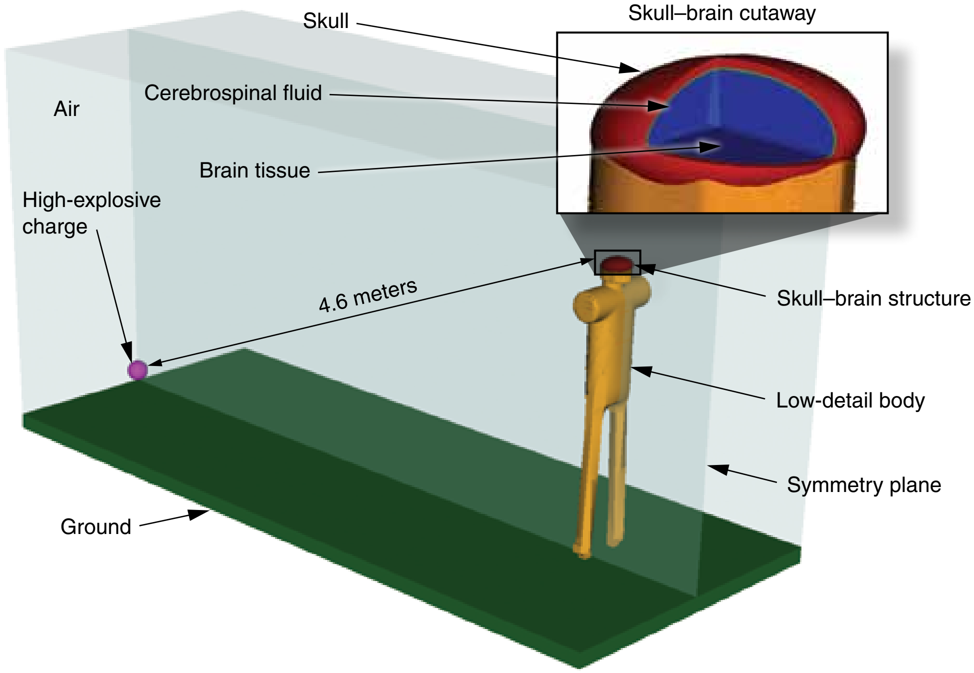
A New Application for a Weapons Code

THE fall and subsequent death last year of actress Natasha Richardson illustrates the complicated nature of traumatic brain injury (TBI). After falling during a ski lesson, Richardson stood up and appeared to feel fine. But a few hours later, she collapsed and eventually died from head injuries suffered in the accident.

Well before Richardson's death, Livermore physicist Willy Moss and engineer Mike King surmised that sophisticated computerized hydrodynamic codes—used for decades to study the fluidlike flow and shock responses of materials exposed to the effects of a nearby detonating weapon—might help researchers understand the mechanisms of TBI. Blast, such as from an improvised explosive device (IED) or a roadside bomb, affects the brain differently than the impact that Richardson experienced. However, in both types of head traumas, notes Moss, "The injuries often do not appear until well after the blast or impact itself."

Working with University of Rochester colleague Eric Blackman, an expert in TBI, Moss and King adapted ALE3D to study TBI. Developed at Livermore, this multiphysics software code is used to model fluid flow and elastic–plastic responses to structures. The TBI simulations unexpectedly revealed that the skull flexes when exposed to a nonlethal blast wave, even one generating pressures as low as 1 atmosphere (or 100 kilopascals) above ambient pressure. In fact, even without direct head impact, nonlethal blasts induce enough skull flexure to generate potentially



In the Livermore simulations of a blast-induced traumatic brain injury, a 2.3-kilogram spherical charge of C4 high explosive is located 4.6 meters from a simplified head consisting of a skull, cerebrospinal fluid, and brain tissue.

damaging pressure loads in the brain, which may contribute to trauma.

IEDs, which are just one cause of TBI, have come to symbolize the current wars in Iraq and Afghanistan. They detonate without warning, killing and maiming tens of thousands of civilians as well as thousands of soldiers. Much improved helmets and body and vehicle armor protect soldiers from shrapnel, bullets, and fragments. But a high incidence of injuries has replaced what would otherwise likely have been many deaths. Explosive devices injured about 65 percent of all Iraq and Afghanistan war veterans who were wounded in action. Overall, between 10 and 20 percent of Iraq war veterans have suffered some degree of head trauma or blast exposure during the war.

The effects of a head impact—hitting the steering wheel in an automobile accident, falling while skiing, or receiving a concussion during a football game—have been extensively studied. “But surprisingly,” says Moss, “blast-induced deformation of the skull has been neglected entirely, perhaps because of the perception that the hard skull protects the brain from nonlethal blast waves.”

Originally funded by the Departments of Defense and Energy under the Joint Munitions Program, the TBI research team has since received support from the Joint IED Defeat Organization (JIEDDO, rhymes with “pie dough”). This Department of Defense organization is dedicated to defeating IEDs as weapons of strategic influence. Other JIEDDO efforts include technology development to improve armor, jam enemy communications, and enhance troop awareness with sophisticated surveillance methods.

The Laboratory brings unique expertise to this research. Livermore’s hydrodynamic codes, which run on massively parallel computing hardware, can simulate how a blast generates waves of pressure and how those waves propagate and interact with any structures in their path, from armor and helmets to vehicles, buildings, and other soldiers. Complementing these computational capabilities are the High Explosives Applications Facility and Site 300, the Laboratory’s remote experimental test site, where experiments can be designed to replicate small-scale battlefield blasts.

The Skull under Pressure

Using ALE3D, the team examined the head’s response to impacts and blast waves. The simulation geometry (shown in the figure above), blast size, and standoff distance from the simulated head were chosen to generate a nonlethal blast wave similar to what might be encountered in the theater of war. The skull was modeled as a hollow elastic ellipsoid containing a viscoelastic brain surrounded by a layer of cerebrospinal fluid. A simplified face (with no lower jaw), neck, and body were included to capture blast-induced accelerations accurately and to appropriately shield the bottom of the braincase from the blast wave.

Anatomical details such as skull thickness variations, gray or white matter, and ventricles were not included, “although we hope to add them in the future,” says King. While these features are needed to predict specific medical traumas, the simplified model quantitatively distinguishes the different mechanisms that affect the brain during an impact or a blast. Says King, "We put in enough complexity to see the blast effects but not too much to prevent us from identifying the underlying mechanisms."

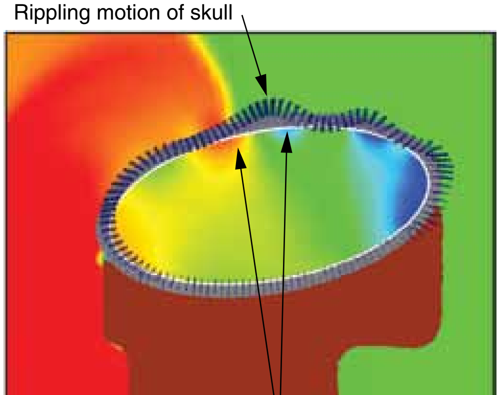
The simulation geometry also provides a means of exploring protective strategies. The head model was encased in a numerically devised steel-shelled helmet containing an inner layer of crushable foam. In the first simulations, the head and helmet were smacked against a rigid wall to duplicate an impact. At maximum deceleration, the brain collides with the decelerating skull and develops large positive pressure. The rebounding brain experiences pressure spikes, pressure gradients, and potentially damaging shear strains. The brain oscillates until the impact energy is dissipated.

An unprotected head—one without a helmet—responds very differently to a blast than to an impact, and the hard skull does not protect the brain from trauma. (See the figure below left.) The most surprising discovery was that the moving pressure wave causes the skull to flex much like dough being pressed under a rolling pin. "We saw it with the very first blast simulation," says Moss. As a result, adds King, "We began running lots of simulations, tweaking each one to make sure this result was neither a computational accident nor an anomaly caused by variations in material parameters or geometry."

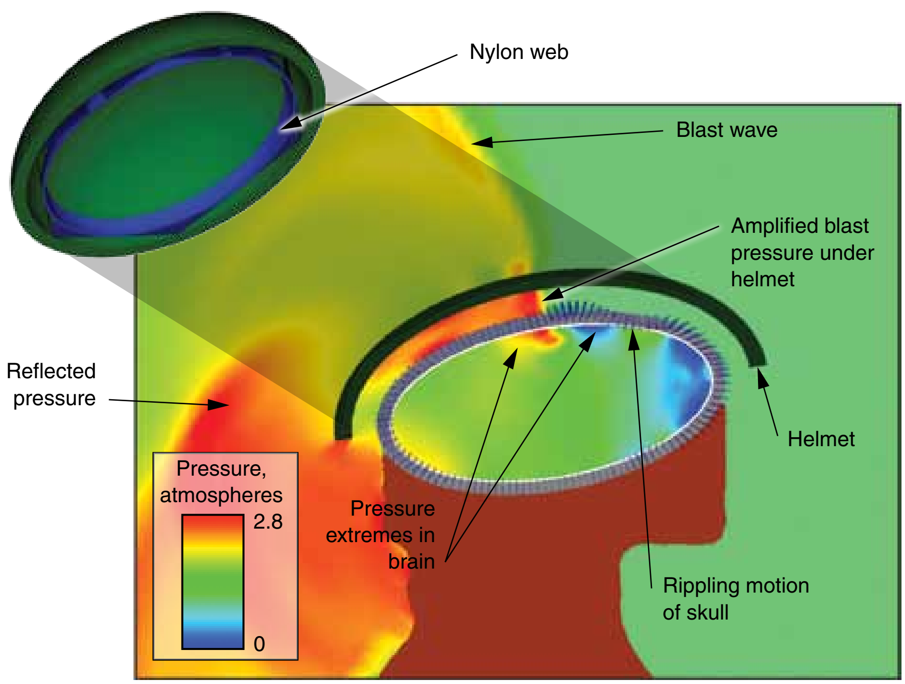
For example, they rotated the body and head 90 degrees to simulate a side-on blast and inserted holes into the skull to represent the spinal column and optical nerve passages. They also varied the material properties of both the skull and the brain, spanning the range of data available in the literature.

Still, every simulation showed the ripple effect from a blast, with the brain receiving the same pressure as it would in an injury-inducing impact. In some places, the pressure on the brain increased as expected, but in others, it decreased. The team discovered that the effect is similar to the pressure ripples on a train track as a train passes over it. "The ripples on the skull were only about 50 micrometers, or just a hair's width," notes Moss. "But even modest skull flexure from a nonlethal blast wave is enough to generate potentially damaging loads in the brain."

The simulations showed that impact creates much larger accelerations in the brain than a blast does, but blast causes much larger pressure gradients, which may cause tissue to rip and tear. Consequently, says Moss, "The metrics used to determine the severity of a TBI from an impact cannot be used to measure blast-induced trauma." Experiments by others have partially validated these findings. For example, blast experiments at Purdue University on a mock head structure derived similar data. Moss adds that further research by the medical community



In simulations of a blast such as from an improvised explosive device, an unprotected skull ripples where the pressure inside the skull is highest, just as pie dough is deformed under a rolling pin.



Simulations show that the older suspension-type helmet amplifies the blast pressure under the helmet, increasing the pressure extremes in the brain.

on cadavers or animals would provide valuable information to help refine the simulations.

Does a Helmet Protect?

Helmets are designed to protect soldiers from bullets, shrapnel, and other flying debris, a task they do well. However, in simulations using the type of helmet formerly worn by some ground troops, the gap created by the web suspension, so essential for ballistic protection, allows the blast wave to wash under the helmet. This underwash effect focuses the blast wave, causing pressure under the helmet to exceed that on the outside. (See the right-hand figure on p. 16.) The helmet does not prevent the rippling deformation of the skull but instead increases it.

Simulations using today's advanced combat helmet revealed that foam pads between the skull and the interior of the helmet prevent much of the underwash effect. However, the pads can become very stiff under the rapid pressure loading created by the blast wave. The blast causes the helmet to deform, and that energy is transferred to the pads. Although the pads block the underwash effect, the blast remains coupled to the skull.

To determine whether a foam's material properties affect the degree of skull flexure, the researchers varied the stiffness of the simulated foam by a factor of as much as 1,000. Stiffer foams transferred greater forces from the helmet to the skull. However, soft foams only partially reduced the blast-induced pressures and pressure gradients in the brain because the back and sides of the head are exposed. Says King, "Even a 'perfect' suspension would allow skull flexure because the helmet cannot completely cover the head."

This inexpensive blast sensor developed by the Livermore team includes a plastic peak-pressure display and is designed for a single use.

Gauging Damage

To correlate TBI cause, effect, and treatment, medical researchers need information on the blast environment around the soldier. The measurement systems currently used by the U.S. military are large, heavy, and of limited use for blasts. Moss and King have investigated two types of sensors to quantify the blast environment, which will help medical personnel diagnose the severity of injuries and triage patients. Both sensor designs are small and lightweight, and says Moss, "They may ultimately help improve the design of armor."

One new sensor uses a tiny microelectromechanical gauge developed by Livermore engineer Jack Kotovsky. Several of these devices could be mounted on a soldier's helmet to form a net of sensors that measure peak pressure, duration of the blast, and the direction from which it came. A companion sensor net placed inside the helmet would measure the stresses transferred to the skull by the helmet and whatever suspension is used. The microelectromechanical system has a patent pending, and the team is looking for funding to further develop and test the system.

The other new sensor (shown at left) is an inexpensive plastic cylinder about as tall as a stack of four quarters. Several of these disposable, easily replaceable devices could be mounted not only on a helmet but elsewhere on a soldier or even inside a vehicle. Each sensor contains a paper that changes color when exposed to specific levels of pressure, which would provide valuable information for medics treating patients in the field. Successful proof-of-principle experiments performed at the High Explosives Applications Facility demonstrated the value of this sensor.

The University of Rochester's Blackman notes, "By comparing the effects of blasts on the head with those from head impacts, we'd be able to make some sense of the distinct mechanisms of injury, the damage a soldier might incur, and how a helmet might be designed to minimize both."

—Katie Walter

Key Words: Afghanistan, blast wave, combat helmet, improvised explosive device (IED), Iraq, traumatic brain injury (TBI).

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