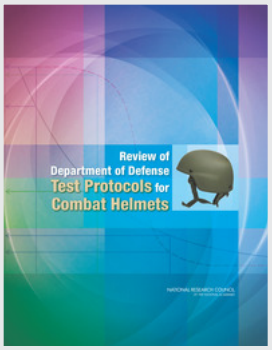

Review of Department of Defense Test Protocols for Combat Helmets

DETAILS

158 pages | 8.5 x 11 | HARDBACK
ISBN 978-0-309-38744-6 | DOI 10.17226/18621

CONTRIBUTORS

Committee on Review of Test Protocols Used by the DoD to Test Combat Helmets; Board on Army Science and Technology; Division on Engineering and Physical Sciences; National Research Council

3

Threats, Head Injuries, and Test Methodologies

3.0 SUMMARY

A variety of threats lead to head injuries in the battlefield. Since World War II (WWII), the predominant threats have been: *fragmentation and ballistic* threats from explosions, artillery, and small arms fire; *blunt trauma* caused by translation from blast, falls, vehicle crashes, and impact with vehicle interiors and from parachute drops; and exposure to *primary blasts*. Key findings in this chapter indicate the following:

- Wounding from an explosive source (e.g., fragmentation from bombs, mines, and artillery) dominates all wounding, including bullets.
- Non-battle causes, including blunt traumatic injuries, produced nearly 50 percent of the hospitalizations for traumatic brain injury in Iraq/Afghanistan.
- There is no biomechanical link in the current test methodology between the backface deformation assessment and head injuries from behind-helmet deformation.

There is a need to revise test methodologies to focus on the dominant threats. The current protocol addresses primarily rounds from 9-mm pistol fire, which is a relatively small contributor to soldier injuries. It is also important to develop better understanding of the scientific connection between head injuries and the performance metrics used in current test methodology.

3.1 INTRODUCTION

The major threats that have caused head injuries in recent conflicts can be classified into three groups: ballistic, blunt, and blast. Table 3-1 identifies their sources and lists potential head injuries. As shown in Figure 3-1, these three categories can also be distinguished by the duration of peak force.[1] For example, for blast loading injuries, the time to peak force and pressure occurs over a timescale of less than 100 microseconds. So, blast injuries of a given severity generally have lower associated momentum and strains/displacements than those for blunt impact, which has peak forces occurring at 3 to 50 milliseconds. On the other hand, ergonomics-related injuries, such as those from heat, weight, lack-of-fit, and long-term usage, typically take days and months.

The rest of this chapter describes head injuries and their typical characteristics. The limitations of current injury test methodologies for assessing head injury risk, including the lack of biomechanical links between test methodology and injury, are also discussed.

3.2 HISTORICAL PATTERNS OF TREATABLE INJURIES

A number of studies have examined military wounding of U.S. forces in major conflicts since WWII. See, for example, Emergency War Surgery (DoD, 2004); Bellamy et al. (1986); Bellamy (1992); Carey (1996); Carey et al. (1998); and Owens et al. (2008). These studies are based on injuries/treatments reported from hospitalizations, including those who died of wounds in hospital. They show that the extremities are the predominant body region injured followed by head/neck (Table 3-2).

Owens et al. (2008) reported that a total of 1,566 U.S. soldiers sustained 6,609 combat wounds in Afghanistan (Operation Enduring Force [OEF]) and Iraq (Operation Enduring Freedom [OIF]). This implies an average of about 4.2 wounds per soldier, likely due to fragments. The data did not include those killed in action, or returned to duty, but did

[1]There has been considerable research related to head and neck injuries over the past 40 years (McIntosh and McCrory, 2005; Fuller et al., 2005; Xydakis et al., 2005; and Brolin et al., 2008). However, much of this work is not applicable to high-impact-rate, low-momentum-transfer scenarios that characterize ballistic impact (Bass et al., 2003).

TABLE 3-1 Broad Categories of Threats

Threats	Sources	Potential Head Injuries
Ballistic and fragment impacts on the helmet	Rifles, handguns, artillery, IEDs	Penetrating trauma, behind-armor-blunt-trauma, BFD
Blunt: Impacts into ground, vehicles, buildings, etc.	Falls, vehicle crashes, blast events, and other potential sources	Closed and open head injuries, skull fracture, hematomas, brain contusions
Blasts	Bombs, artillery, IEDs	Brain trauma, meningeal hematomas, contusions, axonal injuries

NOTE: BFD, backface deformation; IED, improvised explosive device.

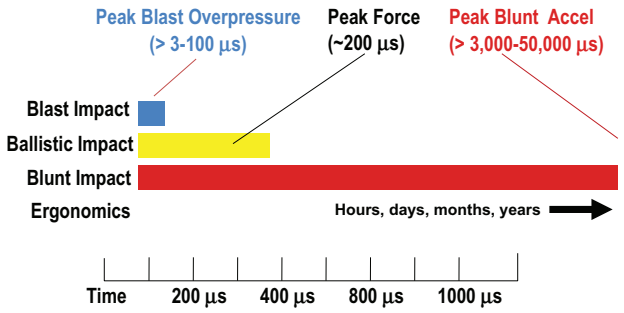

FIGURE 3-1 Typical timeline of blast, ballistic, blunt injuries compared to ergonomics-related injuries.

include those who died of wounds.[2] Table 3-3 shows the locations and distributions of these wounds. The predominant location is extremity (54 percent), followed by the abdomen (11 percent), face (10 percent), and head (8 percent).[3] Data in Owens et al. (2008) also show that the proportion of head and neck wounds in OEF/OIF is higher than those from WWII, Korea, and Vietnam wars (16-21 percent). On the other hand, the proportion of thoracic wounds has decreased by about 50 percent from those for WWII and Vietnam.

Table 3-4 shows that explosions (blast and fragmentation threats) have been the major source of U.S. military wounding since WWII, ranging from 65 percent in Vietnam to more than 80 percent in OEF/OIF (DoD, 2004; Owens et al., 2008; Wojcik et al., 2010). In addition, there is almost a 50 percent reduction in direct gunshot wounds (GSW) from Vietnam to OEF/OIF. This may largely be due to increased thoracic protection (e.g., Belmont et al., 2010; Wood et al., 2012a). The relative success of thoracic body armor likely contributes to the changes in proportion of GSW wounding from previous conflicts to OEF/OIF (Owens et al., 2008).

For Iraq/Afghanistan, Table 3-5 shows that explosions are the primary source of injury across all body regions, ranging from 88 percent for the head to 78 percent for the thorax.

Wojcik et al. (2010) found results comparable to Owens et al. (2008) for hospitalizations for traumatic brain injuries (TBIs) from battlefield causes in OEF/OIF. About 22 percent of personnel had TBIs from all causes (Okie, 2005; Warden, 2006; and U.S. Army Medical Surveillance Activity, 2007). For moderate to severe TBI, about 67 percent of the injuries were attributable to explosions; of these, direct blunt trauma contributed 11 to 13 percent and penetrating injuries contributed 11 to 16 percent (Figure 3-2a). Note, however, that many of the injuries attributable to explosions may have been the result of low-rate blunt trauma following blast events. Figure 3-2b shows that nearly half of the hospitalizations for TBIs in OEF/OIF were noncombat injuries. Since helmets are often worn in noncombat scenarios, these figures emphasize the potential role for the combat helmet in protecting the head from nonbattle TBI from blunt trauma and other causes.

The conclusions from these studies can be summarized as follows:

Finding 3-1.

- Historically, head injuries represent 15 to 30 percent of all wounding by body region.
- Wounding from an explosive source (including fragmentation from bombs, mines, and artillery) dominates injuries in all major modern conflicts since WWII.
- With respect to blast and blunt trauma:
  - —In OEF/OIF, the proportion of blast-associated head injuries (attributed to blast fragments) has increased relative to gunshot wounds.
  - —Nonbattle causes, including blunt traumatic injuries, produced nearly 50 percent of the hospitalizations for TBI in OEF/OIF.

[2]Owens et al. (2008) noted: "Definitions significantly affect the results of casualty analysis. . . . The inclusion of KIAs, RTDs, and NBIs in any cohort analyzed will affect the distribution of wounds and mechanism of injury. For example, the inclusion of KIAs in the cohort analyzed may result in an increase in the number of head and chest wounds seen."

[3]Owens et al. (2008) also reported that there were fluctuations in these figures over time. For example, one of the studies cited there reported a 4-month period of casualties received at Walter Reed Army Medical Center, when they cared for 119 patients with 184 injuries. There were some differences in the breakdowns: head and neck—16 percent, thorax—14 percent, abdomen—11 percent, upper extremity—20 percent, and lower extremity—40 percent. The distribution of the sources of these injuries was also different: 39 percent bullet, 34 percent blunt, and 31 percent explosion. This was during the period of ground warfare and not counterinsurgency.

TABLE 3-2 Relative Body Surface Area and Distribution of Wounds by Body Region (in Percentage)

	Body Surface Area	WWII	Korea	Vietnam	OEF (Afghanistan) and OIF (Iraq)
Head and neck	12	21	21	16	30
Thorax	16	14	10	13	6
Abdomen	11	8	9	10	9
Extremities	61	58	60	61	55

NOTE: Based on injuries/treatments from hospitalizations, including personnel who died of wounds. OEF, Operation Enduring Force; OIF, Operation Iraqi Freedom; WWII, World War II.
SOURCE: Owens et al. (2008).

TABLE 3-3 Distribution of Wounds by Body Region in Operation Enduring Force (Afghanistan) and Operation Iraqi Freedom (Iraq)

Region	Wounds	Percent
Head	509	8
Eyes	380	6
Face	635	10
Ears	175	3
Neck	207	3
Thorax	376	6
Abdomen	709	11
Extremity	3,575	54
Total	6,609	100

NOTE: Based on injuries/treatments from hospitalizations, including personnel who died of wounds.
SOURCE: Owens et al. (2008).

TABLE 3-4 Percentage of Injuries from Gunshot Wounds and Explosions from Previous U.S. Wars

Conflict	Gunshot Wounds (%)	Explosion (%)
WWII	27	73
Korea	31	69
Vietnam	35	65
OIF or OEF	19	81

NOTE: OEF, Operation Enduring Force; OIF, Operation Iraqi Freedom; WWII, World War II.
SOURCE: Owens et al. (2008).

On the other hand, the Department of Defense helmet testing protocols—the subject of this report—focus mainly on protective capabilities against gunfire threats.

Recommendation 3-1. The Department of Defense should ensure that appropriate threats, in particular fragmentation threats, from current and emerging threat profiles are used in testing.

TABLE 3-5 Distributions of Injury Causes by Body Region (in Percentage)

	Gunshot Wounds (%)	Explosion (%)	Motor Vehicle Collision (%)
Head and Neck	8	88	4
Thorax	19	78	3
Abdomen	17	81	2
Extremity	17	81	2

SOURCE: Owens et al. (2008).

Recommendation 3-2. The Department of Defense should investigate the possibility of increasing blunt impact protection of the combat helmet to reduce head injuries.

3.3 THREATS

Bullets

The presentation by the Chief Scientist, Soldier Protective and Individual Equipment,[4] listed repeating pistols, such as Tokarev (7.62×25-mm caliber) and Makarov (9×18-mm caliber), as emerging threats. However, for insurgent and guerrilla warfare, published data and anecdotal evidence suggest that AK-47 (7.62×39-mm) and other Kalashnikov-pattern weapons are the predominant source of ballistic threats in Iraq, Afghanistan, and Somalia (Small Arms Survey, 2012). In a survey of 80,000 small arms and light weapons seizures, they found that the "vast majority of illicit small arms in Afghanistan, Iraq, and Somalia are Kalashnikov-pattern assault rifles. Other types of small arms are comparatively rare" (p. 6). These weapons and their ammunition are inexpensive and widely available with continuing production and large existing supplies (e.g., Small Arms Survey, 2012; Stohl et al., 2007; Perry, 2004; Jones and Ness, 2012).

[4]James Zheng, Chief Scientist, Soldier Protective and Individual Equipment, PEO Soldier, U.S. Army, presentation to the committee, March 21, 2013.

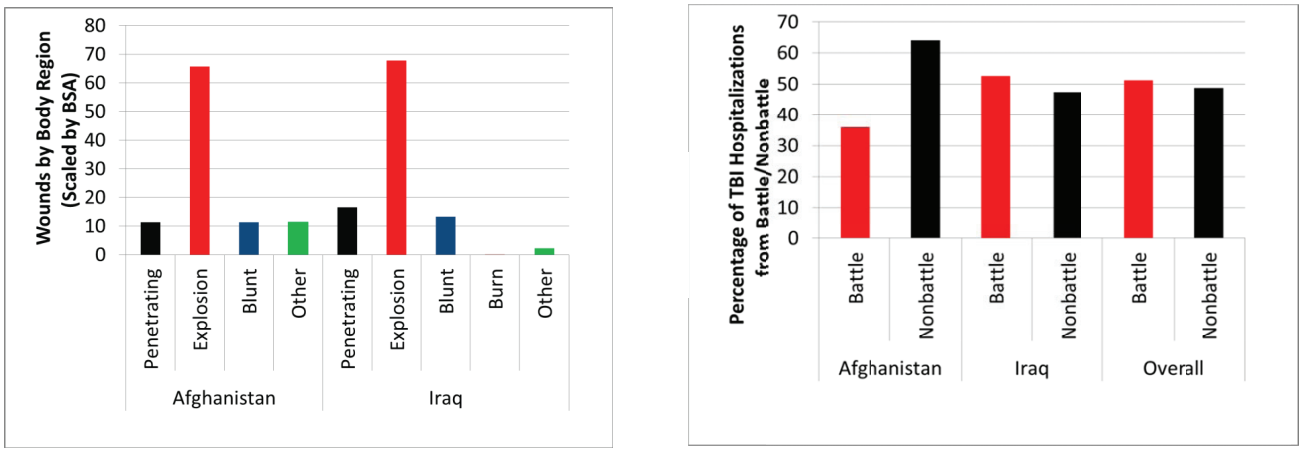

FIGURE 3-2 (a) Traumatic brain injury (TBI) hospitalizations by source for battle injuries categorized by regions in Operation Enduring Force/Operation Iraqi Freedom. (b) TBI hospitalizations by combat/noncombat source. NOTE: BSA, body surface area. SOURCE: Based on data from Wojcik et al. (2010).

TABLE 3-6 Representative Standard-Issue Infantry Rifles and Ammunition for Selected Potential Adversaries

Country	Type	Bullet (mm)	Use	Typical Muzzle Velocity (m/s)
China	Type 56	7.62 × 39	1956-present	790-930
	Type 81	7.62 × 39	1981-present	750
	QBZ-95	5.8 × 42	1995-present	735
	QBZ-97	5.56 × 45	1995-present	
Iran	M1 Garand	7.62 × 63	1950s-present	850
	HK G3A6	7.62 × 51	1980-present	800
	S-5.56	5.56 × 45		990
North Korea	Type 58	7.62 × 39	1958-present	715
	Type 68	7.62 × 39	1968-present	900
	Type 88	5.45 × 39	1988-present	900
Russia	AKM	7.62 × 39	1959-present	715
	AK-74	5.45 × 39	1974-present	900
	AK-74M	5.45 × 39	1991-present	900

SOURCE: Jones and Ness (2012).

Infantry small arms of potential major adversaries including China, Iran, North Korea, and Russia have two predominant calibers (Jones and Ness, 2012). Reserve forces are often issued older types of 7.62×39-mm Kalashnikov-pattern weapons. These have more recently transitioned to 5.45×39-mm or 5.56×45-mm (China) types. Muzzle velocities of these types range from 715 m/s to 990 m/s (Jones and Ness, 2012). Realistic threat profiles, however, may involve velocity at typical engagement ranges rather than muzzle velocities. Available bullet types range from copper-jacketed lead core bullets through armor-piercing incendiary bullets including high explosive fills. Table 3-6 lists the bullets that are potential threats to U.S. forces.

Finding 3-2. Small arms surveys and deployed infantry weapons from major adversaries suggest that 5.56-mm and 7.62-mm rounds at muzzle velocities from 735 m/s to more than 800 m/s are the current predominant ballistic threats.

Fragmentation

As discussed earlier, fragmenting weapons, including artillery, mines, mortars, and other sources of explosions, are the principal source of wounding on the modern battlefield. These weapons, including improvised explosive devices (IEDs), have a multitude of fills/wounding mechanisms. They also have a spatial distribution of fragments that themselves vary by sizes/mass and initial velocities. The relative

risk fragments of each velocity and mass should be included in the threat profile for testing.

However, there is limited published data for arena tests[5] for principal artillery and fragmentation threats. Much of the extensive work is classified. Nevertheless, several studies allow order-of-magnitude analyses for this class of weapon, based on mass, and velocity information from typical 105-mm and 155-mm howitzer shells (e.g., ATEC, 1983; Dehn, 1980; Ramsey et al., 1978; AMC, 1964). A review of these studies leads to the following findings.

Finding 3-3. Results in the open literature indicate that the fragment test velocities used in Advanced Combat Helmet specification are representative of initial fragment velocities from 155-mm artillery shells under high explosive detonation.

Finding 3-4. Results in the open literature show that fragment masses in the ACH specification are generally representative fragment masses from 155-mm artillery shells under high explosive detonation. However, there is a range of fragment masses between 100-grain[6] and 200-grain from artillery shells that have no counterpart in ACH testing.

Finding 3-5. IEDs may have dramatically different distributions of fragment size and velocity compared to other fragmenting weapons such as mortars and artillery. The current ACH threat profile used in testing was selected before the emergence of widespread IED use.

Recommendation 3-3. The Department of Defense should reassess helmet requirements for current and potential future fragmentation threats, especially for fragments energized by blast and for ballistic threats. The reassessment should examine redundancy among design threats, such as the 2-grain versus the 4-grain and the 16-grain versus the 17-grain. Elimination of tests found to be redundant may allow resources to be directed at a wider diversity of realistic ballistic threats, including larger mass artillery fragments, bullets other than the 9-mm, and improvised explosive device fragments. This effort should also examine the effects of shape, mass, and other parameters of current fragmentation threats and differentiate these from important characteristics of design ballistic threats.

Blunt Trauma

Blunt trauma threats on the battlefield are ubiquitous and include falls, vehicle crashes, impact with vehicle interiors, impact from parachute drops, and other sources of blunt impact to the head. In addition, many blast events likely involve blunt trauma (Bass et al., 2012).

Blunt trauma threats may be rated as a function of the change in velocity (often reproduced by drop-testing), as shown in Table 3-7. General threats range from approximately 14 ft/sec for half height falls (falls from 3 ft) to more than 50 ft/sec for typical vehicle crashes at 35 mph. For comparison, the current ACH purchase description specifies a particular acceleration limit (150 g) for a 10 ft/sec drop, far smaller than typical threat velocities.

A recent study of TBI from conflicts in OEF/OIF by Wojcik et al. (2010) found that about 15 percent of the hospitalizations were associated with direct blunt trauma, a figure that is similar to ballistic penetrating injury. Further, it is likely that many of the head injuries associated with blast (about 50 to 60 percent of the cases) were also attributable to low-rate blunt trauma from direct or subsequent contact with vehicle interiors, the ground, and so on. For these injuries, Wojcik et al. (2010) found that almost 80 percent of personnel were wearing a helmet during the incident. It is unclear how much the presence of the helmet mitigates or moderates potential injury, but there is substantial injury exposure even with current combat helmet use.

Data on blunt trauma injuries from more than 120,000 parachute jumps during 1941 to 1998 show that blunt trauma injury rates were approximately 8 per 1,000 drops (Bricknell and Craig, 1999). Bricknell and Craig (1999) reported that head injuries were 4 to19 percent of the total injuries across a range of studies. A more recent study (Knapik et al., 2011) showed that blunt trauma to the head comprised 30 percent of the total injuries, which is quite large. Overall hospitalization rates for TBI in OIF were estimated to be 0.31 percent (Wojcik et al., 2010).

U.S. drop-qualified personnel are required to make 4 jumps/year to retain their jump status (Knapik et al., 2010), and many active personnel make 10-15 or more jumps per year (Knapik et al., 2003, 2010). For exposure over a 10-year career, airborne personnel may have career head injury risk ranging from 10 percent for 4 jumps per year to 34 percent

TABLE 3-7 Representative Battlefield Threats/Impact Velocities

Threat	Impact Velocity m/s	(ft/sec)
Fall—half height (3 ft)	4.3	(14)
Fall—full height (6 ft)	6	(20)
Parachute drop (e.g,. McEntire, 2005)	5.2-6.4	(17-21)
Motor vehicle crash—unrestrained occupant	3-15.2	(10-50)
Motorcycle helmet standards (e.g., FMVSS-218)	5.2-6	(17-20)
Current ACH threat	3	(10)

NOTE: ACH, Advanced Combat Helmet.

[5]Arena tests are standard tests of artillery shells in which fragment number, fragment, and velocity spatial distribution are assessed using high speed video and nondestructive capture mechanisms.

[6]The grain (gr) is a commonly used unit of measure of the mass of bullets. There are 0.0648 grams per grain.

for 15 jumps per year. Thus, there is a great potential for blunt injury from this threat.

Finding 3-6. Common blunt trauma threats have impact velocities of 6.1 m/s (20 ft/s) that are equivalent to drops of 190 cm (75 inches). On the other hand, current blunt trauma threats assessed for the ACH helmet have impact velocities of 3.1 m/s (10 ft/s) which are equivalent to drops of 47 cm (18.6 inches).

Primary Blast

There is limited information on the effect of primary blast on the head (Bass et al., 2012). TBI associated with blast exposure in OEF/OIF is estimated at up to 20 percent of deployed service personnel (e.g., Tanielian and Jaycox, 2008; Ling et al., 2009). The current helmet is not designed with considerations for primary blast, but there is substantial experimental evidence that the ACH helmet is protective against primary blast for most direct exposures (Shridharani et al., 2012). Further, computational models of the human head/helmet system show that helmets with padding do not exacerbate blast exposure for a range of conditions (Panzer et al., 2010; Panzer and Bass, 2012; Nyein et al., 2010). But it is not clear if primary blasts are an important source of wounding. Data presented to the committee[7] indicated that more than 1,500 of the 1,922 reported wounded-in-action incidents produced mild or moderate concussions. However, it is not known if the source of these concussions was primary blasts or falls/tertiary blasts.

Finding 3-7. Epidemiological data, experimental results, and computational models suggest that the ACH helmet does not exacerbate blast exposure.

3.4 ADVANCED COMBAT HELMET TEST METHODOLOGY AND LINKS TO BIOMECHANICS

This section outlines the typical characteristics of each injury type and elucidates the biomechanical basis for penetration and behind-armor blunt trauma assessments.

Penetrating Trauma

Modern ballistic wounding is generally differentiated between rifle and handgun rounds by velocity. For example, high-velocity tumbling rounds such as typical 5.56-mm projectiles (800 m/s or above muzzle velocity) have qualitatively different wounding behavior than .22 caliber handgun ammunition (~330 m/s muzzle velocity), although they have similar diameters. Based on the earlier threat analyses, the committee focuses mainly on military rifle rounds.

Two primary measures are used to assess the performance of helmets: penetration and backface deformation (BFD). (They are formally defined in Chapter 5.) Briefly, a penetration occurs if the ballistic impact causes a projectile to pass though the helmet shell. BFD is a measure of the deformation on the helmet from impact to the head.

The earliest published standard for assessment of penetration with ballistic protective helmets was developed by the National Institute of Standards and Technology's Law Enforcement Standards Laboratory (National Institute of Justice (NIJ) Standard-0106.01–NIJ-1981). This standard specifies inertial impact and penetration assessments for ballistic helmets. Testing of penetration resistance in this standard uses a fixed headform with witness panels located in the mid-coronal plane for a sagittal shot (Figure 3-3) or mid-sagittal planes for a coronal shot. (See Chapter 4 for more details.)

The current ACH standard modifies this NIJ headform to provide deformation resistance using the clay (Roma Plastilina No. 1) used to certify ballistic vests. The empty spaces of the headform are filled with clay, and the permanent plastic backface deformation of the helmet into the clay is recorded as a BFD measurement. Since the head does not undergo plastic deformation in the same manner as the clay, this procedure has no biomechanical basis (NRC, 2012).

Finding 3-8. The mechanical response of clay is qualitatively different from the response of the human head/skull, which may affect both the penetration and backface deformation response of the helmet.

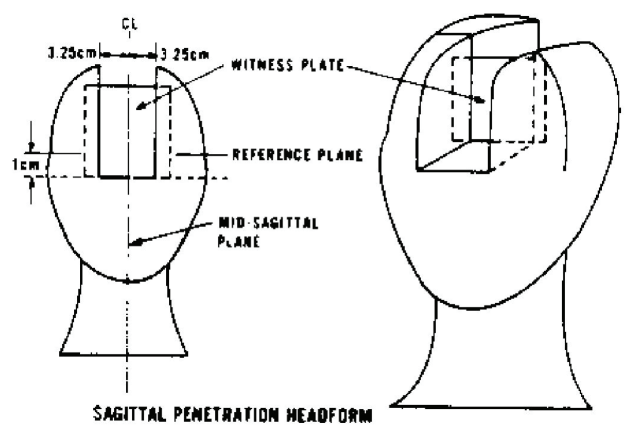

FIGURE 3-3 Sagittal headform specified in National Institute of Justice Penetration Standard, based on the Department of Transportation blunt impact headform. Two similar headforms are used for the helmet tests: A modified version of this headform provides the basis for the advanced combat helmet backface deformation and penetration tests. SOURCE: NIJ (1981).

[7]Natalie Eberius, Predictive Analysis Team Leader, Army Research Laboratory, "Blast Injury Research" presentation to the committee, April 25, 2013.

FIGURE 3-4 Long linear and depressed skull fractures from non-penetrating helmet BFD in a human cadaveric model. SOURCE: Bass et al. (2003).

Modern protective helmet materials (McManus, 1976; Carey et al., 2000) may deform sufficiently for the backface of the helmet to make contact with the head, potentially causing head injuries (e.g., Mayorga et al., 2010; Bass et al., 2002, 2003). Possible injuries include both depressed and long linear skull fractures (Figure 3-4) and other closed-head brain trauma. Owing to the localization from ballistic impact, it is unclear that there is a relationship between low-rate injuries from blunt trauma and potential injuries from BFD. The injuries may occur either from the deforming of the undefeated helmet locally onto the head or underlying skull or from acceleration loads transmitted through the helmet padding to the head (Bass et al., 2003; Mayorga et al., 2010).

The Advisory Group for Aerospace Research and Development (AGARD, 1996) references 29 standards for blunt impact assessment, all of which have a similar underlying basis: the head acts as a rigid body (Bass et al., 2003), and head injury of any type is associated with skull fracture (Versace, 1971; Hodgson and Thomas, 1973; Bass et al., 2003). Recent work by Viano demonstrates poor association between skull fracture and brain injury (Viano, 1988).

There are a few studies of head injury that arises from BFD (e.g., Sarron et al., 2000; Bass et al., 2003). Bass et al. (2003) developed injury criteria for skull fracture and brain injury in human cadaveric heads during ballistic loading of a protective helmet. These tests used ultrahigh-molecular-weight polyethylene helmets with 9-mm full metal jacket (FMJ) test rounds under various impact velocities to 460 m/s (1,510 ft/s). Measurements taken from cadavers with and without skull fracture show no association with existing blunt trauma injury models. Further, there was no obvious association of any acceleration-based response with the occurrence of BFD fracture. Skull force-based injury criteria are available from Bass et al. (2012), which may be useful in future test methodologies.

Clay has been used to assess BFD in military helmets for the past decade.[8] However, there is no existing study linking clay deformation to head injury. For ballistic vests and body armor, Prather et al. (1977) linked backface response to abdominal injury in goats, and by inference to humans by an indirect process. There is no corresponding study for the head. Even then, the biomechanics are likely inappropriate for humans. For example, transient deformation of the abdomen (and by extension the clay) is much larger than the typical deformation to failure from a skin or skull system.

Finding 3-9.

- Prather et al. (1977) is the basis for use of clay to assess BFD injuries. This study linked abdominal response behind deforming soft body armor with abdominal injury in goats through an indirect process.
- There is no biomechanical link between the BFD assessment in the current test methodology and head injuries from behind helmet deformation.

Recommendation 3-4. The Department of Defense should vigorously pursue efforts to provide a biomedical basis for assessing the risk of helmet backface injuries.

Head and neck injuries have been the focus of much research in the past 40 years (e.g., McIntosh and McCrory, 2005; Fuller et al., 2005; Xydakis et al., 2005; Brolin et al., 2008). This work, however, is not necessarily applicable to the high-impact-rate, low-momentum-transfer scenarios that characterize ballistic impact (e.g., Bass et al., 2003).

For BFD scenarios or scenarios in which the bullet remains in the helmet, there is a potential for neck injuries. Such neck injuries are generally associated with large momentum input or resulting velocity changes from impact (e.g., see Bass et al., 2006). Increased helmet mass will tend to delay and decrease neck forces and may mitigate the potential for injury. A number of neck injuries are possible from head motion following momentum transfer from the bullet to the helmet. These include ligamentous injuries (such as strains, tears, or distractions), tensile failure in intervertebral endplates or vertebral bodies, or other injuries to the osteoligamentous spine (Figure 3-5).

Because neck motion following ballistic impact follows a timescale comparable to neck motion from vehicle crashes or falls, automobile criteria are likely appropriate. Current or future helmet ballistic threats have quite low momentum transfer to the head, resulting in quite low injury risk (NRC, 2012). For example, direct measurements have been made of the neck loads following helmet ballistic impact using a 9-mm FMJ round over a range of velocities for human

[8]James Zheng, Chief Scientist, Soldier Protective and Individual Equipment, PEO Soldier, U.S. Army, presentation to the committee, March 21, 2013.

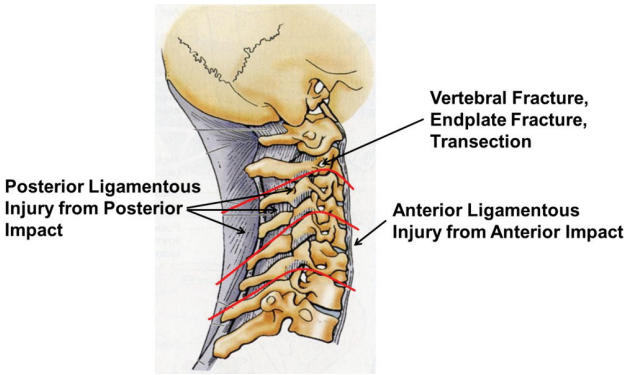

FIGURE 3-5 Typical potential neck injury locations in adults from impact loading. SOURCE: Courtesy of Dale Bass, Duke University.

cadaver tests. Both the NIJ and beam[9] injury assessment values indicate very low risk of neck injuries (<0.1 percent) for these scenarios, and no neck injuries were seen in testing. By extension, injury risk through 7.62×54-mm rounds and beyond to muzzle velocities is low. There is, however, the potential for neck trauma from blunt impact to the head. Improved helmet blunt impact characteristics may reduce the risk of neck injury from blunt trauma.

Finding 3-10. The risk of neck injuries from momentum transfer from ballistic impact of a nonpenetrating round or fragment on the helmet is low for current and near-term future threats up to the 7.62×54-mm rounds at muzzle velocity.

Blunt Trauma

Typical blunt trauma head injuries include skull fractures, hematomas and contusions, and diffuse axonal injuries (e.g., Ommaya et al., 1994). Many tentative mechanical injury tolerances have been established for particular injuries (Figure 3-6), and blunt trauma injury criteria have been promulgated for protective helmets (e.g., AGARD, 1996).

Head protection from blunt impact in vehicles and sports has advanced substantially over the past 30 years. Widespread use of protective helmets has reduced severity and frequency of head injuries. Many of the improvements in helmet technology have arisen from standardized test methodologies based on blunt impact injury criteria. Twenty-nine blunt impact test standards are included in AGARD AR-330 (AGARD, 1996), and the basis for each of these standards is some type of impact acceleration limit. Nineteen have acceleration or force limits alone, and ten use acceleration/duration levels. Acceleration levels specified in these standards vary from 150 g to 400 g, but a standard of approximately

[9]Beam is a neck injury criterion that was developed to assess the risk of neck injury from impacts, including the effect of helmets/night vision and other head-supported mass (Bass et al., 2006).

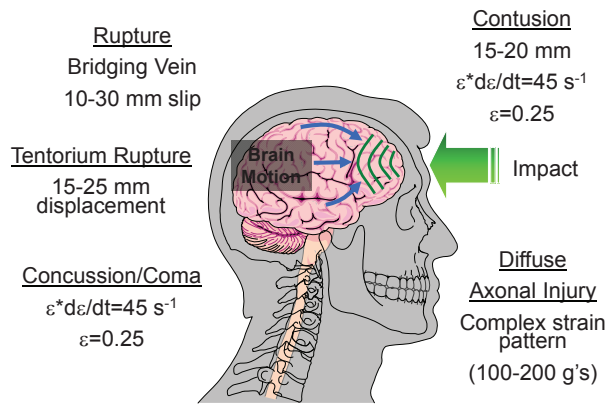

FIGURE 3-6 Typical blunt brain trauma diagram. SOURCE: Based on Ommaya et al. (1994).

80 g has been suggested recently to protect against changes in mentation (cf. Duma et al., 2005). Impact energy limits from these standards are shown in Figure 3-7.

Other potential assessment techniques include the ACH standard (CO/PD-05-04), which is based on the motorcycle helmet Federal Motor Vehicle Safety Standard–218 (49 CFR Sec 571.218); the National Operating Committee on Standards for Athletic Equipment (NOCSAE); and standards that incorporate the International Standards Organization (ISO) headforms. Recent developments include the star rating system for football helmets from the Virginia Polytechnic and State University (Rowson and Duma, 2011). The current ACH blunt impact test assessment (CO/PD-05-04) restricts peak acceleration to a U.S. Department of Transportation (DOT) headform fitted in the ACH to less than 150 g given a headform impact velocity of 3 m/s (10 fps). At approximately 45 J drop energy, the ACH blunt impact assessment is qualitatively different from many typical blunt threats experienced by service personnel.

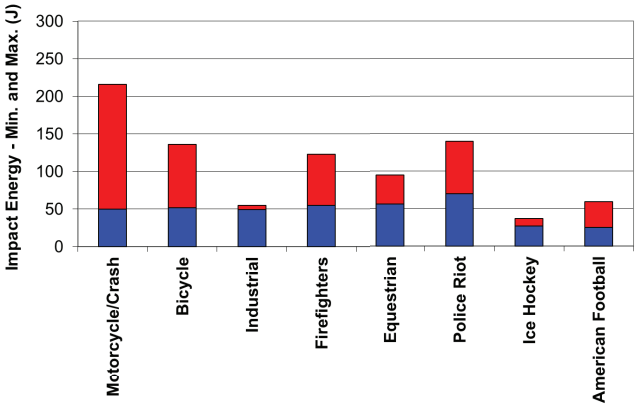

FIGURE 3-7 Energy limits for blunt impact injury assessment in AGARD AR-330. SOURCE: Based on data from AGARD (1996).

Finding 3-11. Numerous established test methodologies are available for assessment of blunt trauma injury with helmets, including supporting injury reference values.

Recommendation 3-5. Whether or not advanced combat helmet design standards are improved to reflect more realistic blunt trauma threats, the current testing protocols should be revised to more fully reflect common blunt trauma threats that are prevalent in training and on the battlefield.

Primary Blast

Models based on animals show that exposure of the isolated head to primary blast impingement can cause various types of injuries including fatality (Säljö et al., 2000, 2008; Rafaels et al., 2011, 2012). The injuries include meningeal bleeding, skull fractures, axonal injuries, and gliosis. However, there are still uncertainties about the relationship between primary blast TBI from animal models and mild TBI during military service (e.g., Bell, 2008). For severe TBI from blast exposure, there may be clear neurological changes, including reduced levels of mentation, unconsciousness, and other dysfunctions (Ling et al., 2009). For milder exposures, possible consequences include neurological deficits, depression, anxiety, memory difficulty, and impaired concentration (Kauvar et al., 2006; Ritenour and Baskin, 2008; Stein and McAllister, 2009). Diagnosis is difficult for milder exposures because these symptoms strongly overlap with posttraumatic stress disorder often seen in service members (Capehart and Bass, 2011; Bass et al., 2012).

Several primary blast injury assessments have been developed recently using animal models (Rafaels et al., 2011, 2012). While scaling of these animal models to human values is not fully established (Wood et al., 2012b), these risk assessments suggest that brain injuries may occur at much lower levels of blast exposure than previously accepted, and potentially much lower levels than pulmonary injury for a soldier wearing body armor.

Finding 3-12. The state of understanding of blast brain trauma is at an early stage, and there is substantial ongoing research.

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