Protecting Warfighters from Blast Injury

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Center for a
New American
Security

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ABOUT THIS REPORT

This report, the third in the *Super Soldiers* series, covers findings from the Center for a New American Security's study on dismounted soldier survivability. This study was conducted for the Army Research Laboratory to identify future concepts and technologies to improve soldier survivability and effectiveness over the next 20-30 years in order to identify high-payoff science and technology investment areas. While the primary audience for this report is the Army science and technology community, the report's findings and recommendations may be of interest to a broader group of stakeholders, including across the Army, the Joint Force, and the wider defense community.

Views expressed in this report are of the authors alone. CNAS does not take institutional positions.

Executive Summary

Key Findings

- Hundreds of thousands of servicemembers suffer from traumatic brain injury (TBI), including from exposure to blasts from improvised explosive devices (IED).
- Emerging evidence suggests that servicemembers may be exposed to high levels of blast overpressure (the pressure wave that comes from explosions) when firing heavy weapons, such as the Carl Gustaf recoilless rifle, even in training.
- DoD studies have demonstrated that some servicemembers experience cognitive deficits in delayed verbal memory, visual-spatial memory, and executive function after firing heavy weapons, even within allowable limits.[1]
- DoD studies have also found higher rates of concussion and post-concussion associated symptoms among individuals with a history of prolonged exposure to low-level blasts from breaching and shoulder-fired weapons.[2]
- Primary blast pressure waves are an important mechanism for brain injury, but the specific causal mechanism is unclear. Multiple theories exist, each with varying degrees of support.
- The Army does not currently have a requirement to protect against brain injury from exposure to blast pressure waves from explosions (aka primary blast injury).
- Computer models and physical experiments have suggested that existing Army helmets provide some modest protection against blast waves and that improved helmet designs, such as adding a modular face shield, could reduce blast pressure in the brain by up to 80 percent.
- In the near term, computational modeling and physical experimentation can be used to assess various existing helmet designs and their response to blasts of various sizes and locations.
- In the longer term, new materials and technologies could be used to mitigate the blast wave through improved helmet design or off-board protection from robotic teammates.

Recommendations

The Army should increase its efforts to protect soldiers against blast-induced brain injury, with increased resources for testing, experimentation, and combat helmet development. Key actions include:

Improve understanding of blast-induced brain injury

- Expand on existing blast pressure monitoring in training and establish a longitudinal medical study on blast pressure exposure during combat and training in order to better understand the relationship between blast pressure exposure and brain injury.

- As part of this study, conduct a blast surveillance program to monitor, record, and maintain data on blast pressure exposure for any soldier, in training or combat, who is likely to be in a position where he or she may be exposed to blasts. Include brain imaging of soldiers who have been exposed to blasts as part of this study to better understand how blasts affect the brain.

- Accelerate computational modeling and experimental research, including with large animal models, into primary blast wave injury in order to better understand how blast overpressure damages the brain.

Improve helmet protection against blast pressure

- Test existing helmets, including commercially available variants with modular mandible and face shields, to determine which configuration and materials best protect against primary blast wave injury as a near-term mitigation against possible brain injury.

- Conduct a tradespace study of the various helmet designs in order to compare the amount of reduced blast pressure to any negative effects, such as increased weight and torque on the neck, reductions in situational awareness, and other operational effectiveness metrics.

- Based on the results of the helmet tradespace study demonstrating the ability of certain designs to reduce overpressure exposure and the drawbacks of various designs, establish an interim requirement for protection against blast overpressure while continuing further research to refine the requirement over time.

Improve safety when training on heavy weapons

- Take prudent precautions to improve soldier safety when training on heavy weapons, while conducting further research to better understand the cumulative effects on the brain of repeat heavy weapons firing.

- Expand ongoing studies of blast exposure in training to include all soldiers who are exposed to high overpressure weapons (e.g., Carl Gustaf, AT4, LAW, .50 caliber sniper rifles, explosives).

    - Require all soldiers to wear blast gauges when training with high overpressure weapons.

    - Blast gauge measurements should be recorded as part of a blast surveillance program and longitudinal medical study on blast pressure exposure and brain injury.

    - Blast exposure history should be included as part of soldier service records (i.e., a "blast exposure record") in order to ensure that, if medical issues arise later, soldiers receive care for any service-connected injuries.

- Review and update firing limits for shoulder-fired heavy weapons, such as the AT4, LAW, and Carl Gustaf. Firing limits should: be revised downward to a level such that allowable exposures are not associated with cognitive deficits after firing; cover exposures across a longer time period, on the order of 72 to 96 hours; include a minimum safe distance for observers and instructors; account for the possibility of multiple types of heavy weapons being fired in a single day; and include cumulative annual and lifetime limits for blast exposure in training.

- Take prudent precautions to improve soldier safety when training on heavy weapons:

    - Increase soldier and commander education about the importance of adhering to firing limits and wearing appropriate protective equipment, such as through a Safety of Use message.

    - Hold commanders accountable, especially in special operations units, for enforcing limits on firing heavy weapons such as the Carl Gustaf in training, and require that units record and report the number of shots fired by each soldier per day in training.

    - Review training guidance for shoulder-fired heavy weapons to maximize the use of sub-caliber training rounds whenever possible, especially by special operations forces.

- Investigate different methods for soldier familiarization and for establishing gunner and assistant gunner proficiency so that gunners, assistant gunners, and instructors are not unnecessarily exposed to blasts.

- Use blast gauges to explore modifying firing procedures, such as adjusting the position of assistant gunners, to reduce blast overpressure exposure.

- Explore the use of prepared firing positions in training with blast-absorbing materials to reduce ground reflection and/or shields to mitigate blast pressure waves.

- Investigate different helmet designs for duty positions that may be at greater risk for blast exposure, such as Carl Gustaf gunners and assistant gunners.

Investigate long-term options for blast protection

- Investigate new helmet materials, shapes, and designs that might dramatically improve protection from primary blast injury.

- Explore opportunities for off-board protection from blast waves, such as from passive or active measures located on robotic teammates.

- Refine the blast pressure protection requirement over time as the understanding of TBI improves.

Introduction

Protecting the head has long been an essential element of armor in warfare. The human skull provides some protection to the brain – a natural form of armor – but the skull can be fractured or penetrated by a sharp blow. Even if the skull remains intact, a heavy blow can cause concussion, damaging the brain. For this reason, soldiers have worn helmets since antiquity. Modern combat helmets are designed to provide some protection against ballistic and blunt trauma injury. The level of protection they provide is balanced with keeping the helmet light enough so that it does not unduly impede mobility or situational awareness.

Threats to the brain that have emerged during the past 15 years of war have revealed that there are injuries that current helmets have not been designed to protect against. Throughout history, helmets have evolved to meet new threats. Leather helmets provided some protection from swords, but steel was needed to protect from projectile fragments in World War I. The increased ballistic speeds of World War II again required improved materials.[3] Since the 1980s, advances in nonmetallic materials have improved the ballistic protection of U.S. military helmets.[4]

Helmets must continue to evolve to address today's threats, particularly from traumatic brain injury (TBI). There is currently no requirement to protect against primary blast-induced brain injury for the Army's existing Advanced Combat Helmet (ACH) or for the planned Integrated Head Protection System (IHPS), part of the new Soldier Protection System. Without a requirement, helmets are not being designed to consider injury from blast overpressure.

Additionally, DoD studies have found that blast exposure from firing heavy weapons such as the Carl Gustaf recoilless rifle, even in training, is associated with short-term cognitive deficits.[5] DoD studies have also found higher rates of concussion and post-concussion associated symptoms among individuals with a history of prolonged exposure to low-level blasts from breaching and shoulder-fired weapons.[6] The Army should take prudent precautions to improve soldier safety when training on heavy weapons, while conducting further research to better understand the cumulative effects on the brain of repeat heavy weapons firing.

Understanding Blast-Induced Brain Injury

TBI is the signature wound of today's wars. While a relatively low-level concern at the start of the wars in Iraq and Afghanistan, by 2007 head injuries exceeded chest or abdominal injuries as those most treated by the U.S. military. Classified broadly as injuries that affect normal brain function, TBI can result from a blow to the head, fall, or penetrating injury.[7] More insidious, however, are injuries resulting from blast overpressure waves impacting the brain. These can occur from explosions, such as from IEDs used by insurgents in recent wars. Soldiers are also repeatedly exposed to blast overpressure when firing heavy weapons, such as anti-tank recoilless rifles or heavy caliber (.50) rifles.[8] Blast-induced TBI can be extremely difficult to detect and diagnose. There are no externally visible signs of brain trauma and many of the symptoms of mild TBI overlap with symptoms of post-traumatic stress disorder (PTSD). These factors make determining blast-induced TBI and its severity exceedingly complicated.

Starting in 2000, DoD began diagnosing and tracking TBI. As of February 2018, nearly 380,000 military personnel had suffered from some form of TBI since 2000.[9] The vast majority of these – over 80 percent – are classified as mild TBI. These numbers do not provide sufficient insight into blast-induced injury specifically, however, as they include all incidents of TBI across the military. These include TBI from blunt force impact to the head, such as from vehicle crashes or secondary blast injury due to being knocked down from an explosion. These figures also include TBI due to concussions from noncombat events, such as sports or vehicle crashes. Some brain injuries may also come from occupational hazard exposure due to blast pressure from firing heavy weapons during training.

There are multiple ways in which blasts can injure the brain. The primary mechanism of injury is the wall of blast pressure from an explosion. This blast wave can travel faster than the speed of sound, up to 1,600 feet per second, causing sudden changes in pressure up to 1,000 times greater than atmospheric pressure.[10] Wind rushes to fill the vacuum left by the pressure wave, which can hurl shrapnel and fragments and result in secondary blunt trauma injuries.[11] People or things can be thrown by this wind, leading to impact concussions (tertiary mechanism). Fires, toxic gases, burns, or crashes can follow (quaternary mechanism). The non-primary mechanisms of injury are relatively easy to understand and protect against through traditional means such as body armor, helmets, fire-resistant uniforms, etc. since these injuries are also more consistent with typical combat injuries. The primary mechanism of injury – the blast pressure wave itself – is less understood.[12] Animal studies have linked higher levels of blast pressure exposure with a greater likelihood of injury and greater severity of injury. Additionally, these studies have shown that multiple exposures lead to a greater likelihood of injury.[13] Studies in a large animal model (porcine/pig) have demonstrated that three exposures in a single day can result in 30-40 percent greater physiological change than a single exposure. Effectively, this translates to a lower threshold of injury following multiple exposures.[14] Additionally, these studies have shown that a rest period of 24 hours is not sufficient to fully recover from blast-induced brain injury.[15] Nonetheless, there is a great deal about TBI induced by primary blast pressure that is unknown. Studying these injuries is challenging for many reasons.

TBI may be under-reported, due to fear of stigma – especially among the special operations community[16] – not realizing the injury occurred during the chaos of combat, or from the compounding effects of repeated exposure to low level blasts. In fact, a 2009 military study of TBI found that military doctors often did not account for harm that did not result in bleeding or a penetrating injury.[17] Additionally, it is very difficult to identify TBI, particularly when it is induced by blast waves, so exams may capture only drastic cases and leave many minor cases unrecognized.[18] Many of the metrics to determine the severity of TBI are conditions that could be easily miscalculated during combat – the duration of consciousness, post-traumatic amnesia, or altered mental state.[19] Many injured soldiers do not initially realize that they have suffered an injury or experience immediate symptoms.[20] Soldiers have even participated in firefights that they later do not remember, losing hours of memory after blast exposure.[21] The possibility of repeated low-level exposure causing brain injury further muddles injury identification. Soldiers could belatedly experience injury symptoms without an obvious corresponding blast event in their past to explain them.

Cognitive and mood challenges can persist and overlap with those of PTSD, complicating diagnosis.[22] Servicemembers with mild TBI are more likely to develop psychiatric disorders than the average population.[23] TBI can result in memory, attention, emotional, and mood problems that can last over a year, including sleep disturbances, fatigue, dizziness, irritability, headaches, and seizures.[24] Studies have shown that many veterans with PTSD also have mild TBI symptoms.[25] TBI can increase the likelihood of developing an anxiety disorder and possibly PTSD due to the ways in which TBI affects the amygdala, the part of the brain that controls emotions, including fear.[26] Changes in the amygdala can modify fear responses and possibly increase susceptibility to PTSD. [27] In some studies, TBI doubled the rate of PTSD in some people.[28]

Brain injury in war, whether physical or psychological in nature, has been studied since the term "shell-shocked" emerged from the trenches of WWI,[29] and anecdotal accounts of blast-induced brain injuries date to mining explosions of the late 18th century.[30] The development and deployment of German artillery happened concurrently with the emerging fields of psychology and neurology, so the budding literature treated shell-shock as an emotional problem rather than a physical injury.[31] Even without the prevalence of today's IED blasts in earlier 20th century wars, it is possible that explosions caused similar brain injuries in previous conflicts.

One cause for the rise in TBI cases in recent conflicts may be that soldiers are surviving wounds that would have been fatal in previous conflicts. As battlefield medicine and body armor have improved, the ratio of wounded soldiers to killed soldiers has increased since Vietnam.[32] Consequently, there are now more soldiers surviving with blast and TBI wounds than ever before. In fact, one research paper identified the improvements in personal protective equipment as the direct cause of increased numbers of TBI, since armor now protects the torso and lungs from blasts that previously would have been lethal.[33]

It is also possible that brain injury may come from repeated blast exposure from soldiers firing heavy weapons. An animal study demonstrated mild brain injury in pigs and rats from blast overpressure from artillery (155mm howitzer), anti-tank weapons (Carl Gustaf 84mm recoilless rifle "bazooka"), and high-caliber military rifles (M82A1 Barrett .50 caliber sniper rifle).[34] Small hemorrhages in the brain, increasing with blast intensity, were seen in 21 percent of pigs exposed to M82A1 .50 caliber rifle fire and 7 percent of those exposed to Carl Gustaf fire, even after as few as three shots from the weapons.[35] In practice, gunners for these weapons could be exposed to significantly more shots during training, sometimes up to 20 or more shots per day.[36] The type of brain injury was consistent with brain damage seen in previous wars from soldiers who died after being exposed to blasts without signs of external injury.[37] While minor, the damage from these blasts has led the Swedish military to limit the number of rounds to which soldiers may be exposed daily.[38] The Army also has limits on the number of times a soldier can fire shoulder-fired weapons per day.[39] Even within approved firing limits, however, DoD studies have demonstrated that servicemembers may experience short-term cognitive deficits in delayed verbal memory, visual-spatial memory, and executive function after heavy weapons firing.[40]

Blast Monitoring Devices

The Army has taken steps to better understand the link between blast overpressure exposure and TBI. To this end, DoD has developed blast monitoring devices, also called blast gauges, to measure the blast overpressure to which servicemembers are exposed. An ideal device could objectively assess in the field whether a soldier has brain injury, analogous to a thermometer assessing whether an individual has a fever. Blast gauges are environmental sensors, however. They cannot and are not intended to perform this function. (Other emerging technologies may yield portable gauges that could directly assess any cognitive deficits in the field.[41]) Blast gauges, however, measure a soldier's exposure to potential environmental hazards: blast overpressure, acceleration, and temperature. In this sense, they are analogous to radiation dosimeters, which measure exposure to radiation levels. Blast monitoring devices serve several purposes.

One, they can be used as screening devices to identify soldiers who may have been exposed to high levels of blast-related stress (pressure, acceleration, and temperature) and should be seen by a medical provider. They are not a diagnostic tool for assessing brain injury and cannot take the place of a medical professional, but they can help identify soldiers for screening. When used as an objective screening tool, blast gauges can be helpful in guarding against soldier under-reporting of TBI.

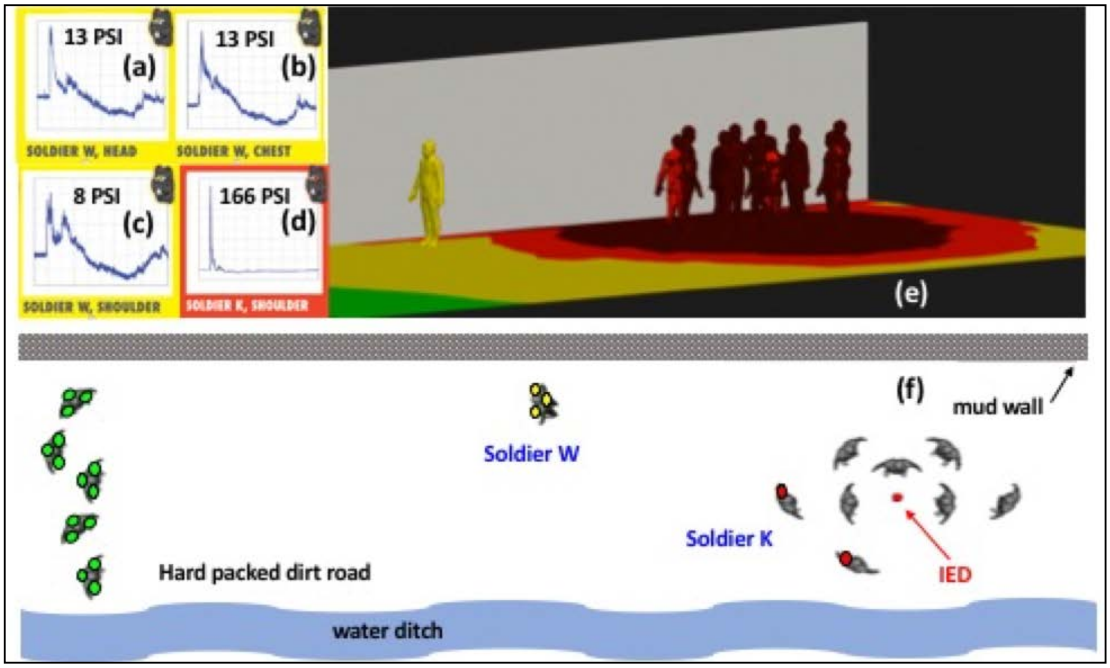
Two, blast gauges can be used to identify tactics and techniques during weapons firing and combat that could mitigate soldier exposure to blast pressure.

Three, with additional data, blast gauges potentially could be used to estimate the probability that a soldier has suffered a brain injury due to primary blast pressure exposure. This would be analogous to a radiation dosimeter, which can be used to help estimate the likelihood of injury from radiation exposure.[42] Using a blast gauge for this purpose would first require additional data to better understand the relationship between blast exposure and brain injury, however.

For example, it is not known whether there is a single threshold for injury or a risk curve, where the probability of injury increases with higher-pressure exposure. It is also not known what the effects are of repeated low-level exposures. Animal studies have linked higher levels of blast pressure exposure with a greater likelihood of injury and greater severity of injury, and multiple exposures with a greater likelihood of injury. More data is needed, however – particularly of human exposure to blast pressure – to better understand the relationship between blast pressure exposure and brain injury.[43]

Blast gauges are an essential tool for collecting this data. Blast gauges are needed to help build a comprehensive database of incidents where soldiers have been exposed to blasts, the recorded blast pressure, and any cognitive deficits afterward. This is particularly the case if low-level blast exposure leads to cumulative effects over time.

Computer Recreation of Real-World Blast Event[44]



Blast gauge data, coupled with contextual data of the event from soldier interviews, was used to build a computer simulation to recreate the blast pressure wave from an IED attack. Figures (a-d) show actual measurements of blast gauges worn on soldiers in the attack; (e) shows the computer simulated blast exposures of soldiers from the event recreation; (f) shows the soldiers' location.
(Source: J.L. Duckworth, G.S.F. Ling, and J.L. Rogers, "Blast Gauge: Quantifying Exposure during an Improvised Explosive Device Attack," Neurocritical Care, 17 no. S84 (2012).)

The Army is using blast gauges in controlled training environments for "specific weaponry (such as the Carl Gustaf)" to collect this data. [45] According to a November 2016 letter by the Secretary of the Army, this data "will allow the DoD to draw valid conclusions between exposure and injury."[46] The Navy is similarly studying blast exposure during training firing heavy weapons (shoulder-fired rockets and recoilless rifles).[47]

It is also essential that the Army record data from enemy-initiated blast events, since they will result in different pressure signatures than heavy weapons firing. The combat environment is less controlled than the training environment, a condition that invariably complicates data collection and analysis, but training cannot (and should not) perfectly simulate the hazards soldiers are exposed to in combat.

In order to refine its understanding of blast-induced brain injury, it is essential that the Army collect data for any combat exposures to blast overpressure. *The Army should expand on existing blast pressure monitoring in training and establish a longitudinal medical study on blast pressure exposure during combat and training in order to better understand the relationship between blast pressure exposure and brain injury. In parallel, the Army should conduct a blast surveillance program to monitor, record, and maintain data on blast pressure exposure for any soldier, in training or combat, who is likely to be in a position where he or she may be exposed to blasts. The Army should include brain imaging of soldiers who have been exposed to blasts as part of their medical study to better understand how blasts affect the brain.* High-quality brain imaging can give quantitative measures of changes within the brain, even at lower levels of blast exposure than may be detected by a neurological exam.[48] This study should be conducted in partnership with research on other causes of TBI, such as from impacts, within the military and the civilian sector in order to better understand brain injury.

In December 2017, the president signed into law the 2018 National Defense Authorization Act, which mandated this study in Section 734, "Longitudinal Medical Study on Blast Pressure Exposure of Members of the Armed Forces."[49]

Mechanism of Injury

Because primary blast-induced TBI often does not result in outward evidence of injury, it is difficult to pinpoint the direct injury mechanism. Modeling how the blast wave travels through the tissue is challenging, requiring complex and detailed computer models that are hard to correlate with experimental data. Experiments are challenging, since the threshold of injury cannot be directly translated from animal experiments to humans. The diversity of sizes and shapes of animal skulls affects how blast waves propagate through the head into the brain. Finally, in addition to the current poor understanding of how blast waves affect the brain in general to determine injury thresholds, the possibility of aggregate damage from many small exposures, each making the brain more susceptible to future injury, multiplies the possible blast exposures researchers must study to evaluate possible correlations to injury.

The mechanism of primary blast injury from pressure waves is unknown, but widely debated

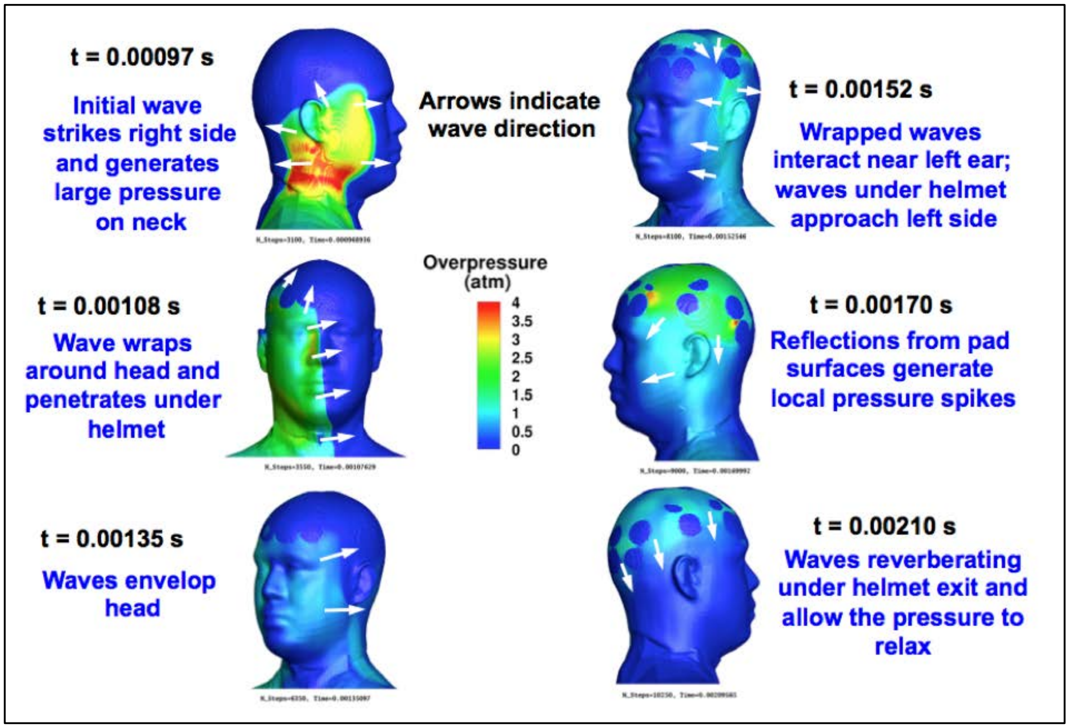
There are competing theories for how blast pressure causes primary brain injury.[50] (These theories may not be mutually exclusive.) Initial analysis assumed blast waves injured the brain in a similar manner to concussions, which result in brain injury due to the rapid acceleration and deceleration of the head, forcing the brain against the skull. The Defense and Veterans Brain Injury Center actually says, "Concussion is another word for a mild TBI."[51] Increasingly, however, some researchers identify symptoms among some veterans with TBI that differ from traditional concussion symptoms.[52] Primary blast injuries at the microscopic level may not be the same as impact-induced concussive injuries.[53] Anecdotal evidence supports this as well – military physicians who have personally experienced and treated blast-induced TBI in the field and have had impact concussions identified differences in the symptoms in themselves and in the soldiers they treated compared to those of traditional concussions.[54]

Various theories for injury mechanism for primary blast waves, and resulting implications for helmet design, include:

- Blast-induced TBI could be caused by the explosive effect on hollow spaces, a concern since the development of explosives.[55] Blast overpressure damages hollow organs like the lungs, which are very sensitive, and can injure the ears and gastrointestinal tract. This theory holds that pressure causes air bubbles in the brain to pop, leaving behind small holes in the brain, instead of the stretches or tears that result from a traditional concussion.[56] Here the injury is primarily from the pressure.

- Another theory postulates that the pressure wave results in tears across media of differing densities in the brain, referred to as barotrauma. The drastic pressure changes associated with blast waves oscillate tissues and affect media of varying densities in the brain differently. These waves can cause damage-inducing imbalances in acoustic impedance between the movement of air and gas-filled organs. This can result in bubble formation at the border between cerebrospinal fluid and the brain. The formation of a bubble or empty space in liquid or solid objects is called cavitation, and its presence can cause damage to brain tissue, capillaries, or axons, which are a part of neurons.[57] In effect, the less dense region of the brain can expand into the dense region: ventricles expand much more than the brain tissue around them, which can tear axons.[58] Similarly, this theory posits the injury is a result of the pressure.

Computational Model of Blast Pressure by Location and Time



Computational models can help predict how blast waves transmit through the skull and brain over time, allowing researchers to understand which parts of the brain experience the greatest pressure changes.
(Source: Army Natick Soldier Research, Development & Engineering Center, Mott, et al., Blast Modeling Progress Report: CIPHER Prototype Subjected to Rear and Side Blasts, HeaDS-UP Program, March 2013.)

- Other research suggests damage is caused by the supersonic speed at which pressure moves through the soft tissue of the eyes, ears, sinuses, and liquid of the brain. Consequently, measures that reduce the speed of the pressure waves could decrease the risk of injury, such as the use of a helmet with a face shield that reduces the force of the waves experienced on the face.[59]

- Yet another theory is that the blast pressure wave results in an electric field in the brain. The bone of the skull is a piezoelectric material that emits a small electric field. The mechanical blast of a pressure wave activates this piezoelectric material and results in an electric field with strength comparable to repetitive transcranial magnetic stimulation, a practice intended for neurological effects, and 10 times greater than Institute of Electrical and Electronics Engineers recommended safe limits.[60] Testing shows the field is consistent with the side of the blast's origin. In one study, wearing a helmet resulted in a lower overall charge density.[61]

- A 2009 study by the Lawrence Livermore National Laboratory suggested the blast wave results in damaging loads on the brain from skull flexure.[62] Hydrodynamical simulations show that the skull's deformation causes injury consistent with impact concussions. The study recommended helmets designed to prevent skull deformation.[63]

- Further, integrin proteins can emit an electrical signal in the brain that disrupts cell connections affecting memory. Damage to these brain connections was shown in a study involving 63 soldiers with blast-related TBI.[64] Further research could help drug manufacturers identify proteins that could mitigate the effects, although funding limits have halted this line of inquiry.

- It is also not clear that a helmet alone can fully protect from blast-induced brain injury. While TBI is specific to the brain, there are indications that blast pressure exposure in other areas of the body can nevertheless lead to brain injury. A 1999 study found that 51 percent of warfighters who only experienced explosive injuries in their lower extremities still had symptoms consistent with TBI, including vertigo, headache, and insomnia.[65] When specifically tested in rabbits and rats, neuronal injury resulted from both body exposure to blast and blasts isolated to the chest cavity while the head was protected by a steel plate.[66] In these cases, the head was not at risk, but the brain was still injured, indicating no specific helmet design would mitigate this mechanism of injury.

Research into the possible injury mechanisms of blast should be continued. *The Army should accelerate computational modeling and experimental research, including with large animal models, into primary blast wave injury in order to better understand how blast overpressure damages the brain.* These efforts should work in tandem with neurologists to improve understanding of TBI and move to refine a theory of injury over time.

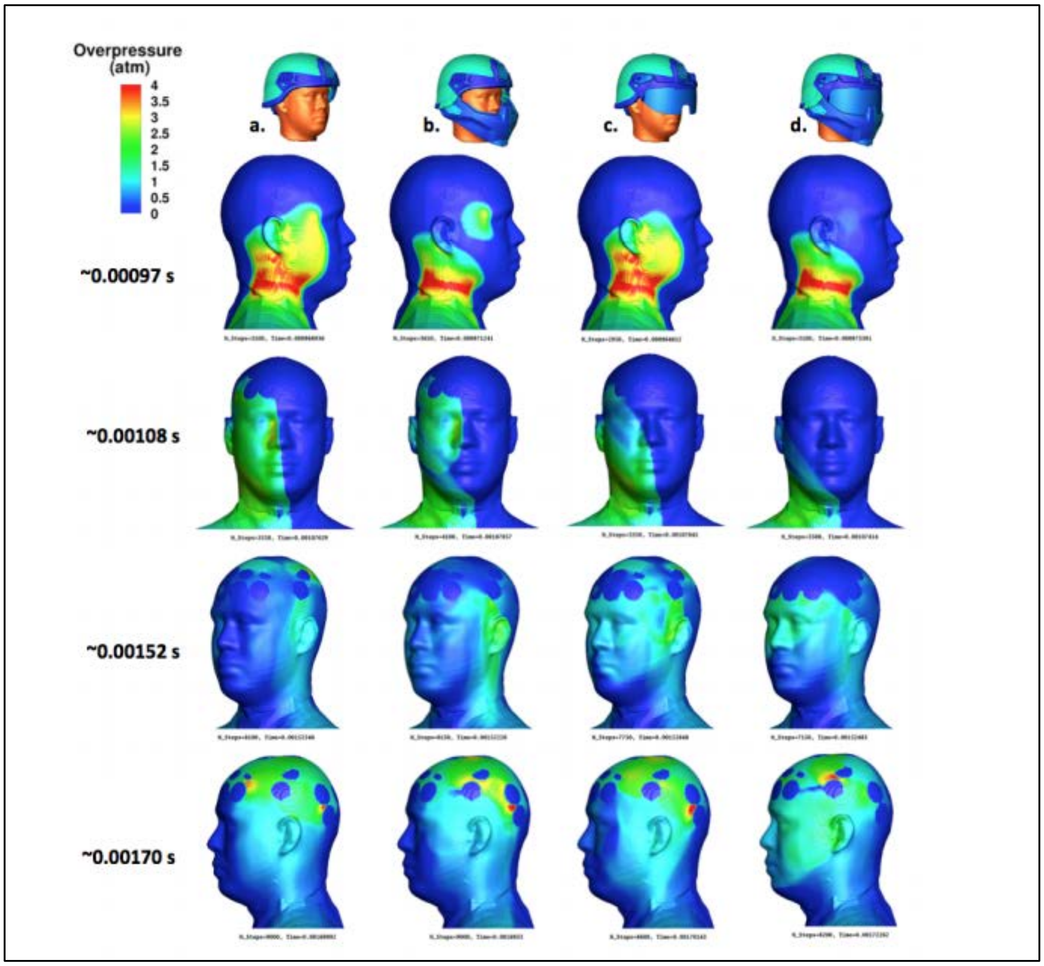
Near-term Options for Mitigating the Effects of Blasts on the Brain

While the science continues to mature, the Army should take near-term steps to mitigate soldiers' brains' exposure to potentially harmful primary blast pressure waves. Research indicates that head protection can mitigate the brain's exposure to injury for most of the theories about the mechanism of injury. Army helmets already include requirements to protect against ballistic and blunt impact injuries (secondary and tertiary injuries). There are limits as to how much protection is feasible in a helmet – there is a tradeoff between protection and weight – but the Army has established standards that balance protection needs against weight for protecting soldiers heads' against injury from bullets, shrapnel, and concussive impact due to falls. There is currently no requirement, however, for protection from primary blast pressure waves.

Research has demonstrated that modifications to helmet designs change the strength and distribution of blast waves inside the head. This research suggests that some helmet designs may be able to mitigate the blast pressure transmitted to the brain, although further research is needed. A 2009 Lawrence Livermore Laboratory article argued that without helmet padding, the pressure on the head would be exacerbated by the "underwash" of the channel between the skull and helmet. The increased pressure is also coupled with movement of the head relative to the helmet, increasing the mechanical load that could cause injury from skull flexure consistent with injury from impacts.[67] A 2010 MIT study using a detailed computational model found helmets could mitigate blast waves, reducing harm.[68] This study found that, while mitigating blast pressure is not its intended purpose, the current ACH decreased the amount of pressure and possibly changed the location of pressure in the brain, benefiting the soldier. While the head still experienced overpressure, it was significantly less than without a helmet. Most significantly, this study found that adding a face shield in computer simulations reduced the blast pressure in the brain by 80 percent.

Similarly, the Army's Helmet Electronics and Display System-Upgradeable Protection (HeaDS-UP) Program has studied changing pressure dynamics within the helmet based on different designs. The study considered wave reflections from interactions with the body, as well as different blast locations to understand the variety of pressure impacts on the skull.[69] The HeaDS-UP modeling found that using a face shield decreased peak pressure in the skull, consistent with the MIT study. However, adding mandible protection increased peak pressure in the forehead due to the wave reflections within the helmet.[70]

Computational Modeling of Blast Pressure in the Head and Neck by Helmet Design



Computational modeling shows the peak pressure differences and locations over time for various helmet configurations as side-initiated blast waves travel through the head. Different helmet configurations can produce different patterns of blast pressure propagation in the head and brain.
(Source: Army Natick Soldier Research, Development & Engineering Center, Mott, et al., Blast Modeling Progress Report: CIPHER Prototype Subjected to Rear and Side Blasts, HeaDS-UP Program, March 2013.)

Collectively, these studies point to the need for further research to understand how various helmet designs could reduce soldiers' exposure to harmful blast pressure waves and how to ensure changes do not worsen the effects of a blast wave. It is possible that existing commercially available helmet designs could reduce the blast pressure transmitted to the brain. One design that should be tested is modular facial coverings, such as a face shield or mandible protection. The commercial MTEK helmet,[71] developed by two Marines, is one among many entering the commercial space[72] offering a modular system with optional face protection. Research conducted by MIT and through the HeaDS-UP program has suggested that face shields could reduce soldier exposure to blast pressure.

These helmets pose tradeoffs due to the increased weight, as well as increased torque on the neck. As with body armor, additional weight on the head could diminish situational awareness and operational effectiveness for the user. Face shields could also obstruct vision. Interoperability with existing night-vision devices and weapons optics could also be a concern with full-face helmets, as well as object detection and ability to rapidly engage targets. Nevertheless, the potential may exist to reduce soldier exposure to blast pressure waves based on readily available off-the-shelf solutions.

The Army should test existing helmets, including commercially available variants with modular mandible and face shields, to determine which configuration and materials best protect against primary blast wave injury as a near-term mitigation against possible brain injury. Helmets should be tested for their ability to decrease blast overpressure from a variety of angles and directions, as well as for different types of blasts – explosive blasts as well as from firing heavy weapons such as artillery, recoilless rifles, or .50 caliber rifles. The same type of helmet may not equally protect from both types of blast. *The Army should then conduct a tradespace study of the various helmet designs in order to compare the amount of reduced blast pressure to any negative effects, such as increased weight and torque on the neck, reductions in situational awareness, and other operational effectiveness metrics.*

The Army is at a crossroads in soldier protection against primary blast-induced brain injury. Helmets are not currently developed with blast injuries in mind, as there is no blast injury requirement. The Army could continue down the current path with no requirement for helmets to protect against blast pressure. The rationale for this course of action would be to wait until the mechanism and threshold of injury for blast pressure waves is more fully understood before creating a requirement. This is the most cautious path from a scientific perspective but the riskiest path for soldiers. It would leave soldiers exposed to potentially harmful blast pressure waves with whatever incidental protection the ACH and IHPS provide. These helmets likely provide some protection against primary blast wave injury relative to no helmet, although their level of protection will almost certainly not be optimal if they are not designed to do so.

An alternative is to establish an interim requirement for protection now, based on what is known, and adjust the requirement over time as the science matures. Fully understanding the causes of blast injury could take years or even decades, but the Army has the opportunity to begin protecting soldiers today. The Army should take this opportunity. *Based on the results of the helmet tradespace study demonstrating the ability of certain designs to reduce overpressure exposure and the drawbacks of various designs, the Army should establish an interim requirement for protection against blast overpressure while continuing further research to refine the requirement over time.*

By instituting a requirement, the equipment community has a metric to target when designing protective equipment, and the broader commercial and scientific communities have a baseline from which to improve. Most importantly, a protection requirement will institute some level of protection today, balanced against other tradeoffs such as weight, as best as is possible given the state of the science. Over time, research and experience may demonstrate that the requirement is too high or too low – or perhaps focused on the wrong metric – and it can be adjusted accordingly as the science matures.

Heavy Weapons Firing

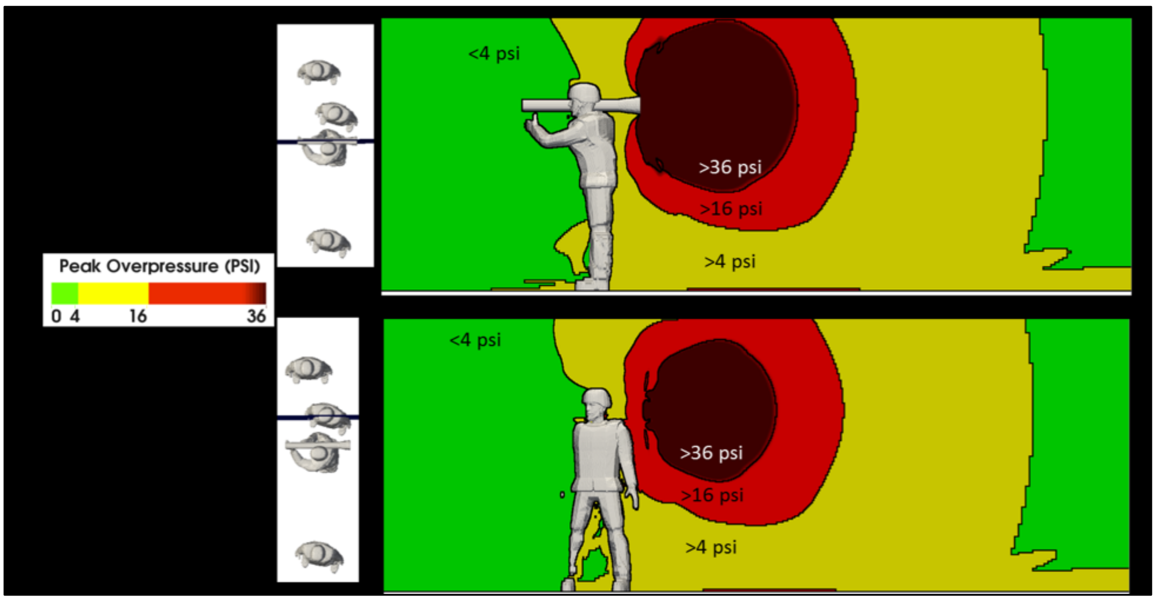
Emerging evidence suggests that soldiers may be exposed to significant levels of blast overpressure when firing heavy weapons, such as the Carl Gustaf recoilless rifle, even in training. As one recent DoD study on blast overpressure from shoulder-fired weapons noted, "There is a growing level of concern about the long-term effects of repetitive sub-concussive head injury."[73]

DoD studies have shown that repeated firing of heavy weapons, even within current firing limits, is associated with short-term cognitive deficits in delayed verbal memory, visual-spatial memory, and executive function.[74] A subset of the population exposed to heavy weapons firing demonstrated cognitive deficits above a blast exposure threshold.[75] Physiological changes can occur even after cumulative exposures to relatively low-level blast exposure, such as those experienced during heavy weapons training.[76]

Animal studies have shown that multiple exposures lead to a greater likelihood of injury.[77] Studies in a large animal model (porcine/pig) have demonstrated that three exposures in a single day can result in 30-40 percent greater physiological change than a single exposure. Effectively, this translates to a lower threshold of injury following multiple exposures,[78] meaning even low-level exposures can have cumulative effects.

Cumulative effects from repeat blast exposure can even occur across multiple days. In DoD studies, servicemember cognitive deficits following heavy weapons firing took 72 to 96 hours to resolve to a level at which they were not statistically significant.[79] Animal studies have shown similar results: A single daily exposure delivered for three consecutive days resulted in 20-30 percent greater physiological change, suggesting there is a cumulative effect of the exposures and that a rest period of 24 hours is not sufficient to fully recover.[80] In some training events, soldiers may fire heavy weapons multiple days in a row.

Peak Overpressure for Carl Gustaf Gunner and Assistant Gunner During Firing[81]



When firing the Carl Gustaf 84mm recoilless rifle, soldiers are supposed to be limited to only six total shots per day as gunner or assistant gunner, but these limits are sometimes violated. In some training environments, soldiers have been exposed to 20 or more total shots per day performing gunner or assistant gunner duties.
(Source: Jason M. Bailie et al., "Blast Exposure from Shoulder Mounted Rocket Launchers," Military Health System Research Symposium, 2015.)

The long-term effect of prolonged exposure to repeat sub-concussive blast events is unknown, but there is some evidence to suggest concern. A 2015 Army survey compared concussion and post-concussion associated symptoms in breachers, who are exposed to repeated low-level blasts, to non-breachers.[82] Breachers reported "more symptoms, more severe symptoms, and more symptoms that interfere with daily living activity."[83] Symptoms were associated with breaching history (the number of past breaching events) and a history of shoulder-fired weapons use.[84] Researchers noted these results "support the hypothesis that there is a positive relation between the amount of blast exposure and reported symptoms."[85] The study concluded: "Repeated low-level blast, from breaching as well as blast from shoulder-fired weapons, is demonstrated in these results as a potential occupational medicine concern."[86]

Additional research is needed on the long-term effects of low-level blast exposure, particularly from shoulder-fired weapons. *The Army should expand ongoing studies of blast exposure in training to include all soldiers who are exposed to high overpressure weapons (e.g., Carl Gustaf, AT4, LAW, .50 caliber sniper rifles, explosives). In order to obtain objective measurements of blast exposure, the Army should require all soldiers to wear blast gauges when training with high overpressure weapons. Blast gauge* *measurements should be recorded as part of the blast surveillance program, in parallel to a longitudinal medical study on blast pressure exposure and brain injury.* The cumulative effect of prolonged exposure to low-level blast events may take years to manifest. Accurate records of soldier blast exposure, including during training, are essential to improving understanding of blast-induced brain injury. One particular concern is that mild TBI may worsen over time.[87] *Blast exposure history should be included as part of soldier service records (i.e., a "blast exposure record") in order to ensure that, if medical issues arise later, soldiers receive care for any service-connected injuries.*

Improving training safety

Understanding the long-term effects of low-level blast exposure will inevitably take years. There are concrete steps that the Army can take today, however, to improve soldier safety during training.

All Army shoulder-fired heavy weapons have limits on the number of rounds that can be fired in a 24-hour period, depending on the firing position (sitting, standing, kneeling, or prone). (The blast overpressure experienced by soldiers depends on the firing position because of reflections from the ground.) According to Army manuals for shoulder-fired weapons, these limits exist because of hazards from overpressure and noise. With the exception of the AT4CS, which is specifically designed for firing in confined spaces, the limit on firing any of these weapons is no higher than six shots per day. For some weapons and firing positions, it may be as low as zero shots in training. Firing restrictions on the M72 LAW (four shots per 24 hours) also apply to any soldiers within a 20-meter radius of the weapon.[88] Many other shoulder-fired heavy weapons do not specify a safe distance that observers or instructors must be from the weapon due to overpressure hazards, however.

Limits on firing some shoulder-fired weapons, such as the AT4, have existed for over 20 years, but these limits have evolved over time.[89] Firing limits on the AT4, LAW, and other shoulder-fired munitions were last updated in 2010.[90] Since then, understanding of blast-induced brain injury has improved significantly. Emerging evidence from DoD studies on blast exposure suggests that current firing limits may fall short of adequately protecting soldiers in significant ways:

- DoD studies have demonstrated that some servicemembers experience cognitive deficits in delayed verbal memory, visual-spatial memory, and executive function after firing heavy weapons even within allowable limits.[91] This suggests that current firing limits may not adequately protect soldiers from excessive blast overpressure exposure and should be revised downward.

- Current firing limits only apply to the maximum number of shots within a 24-hour period. Animal studies and DoD observations of servicemember cognitive deficits following heavy weapons firing have shown that physiological changes can take longer than 24 hours to resolve and that repeat exposures across multiple days can have cumulative effects. Accordingly, firing limits should be changed to cover exposures across a longer time period, on the order of 72 to 96 hours, to account for this cumulative effect.

- With the exception of the M72 LAW, most shoulder-fired heavy weapons lack a minimum safe distance that observers and instructors must be from the weapon in order to avoid excessive overpressure exposure. Blast gauge monitoring combined with computer simulations can help generate pressure maps of the area surrounding the weapon in order to determine a minimum safe distance. Firing limits should include a minimum safe distance for observers and instructors.

Soldiers from the Army's 75th Ranger Regiment fire a Carl Gustaf recoilless rifle during range training at Camp Roberts, California, January 26, 2014. In this case, the assistant gunner is correctly positioned in the center of the weapon.
(Source: U.S. Army)

- Current firing limits are weapon-specific, but do not account for the possibility of soldiers firing multiple different heavy weapons – for example, Carl Gustaf, AT4, and LAW – during a single day. This could occur during range training on heavy weapons, which could lead to excessive exposure to overpressure. Firing limits should be adjusted to account for the possibility of multiple weapons being fired in a single day. This could be done with a point system, which is currently used for the Carl Gustaf firing limits, whereby a given weapon system, munition, and firing position is assigned a point value and soldiers are limits to the total number of points per day.

- Finally, current firing limits do not include cumulative annual and lifetime limits for blast exposure. An Army study found, however, that prolonged exposure to low-level blasts from breaching and shoulder-fired weapons was associated with higher concussion and post-concussion related symptoms. This suggests the need for cumulative annual and lifetime limits for blast exposure – both for shoulder-fired weapons and breaching.

The Army should review and update its firing limits for shoulder-fired heavy weapons, such as the AT4, LAW, and Carl Gustaf. Firing limits should be revised downward to a level such that allowable exposures are not associated with cognitive deficits after firing. Additionally, firing limits should cover exposures across a longer time period, on the order of 72 to 96 hours. Firing limits should include a minimum safe distance for observers and instructors, and should account for the possibility of multiple types of heavy weapons being fired in a single day. Additionally, the Army should establish cumulative annual and lifetime limits for blast exposure in training.

Standards are ineffective if they are not enforced, however. In practice, firing limits are sometimes violated in training. In some environments, soldiers training on the Carl Gustaf have been exposed to 20 or more shots per day performing gunner or assistant gunner duties, far exceeding the current limits.[92] One setting in which this could occur would be a Gustaf-qualified gunner training other soldiers on "familiarization" with the weapon, thus performing repeat assistant gunner duties. The Carl Gustaf weapon system in particular has unique attributes that may lead to multiple, repeat exposures for certain soldiers. Unlike other shoulder-fired weapons, such as the AT4 or LAW, the Gustaf is a duty position weapon, meaning some soldiers are assigned the Gustaf as their primary weapon system. Soldiers for whom the Gustaf is a primary weapon system potentially could be exposed to a large number of overpressure events in training over a period of months or years.

This is most likely to be a concern among special operations forces, who have increased availability to range training time and ammunition. The Army is currently in the process of fielding the Carl Gustaf Army-wide, expanding its use beyond special operations into general-purpose forces infantry platoons. In practice, most general-purpose forces Carl Gustaf gunners are not likely to be in a position where they could exceed current firing limits. The Army's current training plan for general-purpose forces Carl Gustaf gunners and assistant gunners is to fire two practice rounds every six months (one as gunner and one as assistant gunner) and two live fire rounds once per year.[93] Thus, gunners and assistant gunners would be exposed to a cumulative total of six shots – the current daily limit – in a year.

Nevertheless, given the potential for repeated firing of heavy weapons to cause cognitive deficits in soldiers and reports of firing well in excess of firing limits among special operations forces, *the Army should take prudent precautions to improve soldier safety when training on heavy weapons:*

- Increase soldier and commander education about the importance of adhering to firing limits and wearing appropriate protective equipment, such as through a Safety of Use message.
- Hold commanders accountable, especially in special operations units, for enforcing limits on firing heavy weapons, such as the Carl Gustaf, in training, and require that units record and report the number of shots fired by each individual soldier per day in training.
- Review training guidance for shoulder-fired heavy weapons to maximize the use of sub-caliber training rounds whenever possible, especially by special operations forces.
- Investigate different methods for soldier familiarization and for establishing gunner and assistant gunner proficiency so that gunners, assistant gunners, and instructors are not unnecessarily exposed to blasts.
- Use blast gauges to explore modifying firing procedures, such as adjusting the position of assistant gunners, to reduce blast overpressure exposure.
- Explore the use of prepared firing positions in training with blast-absorbing materials to reduce ground reflection and/or shields to mitigate blast pressure waves.

While these mitigation measures can reduce the amount of blasts soldiers are exposed to, they do not reduce the overpressure soldiers experience from a single blast exposure. Specially-designed full face helmets, combined with optics modified for the weapon system that allow the soldier to sight the weapon from behind a face shield, may be a potentially long-term solution that allows soldiers to continue employing heavy weapons safely at lower levels of blast exposure. *The Army should investigate different helmet designs for duty positions that may be at greater risk for blast exposure, such as Carl Gustaf gunners and assistant gunners.*

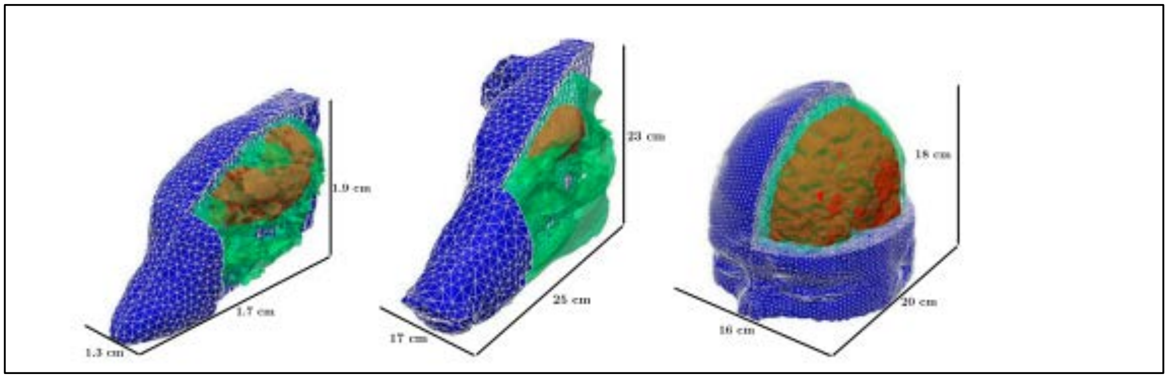
Long-term Options for Mitigating the Effects of Blasts on the Brain

New materials to absorb blast pressure waves

Optimizing helmet design also entails improving materials and structure. Research comparing animal physiology to that of humans indicates that the materials protecting the brain contribute to protecting from blast, and humans have relatively more exposed brains than other animals. Among mammals, the human skull provides very little protection from the transmission of pressure waves.[94]

Many studies have focused on the relation of body or brain mass to injury, but skull anatomy appears to have a better relationship.[95] Researchers have developed a human brain injury criteria based on scaled animal testing, which is relative to the injury threshold for rabbits, while accounting for differences in anatomy and its protection.[96] This allows researchers to more accurately translate findings from animal studies to human models. This research also can help inform better helmet design. An experimentally-verified model for predicting how skull shape and size affects how blast waves are transmitted to the brain could also point the way toward specific helmet materials and structures that would optimally protect the brain. *The Army should investigate new helmet materials, shapes, and designs that might dramatically improve protection from primary blast injury.*

Relative Protection by Species Based on Tissue Structures



Computational modeling reveals that the human brain has relatively less protection from pressure waves than other animals, such as a mouse or pig. The tissue structures depicted include flesh (blue), skull (green), and brain (red). *(Source: Jean, et al., "An animal-to-human scaling law for blast-induced traumatic brain injury risk assessment," Proceedings of the National Academy of Sciences, August 2014.)*

Robotic teammates to shield soldiers from blasts

In the longer term, robotic teammates could augment protection by deploying a shield or other mechanism to protect soldiers from a blast wave. This mobile system could automatically position itself to intercept the blast wave and incorporate a vacuum-type mechanism to reduce the pressure reaching the soldier. Researchers have hypothesized protective shields that would have "low pressure – low density air in between the blast wave and the target" in order to absorb the pressure of an approaching blast wave.[97] In effect, a sponge-like membrane would absorb or collapse the high-pressure wave before it reached a soldier. Research also should be conducted into better materials, such as next-generation polycarbonate, that could generate fibers that could absorb pressure waves as if they were tissue. This would operationalize the research on the difference in animals that are resilient to blast-induced injury compared to humans and aid the development of protective measures. Some of these more revolutionary ideas could help transform a radical helmet capable of reducing pressure waves that damage the brain. *The Army should explore opportunities for off-board protection from blast waves, such as from passive or active measures located on robotic teammates.*

Conclusion

Increased investment in concrete and coordinated research efforts on blast-induced TBI is needed. Like with other major breakthroughs, this process will take time, and increased funding for research is needed to resolve this challenge. The Department of Veterans Affairs estimates that treatment for TBI in fiscal year 2015 was $234 million, a figure estimated to total $2.2 billion over the next 10 years.[98] The Army needs to substantially invest in TBI research across the military research enterprise and civilian scientific institutions in order to improve scientific understanding of brain injury. A 2012 Executive Order established the National Research Action Plan on PTSD and TBI to encourage collaboration across DoD, the VA, the Department of Health and Human Services, and the Department of Education to both conduct research and provide care to those affected. As a part of this plan, DoD and the VA contributed $107 million for research.[99] The 2016 National Defense Authorization Act provided $125 million for DoD's Psychological Health and Traumatic Brain Injury Research Program.[100] Government funding should continue, and private investment should be sought given the public interest in the issue. *The Army should increase its efforts to protect soldiers against blast-induced brain injury, with increased resources for testing, experimentation, and combat helmet development.*

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[89] Headquarters, Department of the Army, FM 23-25, "Light Antiarmor Weapons," August 17, 1994, Table A-1; Headquarters, Department of the Army, FM 3-23.25, "Light Antiarmor Weapons," August 30, 2001, Table A-1; Headquarters, Department of the Army, FM 3-23.25, "Shoulder-Launched Munitions," January 2006, Tables A-2 and A-3; and Headquarters, Department of the Army, TM 3-23.25 (FM 3-23.35), "Shoulder Fired Munitions," September 2010, Table 2-3, 55. These limits have evolved over time. The 1994, 2001, and 2006 field manuals only include limits on the AT4, not the M72 LAW. The 2006 field manual reduced the allowable number of AT4 shots per day in the sitting and prone positions. The 2006 field manual added the M141 Bunker Defeat Munition and included firing limitations for it as well. The 2010 field manual reiterated the limits for the M141 BDM and AT4. The 2010 version omitted guidance that existed in the 2006 version, however, that the AT4 limits applied not only to firers, but also to observers and safety non-commissioned officers (NCO). This is a significant change that could increase soldier exposure to blasts. The 2010 version places no limits on observer or safety NCO exposure to AT4s. The 2010 field manual added guidance on the AT4CS, a specialized version of the AT4 designed for firing inside confined spaces. The 2010 version also added for the first time limits on firing the M72 LAW, establishing a limit of four shots per day. For the M72, these limits apply to any soldiers within 20 meters of the weapon system when it is fired.

[90] Headquarters, Department of the Army, TM 3-23.25 (FM 3-23.35), "Shoulder Fired Munitions," September 2010, Table 2-3, 2-22.

[91] CDR Josh Duckworth, Uniformed Services University of the Health Sciences, U.S. Navy.

[92] Personal communication with Carl Gustaf gunners.

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[95] Ibid.

[96] Ibid.

[97] Sirkanti Rupa Avasarala, "Blast Overpressure Relief Using Air Vacated Buffer Medium," MIT Thesis: School of Engineering, June 2009, http://dspace.mit.edu/bitstream/handle/1721.1/54211/586077698-MIT.pdf?sequence=2, 3.

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