REVIEW

LESSONS LEARNT FROM EXPLOSIVE ATTACKS

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Introduction

A vast amount of material has been published about terrorist attacks using explosives. Contained within these papers are valuable clinical and operational lessons. Some of these lessons can be applied to the current UK military and civilian situation and be used to help to refine our clinical and organisational responses.

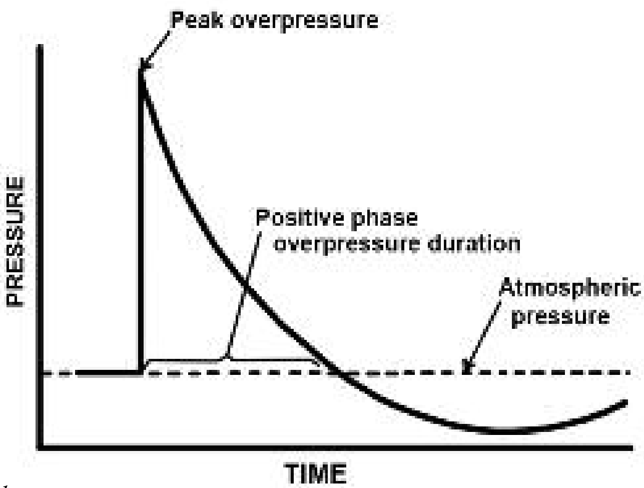
Explosive Injury Mechanisms - a brief overview.

The damage created by a conventional explosion depends on a number of factors, including the type of explosive, the amount of explosive, and the environment within which the detonation takes place.

Whenever and wherever an explosion occurs in air, the principles are the same. An understanding of the principles enables a prediction of likely injury [1][2].

As a substance explodes it rapidly expands from a solid (or liquid) state to a gas, increasing in volume by up to 100,000 times. The speed of expansion depends on the type of explosive. This expansion pushes out whatever is surrounding the explosive, such as casing (which may or may not be designed to fragment) or other items, for example nails or ball bearings.

The explosion also compresses the surrounding air to form a shock-wave. This is a wave of very high pressure which expands away from the explosive at a speed greater than the speed of sound in air. The high pressure lasts for a very short period of time (milliseconds) and in an open air explosion, is relatively short-lived. As a result the peak overpressure decreases rapidly.



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For single shock waves in air, after the initial rise in pressure, the pressure drops to sub-atmospheric levels for a short time due to the elasticity of air (Figure 1). Under water, the shock wave is propagated for a much greater distance and the distance from the detonation at which injury may occur consequently increases.

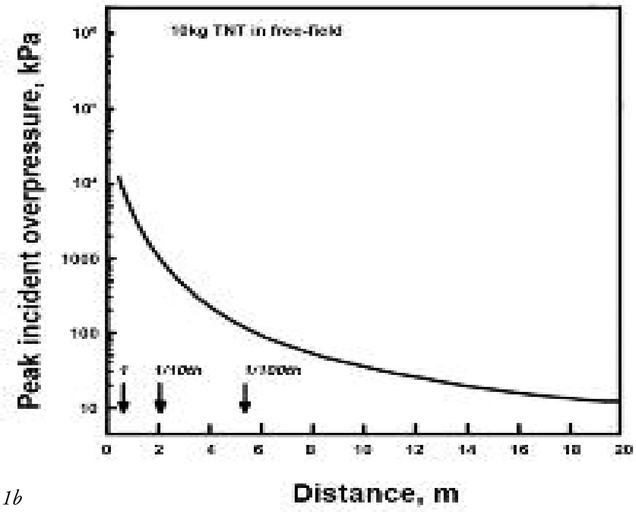

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Figure 1: Schematic representation of a shock wave a. pressure v time at a single point b. pressure v distance from point of detonation

It should be noted that the shock wave travels through air – it is not the mass movement of air and products.

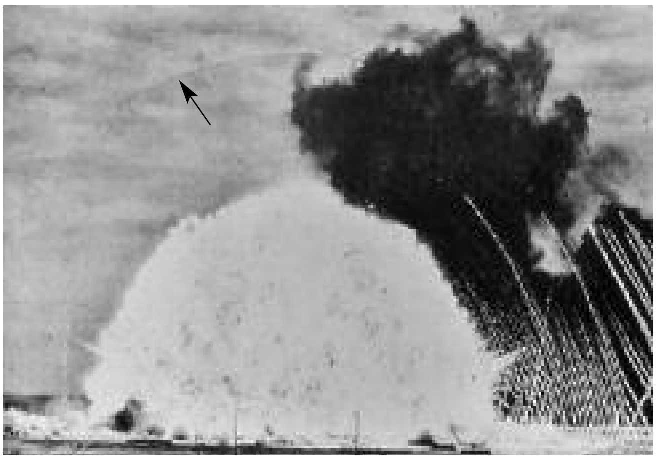

Figure 2: An explosive detonation. Note the shock wave (solid arrow)

Shock waves can be reflected and will then interact with the original wave, leading to complex waves [3] which have a longer duration, multiple pressure peaks and enhanced pressure-related effects in comparison to the original wave. This is of particular significance for an explosion in a confined space, where the initial shock wave will reflect several times, increasing the direct pressure effect considerably.

The explosion will also set the surrounding gas (ambient air and explosive products) in motion, causing the dynamic overpressure or blast wind. The pressure of the blast wind is less

JR Army Med Corps 153(4): 278-282

than that of the shock-wave, but the blast wind has a much longer duration. It will move more slowly than the original shock-wave, but may continue for considerable distances (although the products are confined to the fireball). The blast wind will pick up pieces of debris (or people) in its path and cause the whole, or parts of them to move. The explosion may also cause injury due to the release of toxic fumes, as a result of the radiant and convective heat created by the detonation or as a result of ignition of the environment.

Blast injuries

Blast injuries are classified as shown in table 1. [4][5].

Primary
Injuries due to the interaction of the blast (shock) wave with the body

Secondary
Injries due to fragments

Tertiary
Injuries due to the blast wind (dynamic overpressure)

Quaternary
Burns, crush injury, toxic chemical injury

Table 1: A classification of blast injury

Primary blast injuries

These are caused by the shock wave. Injuries are dependant on the power of the explosion, the proximity of the casualty to the explosion and the environment (open or confined) [6]. The shock wave causes most damage to tissues where there is fluid/air interface predominantly the lungs, and bowel, - but damage does occur in other tissues.

In the lungs the shock wave can cause the alveoli to be damaged, leading to a progressive respiratory impairment. It can also lead to the introduction of air into the pulmonary vasculature leading to embolic injury.

It was previously suggested that eardrum perforation should be used as a marker for primary blast injury following an explosion. It is certainly true that the presence of eardrum rupture is an indicator of significant blast exposure, however the absence of tympanic rupture can not be used to exclude the possibility of significant blast loading. Although it has been challenged [7], in the operational environment it remains safe practice to admit patients with a ruptured eardrum for a period of observation whilst other more significant injuries are excluded.

Secondary blast injuries

Secondary blast injuries are caused by objects energised by the explosion colliding with the casualty. The objects can be split into two groups – 'primary fragments' (part of the explosive device prior to explosion (for example casing or other objects such nails or ball bearings-packed around the explosive) and 'secondary fragments' (objects from the environment picked up and moved by the blast wind – including glass from shattered windows).

Some of the fragments might be human tissue (for example bombers in suicide attacks) [8]. These injuries require early recognition because of the potential risk of transmission of blood borne diseases (including HIV and Hepatitis B).

Figure 3: Secondary blast injury from energised environmental debris

Tertiary injuries

Tertiary injuries are caused by the body of the casualty being moved by the force of the explosion, and colliding with the wall, floor or other objects. Gross disruption of the body and limb amputation may also occur in those very close to the point of detonation (see below). Some authorities include injuries caused by a building or structure collapsing in the tertiary group. In structural collapse casualties can become trapped leading to delayed evacuation and the possibility of the development of crush syndrome.

Quaternary injuries

Quaternary injuries are other miscellaneous injuries, for instance burns or inhalation of hot or toxic gases.

Location	Date	Comments	Further reading
Aldershot, Hampshire	22nd February 1972	The first major attack by the IRA on the UK mainland. Six were killed – five female kitchen staff and a Roman Catholic Padre.	
Guildford, Surrey	5th October 1974	Bombs were placed by the IRA in two public houses. Five people died and 69 persons injured.	[9]
Birmingham, West Midlands	21st November 1974	21 deaths and 119 others injured in two separate IRA bomb attacks on a bar and a public house.	[9, 10]
Musgrove Park Hospital, Northern Ireland	November 1991	IRA bomb targeted at the military wing of a hospital.	[11]
Canary Wharf, London	10th February 1996	This IRA attack ended a seventeen-month ceasefire. Two people died and 39 injured. During the next ten weeks five further devices detonated in London (including the Aldwych Bus bomb) and then in June 1996 a bomb was detonated in central Manchester.	
Omagh, Northern Ireland	15th August 1998	29 deaths and 336 injured. An unclear warning message meant people were next to the car when it exploded.	[12]

Table 2: Selected key Irish Republican Army (IRA) attacks

UK Experience

A major feature of UK domestic history in the late 20th century was the situation in Northern Ireland involving terrorist attacks by both Republican and Loyalist groups. British troops were deployed in to the province in the late 1960's to support the local police services. What was initially envisaged as a short-term deployment resulted in the deaths of 452 military personnel between 1969 and 2006.

According to figures released by the Police Service of Northern Ireland (PSNI), the year when the highest number of bombing devices were detonated or found was 1972 when 1853 devices were deployed. In total the PSNI state that between 1969 and 2006 there were a total of 16457 bombing incidents in Northern Ireland alone [9].

The bomb attacks were not always in Northern Ireland, and nor indeed only within the boundaries of the UK mainland. A list of some of the major Irish Republican Army (IRA) attacks is given in table 2.

The Good Friday Agreement (or Belfast Agreement) was reached in Belfast on Friday, April 10 1998 and set out a plan for devolved government in Northern Ireland on a stable and inclusive basis and provided for the creation of Human Rights and Equality commissions, the early release of paramilitary prisoners, the decommissioning of paramilitary weapons and far reaching reforms of criminal justice and policing.

There were still attacks after this by dissident groups, including in August 2001 when a car bomb was detonated in west London.

Figure 4: The Birmingham Pub Bombing

Types of explosive devices.

Hull described the common types of explosive devices seen in Northern Ireland [13]. While all explosives have similar actions, the amount and type of explosive and construction of the bomb alter the effect produced.

Hull described four main types –

Car bombs.

Car bombs generally contained between 1 and 3 kg of commercial explosive, placed beneath the driver's seat. Detonation (normally by a mercury tilt switch, activated by the car moving) usually resulted in traumatic limb amputations with soft tissue mangling and parts of the car and seat embedded in to the legs of the driver.

Bare Charges

Bare charges were remote, small, improvised explosive devices (IED) whose main effect was secondary-fragment injury.

Lorry or Van Bombs

Lorry or van bombs involved 40kg or more of high explosive producing large fragments causing massive lacerations - examples of secondary blast injury.

Culvert or Roadside Bombs

Culvert or roadside bombs designed to blow-up passing vehicles.

Amputation mechanisms

Hull et al published a series of 34 fatalities from Northern Ireland terrorist bombings [13] and a subsequent study on those who survived similar injuries (either from Northern Ireland or other military operations [14]. It was noted that the most common site for traumatic amputation in both survivors and fatalities was through the upper third of the tibia, a pattern which is very different to those seen in "pure" flailing amputation injuries (such as suffered by fast-jet pilots who have had to eject from their aircraft). This led to further work modelling these injuries, which subsequently demonstrated that primary blast shock-wave is implicated in traumatic amputation [15]. The shockwave causes stress forces resulting in fracture of the bone before the limb is amputated by the blast wind (thus traumatic amputations after blast are a combined primary and tertiary injury).

Figure 5: Amputations as a result of blast exposure

Cooper et al reported in detail on six of the attacks on the UK mainland, combining medical and forensic details [9]. They found that the most common fatal injury was brain damage and that the environment where the device exploded influenced the wound types seen. The explosions inside buildings had a much higher mortality rate, where as an explosion outside had more casualties – but fewer of these needed hospital admission. Cooper et al also showed that after these events a large number of people were taken to hospital but many did not require admission or surgery – just thorough wound cleaning [9]. The need to surgical explore all fragmentary wounds has been questioned [16].

Other attacks within the United Kingdom (UK)

There were attacks by other organisations during this period in the UK. In November 1982, Animal Rights Extremists sent an incendiary device to the Prime Minister's residence, injuring a member of staff. In April 1999 three attacks took place in London. The most serious of these explosions was in the Admiral Duncan Pub in Soho where two people died [17],[18],[19]. David Copeland was subsequently convicted of carrying out these attacks.

In 2001, Greaves published a paper based on presentations from a colloquium at the Royal United Services Institute in June 2000 [20]. It described how new terrorists threats should be identified, and in particular how Copeland had been able to bomb London as a lone bomber, gaining his information from the internet.

What could not have been predicted at this stage was the sheer size of the "9/11" attacks in the United States when four civilian airliners were hijacked on the 11th September 2001 and used as suicide weapons against targets in the USA. This changed the way that terrorism was perceived around the world. Even after 9/11 the UK was still perceived (in a paper published in May 2004) to be at low risk from this type of suicide terrorist attack [21].

On the 7th July 2005 four suicide attacks took place in Central London. Three of these were on underground trains and the last on a bus. In total 56 people died (including the four bombers) and it was reported that over 600 were injured.

Many reports have been written after the 7/7 bombings. These look at several different aspects of these attacks including the pre-hospital response [22], the response from one major hospital (The Royal London) [23] and the response of one Intensive Care Unit (ICU) [24]. There have also been articles looking at how the military were involved in the medical response to these events [25], the effect of an unusual pattern of injury [8] and sharing the experience of the radiology and maxillofacial team [26], [27].

A key paper was written by Aylwin et al which looked at how one hospital reacted to the bombings, and in particular commenting on three key areas – critical mortality, surge and over-triage (see Table 3) [23]. The deployment of the HEMS crew (Helicopter Emergency Medical Service - the London pre-hospital emergency team) – staffed by senior doctors who are either emergency medicine or anaesthetic trained, with additional skills including disaster management) to the scene allowed better triage with a lower over-triage rate (compared to those casualties seen by paramedics).

De Ceballos et al discuss the difference created by moving senior staff forward to deal with an incident compared to the situation after the Madrid attacks in 2005 [28]. The HEMS service used their helicopter to get staff to the right places but not for the transport of patients [22]. This is thought to have helped reduce the critical mortality rate at their hospital to 15%.

Over-triage vs. Under-triage	Over triage is the assignment of non critically injured to higher than appropriate triage groups, resulting in their earlier than necessary evacuation hospitalisation. Under –triage is the reverse (i.e. critically injured personnel being given a low priority for treatment and evacuation). Both can result in increased mortality.
Critical Mortality	Mortality rate of critically injured survivors. Critically injured is defined as Injury Severity Score (ISS) >15. As the majority of survivors do not have life threatening injuries this is considered a better index of care provision.
Surge	The rate of casualties arriving at a facility, or indeed within in a facility arriving at different departments. This allows surge capacity to be assessed, and therefore bottlenecks identified and compensated for.

Table 3: Key terms in assessment of medical response to a terrorist attack.

International Experience

Although the UK has had considerable experience of terrorism, it is necessary to place this in perspective. The United States State Department has recently released a report into international terrorism [29]. It concluded that there had been a 40% increase in the number of deaths due to terrorism in 2006 (to a total of 20,498) and this was mostly due to the increase of violence in Iraq (65% of all deaths due to terrorism were in Iraq).

Several major reviews have been written looking at the medical consequences of terrorism over the past twenty years. Frykberg and Tepas published a review article looking at published experience of terrorist bombings between 1969 and 1983 [30]. They identified 220 terrorist bombings that had been reported in the medical literature. They demonstrated that although every incident had a unique set of circumstances, there were broad principles in dealing with these situations that

Paper and date	Study design	Key findings
Leibovici et al 1996 [33]	Compared four bombings in which similar bombs were used. Two were in confined spaces (inside buses) and two outside.	They found an increased mortality and also more severe injuries amongst survivors in confined space explosions (including primary blast injuries (but not tympanic membrane rupture)). There was no difference in significant penetrating trauma, burns or traumatic amputations between the two settings. The confined space explosions led to a lower total number of victims.
Katz et al [34]	Analysis of bus bombings.	The importance of considering primary blast injuries when an explosion occurs in a confined space is noted. Anomalies do occur though; in some cases being very close to an explosion does not necessarily result in the most severe injuries.
Stein and Hirshberg [35]	A meta-analysis of 11 terrorist attacks resulting in 636 patients.	Secondary blast injuries were the most common type of injury, but when only severe injuries were taken in to account (defined as those with an ISS equal or greater to four) the most common injuries were primary blast injuries.
Kluger et al [36]	A retrospective review of terrorist bombings in Israel between 2000 and 2003 comparing victims with those from other kinds of trauma.	Casualties from terrorist bombings seen in the ED are likely to be significantly more injured, with more body regions injured and more complex injuries compared to other forms of trauma. Comment is also made on the failure of ISS in these patients and recommendation that NISS should be used in preference.
Aschkenasy-Steuer et al [37]	Review of the ICU experience in the only level one trauma centre in Jerusalem over a four-year period. There were 33 attacks, which led to 477 ED admissions and 176 hospital admissions.	By "pushing the Intensive Care forward" in to ED they were able to maintain a normal service to the rest of the hospital. A single doctor was appointed to look after each seriously injured patient, providing continuity of care from ED to ITU. It is important that senior control is present in triaging and planning treatments. The authors also discuss the phases that occur after a terrorist attack. During the initial "latent period" prior to casualties arriving final preparations can be completed (such as clearing ITU beds) and further assistance summoned. It is suggested that monitoring local and regional news stations may often form a useful source for predicting expected casualties.

Table 4: Major papers published by Israeli authors concerning terrorism

could be used. They also established the use of over-triage and critical mortality in assessing these events, and the relationship between over-triage and deaths among critically injured (the higher the over-triage rate the higher the mortality rate of the critically injured).

Arnold et al published a review in 2004, this time looking only at those terrorist events creating mass casualty situations [31]. They identified three separate types of event, each of which had different associated mortality rates and median casualty rates; –

- Structural collapse (mortality - 25%; median casualty 433)
- Internal explosions (mortality - 8%; median casualty 58)
- Outdoor explosions (mortality - 4%; median casualty 94)

They also noted a biphasic distribution of death which was seen in all types of terrorist bombings. More recently reports regarding bombings in Turkey [32] give casualty statistics that fall outside these expected figures. These attacks were in the open air but had much higher than expected casualty rates, with approximately 242 casualties per bombing. The authors put this down to a number of factors, most importantly the size of the bomb and the fact it was set to go off at the perceived busiest time of the day.

Israeli experience

A major amount of information has been published from Israel regarding their experience of terrorism over the past forty years (Table 4).

Conclusions

This is a brief discussion of literature related to explosive terrorist attacks. It is not exhaustive, but it does illustrate the fact that important lessons have been reported previously. It is vital that the DMS learn from the experience of others and ensure that whenever necessary protocols and procedures are refined in line with these lessons.

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