Combat Helmets and Blast Traumatic Brain Injury

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Abstract:

Background: The conflicts in Iraq and Afghanistan and the prominence of traumatic brain injury (TBI), mostly from improvised explosive devices, have focused attention on the effectiveness of combat helmets.

Purpose: This paper examines the importance of TBI, the role and history of the development of combat helmets, current helmet designs and effectiveness, helmet design methodology, helmet sensors, future research and recommendations.

Method: A literature review was conducted using search terms – combat helmets, traumatic brain injury, concussion, Iraq, Afghanistan and helmet sensors, searching PubMed, MEDLINE, ProQuest and Google Scholar.

Conclusions: At present, no existing helmet is able to fully protect against all threats faced on the battlefield. The prominence of traumatic brain injury from improvised explosive devices in the current conflicts in Iraq and Afghanistan has highlighted the limitations in knowledge about blast and how to provide protection from it. As a result, considerable research is currently occurring in how to protect the head from blast over-pressure. Helmet sensors may provide valuable data. Some new combat helmets may be able to protect against rifle rounds, but may result in injuries occurring behind body armour. Optimal combat helmet design requires a balance between the need for protection from trauma and the comfort and practicality of the helmet for the user to ensure the best outcomes.

Keywords: combat helmets, traumatic brain injury, concussion, Iraq, Afghanistan.

No conflicts of interest were identified by the authors.

Introduction

Recent adverse media attention about combat helmets used in Afghanistan by United States forces[1, 2] and the Australian Defence Force[3, 4] has highlighted the importance of this piece of personal protective equipment. Combat helmets were developed primarily to protect wearers from blunt force trauma – from shrapnel, projectiles and objects such as earth and rocks. However, the wars in Iraq and Afghanistan, with their frequent exposure to blast injury and subsequent traumatic brain injury have focused new demands on helmet design. This paper examines the design and ability of current and future helmets to protect users from mTBI gunshot wounds, in addition to the established role of protecting from blunt force trauma.

Method

A literature review was conducted using search terms – combat helmets, traumatic brain injury, concussion, Iraq, Afghanistan and helmet sensors, searching PubMed, MEDLINE, ProQuest and Google Scholar.

Role and history of combat helmets

The primary role of the combat helmet is to protect the soldier's head against injury. In modern warfare there are a variety of threats to a soldier's head which include: gunshot wounds; blunt force trauma such as in hand to hand combat, motor vehicle accidents, aircraft crashes and parachute jumps; and finally, blast impact. Blast effects are complex and can be divided into primary blast injury, produced by the direct effect of air pressure waves travelling faster than the speed of sound; secondary blast injury from shrapnel and debris; tertiary blast injury, when victims are thrown through the air striking other objects; and quaternary blast injury from burns and toxic gases produced by an explosion[5]. Acoustic, light, electromagnetic and thermal energies are also released in a blast, but current data does not permit any firm conclusions about what role they may have in producing TBI[6]. A secondary role for helmets is to serve as a platform for equipment such as night-vision goggles, cameras and communications gear.

At present, no existing helmet is able to protect all persons against such a diverse array of threats[7]. Blackman et al.[8], were critical of current US combat helmets, complaining that they fail to protect against closed head TBI at the level of US National Football League (NFL) helmets. Wocjik et al.[9], illustrated the shortcomings of existing combat helmets with the finding that in Iraq and Afghanistan since 2005, when US data on helmets and TBI began to be tabulated, 77% of soldiers who sustained any type of TBI were wearing their helmets at the time of injury.

To design and produce an effective combat helmet, developers must consider a wide range of factors. These include: overall helmet size and mass, acoustic protection[10], ballistic qualities of the construction material, comfort, maintenance of field of vision and hearing, compatibility with weapons and other equipment, (e.g. communications gear), ease of maintenance and modification in the field, durability, availability of raw materials, manufacturing techniques, ease of decontamination from nuclear, biological and chemical threats, cost and disposability after use[11].

Increases in ballistic protection are likely to lead to increased weight. Increased weight means the helmet is likely to be less comfortable and is likely to be worn less often than it should, resulting in an increased risk of incurring a head injury[12]. Reports from senior US Army neurosurgeons during the Vietnam War indicated that needless injuries from small shell fragments occurred due to soldiers not wearing their M1 helmets because of complaints of excessive heat and discomfort[11]. With this in mind, Ivins et al. stressed the importance of supplementing laboratory testing of helmets with rigorous consumer satisfaction surveys[12].

Carey et al.[11], described the history of development of combat helmets during the twentieth century. In World War I and II, major combatants produced helmets that were made of steel with various types of webbing and straps to secure them to the head. While British and US military authorities specified ballistic criteria that helmets could defeat a pistol bullet at a certain distance[13, 14] in general, helmets were designed to protect against shell fragments and not to stop military rifle bullets.

This was certainly the experience during the Vietnam War, where US forces persisted with the model M1 helmet, developed in 1941. Carey et al. [15], reviewed all US head wounds from that conflict and found that gunshot wounds to the head occurred at close range (average of 40.9 metres), while those from shell fragments were at very close range (average 2.9 metres). They determined that bullets caused more fatal head wounds than shell fragments and concluded that helmets offered no protection against bullets, but gave significant protection against fragments.

Steel helmets were replaced in the US by the Personal Armor System Ground Troop (PASGT) Kevlar helmet introduced from 1982 onwards, and in the UK by the Mark 6 helmet introduced from 1986 and made of nylon fibre. Like it's predecessors, the PASGT was primarily designed to protect against shell fragments, but it could also stop some pistol rounds[11]. Both helmets covered more of the head, were lighter, better balanced and more secure to wear than predecessors.

The prolonged conflicts in Iraq and Afghanistan have produced a need for more effective personal protective equipment (PPE). The US Advanced Combat Helmet was introduced from 2003 and the UK Mark 7 helmet from 2009(16). Both claim to be lighter, stronger and with better fields of vision than their predecessors, with more stability while wearing night-vision goggles.

The ADF replaced its PASGT helmets from 2004, with the Israeli-designed RBH 303AU, badging it the Enhanced Combat Helmet (ECH)[17]. Lighter than the PASGT, it has a better field of vision, slightly better protection against fragments and is reported to be able to stop some pistol rounds, making it similar in characteristics to the US Advanced Combat Helmet (USACH). The ADF ECH has a similar ballistic shell to the USACH, attached by a suspension system with three-point harness, whereas the US helmet has pads and a four-point harness.

Bulletproof helmets?

A new US helmet, called the Enhanced Combat Helmet (ECH), not to be confused with the ADF ECH, has been in development for several years and is due for issue in late 2011. Made of ultra-high molecular weight polyethylene, it is thicker and lighter than the current US helmet[18]. Of concern, one of the major manufacturers has dropped out of production, after its helmets failed to meet US Marine Corps performance requirements[19], posing a risk of a delay in introduction.

Another manufacturer of the US ECH, and unnamed US Army officials, have reported that the new helmet will 'stop penetration by at least some rifle rounds'[20, 21]. There are also anecdotal accounts of the UK Mark 7 helmet stopping rifle rounds in combat in Afghanistan[22]. This then raises the question as to whether true bullet-stopping helmets may present a risk of a 'behind armour effect,' albeit less severe than a penetrating wound, but nevertheless leading to possible severe closed head injury secondary to helmet deformation or cervical spine damage secondary to neck extension/flexion injury[11, 23]. Indeed some cases of closed head TBI(CHTBI) have already occurred from shell fragments causing helmet deformation[6].

To investigate this issue, Sarron et al.[23], used two experimental designs to examine possible injuries imparted through helmets tested with pistol rounds. The trials produced injuries ranging from skin laceration to extensive skull fractures and brain contusion. The authors concluded that a gap of at least 12 mm between helmet and head was an effective means to reduce impact and resultant blunt trauma to the head.

The experience from road trauma may be relevant, in that it has shown convincingly that wearing motorcycle helmets does not cause an increased risk of cervical spine injury in a collision, notwithstanding the fact that motorcycle helmets are not designed to protect against blast injury[24]. Similarly, ice-hockey helmets with face guards have definitely reduced head and face injuries, without an increase in cervical spine injuries[25].

Ran et al.[26], conducted a review of all Israeli Defence Force combat fatalities from 2000 to 2009, mapping the anatomic location of all bullet entry wounds to the skull. They found that fatal gunshot wounds were predominantly grouped in the occipital and anterior-temporal regions, leading to the suggestion that helmet design may provide for bulletproof materials particularly in those areas, thus lessening the total weight of the helmet. While at first glance this sounds like a good idea, in practice, a helmet made of different materials and thicknesses may be very hard to manufacture, as the integrity of the ballistic shell of new lightweight helmets relates to them being produced all in one piece.

Traumatic brain injury

Traumatic brain injury (TBI) has often been referred to as 'the signature wound' of the wars in Iraq and Afghanistan[27, 28]. While it has been argued that this as an unhelpful or debatable concept[29, 30], what is clear is that overall, TBI is a major public health issue, especially with regard to the development of subsequent psychiatric morbidity[31]. Second only to chest and abdominal wounds, TBI was the cause of 35% of allied military deaths in the wars in Iraq and Afghanistan to the end of 2009[32]. Explosive mechanisms, in particular Improvised Explosive Devices (IEDs), were the leading cause of all combat casualties, accounting for 70-75% of allied military killed and wounded[32, 33]. Explosive ordnance accounted for most cases of TBI in US soldiers injured in Iraq to 2007, but only 47% of cases of TBI in Afghanistan to 2007[9]. It is highly likely that the figures for Afghanistan have increased greatly since 2007, with the escalation of the conflict including a surge in the use of IEDs by the Taliban[34].

Moss et al.[35], described TBI as being 'endemic' among military personnel exposed to blasts. However, estimates of prevalence of TBI in the wars in Iraq and Afghanistan have varied greatly for methodological reasons which include: many studies being only screening questionnaires with no clinician diagnosis; screening samples not being representative of all those deployed; studies not measuring impairment[36]; and symptoms of TBI possibly overlapping with symptoms of Acute Stress Disorder or sleep deprivation[37]. The RAND Corporation estimated the probable prevalence of TBI among all US personnel deployed to Iraq and Afghanistan up to 2007 at 19.5%, or 320,000 persons[38]. The US Department of Defense, Defense and Veterans Brain Injury Center total figures for medically diagnosed cases of TBI in serving members of the US military from 2000-2010 were 202,281 of which 155,623 were classified as being mild[39]. This data from medical records includes TBI from any cause, apparently without the ability to specify whether the injury was received in combat.

There are a number of classification systems for TBI(9, 40) which categorise injury according to severity. Ling and Ecklund[41], grouped them according to method of injury into closed head (CHTBI), penetrating (PTBI) and explosive blast traumatic brain injury(EBTBI). They went on to suggest that the mechanism of action for EBTBI may be unique, due to its diffuse nature and frequent characteristic findings of rapid onset of diffuse cerebral oedema, sub-arachnoid haemorrhage, unique fractures, pseudo-aneurysms and vasospasm.

The mechanism by which blast pressure waves produce injury to the Central Nervous System, and, in particular, the brain, is not fully understood[42]. The classic form of blast pressure wave is the Friedlander waveform, where there is a rapid initial rise to a peak positive or over-pressure that is above atmospheric pressure, followed by a sudden drop, resulting in relatively sustained sub-atmospheric under-pressure[43]. In reality, there may be multiple shock waves from a single IED as explosives may detonate at slightly different times, with blast waves reflected off physical surroundings[5]. The negative pressure period may cause cavitation within tissues[42], after the blast wave has passed through the skull. Other possible mechanisms of production of TBI include acceleration-deceleration of the brain within the cranial cavity and passage of the blast wave to the brain through a thoracic mechanism[44], via the vascular system or from the cerebrospinal fluid in the spinal canal to the foramen magnum[5].

Researching helmet design and blast TBI

An accurate experimental model is required to determine exactly how brain injury is produced. However, the complex anatomy of the head has made development of such a model difficult. In the past, a variety of models have been used with various methods to simulate trauma. These have included: drop tests of embalmed cadaver heads on plates, air blasts to exposed cadaver brains and hammer blows to animals[45]; a bare head-form against an anvil[46]; fitting helmets direct to a monorail drop tower or variable weight flat impactor[10]; firing 9 mm pistol rounds at dry skulls and cadavers[23]; subjecting animals to blast via a shock tube[47]; and various types of surrogate human head forms containing sensors subjected to different types of blunt force trauma[48] and blasts[49-51].

Moss et al[35], used a hydrocode, a computer code for modeling fluid flows at various speeds[52], to study blast waves impacting a very simplistic face-head model. They found that even at non-lethal blast pressures, the action of blast waves frontally on the head caused the skull to flex significantly so as to cause 'potentially damaging loads' on the brain, as distinct from the usual coup-contre-coup injury seen with blunt-force trauma. Skull flexure is likely to generate shearing injuries in underlying brain structures.

Further testing was performed with the model wearing a Kevlar helmet shell with either PASGT style webbing or ACH style padding. Their results showed that the helmet with webbing-only generated an 'underwash' that actually focused the blast wave under the helmet to produce pressures exceeding those outside the helmet. The padded helmet mostly prevented this underwash, but strongly linked the head to the helmet, and thus subjected it to more acceleration and deformation. These findings were subsequently replicated by Li et al. [24]. Concerns about under-pressure below helmets dates back to 1943, with reports of US soldiers suffering cervical spine injuries from blast while wearing the chin-strap on their M1 helmets buckled up[53].

Nyein et al.[54] used a sophisticated head model with intra-cranial contents and

a computer programme that simulated coupled fluid-solid dynamic interactions, exposing it to frontal blast wave simulations in three scenarios: when uncovered; wearing an ACH; and wearing an ACH-with a 'conceptual' face shield. While they found that the ACH produced no significant reduction in blast effect on brain tissue, they also concluded that it did not produce any harmful focusing of blast wave under the helmet. Finally, the helmet-face shield combination was found to significantly reduce the magnitude of stresses transmitted to the brain by preventing the soft facial tissues from direct contact with the blast wave.

These findings received considerable coverage in the popular media[2-4]. Some headlines implied that the government was not supporting the troops at the front by supplying ineffective equipment, always a sensitive allegation. However, it should be emphasised that the article reported only one set of experimental findings that have not been replicated

The addition of face-masks to helmets is not new. In World War I, the German 'Coal Scuttle' helmet came with an optional face-shield attachment, but was seldom worn as soldiers found it was too heavy and ungainly[11]. Helmets with face shields are commercially available. A quick Google search will show that they come in a wide variety of designs, from bolt-on accessories to existing helmets through to fully enclosed units for explosive ordnance disposal with their own life-support systems attached. However, face shields can get in the way of sighting a weapon or accessing communications gear, and as with ballistic glasses or goggles, are likely to fog up with exertion producing a reduction in visibility.

Finally, Moss and King[55] suggested that an increase in foam padding by as little as an eighth of an inch could provide a reduction of force to the skull of 24%.[56] Unfortunately, more padding inside helmets would require a bigger and heavier sized helmet, a suggestion likely to be unpopular with troops who already feel weighed down by equipment.

Helmet sensors

Public concern over the prominence of TBI has led the US Government to make a massive investment in research on the subject[41]. As part of this response, the US Naval Research Laboratory and Allen-Vanguard developed the Environmental Helmet Sensor (EHS)[50]. Attached over the occipital area of the helmet, and rather bulky, the sensors contain instruments to measure and record up to 500 concussive events. With battery power for 7 months continuous operation, the sensors are said to be able to measure acceleration up to 4000g in three directions, ambient temperature and peak pressure of up to 17 atmospheres. Furthermore, they claim the sensors can distinguish between blast and blunt trauma events. Several thousand were deployed with the US Army and Marine Corp in both Iraq and Afghanistan[50].

BAE Systems developed the much smaller Headborne Energy Analysis & Diagnostic System (HEADS) which fits inside the crown of a helmet[57]. Said to be capable of recording acceleration in three axes and atmospheric pressure changes, it can download data to a PC via a USB port and uses commercial off the shelf rechargeable batteries[58]. The US Army issued a total of 7,000 helmet sensors to troops from the US 4th Infantry and 101st Airborne Divisions deploying to Afghanistan over 2008-9[59]. However, to date, no findings have been published from data collected by either of these devices.

In 2010, BAE Systems touted the development of the HEADS Generation II device[60]. About the same size, but only a third of the weight of the Generation I system, it too is worn inside the helmet. The manufacturers claim this device can record impact location, magnitude, duration, blast pressure, angular and linear accelerations as well as the exact times of single or even multiple blast events. After an impact of a predetermined threshold, the device activates a LED light that notifies the wearer they may have suffered a significant event that warrants medical assessment. Data about trauma events can be then be transmitted by wireless or via a USB port[61]. The HEADS II sensor was described as 'not a diagnostic medical device, but rather an exposure monitor'[62]. However, there is potential for clinical applications, via the downloading of data on the extent or frequency of impacts, or the indication of over-pressure; especially with unconscious patients.

Cheriyan et al. [63] proposed a design for a multi-sensor system attached inside combat helmets that was capable of recording acceleration, air pressure changes, pulserate, oxygen saturation and electro-encephalographs (EEG) in real time. The same team subsequently suggested further enhancing this technology, through the development of networks of helmet-based nano-sensors that could be linked via wireless to personal electronic health records and forward medical teams, alerting clinical personnel to potential injuries to soldiers while they were still in the field[64].

However, the practical application of such innovative cyber-physical systems is likely to be limited by the need for rapid movement of casualties in combat and the salience of treatment for more immediate, co-occurring life-threatening injuries. Nevertheless, the data obtained from such sensors could provide a wealth of information for less urgent management and for later research.

Future research and recommendations

Blackman et al.'s [8] key recommendations that helmet design needs to provide protection from both blast over pressure and impact are obviously correct. Particular research emphasis is required in the immediate future to determine how best to give protection from high velocity impact from military rifle rounds, as it seems that ballistic materials are now available to manufacture 'bulletproof' helmets. Protection from blast and impact are likely to be achieved through optimising padding inside the helmet and the gap between helmet and head. Vehicles that are likely to be exposed to blast should be provided with generous padding[8] and appropriate compartment lining to reduce the risk of secondary and tertiary blast injury. Other clear directions for future work are in developing more accurate headform models and improved hydrocodes to facilitate research. Processing and publishing the data obtained from combat helmet sensors used in the field should provide valuable information about all types of TBI to inform future research and development.

Blackman et al.[8] also recommended conducting research into the aerodynamic effects of the shape of body armour and helmets and how they might influence the direction of blast waves. With respect to human factors, the same authors suggest that military basic training should include neck-strengthening exercises to improve the coupling of neck to body to deal with impacts, citing the US NFL experience that this strategy has reduced concussion.

Finally, gains made in effectiveness, comfort and acceptability of helmets through use of lighter, stronger high-tech materials risk being lost with the addition of accessories such as helmet sensors and face shields. Human nature being what it is, combat helmets that are too heavy, too hot, uncomfortable or unable to be modified to suit the individual are always likely to be worn less often than they should, with attendant increases in risk of injury.

Conclusions

Science has evolved helmet design to produce combat helmets that can protect wearers from significant blunt force and potentially, penetrating injuries. The recognition of the extent of mTBI in Iraq and Afghanistan, especially from IEDs, has placed new demands on combat helmets, and challenges for helmet designers to meet the threat from blasts. These challenges are being researched and addressed; however, it is likely that there will remain a delicate balance between protection from trauma and the comfort and practicality of the user; and the likely decrease in fatal injuries with an increase in non-fatal injuries, such as mTBI.

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