Blast wave protection in combat helmet design - a historical comparison

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ABSTRACT

Since World War I, helmets have been used to protect the head in warfare. They have been designed primarily for protection against artillery shrapnel. More recently, helmet requirements have included ballistic and blunt trauma protection, but neurotrauma from primary blast has not been a key concern in helmet design. This study compares the blast protective effect of historical (WWI) and current combat helmets, against each other and the 'no helmet' case, for realistic shock wave impingement on the helmet crown. Helmets included WWI helmets from the UK/US(Brodie), France (Adrian), Germany (Stahlhelm), and a current US combat helmet (ACH). Helmets were mounted on a Hybrid III® (Humanetics) dummy head and neck and faced towards the ground with a cylindrical blast tube (30.5 cm diameter) aligned along the crown of the head to simulate an overhead blast. Primary blast waves of different magnitudes were generated. Peak reflected overpressure at the open end of the blast tube was compared to peak reflected overpressure at the crown of the head. A general linear model was used to assess the effect of helmet type and tube pressure on the resultant crown pressure response. The interaction between helmet type and tube pressure was found to have a significant effect on the outcome. 'No helmet' and the Adrian helmet were each found to be statistically significantly different from all other helmets. The peak crown pressure was lowest in the Adrian helmet and highest in the 'no helmet' case. The Stahlhelm, Brodie, and ACH were not found to be statistically different from each other. The study demonstrates that both the historical and current helmets have some primary blast protective capabilities, and that simple design features may improve this capability for future helmet systems.

INTRODUCTION

"That men do not learn very much from the lessons of history is the most important of all the lessons that history has to teach." - Aldous Huxley

At the start of World War I (WWI) in July 1914, helmets were not part of the standard military equipment for any of the allied or central powers (Dean, 1920). Most headwear consisted of cloth (e.g. French Kepi (Coune, 2012)) or leather (e.g. German Pickelhaube (Bull, 2000)) and did not offer the wearer any protection from blasts, shrapnel, or ballistic impacts. They served mostly decorative/esprit de corps purposes or offered protection from the cold (Dean, 1920). Months into the war, medical personnel realized head injuries could be dramatically reduced by providing soldiers with head protection (Atlas, 2007). Multiple reports at the time estimate that over 50% of fatalities occurred due to shrapnel or artillery shell fragments, against which steel helmets could be effective (Dean, 1920). Head wounds reported by doctors constituted 10-15% of total wounds (Dean, 1920), but this number is likely lower than the true proportion of head injuries due to the high morbidity of these wounds causing soldiers to die on the battlefield rather than survive and reach medical assistance. As the war progressed, increasingly more trenches were dug, often causing heads to be the most exposed part the body, and thus the need for head protection increased (Griffith, 2013).

France was the first nation in WWI to develop steel helmets and issue them as part of the standard equipment for soldiers (Amalric, 2008). Inspired by the effectiveness of a simple steel cap-lining inserted under the Kepi, General Adrian designed a steel military helmet that was produced and distributed in the spring and summer of 1915. This helmet is now known as the M15 Adrian Helmet (Amalric, 2008). The Adrian helmet was constructed with parts of multiple steel plates, requiring more than 70 manufacturing operations to produce (Dean, 1920).

At the same time, the British faced the same need for head protection. Inventor John L. Brodie designed a helmet focusing on shrapnel protection and ease of manufacturing. The Brodie helmet was made with thicker steel and a wider flared brim than the Adrian helmet. Beginning September 1915, helmets were provided to front line soldiers as fast as they could be manufactured, covering most troops by early 1916 (Dunstan, 1984). Other nations also used the Brodie helmet, including the United States when they joined the war in France in late 1917. Initially, the US bought helmets from Britain, but later produced their own similar version called M1917 (known as Doughboy helmet) (Arnold, 1997).

The development of a standard issue helmet for the German army took more time. After extensive testing of Allied helmets and prototypes, the Stahlhelm (translation: steel helmet) was approved for production at the start of 1916 (Baer, 1985). The Stahlhelm provided more protection for the sides and back of the head but was heavier than both the French and British helmets (Dean, 1920). It was distributed to soldiers in February 1916, at the Battle of Verdun (Baer, 1985).

These helmets were primarily designed to protect against artillery shell shrapnel, and they were effective in doing so (Dean, 1920). Besides propelling shrapnel, exploding artillery shells also create a shock wave. In WWI, the effects of these blast waves were experienced on a large scale for the first time. Soldiers who experienced explosions in close vicinity were delivered to field hospitals despite having little to no signs of external trauma. They reported loss of consciousness, memory loss, speech impediment, vision impairment, hearing impairment, headaches, anxiety, insomnia, depression, and spasms. British physician Charles Myers used the term ‘Shell Shock’ in 1915 to describe this traumatic brain injury (TBI) (Jones, 2007; Myers, 1915).

Since the Napoleonic wars, exploding artillery shells have been the largest cause of combat casualties in major conflicts (Holmes, 2001). These numbers include shrapnel by the shells as well as blast wave effects. In U.S. wars since WWI, there has been an increasing trend towards greater number of casualties being caused by explosions, with 78% of all injuries in the 2001-2005 period of the conflict in Iraq being caused by explosions (Owens, 2008). In the conflicts in Iraq and

Afghanistan, over 65% of reports of TBI were associated with an explosion (Wojcik, 2010). In a 2008 study of U.S. Army Infantry soldiers returning from deployment in Iraq, more than 15% of them were found to have some form of mild traumatic brain injury (mTBI) (Hoge, 2008). Recently, blast neurotrauma criteria have been developed by Rafaels et al. (Rafaels, 2012; Rafaels, 2011) that provide assessment tools for primary blast effects on the head.

This study assesses the blast protective capabilities of principal military helmets from WWI combatants compared with a modern composite helmet. For the three historical helmets discussed in this study, no record of primary blast evaluation was found in the scientific literature, the current study is to our knowledge the first to assess the protective capabilities of these historic combat helmets against blast. Blast brain injury was first recognized around the same time these helmets were being developed and is a now a generally recognized mechanism of injury. We investigate whether improvements have been made in combat helmet primary blast protection, or if there is something we might learn from these 100-year-old designs.

METHODS

Helmets

Three authentic historical WWI infantry combat helmets including original lining were acquired for blast testing: an M15 (1915 model) Adrian Helmet used by the French Army, an M1916 Stahlhelm used by the Imperial German Army, and an M1917 Brodie Helmet used by the U.S. Army (based on the M1915 British design). As a comparison to current combat helmets, the Advanced Combat Helmet, the current combat helmet used by the U.S. Army, was included (size large). A 'no helmet' bare head case was used as a control.

The three WWI helmets are made of formed steel, and the Advanced Combat Helmet (ACH) has a fiber composite construction. Weight and wall thickness of each of the helmets, and abbreviations used in this manuscript are described in Table 1. High resolution X-ray computed tomography (Nikon XTH 225 ST, Nikon Inc.; Minato, Tokyo, Japan) images were made of the historical helmets and coronal sections are displayed in Figure 1.

Table 1: Helmet abbreviations and properties

Helmet	Abbreviation	Weight (kg)	Thickness (mm)
Adrian M15 helmet	FRC	0.67	0.75
Stahlhelm M1916	GER	1.23	1.20
Brodie M1917 helmet	AMR	0.88	0.95
Advanced Combat Helmet	ACH	1.51	8.40
Bare head	BAR	/	/

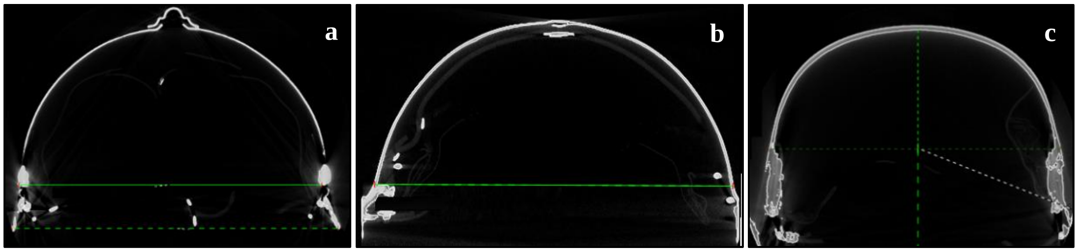

Figure 1: Coronal CT sections of (a) Adrian helmet, (b) Brodie helmet, (c) Stahlhelm. The Adrian helmet (a) is the thinnest steel followed by the Brodie (b) and the Stahlhelm (c).

Blast Setup

Helmets were mounted on a Hybrid III® 50th percentile male dummy (Humanetics; Farmington Hills, MI) head and neck and were secured in place by cable ties around the chin and back of the dummy head (Figure 2). For the ACH, original helmet straps were used. Each helmet had both the external steel components and internal textile/leather components intact. The dummy head was faced downwards, and the center of the head was aligned with the open end of a cylindrical blast tube (schematic in Figure 3). This simulates an overhead blast scenario, as would have been common in trench warfare due to artillery shells exploding above trenches.

The top of the helmet was aligned with the end of the blast tube. The blast tube has a diameter of 305 mm and consists of a driver section (305 mm length), where helium gas is compressed, and a driven section (3.05 m length). The driver and driven section are separated by a diaphragm consisting of a number of polyethylene terephthalate (PET) membranes, with a thickness of 0.254 mm each. Pressure is increased in the driver section until the PET diaphragm bursts, allowing a shock wave to travel down the driven section of the blast tube. The 10:1 driven length to driver length ratio allows the shockwave to develop a uniform shock front, with approximate equal pressure across the tube section (Yu, 2014).

The helmets were exposed to blast waves generated by bursting 2 (total thickness: 0.508 mm), 9 (2.286 mm), and 12 (3.048 mm) PET membranes. These choices for membrane thickness and resulting blast intensity were made to approximate blast levels corresponding to 50% risk for respectively mild meningeal bleeding, moderate meningeal bleeding, and severe meningeal bleeding based on ferret brain blast data by Rafaels et al. (Rafaels, 2012), for a bare head scenario. In total, 46 blast tests were performed, detailed in Table 2.

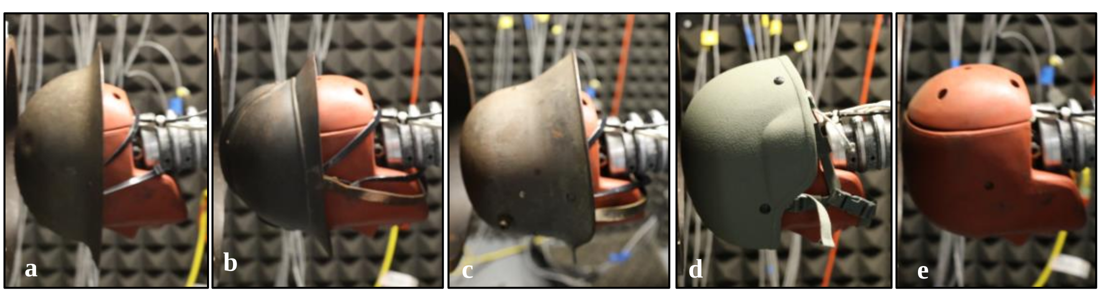

Figure 2: (a) Brodie helmet, (b) Adrian helmet, (c) Stahlhelm, (d) Advanced Combat Helmet, (e) No helmet.

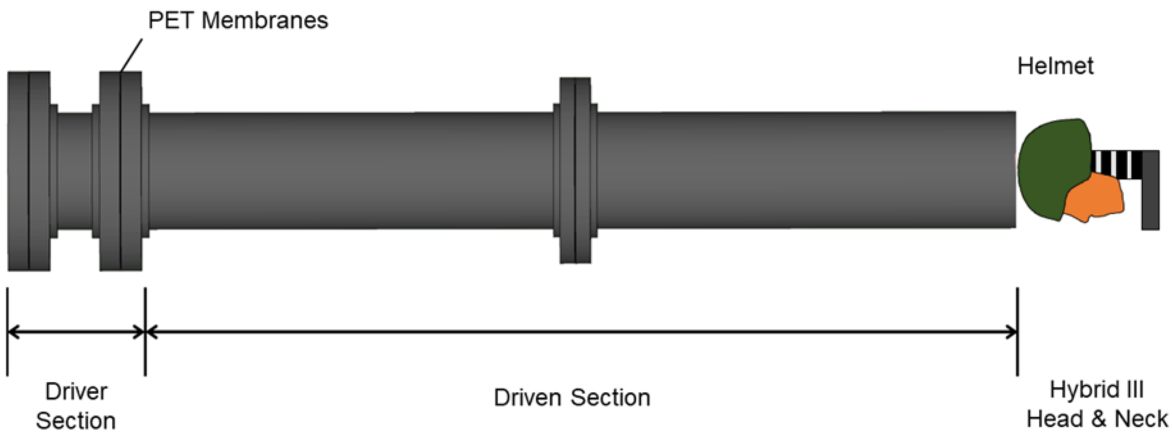

Figure 3: Blast tube setup for this study. Exposure is in the direction of the crown, simulating overhead blast that is typical exposure for personnel in trenches or prone on the ground.

Table 2: Number of blast tests performed for each case, 46 in total

	Number (thickness) of PET burst membranes		
Helmet	2 (0.508 mm)	9 (2.286 mm)	12 (3.048 mm)
BAR	4	4	3
ACH	3	3	3
GER	3	4	2
AMR	3	3	2
FRC	3	3	2

Data acquisition

Blast overpressure was measured using 3 pressure transducers (Endevco 8530B; San Juan Capistrano, CA) at the exit of the blast tube, inside the tube wall, incident to the direction of the wave. One transducer was positioned at the top of the tube, with the two others symmetrically positioned 120° clockwise and counterclockwise from the position of the first. In addition to tube pressure measurements, 5 pressure transducers were inserted in the Hybrid III dummy head. Oriented radially outward, transducers were located at the crown, forehead, right ear, left eye, and back of the head. In this study, only the pressure at the crown of the head (Figure 4) is analyzed. A 3-axis load cell (Model 2564, Robert A. Denton, Inc; Rochester Hills, MI) was mounted between the Hybrid III Head and Neck, to examine neck forces and bending moment. Neck load cell data were not analyzed in this study. Pressure and neck force were sampled at 200 kHz, using a meDAQ® (Hi-Techniques, Inc.; Madison, WI) data acquisition system. High speed video of each blast was collected at 8000 fps using a Phantom® V711 camera (Vision Research; Wayne, NJ).

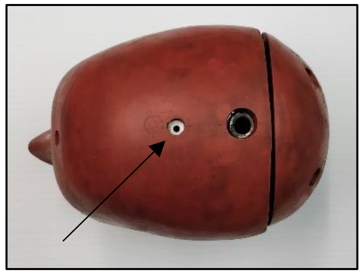

Figure 4: Top view of Hybrid III® head with crown pressure sensor location indicated.

Pressure conversion

To compare pressure measured by 'side-on' transducers in the wall of the blast tube to pressure measured by the 'face-on' transducer at the crown of the head, Rankine-Hugoniot relationships were used to convert the incident pressure to reflected pressure (Bass, 2012). The relationship between incident and reflected pressure in air is given by Equation 1.

$$P_{refl} = 2P_{inc}\left(\frac{7P_{atm}+4P_{inc}}{7P_{atm}+P_{inc}}\right) \quad (1)$$

In Equation 1, P_{refl} is the reflected pressure (gauge), P_{atm} is the atmospheric pressure, set to 101.325 kPa, and P_{inc} is the measured incident pressure (gauge).

Injury risk curves

Injury risk curves from Rafaels et al. (Rafaels, 2012) were used to provide a brain injury risk value for the measured crown overpressure. Mild, moderate, and severe meningeal bleeding risk curves were obtained from scaled ferret blast brain experiments. Using Equation 1, the risk curves were converted from incident to reflected pressure.

Blast simulation

Tested blast conditions were compared to German artillery shell explosions from WWI. Information on German artillery shells is shown in Table 3 (Great Britain War Office, 1916). The distance from the charge to experience a blast similar to the tested conditions was calculated for each of these shells using ConWep (U.S. Army Corps of Engineers, Protective Design Center). Tested blast conditions were binned into 3 severity groups based on PET membrane thickness used to generate the blast (Table 4). Mean bare head crown pressure and positive phase duration were used as a representative blast for each severity level. The results of the simulations are displayed in Figure 5, showing at what range the tested blast conditions would compare to WWI German artillery shell explosions.

Table 3: German artillery rounds used in WWI (Great Britain War Office, 1916)

German Artillery	**Shell Weight (kg)**	**Explosive Charge (kg-TNT)**	**Rounds Fired (million)**
77 mm FK	6.5	0.4	156
105 mm FH	15	1.5	67
150 mm FH/K	38.6	5.6	42
210 mm Mörser	114.5	11.6	7

Table 4: Severity bins for bare head blasting conditions

Severity	PET membranes (thickness mm)	Peak Crown Pressure (kPa +/- SD)	Positive Phase Duration (ms +/- SD)
Low	2 (0.508)	880 +/- 91	1.47 +/- 0.11
Medium	9 (2.286)	3558 +/- 224	3.25 +/- 0.07
High	12 (3.048)	4521 +/- 488	3.66 +/- 0.13

Statistical Analysis

JMP® Pro 13.0.0 (SAS Institute Inc.; Cary, NC) was used for statistical analysis. A general linear model (GLM) was constructed using least squares fitting with peak crown pressure as the outcome variable. The independent variables were helmet type and measured peak tube pressure. The interaction between helmet type and peak tube pressure was found to be significant and was included in the model. The difference between effect of helmet types on the resultant crown pressure was compared using a Tukey HSD (honest significant differences) test, with the peak tube pressure as a covariate. The threshold for statistical significance was chosen to be $p < \alpha = 0.05$.

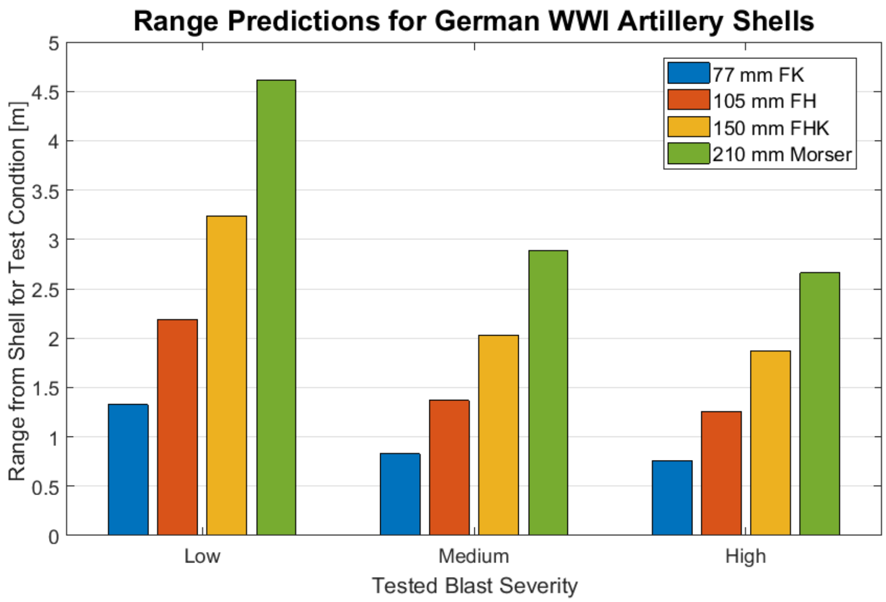

Figure 5: Distance from a WWI German shell explosion to experience blast conditions tested in this study. Bare head testing conditions were used to find these distances.

RESULTS

In total, 46 blast tests were performed for the 5 cases, described in Table 2. After observing deformations that may affect the structural integrity in the Brodie and Adrian helmet (Figure 6) at the highest tested peak pressures, it was decided to keep the number of 3.048 mm PET tests at 2 for the historic helmets.

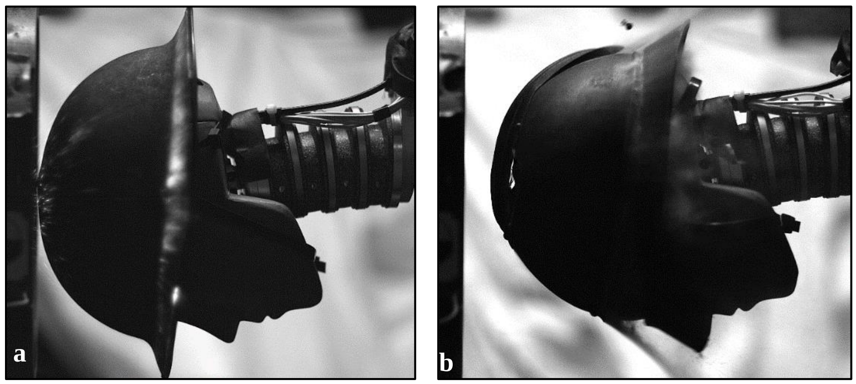

Figure 6: Frames from high speed video recording of high intensity blast tests immediately after blast wave impingement on the (a) Brodie helmet and (b) Adrian helmet .

Peak tube pressure, helmet type, and their interaction were each found to have a statistically significant effect on the crown pressure ($p < 0.0001$). The 'no helmet' control case was found to be significantly different from all helmet cases ($p < 0.0001$ for all comparisons), with a higher resultant crown pressure. The French Adrian helmet (FRC) was significantly different from the ACH ($p < 0.005$), GER ($p < 0.005$), and AMR ($p < 0.05$), and had a lower crown pressure measurement outcome. The ACH, Stahlhelm (GER), and Brodie helmet (AMR) were not found to be significantly different from each other ($p > 0.05$). The results of the general linear model are shown in Figure 7.

The blast tests carried out at different amplitudes were found to be in the 50% risk range for mild (0.508 mm PET), moderate (2.286 mm PET) and severe (3.048 mm PET) meningeal bleeding for the bare head (Figure 8) based on the scaled ferret risk curves. Wearing a helmet was associated with a decrease in bleeding risk. This shows that the tests carried out simulate realistic exposures where wearing a helmet might change physiological outcomes in the brain. In Figure 9, the 50% moderate meningeal bleeding case for the bare head is compared to the helmet results at that level. For the same blast conditions, risk of moderate bleeding is lower than 10% in all helmets, and close to 1% for the Adrian helmet.

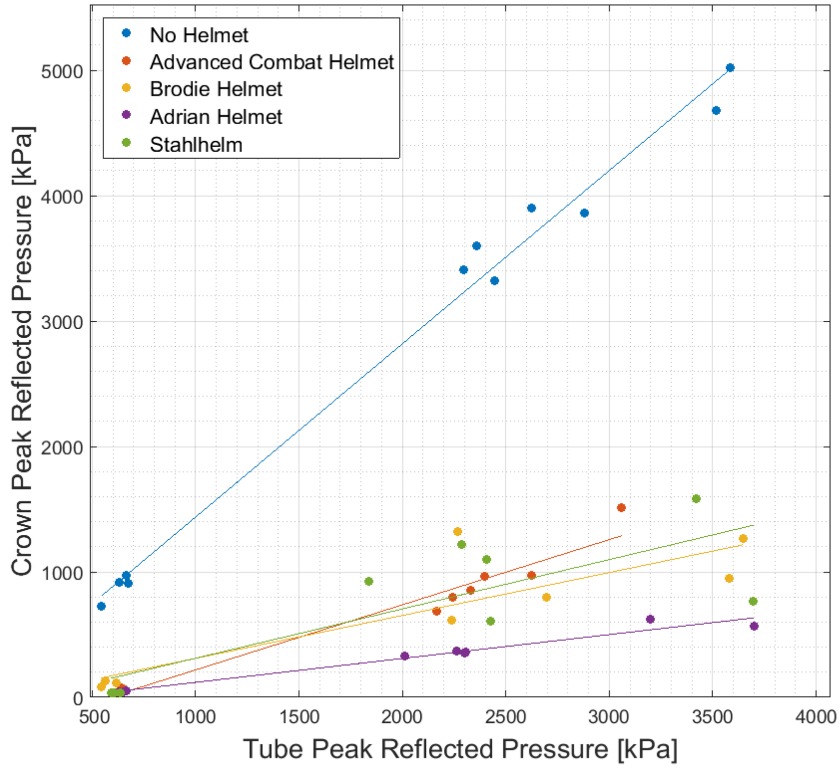

Figure 7: Measured tube and crown pressure for each test performed, and the linear model fit for each helmet type. Bare head crown pressure is higher than all helmets ($p<0.0001$), and the French Adrian helmet crown pressure is lower than the other helmets ($p<0.05$).

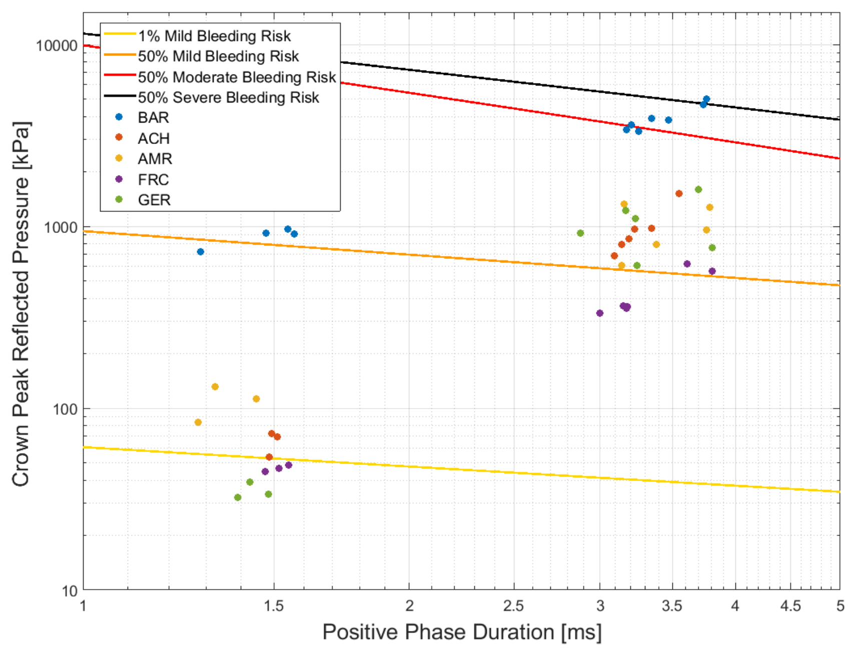

Figure 8: Tested blast conditions plotted on brain blast meningeal bleeding risk curves from Rafaels et al. (Rafaels, 2012). Bare head testing conditions are roughly situated in the 50% mild, moderate, and severe meningeal bleed risk range, whereas the bleeding risk for helmeted tests is much lower (see Figure 9 for a more detailed example).

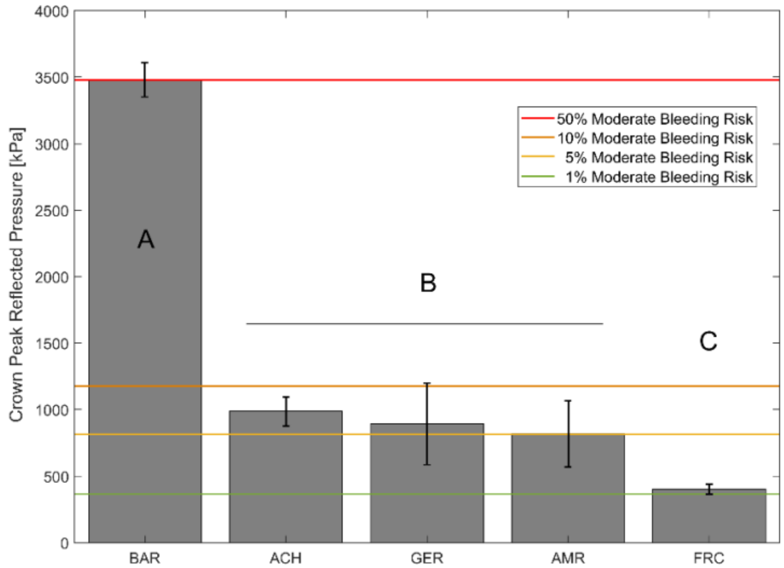

Figure 9: Peak reflected crown pressure prediction by the model at 2480 kPa tube pressure (50% bare head moderate bleeding), including 95% confidence intervals. Helmets with a different letter designation have a statistically different response. For a 50% moderate bleeding risk in the bare head scenario, moderate bleeding risks for all helmets is more than 5x lower for the same testing condition.

DISCUSSION

The bare head exposure was more severe than helmet exposure in every blast scenario. The bare head experienced substantial higher peak pressures (at similar positive phase durations), which correspond to higher risk of meningeal bleeding and other potential brain injuries. At lower pressure levels, helmets provided more shock wave attenuation than at higher levels (Figure 7), suggesting that helmets might play an especially important role in protection against mild traumatic brain injuries (mTBI). We want to emphasize here that the effect of wearing a helmet, especially for short positive phase durations (0.5-5 ms), corresponds with a clear reduction in risk of blast brain injury. In recent literature, the idea of an 'underwash' effect has been proposed (Ganpule, 2012; Kulkarni, 2013; Moss, 2009; Sarvghad-Moghaddam, 2017), amplifying pressures by reflections in the space between the helmet and head, possibly increasing the risk of injury. Often in these discussions, the purported increase in pressure is a misunderstanding of relationship between reflected pressure and incident pressure at the same point in a blast field. Reflected pressure measurements can be 2-8 times greater than incident pressure measurements (Bass, 2012).

An interesting result from these experiments is the blast protective effect provided by the French M15 Adrian helmet, which had a lower crown pressure than all other helmets, despite being manufactured using similar materials as the Stahlhelm and Brodie Helmet, with a thinner helmet wall (Table 1). We suspect this result might stem from the deflector crest along the midline of the helmet (Figure 1a). Specifically added with overhead shrapnel in mind (Jouineau, 2009), this feature of the helmet could deflect the shock wave off to the side of the head, rather than allow shockwave impingement onto a more planar surface seen in the other helmets. The crest also provides an added first layer for shock wave reflection before reflecting a second time off the helmet itself. The crown pressure sensor used in the measurements was located under the deflector crest and may have experienced a decreased peak pressure because of this. Further studies are needed to see if surface geometry manipulation or helmet attachments may augment the protective capabilities of helmets against blast exposure.

While ballistic protection provided by helmets has increased significantly since WWI and saved many lives (Kulkarni, 2013), the results found here suggest that the ACH did not perform better than the Stahlhelm and Brodie helmet, and performed worse than the Adrian helmet for primary blast, the last three all being 100-year-old steel helmets. While ballistic protection has been an active focus in combat helmets design, protection from primary blast has not been an important design element (Kulkarni, 2013). One of the reasons for this is that the mechanism for blast protection was poorly understood for the first 60-70 year following WWI, before the scientific community (cf. (Cooper, 1991)) identified acoustic impedance as the key to protect against blast waves.

The protection mechanism against blast trauma is different than against ballistic trauma. An ideal protection against ballistic impacts can locally absorb high energy impacts without failure or excessive deformation, by distributing the energy through the material (Jacobs, 2001). Desirable materials have high strength, high modulus, and a high local speed of sound. Protection from primary blast waves can be obtained by attenuating the blast wave using an acoustic impedance mismatch at an interface the wave is travelling through. An increased difference in acoustic impedance causes a higher proportion of the blast wave to be reflected, rather than penetrate into the body where it causes local stresses that can damage tissues (Cooper, 1991). Ideal materials have a high local speed of sound, and a high density. Steel has a greater acoustic impedance than composite fibers have, but since both impedances are magnitudes higher than those of air and tissue, reflection will be relatively similar. This explains the similar results for the ACH, Brodie helmet, and Stahlhelm. Because a shock wave reflection occurs at every interface where there is an acoustic impedance mismatch, primary blast protection can be improved by using multi-layered configurations, with each layer reflecting a proportion of the penetrating wave. Many helmet and body armor materials have properties that are desirable for both ballistic and blast trauma.

Helmet wall thickness improves ballistic protection by providing higher strength and energy absorption, but it doesn't affect blast protection since reflection only occurs at interfaces. While we saw that the Adrian helmet provided superior blast protection in this study, Dean (Dean, 1920) noted that the ballistic protection it provided was less than both the Brodie helmet and Stahlhelm.

One of the limitations of this study is that only an overhead blast scenario was examined. While this would be an accurate approximation of blasts in trench warfare as in WWI or air bombings of soldiers in the field during major unit action, it wouldn't be as applicable to other cases such as improvised explosive devices (IEDs) used as roadside bombs, a significant cause of injury and death in conflicts in Iraq and Afghanistan (Wilson, 2007). Another limitation is that the historic helmets tested are over 100 years old, and their material properties might not be the same as they were originally. While properties of steel are relatively stable, the helmet linings may have degraded. However, there is no guarantee that replicas would be identical copies of the original either, so this study stays as true to the original helmets as possible.

CONCLUSIONS

There is considerable overlap in helmet materials that have good qualities for ballistic and blast protection, but the protection mechanisms are different. Both historical and modern combat helmets provide some primary blast protection capabilities, and modern helmets are not more protective than historic ones. Helmet protection against primary blast might be improved by material choice, multiple layers, or the geometry of the helmet.

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