Chapter 24

EYE INJURIES ASSOCIATED WITH TERRORIST BOMBINGS

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INTRODUCTION

On 23 October 1983, terrorists drove a truck into the US Marine Corps headquarters in Beirut, Lebanon, that exploded with the force of 12,000 pounds of TNT (trinitrotoluene), killing 241 and injuring 105.[1,2] On 26 February 1993, in the first terrorist bombing of the World Trade Center in New York, New York, terrorists detonated a bomb in the parking garage beneath the Twin Towers, killing 6 and injuring 548.[3] One of the most devastating terrorist attacks was the bombing of the Murrah Building in Oklahoma City, Oklahoma, on 19 April 1995, which killed 167 and resulted in 692 injuries.[4] The Olympic Games in Atlanta, Georgia, were marred by a bombing in Centennial Olympic Park on 27 July 1996, which caused 2 deaths and 111 injuries.[5] The bombing of the US Air Force barracks, Khobar Towers, in Saudi Arabia on 25 June 1996 caused 500 injuries and 19 fatalities (Figure 24-1).[6] On 7 August 1998, terrorists attacked the US embassies in Nairobi, Kenya, and Dar es Salaam, Tanzania, on the same day and at approximately the same time (Figure 24-2). The explosion in Kenya killed more than 240 individuals and injured more than 5,000.[7] And on 11 September 2001, two jet aircraft crashed into the World Trade Center in New York, New York. More than 3,000 individuals died as a result of this terrorist attack. Of the 790 survivors and rescue workers with injuries who reported to nearby hospitals, 204 (26%) had ocular injuries, most of which were attributed to smoke, dust, debris, or fumes.[8]

Statistics compiled by the Federal Bureau of Investigation from 1990 to 1995 show that there have

Fig. 24-1. Remains of Khobar Towers in Dhahran, Saudi Arabia. On 25 June 1996, terrorists bombed this complex, which was used as a barracks for US Air Force personnel. Note the large crater in front of the building and the loss of the building closest to where the truck bomb was parked. This bombing caused 19 deaths and 500 injuries.

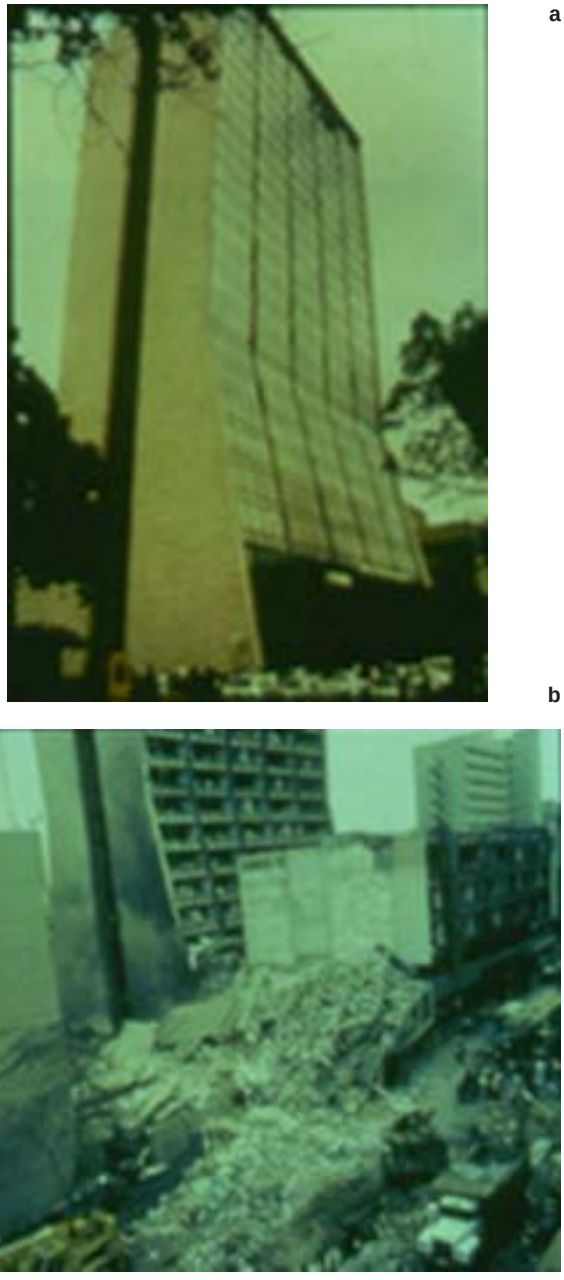

Fig. 24-2. (**a**) The bank building pictured was adjacent to the US embassy in Kenya before the terrorist bombing on August 7, 1998. (**b**) After the explosion, the same bank building (rear) has lost of most of the windows on the side closest to the explosion.

been 15,790 criminal bombing incidents in the United States that have killed 355 individuals, injured 3,176, and caused more than $650 million worth of damage.[9] These data do not, of course, include the horrendous loss of life and massive loss of property caused by the destruction of the World Trade Center on 11 September 2001, nor do they include the terrorist ramming of the USS *Cole* and its subsequent explosions, deaths, and injuries off the coast of Aden, Yemen, on 12 October 2000. Whether the targets were civilian or military, however, the bombings caused injuries that are usually associated with military conflicts. Eye injuries make up an important percentage of these injuries.

BLASTS

Detonation of an explosive device causes a high-speed chemical decomposition of a solid or liquid into a gas.[10–12] The explosion creates a wave of very high pressure that moves rapidly away from the point of explosion (10,000–30,000 m/s). The leading edge of the blast wave is a shock front that causes an instantaneous rise in the air pressure (Figure 24-3). The magnitude and duration of the pressure are principally governed by

- the size of the explosive charge, with larger explosions producing a shock wave of faster velocity and longer duration;
- the surrounding medium, with denser media (eg, water compared to air) allowing the shock wave to move faster and making the duration of the positive pressure longer; and
- the distance from the explosion, with greater distance from the explosion resulting in a slower shock-wave velocity and longer duration.

The blast wave front decreases exponentially in pressure and velocity as the distance from the explosion increases. The level of peak pressure and the duration of the shock wave determine the type and extent of the injury. At the end of the decay of the pressure front is an underpressure, which can last about 10 times longer than the overpressure phase. The negative pressure sucks debris into the explosion area, even pulling windows out of buildings.

Even small changes in atmospheric pressure can lead to high-velocity winds. For example, a peak pressure of as little as 0.25 psi can generate winds as high as 125 mph (Table 24-1). Loose objects,

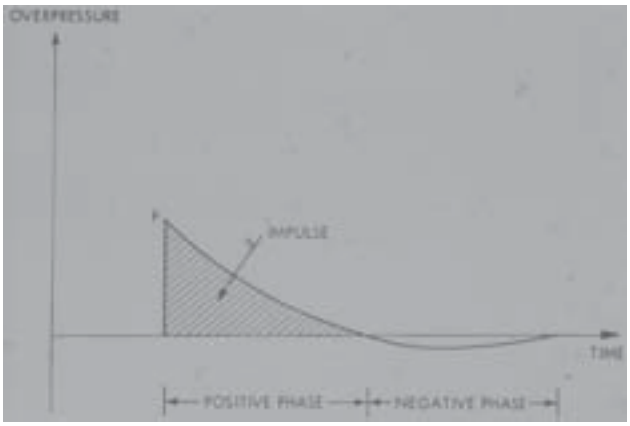

Fig. 24-3. The idealized graph shows the immediate pressure rise (overpressure; P represents peak overpressure) after an explosion with subsequent decrease in pressure after the explosion (underpressure). In an actual blast, the negative phase can last as much as 10 times longer than the positive. Reproduced from Stuhmiller JH, Phillips YY, Richmond DR. The physics and mechanisms of primary blast injury. In: Bellamy RF, Zajtchuk R, eds. *Conventional Warfare: Ballistic, Blast, and Burn Injuries.* In: Zajtchuk R, Bellamy RF, eds. *Textbook of Military Medicine.* Washington, DC: Department of the Army, Office of The Surgeon General, Borden Institute; 1990: 244.

TABLE 24-1

RELATIONSHIP BETWEEN PEAK PRESSURE AND WIND VELOCITY

Maximum Overpressure (psi, at Sea Level)	Wind Velocity (mph)
0.02	40
0.10	70
0.25	125
0.60	160
2.00	290
8.00	470
16.00	670
40.00	940
125.00	1,500

Adapted from Stuhmiller JH, Phillips YY, Richmond DR. The physics and mechanisms of primary blast injury. In: Bellamy RF; Zajtchuk R, eds. *Conventional Warfare: Ballistic, Blast, and Burn Injuries*. In: Zajtchuk R, Bellamy RF, eds. *Textbook of Military Medicine.* Washington, DC: Department of the Army, Office of The Surgeon General, Borden Institute; 1990: 252.

which may be moved by the initial shock wave, achieve their ultimate velocity depending on the blast wind. Blast winds are generated when large volumes of air are displaced by the expanding gases of the explosion (overpressure) or the subsequent underpressure. The victim of a blast may be struck by small objects that may penetrate the body, or the blast may accelerate the victim, hurling him or her with great velocity. The human body might be able to tolerate the instantaneous acceleration but would most likely be injured if it were to hit a hard, stationary object.

Explosive devices also create a short-lived pulse of thermal energy. The intense heat may cause burns of the skin or lead to combustion of surrounding materials. If an explosive device contains flammable fuel, the thermal injuries can be more severe and occur at greater distances from the source.

TABLE 24-2

RELATIONSHIP OF PRESSURE TO PRIMARY BLAST EFFECT

Critical Organ or Event	Related Maximum Overpressure (psi)
Eardrum Rupture	5
Lung Damage	15
Lethality:	
Threshold	30–42
50%	42–57
95%–100%	58–80

Adapted from White CS. *Biologic Blast Effects.* Albuquerque, NM: Lovelace Foundation for Medical Education and Research; 1959. USAEC Report TID-5564.

Types of Blast Injuries

Primary blast injuries are caused by the sudden change in environmental pressure associated with explosive blasts, and they tend to occur in tissues in which variations in tissue density are greatest.[10–16] The air-containing organs (eg, lungs, ears, bowel) are the most susceptible tissues to primary blast injury, although organs that contain both liquid and air (eg, the gastrointestinal tract) are also vulnerable. Damage to the lungs is the cause of the greatest morbidity and mortality. The blast can lead to massive hemorrhage, rupture of the alveoli, and air emboli. An air embolism can occlude the vascular system in the central nervous system and the coronary arterial system, leading to severe disability or death. Pulmonary contusion can cause pulmonary edema and make oxygenation difficult.

The ear is the most susceptible organ to primary blast injury. The eardrums may rupture after a shock wave with no evidence of injury elsewhere. The rupture can occur with an overpressure of as little as 5 psi, compared with the 15 psi needed to cause damage to the lungs (Table 24-2). In addition to eardrum rupture, the ossicles may also fracture or dislocate.

The bowel is also prone to primary blast injury. The large bowel is more susceptible than the small because of the greater volume of air within the colon. Most primary blast injuries of the bowel are associated with underwater explosions and are not as likely to occur with a detonation in air. Injuries range from small, serosal hemorrhages to rupture of the bowel.

Although unusual, rupture of the liver or spleen can occur without accompanying blunt abdominal trauma.

Secondary blast injuries are the result of missiles accelerated by the blast wave.[11–15] The missiles may be a part of the explosive device (primary fragment) or may be secondary missiles, such as glass, masonry, and trees. Depending on the mass and velocity of the projectile, the injuries can include contusions, lacerations, penetration, and fractures.

Tertiary blast injuries result from movement of the human body by the blast wind.[11–15] The acceleration injuries occur if the body is unprotected or only partly protected from the blast. Exposed body parts may suffer traumatic amputation. When the entire body is set in motion, it may be carried a considerable distance from the blast. The type and severity of injury depends mostly on the type of surface against which the body strikes and the body's velocity on impact. Most tertiary blast injuries are blunt in nature and result in fractures and damage to the solid organs of the body.

Thermal (quaternary) injuries result when very high temperatures are generated for a short time after the explosion.[11,12,15] The heat produced by the explosion can produce significant burns of the skin. Flash burns tend to be superficial because of the short exposure time, but the intense heat may ignite the victim's clothing, leading to more extensive and deeper burns. Although most burns are external, they can take the form of inhalational injury, due either to the thermal effects of the explosion or the release of gases.

Other blast-associated injuries, although not classified as one of the types above, include those caused by the collapse of walls and ceilings of build-

TABLE 24-3

TERRORIST INCIDENTS: MORBIDITY, MORTALITY, AND EYE INJURY RATES

Incident	Date	Deaths	Injuries	Eye Injuries (% of All Injuries)
Belfast, Northern Ireland[1]	1969–1972	117	1,532	12 (0.8)
Old Bailey, London[2]	1973	0	160	Not reported
Birmingham, England[3]	1974	2	80	5 (6.3)
Tower of London[4]	1974	0	37	4 (10.8)
Jerusalem[5]	1975–1979	26	340	Not reported
Bologna, Italy[6]	1980	73	218	7 (3.2)
Northern Ireland[7]	1972–1980	5+	339	16 (4.7)
Beirut (Marine Headquarters)[8,9]	1983	241	105	5 (4.8)
Paris, France[10]	1985–1986	20	248	12 (4.8)
Jerusalem[11]	1988	6	52	5 (9.6)
Victoria Station, London[12]	1991	1	50	1 (2.0)
World Trade Center[13]	1993	6	548	0 (0)
Oklahoma City, Oklahoma[14,15]	1995	167	684	55 (8.0)
Centennial Park, Atlanta, Georgia[16]	1996	2	111	Not reported
Manchester, England[17]	1996	0	208	6 (2.9)
Khobar Towers, Dhahran, Saudi Arabia[18]	1996	19	500	3 (0.6)
US Embassy in Kenya[19]	1998	247	> 5,000	> 70 (~ 1.4)
World Trade Center, New York, New York[20]	2001	> 3,000	790	204 (26)

Data sources: (1) Hadden WA, Rutherford WH, Merrett JD. The injuries of terrorist bombing: A study of 1532 consecutive patients. *Br J Surg.* 1978;65:525–531. (2) Caro D, Irving M. The Old Bailey bomb explosion. *Lancet.* 1973;1:1433–1435. (3) Waterworth TA, Carr MJT. Report on injuries sustained by patients treated at the Birmingham General Hospital following the recent bomb explosions. *Br Med J.* 1975;2:25–27. (4) Tucker K, Lettin A. The Tower of London bomb explosion. *Br Med J.* 1975;3:287–290. (5) Adler J, Golan E, Golan J, Yitzhaki M, Ben-Hur N. Terrorist bombing experience during 1975–1979. Casualties admitted to the Shaare Zedek Medical Center. *Isr J Med Sci.* 1983;19:189–193. (6) Brismar B, Bergenwald L. The terrorist bomb explosion in Bologna, Italy, 1980: An analysis of the effects and injuries sustained. *J Trauma.* 1982;22:216–220. (7) Pyper PC, Graham WJH. Analysis of terrorist injuries treated at Craigavon Area Hospital, Northern Ireland, 1972–1980. *Injury.* 1983;14:332–338. (8) Frykberg ER, Tepas JJ III. Terrorist bombings: Lessons learned from Belfast to Beirut. *Ann Surg.* 1988;208:569–576. (9) Frykberg ER, Tepas JJ III, Alexander RH. The 1983 Beirut airport terrorist bombing: Injury patterns and implications for disaster management. *Am Surg.* 1989;55:134–141. (10) Rignault DP, Deligny MC. The 1986 terrorist bombing experience in Paris. *Ann Surg.* 1989;209:368–373. (11) Katz E, Ofek B, Adler J, Abramowitz HB, Krausz MM. Primary blast injury after a bomb explosion in a civilian bus. *Ann Surg.* 1989;209:484–488. (12) Johnstone DJ, Evans SC, Field RE, Booth SJ. The Victoria bomb: A report from the Westminster Hospital. *Injury.* 1993;24:5–9. (13) Quenonmoen LE, Davis YM, Malilay J, Sinks T, Noji EK, Klitzman S. The World Trade Center bombing: Injury prevention strategies for high-rise building fires. *Disasters.* 1996;20:125–132. (14) Mallonee S, Shariat S, Stennies G, Waxweiler R, Hogan D, Jordan F. Physical injuries and fatalities resulting from the Oklahoma City bombing. *JAMA.* 1996;276:382–387. (15) Mines M, Thach A, Mallonee S, Hildebrand L, Shariat S. Ocular injuries sustained by survivors of the Oklahoma City bombing. *Ophthalmology.* 2000;107:837–843. (16) Anderson GV Jr, Feliciano DV. The Centennial Olympic Park bombing: Grady's response. *J Med Assoc Ga.* 1997;86:42–46. (17) Carley SD, Mackway-Jones K. The casualty profile from the Manchester bombing 1996: A proposal for the construction and dissemination of casualty profiles from major incidents. *J Accid Emerg Med.* 1997;14:76–80. (18) Thach AB, Ward TP, Hollifield RD, Cockerham K, Birdsong R, Kramer KK. Eye injuries in a terrorist bombing: Dhahran, Saudi Arabia, June 25, 1996. *Ophthalmology.* 2000; 107:844–847. (19) News Journal Online. Kenya struggles to cope with dozens blinded from embassy bomb. 2 Sep 1998. Available at: http://www.n-jcenter.com/1998Sep/2/WOR4.htm. Accessed 8 April 2000. (20) Centers for Disease Control and Prevention. Rapid assessment of injuries among survivors of the terrorist attack on the World Trade Center—New York City, September 2001. *MMWR.* 2001;51(1):1–5.

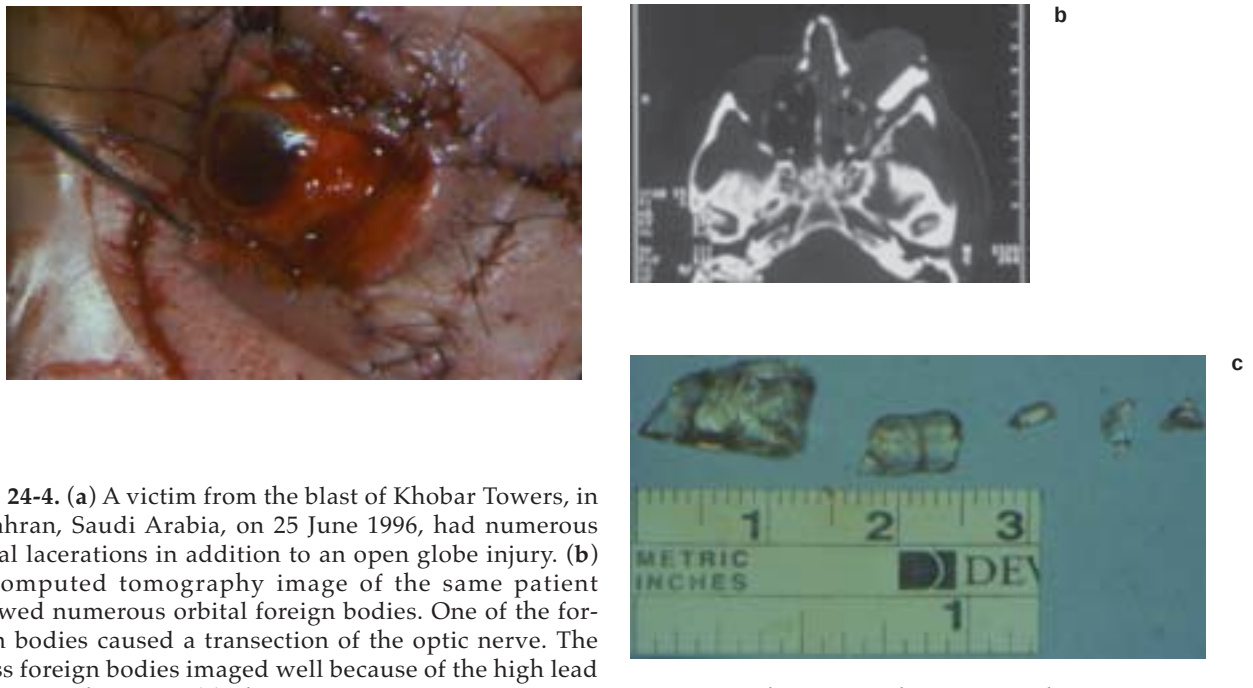

Fig. 24-4. (**a**) A victim from the blast of Khobar Towers, in Dhahran, Saudi Arabia, on 25 June 1996, had numerous facial lacerations in addition to an open globe injury. (**b**) A computed tomography image of the same patient showed numerous orbital foreign bodies. One of the foreign bodies caused a transection of the optic nerve. The glass foreign bodies imaged well because of the high lead content of this glass. (**c**) These glass foreign bodies were removed from the orbit of this patient. The longest piece of glass was thought to have caused the optic nerve transection. Reproduced with permission from Thach AB, Ward TP, Hollifield RD, Cockerham K, Birdsong R, Kramer KK. Eye injuries in a terrorist bombing: Dhahran, Saudi Arabia, June 25, 1996. *Ophthalmology.* 2000;107:846.

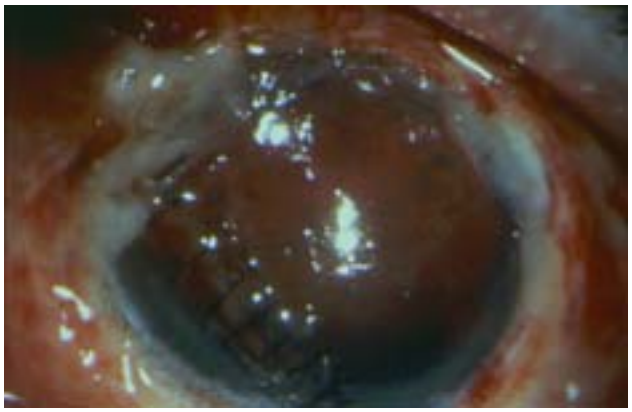

Fig. 24-5. A victim of the terrorist bombing of the Khobar Towers, in Dhahran, Saudi Arabia, on 25 June 1996. This individual suffered a bilateral corneoscleral laceration with loss of his lens at the time of injury. Associated injuries included a hyphema, vitreous hemorrhage, retinal detachment, and choroidal hemorrhage. Reproduced with permission from Thach AB, Ward TP, Hollifield RD, Cockerham K, Birdsong R, Kramer KK. Eye injuries in a terrorist bombing: Dhahran, Saudi Arabia, June 25, 1996. *Ophthalmology.* 2000;107:846.

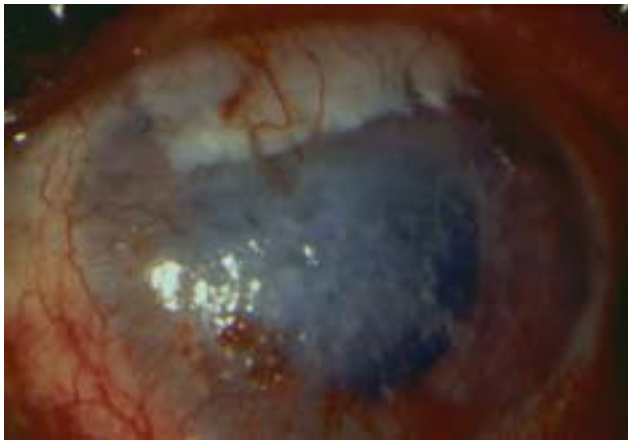

Fig. 24-6. This patient's cornea was "peppered" with small glass fragments as a result of the terrorist explosion at the US embassy in Nairobi, Kenya, on 7 August 1998. Additionally, the patient had a bilateral corneoscleral laceration, hyphema, vitreous hemorrhage, intraocular foreign bodies, and a retinal detachment. Photograph: Courtesy of Edward W. Trudo, MD, and K. Scot Bower, MD, Department of Ophthalmology, Walter Reed Army Medical Center, Washington, DC.

EXHIBIT 24-1

TYPES OF OCULAR INJURIES ASSOCIATED WITH TERRORIST EXPLOSIONS

Eyelid, Orbit, and Adnexa
- Eyelid and/or eyebrow laceration
- Orbital fracture
- Orbital foreign body
- Lacrimal system injury

Anterior Segment
- Corneal abrasion
- Corneal laceration
- Corneoscleral laceration
- Conjunctivitis and/or conjunctival irritation
- Hyphema
- Corneal burn
- Traumatic cataract
- Subconjunctival hemorrhage

Posterior Segment
- Scleral laceration
- Retinal detachment
- Intraocular foreign body
- Vitreous hemorrhage

Miscellaneous
- Ocular contusion
- Cranial and/or optic nerve injury
- Rectus muscle transection

ings within the blast zone. These are a significant cause of death and injury. Victims in a building that collapses may suffer blunt and crush injuries without other injuries associated with a blast.

Ocular Injuries Associated With Explosive Blasts

Although the eye is subject to all the types of injuries described above, the most common and devastating ocular injuries result from the missiles created by a blast (ie, secondary blast injuries). Just as with wartime ocular injuries, those associated with terrorist blasts are most commonly due to fragments that damage the eye. Table 24-3 describes some of the terrorist bombings that have occurred over the last several years.[1–8,17–28] Most blasts cause at least some ocular injuries. A notable exception is the 1993 World Trade Center bombing, in which explosives were detonated underground and most injuries were therefore due to smoke inhalation, not fragmentation missiles. The other reported bombings occurred in crowded public places or in the open, causing injuries due to the blast itself, collapse of a building, or secondary missiles from the blast effect. Although most deaths are probably due to the initial blast or collapse of a building, most eye injuries are related to fragments (eg, glass, bomb casing, masonry, other unsecured items) and debris.

Ocular injuries due to missile fragments during wartime are very similar to ocular injuries that occur from a terrorist bombing. In recent conflicts, most eye injuries stemmed from fragmentation projectiles rather than bullets.[29,30] Unlike the metallic fragments that injure the eye in the military environment, most severe eye injuries from terrorist bombings occur from fragments of glass (Figures 24-4 through 24-6).[6,27,31,32] Glass, particularly monolithic glass, was a major contributing factor for eye injuries in the Oklahoma City bombing.[27,33] Such injuries might be prevented by the use of shatter-resistant glass, laminated glass, Mylar curtains, filmed glass, and catch bars over the windows.

Although the eye makes up much less than 1% of the frontal body surface area, it is very susceptible to injury. Small fragments that may not penetrate clothing or that barely penetrate the skin are able to cause blinding damage to the eye. Ocular injuries that occur in a terrorist blast can be as minor as a superficial foreign body from debris, a subconjunctival hemorrhage, or a corneal abrasion, and as severe as an open globe injury, orbital fracture, or damage to the optic nerve (Exhibit 24-1). Modern microsurgical techniques, the operating room microscope, and the use of vitrectomy enable the ophthalmologist to restore vision in eyes with injuries that in the past may have led to blindness and enucleation.

SUMMARY

Terrorist bombings—overseas and in the United States—affect military personnel and civilians alike. The detonation of an explosive device leads to a rapid increase in atmospheric pressure (blast wave) followed by a decrease in the atmospheric pressure, both of which lead to displacement of air creating a blast wind.

The blast wave can lead to primary blast injury,

which usually affects air-containing organs (lungs, ears, gastrointestinal tract). These injuries can cause air emboli, pulmonary contusion, ruptured eardrums, and ruptured bowel. Secondary blast injuries are due to missiles and fragments that are propelled by the explosion. Tertiary blast injuries are due to movement of parts of or the entire human body and can result in traumatic amputations and blunt injuries. Thermal injuries, including burns of the skin and inhalational injury, can also be produced by an explosion.

Although the eye constitutes only a small portion of the frontal body surface area, it is very susceptible to fragmentation missiles. Fragments that may cause minimal damage to other parts of the body can cause severe injuries to the globe. Most fragments tend to be glass, bomb casing, and masonry, but any unsecured item may act like a missile and cause damage to the eye. Injuries created by a terrorist explosion have included corneoscleral lacerations, orbital fractures, hyphemas, eyelid lacerations, traumatic cataracts, and optic nerve injuries, to name a few. Techniques developed over the years to treat ocular injuries have led to an improved prognosis for these once-devastating injuries.

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