Blast Mitigation Status of Police Crowd Management Ensembles

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Introduction

Blast: not just a military concern

Between 1992 and 2002, more U.S. citizens were wounded or killed from explosives within U.S. borders than all of the international terrorist incidents that occurred during this same time [1-7]. Yet, according to some researchers, the U.S. healthcare system still considers terrorism an international affair and therefore lacks the knowledge of the public health impact after bombings [8]. Kapur in 2005 and more recently Lerner (2007) published articles outlining the need for non-military terrorism preparedness and the resulting disaster response of civilian factions [9, 10]. These research groups state that criminal bombings utilizing homemade materials occur daily, nearly 5 times a day on average in the U.S. [9, 10]. Although the events of September 11, 2001 have significantly raised awareness of the management of blast injuries in the civilian healthcare community, these research groups still stress that additional explosion specific mass-casualty incidents should be prepared for by civilian disaster management teams, emergency medical services (EMS) personnel, emergency physicians, trauma surgeons, and critical care/burn specialists [9, 10].

Civilian Firefighters and Police Bomb Squad Officers are at particular risk. For example, on June 17, 2001, three firefighters were killed and 80 other emergency services personnel were injured in an explosion at a hardware store in New York City. Further, in the early hours of

March 11, 2004, an unknown number of terrorists boarded four commuter trains in Madrid and distributed 13 bags, each loaded with approximately 10 kg of dynamite. Delayed detonation was designed to achieve maximum damage. The devices killed 191 and injured an additional 388 civilians [11]. The aforementioned statistics and explosive accidents clearly indicate that personal protective equipment (PPE) offering blast protection for first responders such as law enforcement and EMS personnel would be of relevance, when an explosive threat is suspected. The present work is aimed at investigating the blast mitigation properties of standard off-the-shelf riot control gear, which has not been designed for blast protection, against a representative blast threat (no fragmentation).

Integrating Protective Equipment Standards

In military conflicts, fragmentation and bullets typically account for a large percentage of injuries in soldiers deployed in combat and peacekeeping operations [12, 13]. Hence, PPE such as ballistic vests and helmets worn are designed to thwart these typical threats. Some believe that the decline in mortality in Iraq and Afghanistan compared to other wars is due to the advances in body armor worn by the deployed military personnel [14, 15].

On the other hand, it has been shown by researchers at the Walter Reed Army Institute of Research in Washington, D.C. and others, that cloth ballistic vests, although important in limiting critical wounds from fragments and small-arms fire, may actually increase the effective blast pressure experienced by the persons wearing them [16-18]. It is therefore imperative to ensure that PPE worn in an explosive threat environment provide a reasonable level of blast protection, or at the very least does not amplify the effect of blast.

Government agencies and companies contracted to develop products against the emerging blast threat from improvised explosive devices (IEDs), such as Canada's Allen

Vanguard (formerly Med-Eng Systems Incorporated) and the U.S. Army's Program Executive Officer Soldier have not only shown the need for enhanced blast protection for soldiers exposed to IEDs but have also been forced to adopt rapid development projects in order to meet these demands (Figure 1), as is the case of gunners located at the Cupola of High Mobility Multi-Wheeled Vehicles (HMMWV) [19].

Figure 1: Rapid development projects flow chart (top). System concept of Cupola Protective Ensemble in use (bottom). Source: Allen Vanguard Technologies (formerly Med-Eng Systems), Ottawa, ON, Canada 2006

Unfortunately, there is currently no public standard for blast protection, although the U.S. military has developed the Operational Requirements Document (ORD) and a draft Performance Specification for their Explosive Ordnance Disposal Advanced Bomb Suit (EOD-ABS) in the early 2000s. However, the National Institute of Justice is expected to release a new standard for Explosive Ordnance Disposal (EOD) PPE in early 2009 [20]. The main threat that was used to develop the standard was the pipe bomb, which is deemed the most prevalent blast threat for domestic civilians. Preliminary recommendations for the development of blast requirements for this standard have been made by the U.S. Army Natick Soldier Center and the University of Virginia's Center for Applied Biomechanics, based on blast testing involving anthropomorphic mannequins [21].

While EOD personnel are often exposed to blast threats, many other military personnel, firefighters, and police department members are also at high risk. As such, research is conducted to investigate the blast mitigation effectiveness of various PPE, including accessories aimed at enhancing blast protection. For instance, a number of blast mitigating liners for standard issue ballistic helmets are being manufactured and distributed to soldiers in Iraq and Afghanistan through unregulated but legal means [22, 23]. Although widely distributed, few publicly scrutinized blast tests have actually occurred with these devices. In a test conducted in cooperation with Defence Research and Development Canada – Valcartier (DRDC – Valcartier), Biokinetics and Associates Ltd., and Human Systems Inc. the blast attenuation of five off the shelf manufacturer's helmet liners, four different materials of varying densities and thicknesses and current U.S. issue advanced combat helmet suspension system were compared [24]. The results showed that 2 layers of 3/8" VN600 vinyl nitrile outperformed the current manufactured blast mitigating inserts and was found to be the most efficient at blast attenuation. However, mechanical properties of materials such as vinyl nitrile are typically very sensitive to environmental temperatures [25]. Therefore, performance at laboratory temperatures does not necessarily imply good performance at high (Iraqi summer) or low (Afghan winter) temperatures. Blast testing with samples conditioned at various temperatures is warranted.

While a bomb suit standard should be released sometime in early 2009 there is no formal blast attenuation requirement for military, police or firefighting helmets (NIJ Standard-0106.01; NIJ Standard-0104.02; NFPA Standard-1971).) The National Fire Protection Association requirement – NFPA 1971 Standard on Protective Ensemble for Structural Fire Fighting: 2000 Ed. integrates a suitable test for impact attenuation but does not include reference to blast exposure. However, the National Institute of Justice's Riot Helmets and Face Shields – NIJ Standard-0104.02 is currently undergoing extensive review to meet the current overall function of quelling riots and the changing threats that police officers are now exposed to, including blast attenuation from IEDs such as pipe bombs. Further, current PPE are being investigated by the military to adapt to the fragmentation threats of IEDs that typically correspond to larger fragments than those for which the vests were originally designed. For example, introduction of 104 grain, and 207 grain fragments in testing, as opposed to the maximum 64-grain in the current Outer Tactical Vest (OTV) standard [26].

This study aims to evaluate the air blast (only) mitigation effects of a commercially available crowd management ensemble to provide a baseline for the blast protection provided by blunt impact protective equipment not specifically designed for blast protection. It is hoped that these results can be used in the field expeditiously to determine how much additional blast protection might be needed depending on the operational requirements and threats, and eventually help with future designs slated for rapid development.

Methods

Full-Scale Blast Set-up

Full-scale blast testing of the blast mitigation performance of crowd management gear was carried out at the blast-test facility of DRDC - Valcartier, located near Québec City. An instrumented pedestrian model anthropomorphic test device, i.e., automotive crash test mannequin (Hybrid II), which is representative of a 50th percentile North American male subject (height: 1.75 m, mass: 77 kg), was set in a standing position and faced blasts from detonating charges of C4 explosive both with and without the protection from the V-Top crowd management ensemble which includes the CM-1 riot helmet with face shield (Allen Vanguard, Ottawa, Canada – discontinued) (Figure 2).

Figure 2: CM-1 riot helmet with face shield (left) and V-Top Crowd Management Ensemble (center) with coveralls in live riot incident (right).

To support the mannequin in its standing position, supporting bars from a specially designed apparatus were placed underneath each arm. This apparatus allowed the mannequin to fall back with the pressure of the explosion, thus not interfering with its initial natural response to blast exposure (Figure 3).

Figure 3: Typical test set-up with a mannequin unprotected (left) and wearing a V-Top crowd management ensemble with CM-1 riot helmet with face shield (front view – middle, and side view – right). The underarm mannequin supports did not interfere with natural response to blast exposure (bottom).

In all tests, a single explosive charge consisting of 5 kg C4 explosive was detonated from a height 1.5 m above the ground surface (a disposable cardboard stand supported the charge before the test). The charges were square-cylindrical, meaning that their diameter was equal to their height. A remotely initiated detonator served to set off the explosive charge. The standoff distance between the mannequin and the charge (3 m to 5 m) was controlled for each test to obtain the desired blast conditions (Figure 4).

Figure 4: Full-scale blast test set-up using 5kg of square-cylindrical C4 explosive place 1.5 m off the ground (left) and test mannequin (right).

Instrumentation, Acquisition and Filtering

The instrumentation in place on the mannequin consisted of a tri-axial cluster of linear PCB accelerometers in the head in addition to PCB pressure transducers mounted flush to the dummy skin at the approximate locations of the ear and sternum. The side-on (static) ambient overpressure of the blast wave was recorded with a similar pressure sensor located immediately to the right of the mannequin and at the same standoff distance from the explosive charge as the mannequin (Figure 4). The height of the side-on sensors was approximately the same as the height of the pressure sensor on the mannequin's chest.

Instrumentation lines were sampled at 200 kHz for acceleration and 500 kHz for pressure, with an anti-aliasing low-pass filter frequency of 40 kHz applied to all signals. The signals from the accelerometers in the mannequin's head and chest were subsequently filtered (digitally) using a four-pole Butterworth filter set to attenuate signals above 1650 and 600 Hz respectively. The signals from the pressure transducers were also digitally filtered to remove spurious signals, using a two-pole Butterworth filter set to 10 kHz.

Results

Qualitative Analysis

Minor tearing of the protective suit was noticed in this test series. Typical damage consisted of open or torn Velcro closures which resulted in a V-Top shin guard falling off in one case, as well as some ripping of the fleece covering the mannequin in the unprotected tests. The V-Top chest protector and shin guards displayed some cracks, but no dramatic failure occurred. Further, minor damage to the CM-1 helmet occurred; the rubber seal between the shield and helmet was removed during exposure and minor cracking of the face shield occurred near its pivot points. Finally, charring (burn) was not detected on the suit.

Quantitative Analysis

Ear Overpressure

Sample ear overpressure traces are shown in Figure 5 and a summary of the peak ear overpressures recorded is presented in Table 1. The CM-1 riot helmet equipped with a visor is found to help in reducing the ear overpressure, as it allowed an average pressure of 2.06 bar to impinge on the ear while the unprotected ear was exposed to 3.77 bar. It must be mentioned that the CM-1 helmet is not interfaced with any collar when worn with a V-Top ensemble. Collars are known to provide additional blast protection. In the case of EOD PPE a collar is used to provide continuous and enhanced blast protection from the chest to the helmet.

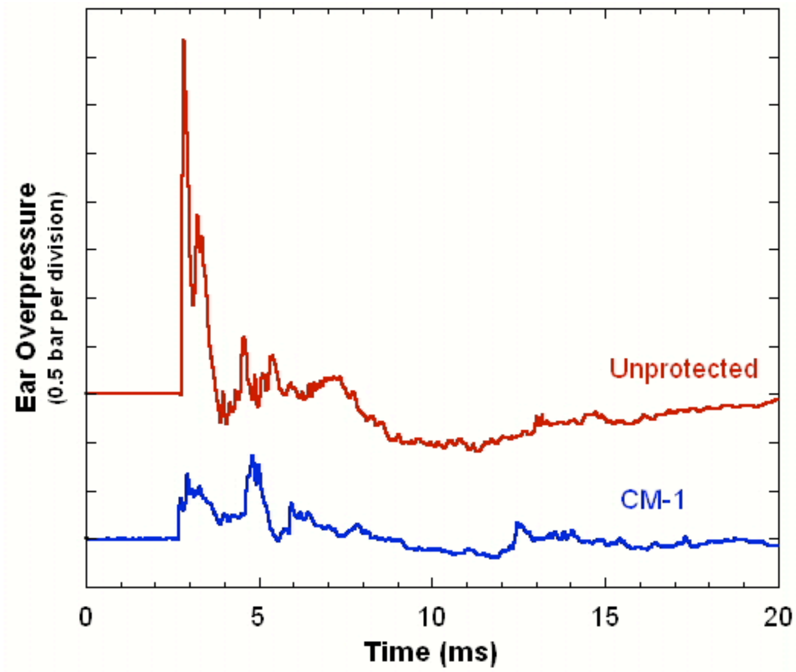

Figure 5: Ear overpressure signals for mannequins facing 5.0kg C4 at a standoff distance of 3 m, either unprotected (red), or underneath the CM-1 protective helmet (blue)

Table 1: Peak overpressure in bar (mean(SD)) measured at the ear of an unprotected Hybrid II mannequin or wearing a CM-1 riot helmet with visor while exposed to a blast from a 5 kg charge of C4 at different standoff distances.

Helmet	**Standoff Distance**			
	3 m	**3.5 m**	**4 m**	**5 m**
Unprotected	3.77 (-)	2.26 (0.471)	1.6 (0.043)	0.92 (0.096)
CM-1	2.06 (0.285)	---	---	---

Blast-Induced Head Acceleration

The resultant blast-induced head acceleration is obtained by combining the results from individual acceleration traces in the X, Y, and Z directions (Figure 6). Sample blast-induced head acceleration traces for both the unprotected and protected (CM-1 helmet) cases are shown in Figure 7 and a summary of the peak resultant head accelerations recorded using the Hybrid II mannequin is presented in Table 2. During the CM-1 helmet donned trials, the resultant head acceleration reached 253 g's, as compared to a value of 374 g's for the unprotected mannequin (for a slightly different explosive charge of 5.1 kg C4).

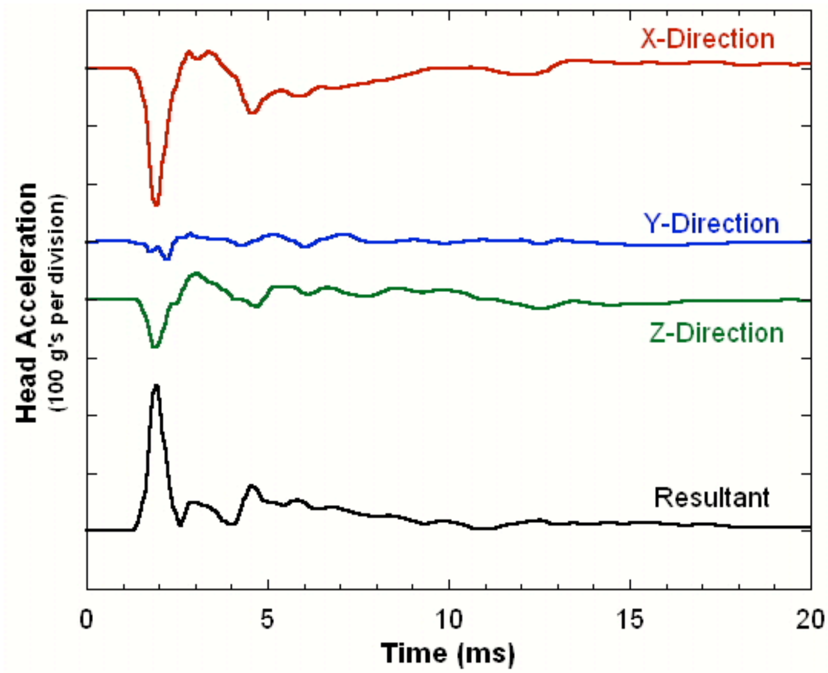

Figure 6: Calculation of the resultant head acceleration for the CM-1 case, when facing 5.0 kg of C4 explosive at a standoff of 3 m. The resultant acceleration trace is obtained by combining the results from the accelerations in the X, Y and Z directions.

conditions) [27].

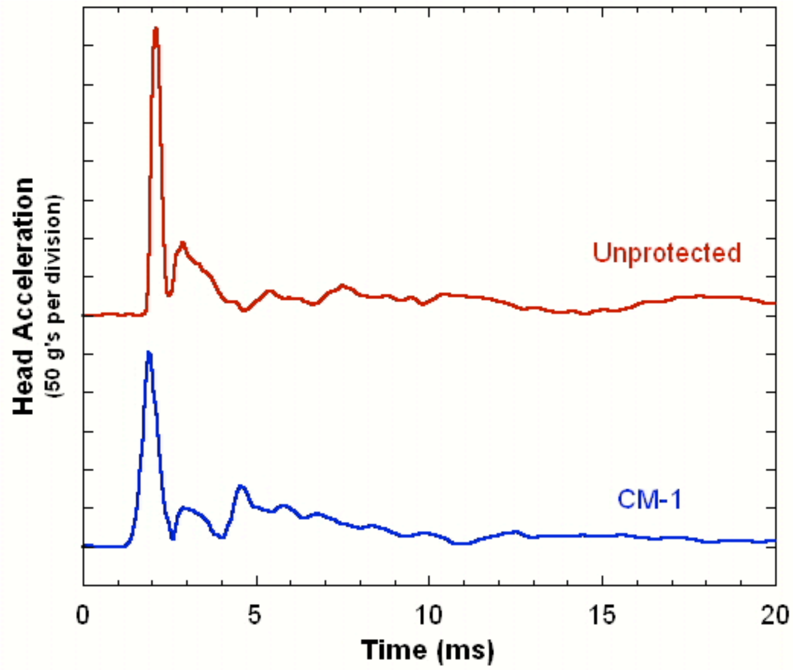

Figure 7: Blast-induced head acceleration signals for an unprotected mannequin facing 5.1 kg C4 at a standoff distance of 3 m (red), and for a mannequin protected with the CM-1 protective helmet (blue) against a 5.0 kg C4 charge at the same standoff of 3 m.

Table 2: Peak resultant acceleration in g's (mean (SD)) measured at the center of gravity of the head of a Hybrid II mannequin either unprotected or wearing a CM-1 riot helmet with visor while exposed to a 5 kg charge of C4 at different standoff distances.

Helmet	**Standoff Distance**			
	3 m	**3.5 m**	**4 m**	**5 m**
Unprotected	374.4 (53.9)*	383.3 (34.2)	331.6 (73.3)	146.3 (25.3)
CM-1	253.5 (-)	---	---	---

* Data obtained with 5.1 kg C4, instead of 5.0 kg C4, from a different test series. All other testing parameters identical.

Chest Overpressure

Sample chest overpressure traces are shown in Figure 8 and a summary of the average peak chest overpressures (bar) from this test series is presented in Table 3. The V-Top chest protector showed a chest overpressure of 4.0 bar while the unprotected chest had an average of 10.1 bar, thereby indicating a reasonable level of blast attenuation, although significantly inferior to what an EOD Ensemble would provide (typically in excess of 90% for similar explosive conditions) [27].

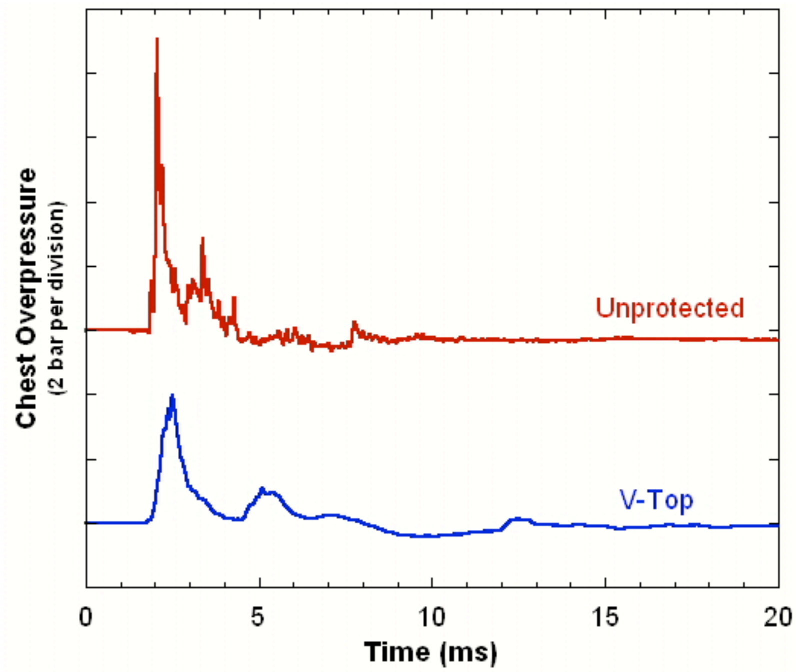

Figure 8: Chest overpressure signals for mannequins facing 5.0 kg C4 at a standoff distance of 3 m, either unprotected (red), or underneath the V-Top protective ensemble (blue)

Table 3: Peak chest overpressure in bar (mean (SD)) measured at the sternum of a Hybrid II mannequin either unprotected or wearing a V-Top crowd management ensemble while exposed to a 5 kg charge of C4 at different standoff distances.

Suit	**Standoff Distance**			
	3 m	**3.5 m**	**4 m**	**5 m**
Unprotected	10.1 (6.0)	9.5 (3.6)	4.5 (0.8)	3.0 (0.2)
V-Top	4.0 (-)	---	---	---

Injury Assessment

Head Injury Criterion

The head injury criterion (HIC) values computed from the test series' resultant head acceleration traces are summarized in Table 4. The HIC value for a Hybrid II protected with the CM-1 helmet was 291, as opposed to 1043 for an unprotected mannequin, showing a significant attenuation in HIC when wearing the CM-1 helmet (it must be noted that a slightly different explosive charge of 5.1 kg C4 was used for the unprotected tests).

Table 4: Peak Head Injury Criterion levels (mean (SD)) measured from the resultant head acceleration of a Hybrid II mannequin either unprotected or wearing a CM1 riot helmet with face shield while exposed to a 5 kg charge of C4 at different standoff distances.

Helmet	Standoff Distance			
	3 m	**3.5 m**	**4 m**	**5 m**
Unprotected	1043 (1032)*	744 (116)	434 (222)	87 (90)
CM-1	291 (-)	---	---	---

* Data obtained with 5.1 kg C4, instead of 5.0 kg C4, from a different test series. All other testing parameters identical.

Chest Overpressure Risk using Recently Developed Injury Charts

The Bowen Charts are a series of injury potential threshold lines, ranging from the 'threshold of lung injury', to '1% survivability' [28]. Recently, similar injury curves ("UVa" curves) have been developed at the University of Virginia (Figure 9). These up to date curves include data from the Bowen Charts as well as more recent data and correlate well to an unfortunate but carefully documented human blast injury accident [29]. Using the UVa curves the equivalent peak side-on overpressure and durations of the measured face-on pressure signal was plotted against these charts to indicate level of injury potential. The severity of the predicted injury for the unprotected case increased as standoff distance was reduced but all hovered on the '50% Survivability' line while the V-Top ensemble reduced the risk to greater than the '90% Survivability' line for the same exposure.

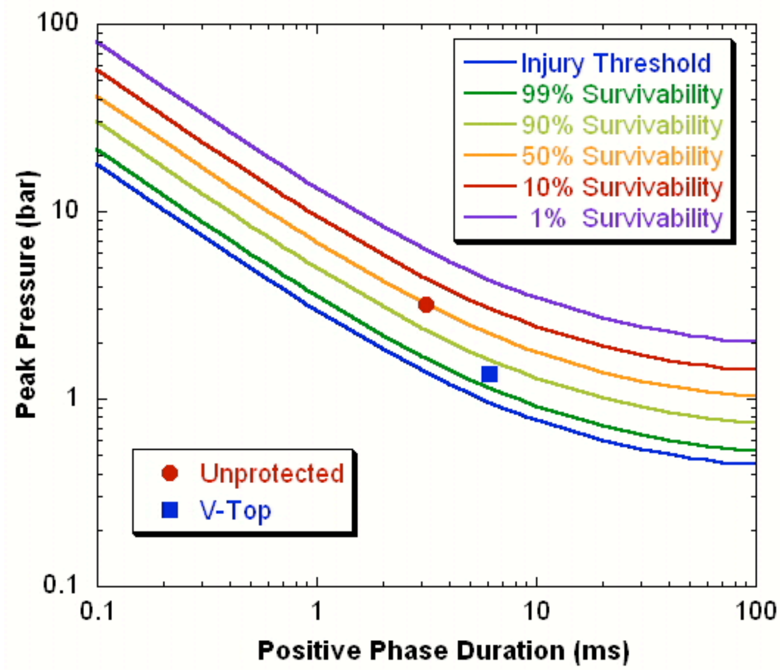

Figure 9: Recently developed University of Virginia Injury Charts for Blast Exposure. Unprotected (circle) and V-Top protection (square) survival probabilities have been plotted for the same exposure.

Discussion

Ear Overpressure

The ear is the most susceptible organ to injury from overpressure and is known for impairing combat effectiveness. The threshold of eardrum perforation lies at a mere 0.35 bar (5 psi). However, damage to the inner ear, which will invariably result in some degree of permanent and irreversible loss of hearing, generally occurs for overpressures above 1 bar (14.5 psi). Although eardrum perforation and loss of hearing are not life-threatening injuries, they can be a life-long handicap with potentially detrimental social consequences. Further, the eardrum acts as a conduit to brain cells and injury to the brain cannot be ruled out should the eardrum be perforated. While both protected and unprotected tests would have resulted in ear perforation and possible brain injury due to uncontrolled overpressure, the CM-1 helmet with visor significantly reduced exposure levels, which means that against lower level blast threats such as pipe bombs typical of police exposure, the CM-1 helmet may have brought the pressure down below the threshold for eardrum perforation.

Head Injury Criterion

When the blast from an explosive impacts the human body, dangerous levels of acceleration can be induced in the head. As a result, concussive injuries, ranging from minor to unsurvivable, can occur. A properly designed protective helmet and suit will be able to effectively reduce head acceleration and therefore reduce injury potential. The CM-1 helmet attenuated the blast-induced acceleration and resulting head injury criterion (HIC) by an important margin. It is reasonable to assume that a reduction in peak head acceleration would help reduce or prevent injuries in most cases. However, the exact design trait to reduce air blast-induced head acceleration is unknown at this time and will be successful only if head acceleration is a major mechanism of brain injury. There is much speculation on this topic and exact helmet design will need to consider the mechanism of injury carefully.

Chest Overpressure Risk

If the blast wave emanating from an explosive, with its sudden rise in overpressure, is transmitted to the torso of an individual, injury to gas containing organs (e.g., lungs and bowels) can result due to tissue impedance mismatch. Shock reflections, along with localized pressure increases, if of sufficient strength, can cause alveoli and other blood vessels to rupture leading to hemorrhaging. Worst-case scenario, the hemorrhaging in the lungs can lead to lethal suffocation. Moreover, hemorrhaging of the bowels can cause fatal internal bleeding and infection. The peak overpressure that impinges on the chest relates closely to these injuries. In stark contrast to the unprotected case, for the particular explosive configuration tested, all full figures were found to lie well below the 90% Survivability lines, which means that injury to the chest internal organs would be significantly reduced when facing these blasts while wearing a V-Top chest protector.

Design considerations

While it is apparent that wearing the V-Top crowd management ensemble and the CM-1 helmet with visor helped protect against air-blast effects, it must be emphasized that fragmentation threats were excluded of the current study by making use of base C4 explosive charges. The V-Top and CM-1 are not designed for fragmentation protection and would perform poorly against such threats. This is critical, given that in most cases where explosive threats are present, fragmentation is the primary mechanism of injury. To prevent such injuries, additional fragmentation or ballistic protection should be worn underneath the V-Top ensemble, or integrated with blunt impact protective components during future modifications.

It must be mentioned that only one explosive configuration was tested, and that the V-Top and CM-1 are not expected to perform well under more severe blast loading typical of military exposures. Furthermore, the results obtained here might not be representative of other crowd management PPE. For instance, the full-face visor, the effective blunt impact liner, and the overall weight of the CM-1 helmet are thought to have significantly contributed to reduction in blast-induced acceleration. Aerodynamic considerations might also have been responsible for some reduction in the total load being applied to the head and helmet. Lighter helmets with less visor coverage might not perform as well since it has been noted that air blast introduced under the visor allows the helmet to act as a parachute and creates large neck loads through the chinstrap. Rather, an aerodynamically designed full-face helmet with an integrated collar may have performed much better. Although it is suspected that the visor coverage is of much more importance than placing emphasis on an integrated collar when using a visor with less coverage. As such, each ensemble should be tested separately to ensure positive results.

Other considerations involve using head acceleration as the sole evaluation of head injury. It is possible and quite likely that brain injury is multi-modal and cellular loading mechanisms occurs through various means such as skull compression without head acceleration or neck and gullet overpressure loading that is then transmitted to brain or lung tissue. In this case, neck and gullet coverage from chest to head would be required.

To mitigate chest overpressure one must consider chest plate lamination. Again careful consideration of material and its mechanical properties must be maintained since certain chest laminations lead to increased chest overpressure and result in increased injuries [17]. Although some level of blast attenuation was provided by the V-Top ensemble, much more effective blast mitigation can be achieved through the use of various materials [30].

Nevertheless, the current results seem to indicate that some level of blast overpressure protection is provided by commercially available crowd management equipment. It must be emphasized again that crowd management ensembles are not suitable for EOD or mine clearance work, as they provide no fragmentation protection, which is the main source of injuries from IEDs.

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