SHAPED CHARGES AND EXPLOSIVELY FORMED PENETRATORS: BACKGROUND FOR CLINICIANS

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Abstract

Shaped Charges (SC) have been used in High Explosive Anti-Tank (HEAT) munitions and the mining industry since World War II. An explosive is used to propel a liner material of low mass at speeds in excess of 5 times the speed of sound. The subsequent projectile is capable of penetrating the steel of armoured vehicles and inflicting significant injury to any enclosed personnel. Explosively Formed Penetrators (EFP) are a variant of a SC, using higher mass at lower speed to deliver their kinetic energy. The Iraq conflict has seen the use of Improvised Explosive Devices utilising EFP (IED-EFP) by insurgent groups attacking military vehicles. The major wounding mechanisms are from fragmentation and burns. This article is a brief overview of the history and science behind SC and EFP.

Introduction

The "Roadside-Bomb", as described by the lay-press (1,2), has become a prominent feature of operations in Iraq in its use against both military and civilian targets. This term encompasses a plethora of weapon systems from rudimentary bulk explosives to sophisticated Improvised Explosive Devices utilising Explosively Formed Projectiles (IED-EFP).

An important distinction of the latter type is that it is in fact not a bomb, but a ballistic weapon designed to penetrate armoured vehicles. EFP use a shaped explosive, which upon ignition moulds a 'liner' material (generally metal) into a projectile. The EFP can travel at speeds of 2-3 km/s (3) penetrating vehicles and inflicting serious and often fatal injuries to enclosed personnel.

The principle underlying EFP has been derived from experience with Shaped Charges. In a military context, High Explosive Anti-Tank (HEAT) munitions use a SC to fire a narrow, but long 'jet' penetrator as an anti-armour weapon (4-6). The low mass jet of a HEAT munition is formed over a certain distance, referred to as "standoff distance" and can achieve velocities of up to 10-15 km/s. The stand off distance varies with the diameter of the 'cone' in the weapon (Figure 1). A small cone requires a smaller standoff distance than a large cone. This necessitates the use of a delivery system such as a tank shell or missile to deliver the HEAT munition to a suitable distance from its target. It also requires complex engineering to ensure that detonation of the explosive within the rapidly moving shell and formation of the 'jet' occur in the required time frame.

An EFP utilises a different liner configuration with a higher mass to allow a longer stand off distance than with HEAT but producing a projectile with a reduced velocity than that produced by HEAT weapons. This eliminates the requirement for a delivery system to bring the weapon to the target and thus has a tactical benefit for irregular forces.

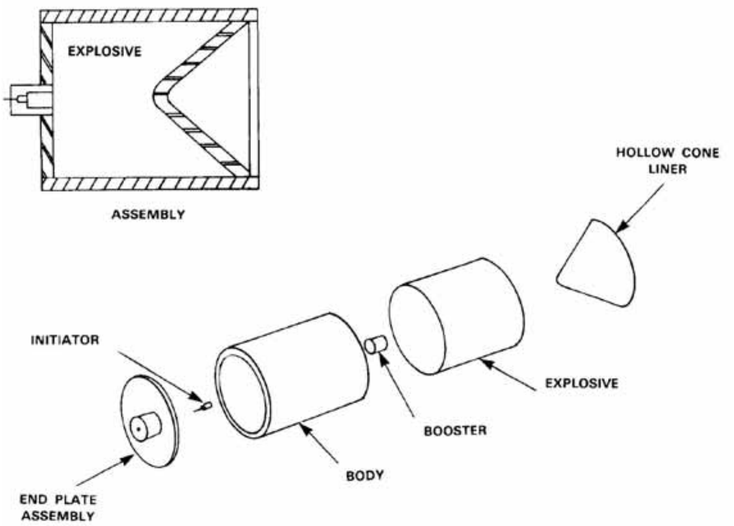

Figure 1: A line drawing of a generic Shaped Charge Weapon (From: Weickert CA. Demolitions. In: Zukas JA, Walters WP, eds. Explosive Effects and Applications. New York: Springer-Verlag 2003: 382. With kind permission of Springer Science and Business Media.)

The use of IED-EFPs by insurgent groups in Iraq has been the cause of significant mortality and morbidity. To manage these patients effectively, clinicians treating these injuries need to be aware of wounding mechanisms and injury pattern. The aim of this article is to review the science and history behind shaped charges using open source literature from medical, media and open defence sources.

As the use of IED-EFPs within the Iraq conflict is a relatively

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new innovation, open source data on the physical and clinical characteristics is limited. Thus, although HEAT and EFP have a significant number of technical differences, we have included literature in relation to armoured vehicle crews injured by HEAT munitions. We accept that a direct comparison of these weapon systems cannot be made, but it provides a useful starting point until more specific data is available. It is hoped this will provide useful background information for Defence Medical Services personnel who will encounter casualties caused by this weapon system.

The History of Shaped Charge Weapons

The history of the development of shaped charges is open to debate. It is generally accepted that the first published report was by von Baader in 1792 who discussed bore hole drilling and the behaviour of confined explosives. The essence of his analysis was that one could focus the explosive power of a charge by forming a hollow in the explosive. He did not specifically use the term "hollow charge" (3) although subsequent researchers used this in deference to his findings.

The hollow charge effect was more fully demonstrated by von Fœrster in 1883 who used shaped guncotton to propel a coin into a wrought-iron plate. This was repeated in 1888 by Charles Munroe in America who used this technique to engrave lettering into a steel plate. Munroe made detailed observations that for the same mass of non-shaped explosive, only minor indentation could be achieved in the same steel plate (6). The phenomenon of a hollow charge is known in Europe as the von Fœrster Effect and in the UK and US as the Munroe Effect.

In 1910, Neuman of Germany used the first metal liner in conjunction with a hollow charge, creating the modern "explosively formed projectile". Neuman used a tin can with a hole in the top, filled with dynamite to punch a hole through a steel safe.

During the build-up to the Second World War, the Swiss chemical engineer Mohaupt experimented with Shaped Charge Weapons (SCW) while developing a hand held anti-tank weapon. He noted that when he tried to propel steel cones (the weapon liner) at a target using conically shaped explosives, the hole produced in the target was smaller than the liner. He also noted that penetration of the target was far greater than expected, with no evidence of liner fragmentation.

With these established principles, a number of countries began developing SCW for soldiers to defeat steel armour. Mohaupt initially lead research for the French, although later he worked for the Americans on the Bazooka Project. The likely first SCW was the British No. 68 rifle grenade which entered service May 1940. This could only penetrate up to 50 mm of steel armour, rendering it ineffective against the thickly armoured German Panzer Tanks. Subsequent devices included the British PIAT spigot mortar and the German Panzerfaust (6).

Following the end of the Second World War, it became apparent that SCs could be utilised by certain industries in addition to military application. Mohaupt continued to lead the field, experimenting with bigger devices and different liner material. These type of devices are utilised extensively by the mining industry as a cutting tool to open up rock formations and in demolitions (7). They are preferable to bulk charges as SCs are directional and thus more predictable in their behaviour.

HEAT weapons have become one of the main munitions of choice for Main Battle Tank (MBT) combat. HEAT munitions accounted for around 20-25% of "hits" by Israeli MBTs against Arab armoured units in the 1973 Arab-Israeli conflict (4). In the 1991 Gulf War, this figure increased to 70% of "hits" by coalition forces based on the analysis of 308 recovered Iraqi MBTs (8). Further examples of HEAT munitions include the missile based systems such as Maverick and Hellfire.

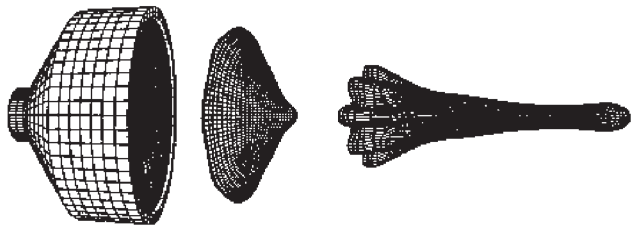

Figure 2: A computer generated image of the stages of formation of an Explosively Formed Penetrator. Left image: liner prior to detonation. Middle image: liner collapse and distortion during detonation. Right image: the Explosively Formed Penetrator in flight. (Reprinted from Int J Solids Structures 27, Florence AL, Gefken PR, Kirkpatrick SW. Dynamic Plastic Buckling of Copper Cylindrical Shells.; p89-103, 1991; with permission from Elsevier)

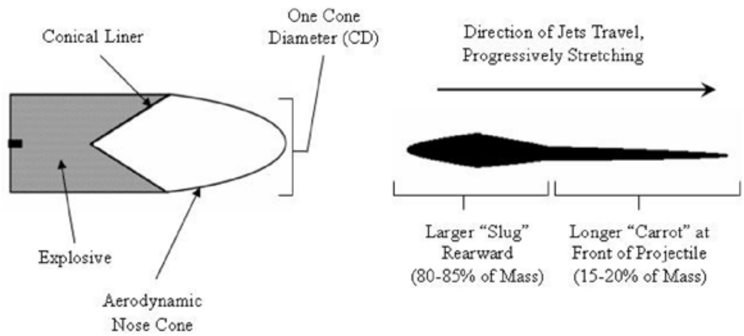

Figure 3: A drawing of a HEAT Munition (left image) and the resultant projectile (right image. The projectile will progressively stretch until it breaks up into small fragments.

The Physics behind Shaped Charges and Explosively Formed Projectiles

HEAT munitions and EFP are two facets of SC weapons (SCW). They have different constructions which are important to understand to appreciate the difference in function. The basic construction of an SC is a tube of explosive with an axis-symmetric geometric shape hollowed out at its distal end (3). The most common shape is conical, although an ellipse, tulip or similar also work. Within this is placed the liner, which reproduces the hollowed shape.

The liner can be made from materials such as glass and ceramic although a metallic material such as copper or steel is generally employed (9,10). Figure 1 is a line drawing cross-section of a schematic for a generic SC device.

Upon detonation of the shaped charge, the rapidly expanding gaseous products push a high pressure wave along the axis of symmetry towards the liner at around 8 km/s, concentrating the power of the detonation along an axis (the Munroe Effect described previously). Upon reaching the liner, the detonation wave exerts enormous pressures, up to 200 GPa (30 million psi) for a few microseconds. This collapses and distorts the liner on its central axis, driving it into a jet shaped projectile with the tip travelling in excess of 10 km/s. About 80-85% of the jet mass is rearward and travels more slowly at around 1 km/s (3,7). The penetration *potential* of a shaped charge is proportional to the penetrator length and the square root of the penetrator density (10). While airborne the penetrator length is not constant due to the different speeds of the tip and the base and it will stretch until it eventually undergoes *particulation*. Particulation diminishes the ability to penetrate the target. The distance at which the projectile is formed so that it can "optimally" penetrate its target is the standoff distance.

Figure 2 is a computer illustration of a collapsing liner and Figure 3 is a schematic drawing of a HEAT munition and the formation of a jet.

The density of the penetrator is a reflection of the density of

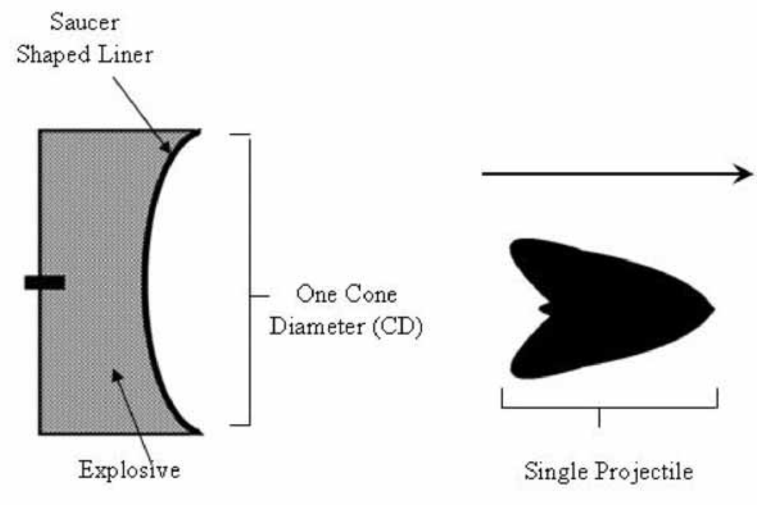

Figure 4: A Drawing of an EFP device with saucer configuration of liner and resultant projectile. The projectile remains intact throughout flight.

Figure 5: A captured Iraqi Insurgent IED-EFP. (Source: Joint (UK) EOD Group.)

the original liner material. Tantalum is a commonly used liner combining high mass with a density of 16.6 g/cm^3 (11).

The real measure of a shaped charge is its capacity to penetrate the target material. This being rocks in the oil industry or the armour of military vehicles. On impact of the penetrator with its target, exceptionally high pressures are generated. These maybe from one hundred to two hundred Giga Pa and the target metals temperature rises to between twenty five and fifty percent of its melting point. The penetrator creates a cavity and begins to propel through the target material. This effect is not a thermal phenomenon but related to the enormous pressures pushing the target metal aside. The overall mass of the target should theoretically remain stable throughout impact, although some will be lost through vaporization and spall (debris from the internal surface of the vehicles armour).

An EFP utilises the Munroe effect, just as the HEAT round does. The EFP uses a wider diameter of liner compared with a HEAT round in a saucer configuration. Figure 4 is a drawing of an EFP and the resultant projectile. Figure 5 is a picture of a captured Iraqi IED-EFP (note the saucer shape of the liner).

The saucer liner has a number of effects. Crucially, it changes the shape of the resultant projectile: detonation of an EFP collapses the liner into a single projectile which remains intact throughout its flight. This has the effect of increasing standoff distance but a single piece EFP will penetrate armour to a lesser distance than a HEAT munition (3).

In summary, SCs use conically shaped liners to produce high-velocity, low mass projectiles with a very narrow standoff performance and complex engineering requirements.

EFPs use a wider saucer shaped liner to achieve greater standoff performance, albeit with reduced penetration potential (11).

Discussion

A recent report from the Congressional Research Service highlighted the emergence of IED-EFPs to attack armoured vehicles in Iraq (12). Such devices have become quite sophisticated in their construction and initiation. As their use is a relatively new phenomenon, the best comparator of injury pattern is that of HEAT munitions although one needs to appreciate limitations of this evaluation.

Past experience of injuries sustained by armoured vehicle crew has identified ballistic (fragment) and burns as major mechanisms. Ballistic injury has accounted for around 75% of all injuries (4,6,13,14). Burns made up about 26% of injuries incurred by crews in the 1982 Lebanon War (14). Vehicle design improvements to protect crews against fragment and fire include spall-suppression linings, compartmentalising fuel and munitions, flame resistant clothing and automatic fire suppression systems (15).

Blast overpressure, toxic fumes and blunt trauma were less frequent causes of injury in Dougherty's paper (4). Toxic fumes and blunt trauma depend upon the construction material and strength of the vehicle under attack. Blunt trauma is also influenced by the shape of the passenger compartments and whether there are exposed bolts and other structures for crew members to be thrown against.

Primary blast injury (PBI) is common in fatalities (16). The effect of a blast wave is exaggerated by the “confined” nature of vehicles compared with ‘open-air’ explosions (17). The exact incidence of primary blast injury in survivors is uncertain. Ripple and Phillips (15) quote closed source US Army Medical Research and Developmental Command (USA MRDC) studies indicating a probable incidence of between 1 and 20 percent PBI in survivors from a large warhead penetrating an armoured vehicle (in addition to their other injuries).

It is difficult to precisely quantify the casualties from IED-EFP in Iraq, as specific statistics regarding this weapon system are not published. The term IED, by definition, encompasses all manner of hostile explosions from vehicle borne attacks to human beings wearing suicide vests. There have been a number of general articles and epidemiological studies published in the open literature providing a breakdown of casualties and injury patterns in the Iraq theatre (18-22). These studies all pertain to the combat and occupation phases of operations in Iraq, 2003 i.e. Operation Telic I and II (UK) and Operation Iraqi Freedom I and II (US).

As each publication uses a different system of classification and way of presenting their data, only broad comparisons can be made. A point to note is that the use of exploding munitions exceed that of small-arms reflecting the nature of insurgency warfare.

There is no specific analysis of injuries/deaths related to the use of IED-EFP Most available data pertains to the generic description of a 'road-side bomb'. The Pentagon is quoted by the Telegraph as reporting 5,607 such incidents in 2004 rising to 10,953 in 2005, although there is no detailed comment on type of weapon system employed (2).

Conclusions

Shaped Charge Weapons have long been used by anti-armour HEAT munitions. IED-EFPs have been adopted by irregular forces in Iraq.

The source of mortality and morbidity for both civilian and military personnel is multi-factorial, although the high velocity of the projectile and density of material used are significant contributors.

DMS personnel can expect to care for patients suffering from fragment and burn injury. Blunt trauma and the effects of toxic fumes also need to be considered as does blast injury although the exact incidence of blast has yet to be determined.

Acknowledgements

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