of both civilian and military populations. Although the research focus on explosion injuries is justifiably broadening to include the entire spectrum of blast injury and its physical and psychologic consequences, it remains clear that there are certain areas of biomedical research that, because of their military significance, will only be addressed by DoD resources. Injuries from explosions constitute one of these areas, arguably the most important. In particular, we need to gain an understanding of the impact of multimechanistic, high-rate energy coupling on healing and regeneration.

Wars exact a terrible price, but have always resulted in improved trauma care.[45–47] Time and again throughout history, decline of a war effort and investment reduces military medical resourcing and medical research commitment to force health protection.[47,48] As the casualties diminish and impatience to end the wars is palpable, it is imperative that the required research on injury from explosions not be left as unfinished business. Sustaining sufficient levels of research funding within the DoD could have consequences that spread far beyond the near and present to future dangers that mandate a commitment to force health protection.

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EDITORIAL COMMENT

The authors of the timely manuscript "Injuries from explosions: physics, biophysics, pathology, and required research focus" bring to our attention a topic critical in current combat operations in Iraq and Afghanistan. One of their arguments in favor of more research into the effects of blast injury is that new and timely information could be translated into "a public health model of primary, secondary, and tertiary blast injury prevention."

Every reasonable person favors improving protection to reduce the number and severity. But an alternative perspective is that there are limited funds available to support military medical research, and the policy makers need to decide where to most effectively spend those funds. In my opinion, these funds should be spent on devising new treatments for injured combatants and not injury prevention. The stark reality is the risk of injuries when our soldiers, sailors and Marines engage the enemy. Injury patterns after explosions are of vital interest to those military professionals who design protective gear and vehicles, but at some point in that process those designers must balance protection against impeding a soldier's combat efficiency by adding restrictive clothing or devices.

Funding for injury prevention of combatants should not compromise the funding for other categories of medical research in the DOD budget. We desperately need to know more about how to achieve optimal recovery from injury, particularly those injuries sustained when an explosive device is the enemy's weapon. To the extent that studies of injury pathophysiology after explosions lead to novel therapies, the quality of outcome of injured soldiers will improve. There remain many problems for which improved treatments are needed ranging from delayed manifestations of "mild" traumatic brain injury to clinically effective methods for reducing systemic injury after an ischemia reperfusion insult to the extremities. Military medical research funds will provide optimal return on the investment and directly benefit military members engaged with the enemy if they support a balanced program in which injury prevention research is integrated with research focused on discovery of effective treatments.

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