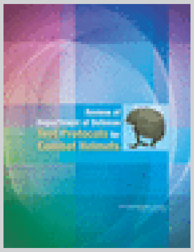

Review of Department of Defense Test Protocols for Combat Helmets

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Preface

Rep. Louise Slaughter (D-NY) wrote to Secretary of Defense Leon Panetta in June 2012 to express her concerns that the new protocol for testing Advanced Combat Helmets (ACHs) posed "an unacceptably high risk" for such protective equipment. In responding to Rep. Slaughter, Dr. Michael Gilmore, Director of Operational Test and Evaluation (DOT&E) of the Department of Defense (DoD), indicated that he had requested the National Academies' National Research Council (NRC) to conduct an independent review of DOT&E's test protocols. The Committee on Review of Test Protocols Used by the DoD to Test Combat Helmets was formed to conduct this review. This report is the result of that study.

The committee held six meetings, including a site visit to the combat helmet test range at the Aberdeen Test Center in Maryland. It received presentations from some two dozen entities, including offices within the U.S. Army, the U.S. Marine Corps, and the Special Operations Forces; the Institute for Defense Analysis; DOT&E; manufacturers of combat helmets; and the Office of the DoD Inspector General. The committee appreciates the assistance offered by Chris Moosmann, a staff member in the DOT&E Office of Live Fire Test and Evaluation, in the course of its deliberations. The study was conducted under the auspices of the NRC Board on Army Science and Technology (BAST). The committee appreciates the assistance of Bruce A. Braun, director of BAST, and Nancy T. Schulte, study director, for their very effective support in the conduct of this study. It also offers its thanks to the BAST staff members who capably assisted in information-gathering activities, meeting and trip arrangements, and the production of this report; they include Nia D. Johnson, associate research assistant, and Deanna Sparger, senior program assistant.

Finally, and most importantly, I want to express my appreciation to my fellow committee members for all of their work in developing the findings and recommendations and in preparing the report. This was an especially collegial group of experts, and I learned a lot from interacting with them. Rob Easterling and Ernest Seglie, two of the committee members, deserve special mention for their contributions as part of the editorial team. I am also grateful to Naveen Narisetty at the University of Michigan for his work on the numerical studies to examine the robustness properties of test plans.

Vijay Nair, *Chair*
Committee on Review of Test Protocols
Used by the DoD to Test Combat Helmets

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Gordon R. England, NAE, E6 Partners LLC,
Karen Kafadar, Indiana University,
Harvey S. Levin, Baylor College of Medicine,
William Q. Meeker, Jr., Iowa State University,
James R. Moran, The Boeing Company,
John E. Rolph, University of Southern California, and
Dean L. Sicking, The University of Alabama at Birmingham.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by James O. Berger, NAS, Duke University. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Tables, Figures, and Box

TABLES

FIGURES

BOX

Acronyms and Abbreviations

ACH	advanced combat helmet (Army)
ANSI	American National Standards Institute
AQL	acceptance quality limit
ATC	U.S. Army Aberdeen Test Center
ATD	anthropometric test device
BFD	backface deformation
BTD	ballistic transient deformation
DAI	diffuse axonal injury
DCMA	Defense Contract Management Agency
DoD	Department of Defense
DOT	Department of Transportation
DOT&E	Director, Operational Test and Evaluation
DTI	diffusion tensor imaging
ECH	enhanced combat helmet
FAST	Future Assault Shell Technology
FAT	first article testing
FMJ	full metal jacket
FSP	fragment simulating projectile
GSW	gunshot wounds
HEaDS-UP	Helmet Electronics and Display System – Upgradeable Protection
HIC	head injury criteria
ICP	intracranial pressure
IED	improvised explosive device
IG	Inspector General
ISO	International Standards Organization
L	large
LAT	lot acceptance testing
LWH	lightweight helmet (Marine Corps)
M	medium
M&S	modeling and simulation
MICH	Modular Integrated Communications Helmet
MIL-STD	military standard
MRI	magnetic resonance imaging
mTBI	mild traumatic brain injury
NHTSA	National Highway Traffic Safety Administration
NIJ	National Institute of Justice
NIST	National Institute of Standards and Technology
NRC	National Research Council
OC	operating characteristic (curve)
OEF	Operation Enduring Freedom (Afghanistan)
OIF	Operation Iraqi Freedom
P	probability
PASGT	Personnel Armor System for Ground Troops
PEO-S	U.S. Army Program Executive Office Soldier
PET	positron emission tomography
P(nP)	probability of no penetration
Pr(pen)	probability of penetration
R&R	repeatability and reproducibility
RCC	right circular cylinder
RTP	resistance to penetration
S	small
SIMon	simulated injury monitor
TBI	traumatic brain injury

UCB	upper confidence bound
UHMWPE	ultra-high molecular weight polyethylene
USSOCOM	United States Special Operations Command
UTL	upper tolerance limit
UVA	University of Virginia
WWII	World War II
XL	extra large

Summary

CONTEXT AND TASKING

In 2007, the Secretary of Defense asked the Director of Operational Test and Evaluation (DOT&E) to take over the responsibility to prescribe policy and procedures for the conduct of live-fire test and evaluation of body armor and helmets. A 2009 report by the Department of Defense's (DoD) Inspector General recommended that the DOT&E "develop for Department-wide implementation a standard test operations procedure for body armor inserts" that includes "statistical specification of probability of performance and associated confidence in that performance" (DoD IG, 2009). As a result of this recommendation, DOT&E developed and published statistically based test protocols for body armor and for combat helmets, in April and December, 2010, respectively.

In June 2012, Rep. Louise Slaughter (D-NY) sent a letter (Slaughter, 2012)[1] to Secretary of Defense Leon Panetta expressing concerns that the new protocol[2] for ballistic testing for the Advanced Combat Helmet (ACH) posed "an unacceptably high risk" for such protective equipment. Dr. Michael Gilmore, DOT&E, responded to Rep. Slaughter's letter (Gilmore, 2012)[3] on July 13, 2012. As part of this response, he noted that DOT&E would request the assistance of the National Academies' National Research Council (NRC) to determine the adequacy of the ballistic helmet testing methodology.

The NRC set up the Committee on Review of Test Protocols Used by the DoD to Test Combat Helmets to consider the technical issues relating to test protocols for military combat helmets and prepare a report. The statement of task for the committee is as follows:

- Evaluate the adequacy of the Advanced Combat Helmet test protocol for both first article testing and lot acceptance testing, including its use of the metrics of probability of no penetration and the upper tolerance limit (used to evaluate backface deformation).
- Evaluate the appropriate use of statistical techniques (e.g., rounding numbers, choosing sample sizes, or test designs) in gathering the data.
- Evaluate the adequacy of the current helmet testing procedure to determine the level of protection provided by current helmet performance specifications.
- Evaluate procedures for the conduct of additional analysis of penetration and backface deformation data to determine whether differences in performance exist.
- Evaluate the scope of characterization testing relative to the benefit of the information obtained.

This report is the result of the committee's deliberations.

CURRENT PROTOCOLS

The ACH was introduced by the Army in 2002 and continues to be produced. The advance production order was for 1.08 million helmets, and these are in sustainment. When a manufacturer proposes to produce ACHs for the Army, it submits a sample for first article testing (FAT). If the helmet design passes the FAT, the manufacturer will start production. The produced helmets must be subjected to a lot acceptance test (LAT) for a quality check before the lot is accepted.

The FAT process involves a suite of ballistic shots, with the primary one being 9-mm shots at a specified velocity and at specified helmet locations. Two measures are used to assess the performance of helmets during the test process:

[1]The full text of Rep. Slaughter's letter to Secretary Panetta is in Appendix A.

[2]The December 7, 2010, protocol for first article testing is superseded by the September 20, 2011, protocol for first article testing. This protocol, including the May 4, 2012, protocol for lot acceptance testing, is found in Appendix B.

[3]The full text of Director Gilmore's response to Rep. Slaughter is in Appendix A.

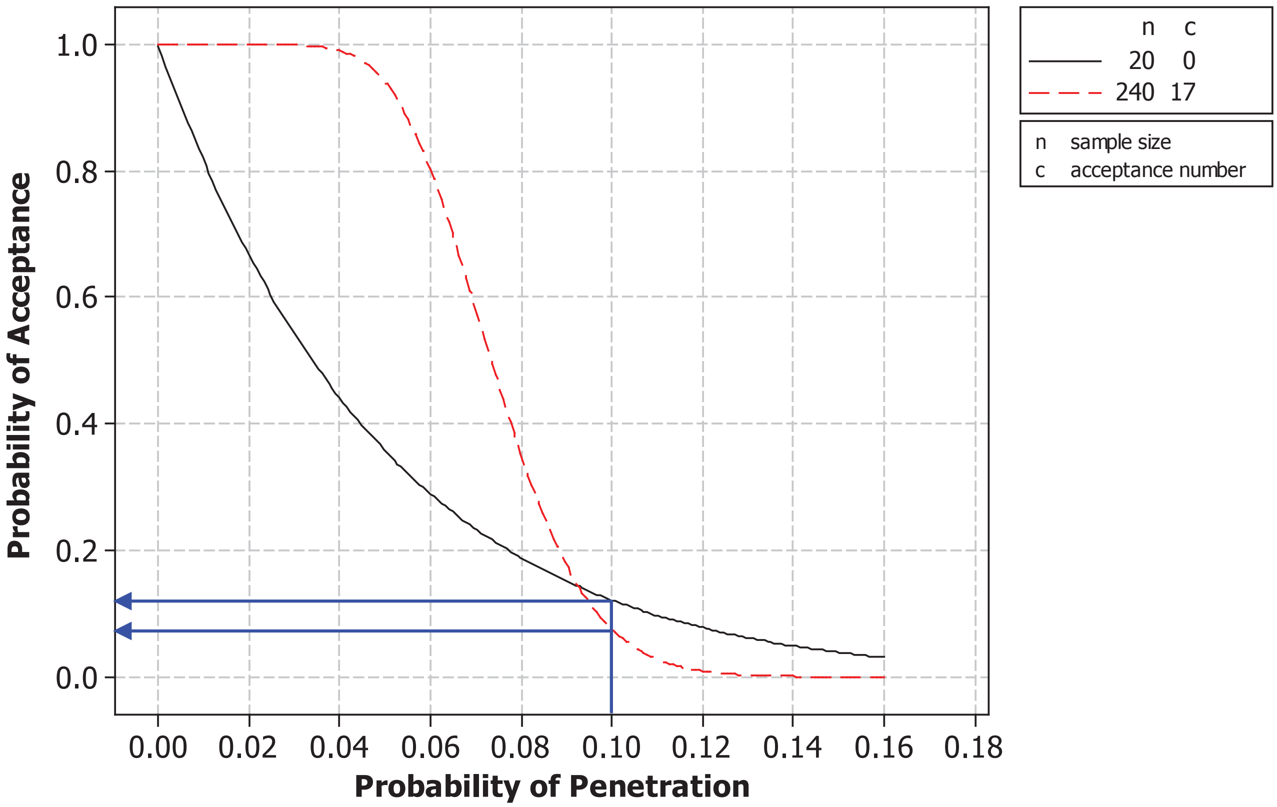

FIGURE S-1 Operating characteristic curves for the Army's and the Director of Operational Test and Evaluation's first article testing protocols for penetration. The blue lines show the probabilities of acceptance for the two plans when the true probability of penetration is 0.1.

resistance to penetration (RTP) and backface deformation (BFD).[4]

The original Army FAT protocol consisted of 20 9-mm shots (four helmets and shots at five specified locations on a helmet). The helmets were all the same size, and one helmet each was exposed to one of four environmental conditions. A manufacturer's helmet design was deemed to pass FAT for penetration if there were zero penetrations out of the 20 shots. This is an example of a *c-out-of-n* test plan in the statistical quality control literature; in this case, $c = 0$ and $n = 20$.

The properties of a test plan can be obtained from its operating characteristic (OC) curve, which is a plot of the probability of passing the test (y-axis) as a function of the penetration probability of a single shot (x-axis). The solid black curve in Figure S-1 gives the OC curve for the Army's 0-out-of-20 plan. The blue line shows that, if the true probability of penetration is 0.10, the probability of passing the test is about[5] 0.10. This property has been referred to as the *90/90 standard* in Director Gilmore's letter and elsewhere by DOT&E: *If the probability of non-penetration is 0.9 or less, then the helmet design has at least a 90 percent chance of failing the FAT.*

In developing its protocol, DOT&E decided to increase the number of helmets tested from 4 to 48. Five shots were taken at five different locations on a helmet (as was the case with the Army's protocol), leading to a total of $n = 240$ shots. DOT&E applied the same 90/90 standard to get the number of acceptable penetrations as $c = 17$. In other words, the helmet design passes FAT if there are17 or fewer penetrations in 240 shots and fails otherwise. The dashed red curve in Figure S-1 shows the OC curve for this plan developed by DOT&E. It can be seen that, if the true probability of penetration is 0.10, the probability of acceptance equals 0.10 (satisfying the 90/90 standard).

It is this change in the protocol, from zero penetrations (out of 20 shots) to allowing as many as 17 penetrations (out of 240 shots), that resulted in Rep. Slaughter's concern with the safety of Army combat helmets. In his response, Director Gilmore noted that DOT&E's plan had (essentially[6]) the same 90/90 property as the Army's legacy plan. Further, it had better statistical properties because a larger number of

[4]RTP is a binary outcome indicating whether or not there is a complete penetration of the helmet shell. BFD is measured by the maximum depth of the deformation that is imprinted by the helmet on the clay surface of the headform. (Formal definitions are given in Chapter 5.)

[5]The actual probability of acceptance for the 0-out-of-20 plan is slightly higher than 0.10. The 0-out-of-22 plan is closer to the 90/90 standard. This was noted in Dr. Gilmore's response to Rep. Slaughter.

[6]See footnote 5.

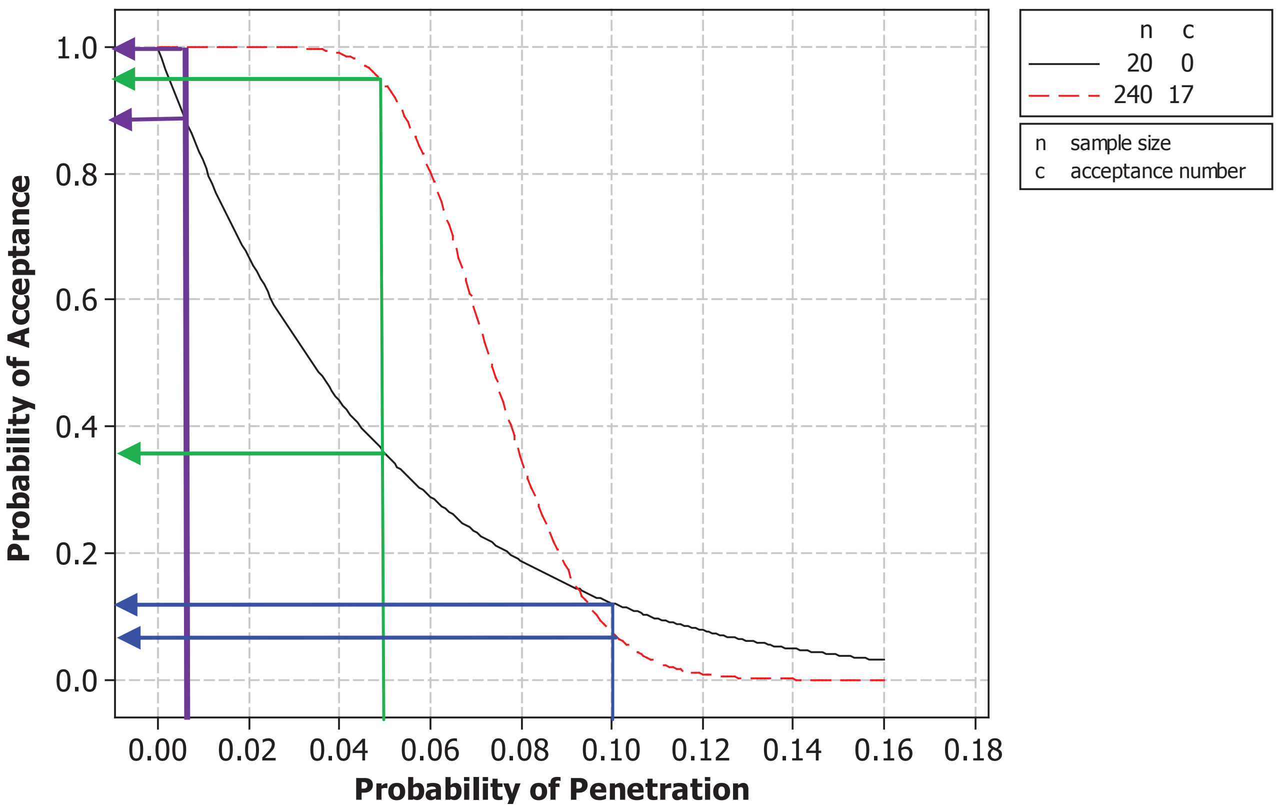

FIGURE S-2 Further comparisons of the operating characteristic curves for the Army's and the Director of Operational Test and Evaluation's first article testing protocols for penetration. The blue lines show the probabilities of acceptance for the two plans when the true probability of penetration is 0.1; the purple and green lines show the corresponding acceptance probabilities when the true penetration probabilities are, respectively, 0.005 and 0.05.

helmets and multiple helmet sizes were tested under different environmental conditions, and, therefore, the new protocol was an improvement.

Comparison of FAT Protocols for Penetration

The committee first considers FAT protocols for RTP because these were the focus of the correspondence between Rep. Slaughter and Director Gilmore. FAT protocols involving BFD are discussed in Chapter 7. LAT protocols for both RTP and BFD are considered in Chapter 8.

The committee emphasizes an obvious point: The Army's legacy protocol allowed zero penetrations in 20 shots, but that did not imply that a helmet design that passes FAT has zero probability of penetration.

Further, there are good statistical reasons to justify DOT&E's increase in the number of helmets tested to 48 helmets from the Army's 5. One gets more precise estimates of the penetration probability from 240 shots than 20 shots. In addition, DOT&E's plan allows better statistical comparison of possible differences between helmet sizes and environmental conditions. So, as pointed out in Dr. Gilmore's letter, there are indeed advantages associated with increasing the number of helmets tested.

However, a key issue is whether the 90/90 standard, which was used to develop the protocol, is appropriate. In addition, that standard specifies only one point on the OC curve in developing the test plan, but, in fact, the whole curve and the plan's incentives and risks need to be considered. Figure S-2 provides a re-examination of the OC curves for the Army's and DOT&E's protocols. As in Figure S-1, the black curve is for the Army's 0-out-of-20 plan, and the red curve is for DOT&E's 17-out-of-240 plan. Each curve shows how the probability of accepting a helmet design (y-axis) varies as the underlying probability of penetration (x-axis) varies. As noted in Figure S-1, the two curves cross at a point close to penetration probability of 0.10 (blue line). To the left of this curve, DOT&E's plan (in red) has higher probabilities of acceptance (passing FAT); to the right it has lower probabilities. In other words, the DOT&E's plan is less stringent (easier to pass) than the original 0-out-of-20 plan if the actual penetration probability is less than 0.10 and more difficult to pass if the penetration probability is higher than 0.10. However, as we will see below, there are more pertinent penetration probabilities at which the plans should be compared.

Data made available to the committee show that manufacturers are currently producing ACHs with penetration probabilities around 0.005 or less (overall, there were 7 penetrations in 12,147 shots; see Chapter 5). This corresponds to the purple line in Figure S-2. At this penetration probability of 0.005, the probability of passing the FAT is close to 1.0 for DOT&E's protocol (red curve), while it is about 0.9 for the Army's legacy protocol (black curve). So the manufacturer's risks (probabilities of *not passing* the FAT) at a penetration probability of 0.005 are zero and 0.1 respectively. These are relatively small values, as they should be.

Consider the green line in Figure S-2 that corresponds to a penetration probability of 0.05, an order of magnitude higher than the current penetration level of 0.005. For this value, the DOT&E's plan (red curve), has an acceptance probability of about 0.95, while the Army's legacy plan (black curve) has a probability of about 0.38. In other words, if manufacturers produce helmets with a penetration probability of 0.05 (as noted, an order of magnitude higher than the current level), they have a 95 percent chance of passing the FAT under the current DOT&E protocol; that is, the government's risk is 0.95. In comparison, the government's risk under the Army's legacy plan is 0.38.

So the question comes down to the following: *What is the appropriate level of penetration probability at which the government's risk should be controlled*? By selecting the 90/90 standard, DOT&E has set this penetration probability at 0.10, a value that is roughly two orders of magnitude greater than where the manufacturers are currently operating.

Now, for business reasons, the manufacturers would want to design a helmet that has a high chance of passing the test while meeting the other helmet criteria such as weight. If there is a high probability of passing the test, even if the penetration probability is an order of magnitude higher than the current levels, manufacturers may not have an incentive to sustain the current levels of penetration-resistance, and, hence, helmet safety could possibly be degraded.

As noted in Chapters 3, 6, and 10, there is currently no scientific basis for linking performance metrics to brain injuries. The report notes, in Chapter 3 and elsewhere, that there is a need to initiate research that connects performance metrics to brain injuries.

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

While these links are being developed, it is important that the performance of new helmet systems is at least as good as previous helmet systems, as measured by current performance metrics.

Recommendation 6-2. If there is a scientific basis to link brain injury with performance metrics (such as penetration frequency and backface deformation), the Director of Operational Test and Evaluation (DOT&E), should use this information to set the appropriate standard for performance metrics in the test protocols. In the absence of such a scientific basis, DOT&E should develop a plan that provides assurance that it leads to the production of helmets that are at least as penetration resistant as currently fielded helmets.

Director Gilmore's response to Rep. Slaughter notes that the "Services and the U.S. Special Operations Command have endorsed the 90/90 standard for no perforation."[7] Despite this assurance, the committee is concerned that DOT&E's protocol may have unintended consequences. As noted earlier, under the new DOT&E protocol, there is a high probability of passing the test even if the penetration probability is an order of magnitude higher than the current levels. Therefore manufacturers may not have an incentive to sustain the current levels of penetration resistance.

Of course, future designs of helmets may involve other considerations such as lower weight and added mobility. It is possible that manufacturers and the government have to compromise on the penetration probability levels in order to produce lighter helmets. However, the added benefits of such design changes would have to be studied and demonstrated before one accepts higher levels of penetration. In the case of the ACH, there have been no such design changes.

The Army's Modified Protocol

In 2012, with DOT&E's approval, the Army modified the 17-out-of-240 plan to a two-stage protocol. The two stages involve conducting a 0-out-of-22 plan in the first stage, and, if the helmet design passes this test, then a second 17-out-of-218 plan is used, for a total of 240 shots and a combined acceptable number of penetrations of 17. The first stage, the 0-out-of-22 plan, is slightly more stringent than the Army's 0-out-of-20 legacy plan, so this modified plan provides an incentive for manufacturers to achieve a penetration probability of 0.005 or less.

Finding 6-4. The Army's modified plan satisfies the criterion that it provides an incentive for manufacturers to produce helmets that are at least as penetration-resistant as current helmets.

The second stage of this plan allows 17 penetrations out of 218 shots, or equivalently, a penetration probability level of 17/218 = 0.08. However, a helmet design with 0.08 penetration probability has a very small chance of being

[7]Director Gilmore's letter, reprinted in Appendix A, also noted, "The National Research Council (NRC), in its recent independent technical review of the Department's testing of body armor, indicated that this approach to testing is scientifically defensible." It should be emphasized, however, that the Committee on Testing of Body Armor Materials for Use by the U.S. Army—Phase III did not explicitly endorse the 90/90 standard. Further, the standards for helmets should be determined independently of those for body armor.

accepted in the first stage, so the two-stage plan will reject such a helmet design.

CONSIDERATIONS IN DEVELOPING NEW PROTOCOLS

Although the Army's modified protocol can be a short-term solution, the committee encourages DOT&E to consider the various findings and recommendations in the report and develop a better alternative to its current protocols. These findings and recommendations are described in Chapters 5 through 9 of the report. Some of the important considerations identified in the report include the following:

- What is the appropriate level at which government's risk should be controlled? The 90/90 standard implies that it should be controlled at a penetration probability of 0.10. However, manufacturers are currently producing ACHs with a penetration probability of around 0.005 or less, which is substantially lower than 0.10.

Recommendation 6-3. The government's risk should be controlled at much lower penetration levels than the 0.10 value specified by the 90/90 standard.

- When DoD adopts new helmets with changes to the design (such as lighter weight and added mobility), it will be necessary to reevaluate the protocols. For example, it may not be possible for manufacturers to produce lighter helmets at current levels of penetration.

Recommendation 9-1. When combat helmets with new designs are introduced, the Department of Defense should conduct appropriate characterization studies and cost-benefit analyses to evaluate the design changes before making decisions. It is not advisable to automatically apply the same standard (such as the 90/90 rule or others) when these tests could potentially be across different protective equipment (body armor, helmets, etc.), different numbers of tests (e.g., 96 tests for the Enhanced Combat Helmet, 240 tests for the Advanced Combat Helmet), or over time.

- The current BFD protocols use upper tolerance limits based on the assumption that the data are normally distributed. One has to be cautious in using protocols that are sensitive to such parametric assumptions. Further, the use of pretests to check on assumptions of homogeneity, as has been proposed by DOT&E, would lead to complexity in the analysis and, more importantly, the properties of the BFD protocols. When the test sample size is large (as is the case with DOT&E's proposed plan of 240 shots), it is preferable to use protocols that do not rely on parametric assumptions, are more transparent, and are easier to interpret.

Recommendation 7-1. The Director of Operational Test and Evaluation should revert to the more transparent and robust analysis of backface deformation data based on pass/fail scoring of each measurement.

However, it is important to conduct post-test analysis of the continuous BFD measurements and monitor them over time.

Recommendation 7-3. The Office of the Director, Operational Test and Evaluation, and the Services should analyze the continuous backface deformation measurements, compute the margins, and track them over time to assess any changes over time.

- The different-sized helmets are intrinsically different products with different shells, molds, and manufacturing settings, and consideration should be given to testing them separately. Further, separating by helmet sizes will simplify some of the complexities associated with current test processes.

Recommendation 5-5. Current Office of the Director, Operational Test and Evaluation, protocols should be revised and implemented separately by helmet size.

- Data made available to the committee indicate that there may be considerable differences in the distributions of the BFD data across helmet sizes and shot locations. DOT&E is considering the use of preliminary hypothesis tests on BFD data and pooling the data across the different settings if the hypotheses are not rejected. The committee has reservations about the use of such procedures. The changes to binary data for BFD test plans and the implementation of protocols by helmet size will mediate the effect of heterogeneity among shot locations.

It was not part of the committee's charge to offer specific alternative test protocols. However, several alternative plans and their properties are discussed in this report to assist in DOT&E's efforts to develop an appropriate plan.

DOT&E has indicated that as data are obtained its protocol will be updated and modified. The committee's findings are in that spirit: Available data indicate that penetrations are rare events (penetration probability of 0.005 or less). Therefore, an alternative protocol has to be developed such that ACH manufacturers have an incentive to maintain that level of penetration-resistance. The 17-out-of-240 FAT protocol does not provide such incentive.

The report compares the performance of DOT&E's 17-out-of-240 with the Army's legacy plan of 0-out-of-20 at various places. The main reason for such comparisons, as discussed earlier, is that any new plan should lead to the production of helmets that are at least as penetration-resistant as currently fielded helmets. However, the committee reiterates that there are important advantages to the increased test size in DOT&E's plan compared to the Army's legacy plan. Any modification to DOT&E's plan should retain the benefits obtained from the increased test size, although the report does not make any specific recommendation on test size.

ORGANIZATION OF THE REPORT

This report includes 10 chapters and several appendixes. Chapter 1 provides an introduction and overview. Chapter 2 describes the history and evolution of the combat helmet as well as recent advances in design, materials, and manufacturing processes.

Chapter 3 describes historical wounding patterns and recent and emerging threats as well as the biomechanical basis for penetration and blunt trauma. The latter topic is taken up in more detail in Chapter 10, which presents the gaps in medical knowledge of brain injury tolerances relative to current standards of helmet protection. The key findings and recommendations from these two chapters include the following:

- Wounding from an explosive source (including fragmentation from bombs, mines, and artillery) has dominated injuries in all major modern conflicts since World War II. Blast and blunt trauma are increasingly becoming a major source of injuries.

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.

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.

- Unlike body armor, there is not any indirect biomechanical connection between the backface deformation assessment in the current test methodology and brain injuries from behind-helmet deformation.
- Brain injury tolerances determined in the past, and continuing to be developed for vehicle and sports collisions, are based on stresses and stress rates that are significantly different from those for ballistic and blast stresses.

Most of the findings are recommendations in Chapters 3 and 10 are in response to the third point in the committee's statement of task: Evaluate the adequacy of current testing to determine the level of protection provided by the ACH.

Chapters 4-9 deal primarily with statistical issues. Chapter 4 describes the testing and measurement processes for combat helmets, including the test threats and the different sources of variation. The Phase II report on body armor testing noted the need to conduct a formal gauge repeatability and reproducibility (R&R) study to determine the sources of variation in the test process (NRC, 2012). It appears that such a study has not been done. In view of the costs involved in testing and the benefits to be gained from an R&R study, the committee reiterates the importance of carrying out such a study.

Recommendation 4-1. The Department of Defense should conduct a formal gauge repeatability and reproducibility study to determine the magnitudes of the sources of test variation, particularly the relative contributions of the various sources from the testing methodology versus the variation inherent in the helmets. The Army and the Office of the Director, Operational Test and Evaluation, should use the results of the gauge repeatability and reproducibility study to make informed decisions about whether and how to improve the testing process.

Chapter 5 provides a formal definition of the performance measures—resistance to penetration (RTP) and backface deformation (BFD)—and discusses their limitations. The results from analyses of FAT and LAT data made available to the committee are also described here. These data showed considerable heterogeneity among helmet sizes and shot locations.

Chapters 6 and 7 are concerned with the evaluation and comparison of FAT protocols for RTP and BFD, respectively. Most of the key findings and recommendations from these chapters are summarized above.

Chapter 8 deals with LAT, with major findings and recommendations that mirror those for FAT. In addition, Chapter 8 describes how the current LAT protocols can be modified to conform to American National Standards Institute standard.

Chapter 9 responds to the committee's charge to evaluate the scope of current characterization testing and recommend additional studies. A number of additional characterization studies for new helmet designs as part of a broader program on characterization are suggested.

CONCLUDING REMARKS

The committee commends the Director of Operational Test and Evaluation and his office for their efforts to bring scientific rigor to the testing of combat helmets. These efforts are of critical importance to the safety and morale of the men and women of the U.S. armed services. The committee also applauds Rep. Slaughter for her active oversight in this area.

The overarching messages in this report are:

- There is an urgent need for the Department of Defense to establish a research program to develop helmet test metrics that have a clear scientific link to the modes of human injury from ballistic impact, blast, and blunt trauma.
- It is critical that test profiles for combat helmets be modified to include appropriate threats from current and emerging threats.
- The development of test protocols must be based on appropriately derived OC curves, where such curves will likely be unique to each helmet type and design, which is intentionally chosen to match current technology capability and the needs of the soldier on the battlefield. Further, it is important that the design of test plans focus on that region of the OC curve at which the helmet is expected to perform.

Throughout the course of the committee's research and deliberations, it became quite clear that DOT&E's and the Army's goal is to ensure that combat helmets (and all personal protective equipment) are manufactured and tested to the highest possible standards. It is the committee's hope that this report helps DOT&E and DoD in their continued pursuit of this goal.

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1

Introduction

This chapter provides the study context and statement of task. It also describes the scope of the study and includes summaries of the various chapters in the report.

In June 2012, Rep. Louise Slaughter (D-NY) sent a letter (Slaughter, 2012)[1] to Secretary of Defense Leon Panetta expressing concerns that a recent modification to the standard for ballistic testing for the Advanced Combat Helmet (ACH) posed "an unacceptably high risk" for such protective equipment. She urged that ballistics testing procedures be modified.

The July 13, 2012, response to Rep. Slaughter (Gilmore, 2012)[2] was made by J. Michael Gilmore, Director of Operational Test and Evaluation (DOT&E), the principal staff assistant and advisor to the Secretary and Deputy Secretary of Defense for operational test and evaluation and live-fire test and evaluation matters. He expressed the view that the revised test protocol for the ACH is "better in several ways that the previously used protocol while being designed to demonstrate the same level of protection (probability of perforation) and also the same level of certainty of our knowledge of the level of protection." However, he also noted that DOT&E was requesting that the National Research Council conduct a study to review the revised protocol for testing military combat helmets. This report is the result of that request. Following is the statement of task.

> The National Research Council will establish an ad hoc committee to consider the technical issues relating to test protocols for military combat helmets and prepare a report. The committee will examine the testing protocols along the following lines:
>
> - Evaluate the adequacy of the Advanced Combat Helmet test protocol for both first article testing and lot acceptance testing, including its use of the metrics of probability of no penetration and the upper tolerance limit (used to evaluate backface deformation).
> - Evaluate the appropriate use of statistical techniques (e.g., rounding numbers, choosing sample sizes, or test designs) in gathering the data.
> - Evaluate the adequacy of the current helmet testing procedure to determine the level of protection provided by current helmet performance specifications.
> - Evaluate procedures for the conduct of additional analysis of penetration and backface deformation data to determine whether differences in performance exist.
> - Evaluate the scope of characterization testing relative to the benefit of the information obtained.

[1]The text of Rep. Slaughter's letter to Secretary Panetta is found in Appendix A.

[2]The text of Director Gilmore's letter to Rep. Slaughter is found in Appendix A.

1.0 INFORMATION GATHERING

The committee held six meetings. The first was held in Aberdeen, Maryland, and included a site visit to the combat helmet test range at the Aberdeen Test Center. The second through sixth meetings were held at the Academies' facilities in Washington, D.C., and Woods Hole, Massachusetts. A total of 18 presentations were received from the following entities:

- Offices within the United States Army, the Marine Corps, and the Special Operations Forces
- Manufacturers of combat helmets
- Office of the Department of Defense (DoD) Inspector General

The titles of the presentations are listed in Appendix C.

1.1 SUMMARY OF THE REPORT

The report contains 10 chapters and several appendices. This is an introductory chapter. Summaries of the remaining chapters are given below.

Chapter 2: Evolution of Combat Helmets

Chapter 2 describes the changes in design and materials, from those used in World War I to today's ACH. One of the key advances was the development of aramid fibers in the 1960s, which led to today's Kevlar-based helmets. The DoD is continuing to invest in research to improve helmet performance, through better design and materials as well as better manufacturing processes.

Chapter 3: Threats, Head Injuries, and Test Methodologies

A variety of threats lead to head injuries in the battlefield. Since World War II, the predominant threats have been from the following: *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.
- Nonbattle 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 (BFD) 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.

Chapter 4: Combat Helmet Testing

Chapter 4 describes how combat helmets are tested. It includes a brief summary of the testing process, a description of the test threats, and a discussion of the various sources of variation in the testing process.

Chapter 5: Helmet Performance Measures and Trends in Test Data

A helmet's protective capabilities are evaluated on the basis of two primary test measures: resistance to penetration (RTP) and BFD. These are formally defined, and their limitations are discussed in this chapter. RTP data available to the committee indicate that the probability of penetration of a helmet shell by a 9-mm bullet, fired under specified conditions, is on the order of 0.005 or less. Available BFD data show that the probability of exceeding the BFD thresholds is also around 0.005 or less. The distributions of the BFD data also demonstrate significant differences among helmet sizes and shot locations. Some of the performance differences among helmet sizes may be attributed to the test process, such as headforms and standoffs. Many others are likely to be due to the differences in the geometry of helmet shells, molds, manufacturing processes, and other factors. In fact, helmets of different sizes are intrinsically different products. Based on this, Recommendation 5-5 proposes changes to DoD's test protocols. This is one of the major recommendations in the report.

Chapter 6: FAT Protocols for Resistance to Penetration: Statistical Considerations and Evaluation of DOD Test Plans

The test protocols for Army helmets were originally based on a requirement of zero penetrations in 20 shots (5 shots on 4 helmets). The DOT&E protocol replaced this legacy plan with a requirement of 17 or fewer penetrations in 240 shots (5 shots on each of 48 helmets). The helmets spanned four sizes and were tested in four different environments. The 0-out-of-20 (0, 20) plan and DOT&E's 17-out-of-240 (17, 240) plan have comparable performance if the probability of penetrating a helmet shell on a single shot is around 0.10. As noted in the Chapter 5, available data indicate that these penetration probabilities are around 0.005 or less. Near this value of penetration probability, both plans have a 90 percent or higher chance of passing the test, so the manufacturer's risk is small, as it should be. However, if there is a 10-fold increase in the penetration probability from the current level of 0.005 to 0.05, DOT&E's (17, 240) plan still has a 95 percent chance of acceptance. This provides little incentive for the manufacturer to sustain current penetration levels. The (0, 20) plan, on the other hand, has only a 38 percent chance of acceptance. Thus, the (17, 240) plan may have the unintended effect of leading to a reduction in helmet penetration resistance. In the absence of a link between penetration probability and human injury, there is no scientific basis for setting a limit on the penetration probability. In such a circumstance, the committee's view is that the objective of a new test plan should be to provide assurance that newly submitted helmets are at least as penetration resistant as current helmets. Chapter 6 also proposes appropriate criteria for selecting test protocols and illustrates their use through several plans.

Chapter 7: Test Protocols for Backface Deformation: Statistical Considerations and Assessment

The original Army protocols for BFD were based on binary (0-1) data. The BFD measurement at each location was compared against its specified threshold, and the outcome was scored as a "1" (failure) if it exceeded its threshold. This original plan was based on 20 shots; if no BFD measurements exceeded their limit, the demonstration was successful. In this sense, it was similar to Army's legacy protocol for RTP. The DOT&E protocol expanded the number of shots to 240 and used the continuous measurements together with an assumption that the data are normally distributed. Specifically, the plan compared the 90 percent "upper-tolerance limits" computed at 90 percent confidence level (90/90 rule) with their thresholds for the corresponding location on the helmet. As noted in Chapter 5, available BFD test data show that the probability of BFD exceeding its limits is quite small—on the order of 0.005. As this chapter observes, DOT&E's BFD protocol has about a 90 percent chance of accepting the helmet design, even if there is an order of magnitude increase in the exceedance probability (from 0.005 to 0.05). This weakens the incentive for manufacturers to produce helmets that are at least as good as current helmets with respect to BFD. In addition, the DOT&E protocols are based on an (a priori untestable) assumption of normality and the complex notion of an upper tolerance limit. Recommendation 7-1 proposes that DOT&E's protocol for BDF data be changed. This change has the added advantage that the BFD protocol would exactly parallel the RTP protocol and would be easy for designers and manufacturers to understand and interpret. However, it is important that, after testing, the continuous BFD measurements be analyzed to assess the actual BFD levels and monitor them for changes over time.

Chapter 8: Lot Acceptance Testing

Lot acceptance testing (LAT) is used to ensure that manufacturers continue to produce helmets that conform to contract specifications. A random sample of helmets is selected from the production lot, and the helmet shells, as well as hardware, are tested according to the LAT protocol. The number of helmets in the protocols is determined from an American National Standards Institute (ANSI) standard, and they vary by lot size. Chapter 8 examines the operating characteristic (OC) curves for DOT&E's LAT plans and compares them with FAT protocols in the Army's legacy plans and DOT&E's plans. The OC curves for the LAT plans for the different lot sizes can vary a lot, indicating that the manufacturer's and government's risks can be quite different across lot sizes. This is primarily due to the different sample sizes (number of helmets and number of shots) as determined from an ANSI standard. Further, DOT&E's first article testing (FAT) protocols are considerably less stringent (higher probabilities of acceptance for the OC curves) than their corresponding LAT protocols. This is counter to the philosophy that it should be more difficult for manufacturers to pass FAT than LAT. This issue can be addressed if DOT&E makes changes to the (17, 240) FAT protocol as discussed in Chapters 6 and 7. Chapter 8 also proposes using binary data for BFD LAT protocols, to make them consistent with the recommendations for FAT. Finally, the committee examines the properties of LAT protocols based on helmets as the unit of testing.

Chapter 9: Characterization Tests for ACH and Future Helmets

The committee was tasked to "evaluate the scope of characterization testing relative to the benefit of the information obtained." The term "characterization" is broad and is used in different ways in different contexts. However, DOT&E provided additional information to elaborate on this task. Most of the issues raised by DOT&E that relate to this task are addressed in this chapter. Chapter 9 also describes additional characterization tests that are needed. Some of these are intended for future helmet designs. A number of these additional tests have been discussed in earlier chapters and are repeated here because they can be viewed as being related to characterization studies. These include the following: evaluating helmet performance across a more realistic, broader range of threats; assessing the effect of aging; understanding the relationship between helmet offsets and helmet protection; and conducting gauge repeatability and reproducibility studies to understand the different sources of variation in the test process and possibly providing opportunities to reduce some of the variation. Chapter 9 also includes a discussion of current V_{50}—the velocity at which complete penetration and partial penetration are equally likely to occur—testing and an alternative methodology as well as a discussion of industrial practices in characterizing process capability.

Chapter 10: Linking Helmet Protection to Brain Injury

The relationships between helmet deformation and brain injury are not well known. Most of the studies in biomechanical engineering and medicine are related to sports and vehicle collisions, and these investigations are based on a different range of stresses and stress rates from those encountered in the battlefield. The aim of Chapter 10 is to present information on what is known, and the gaps in knowledge, about the linkage between brain injury and current battlefield threats. The major finding is that helmet protection from penetration and BFD greater than a particular value does not protect the brain from occurrence of many categories of tissue injury. This chapter discusses recommendations that can help focus research, including determination of the prevalence of reversible declines in hormonal function years after brain trauma and acceleration of research in computational modeling and simulation that can show shear stress fields associated with the known spectrum of threats and the protective capabilities of helmets.

1.2 REFERENCES

Gilmore, J.M. 2012. Letter from J. Michael Gilmore, Director of Operational Test and Evaluation, to Representative Louise M. Slaughter, July 13.

Slaughter, L.M. 2012. Letter from Representative Louise M. Slaughter to Secretary of Defense Leon Panetta, June 26.

2

Evolution of Combat Helmets

2.0 SUMMARY

Combat helmets have evolved considerably over the years. This chapter describes the changes in design and materials, from those used in World War I to today's Advanced Combat Helmet (ACH). One of the key advances was the development of aramid fibers in the 1960s, which led to today's Kevlar-based helmets. The Department of Defense (DoD) is continuing to invest in research to improve helmet performance, through better design and materials as well as better manufacturing processes.

2.1 INTRODUCTION

In early usage, soldiers wore equipment made of leather or cloth in an attempt to protect their heads from sword cuts and other blows. When rifled firearms were introduced in the late 1700s, this equipment was found to be inadequate, and its use declined considerably. Over time, the equipment transitioned from providing protection to being an accessory worn for pageantry and unit recognition.

World War I saw a substantial increase in the effectiveness and lethality of artillery, resulting in a new focus on protective equipment, including helmets. The primary threat during this conflict was fragmenting projectiles, and helmets made with steel were introduced for protection in Europe in 1915. Even though stopping a rifle bullet was considered beyond the ability of the helmet materials at the time (due to weight considerations), there were enough benefits to warrant issuing a helmet to all ground troops.

Around this time, the governments in Europe started to invest considerable efforts on research dealing with helmet design, materials, and support systems (such as chin straps and liners). This research resulted, among other advances, in a new grade of metal known as Hadfield steel. Different variations of these steel helmets were used by forces in the United Kingdom and the British Commonwealth during World War I and later. The U.S. military adopted helmets based on Hadfield steel, called the M1 "steel pot," in 1942. These helmets remained in service until the mid-1980s when they were replaced with helmets manufactured from a nonmetallic material. Small numbers of the M1 helmet are still used today in special missions such as shipboard firefighting.

The beginning of World War II also saw an escalation in the lethality of ballistic threats, resulting in higher fatalities and injuries. The bullets and shrapnel in World War II had greater mass and higher velocities. As was the case with World War I, soldiers initially resisted wearing helmets. They felt that the 3.5-lb helmet was too heavy, and that it limited hearing, vision, and mobility of the wearer. However, the troops quickly accepted the trade-off when they observed the lethality of the munitions on the battlefield and recognized the protection provided by the helmet.

Figure 2-1 illustrates the evolution of U.S. military helmets since World War I. The rest of this chapter discusses the evolution and developments in some detail.

2.2 NEW MATERIALS AND DESIGNS

DuPont invented a new material called aramid fiber in the 1960s. This was a class of strong, heat-resistant synthetic fibers that had many desirable properties. It was eventually marketed under the trade name of Kevlar, and the name would become synonymous with "bulletproof material." Kevlar represented a breakthrough, enabling a leap ahead in technology of synthetic composite materials. The U.S. government selected Kevlar over other materials that were available at the time, such as nylon, e-glass fiber, and stretched polypropylene. The government was already molding the M1 helmet liner with a similar matched-tool compression molding process, so that the same manufacturing process could be used to make Kevlar helmets.

The Personnel Armor System for Ground Troops (PASGT) was the first helmet to use Kevlar. PASGT refers to both vests and helmets made of Kevlar, and they were used by all military services from the mid-1980s to around the middle of

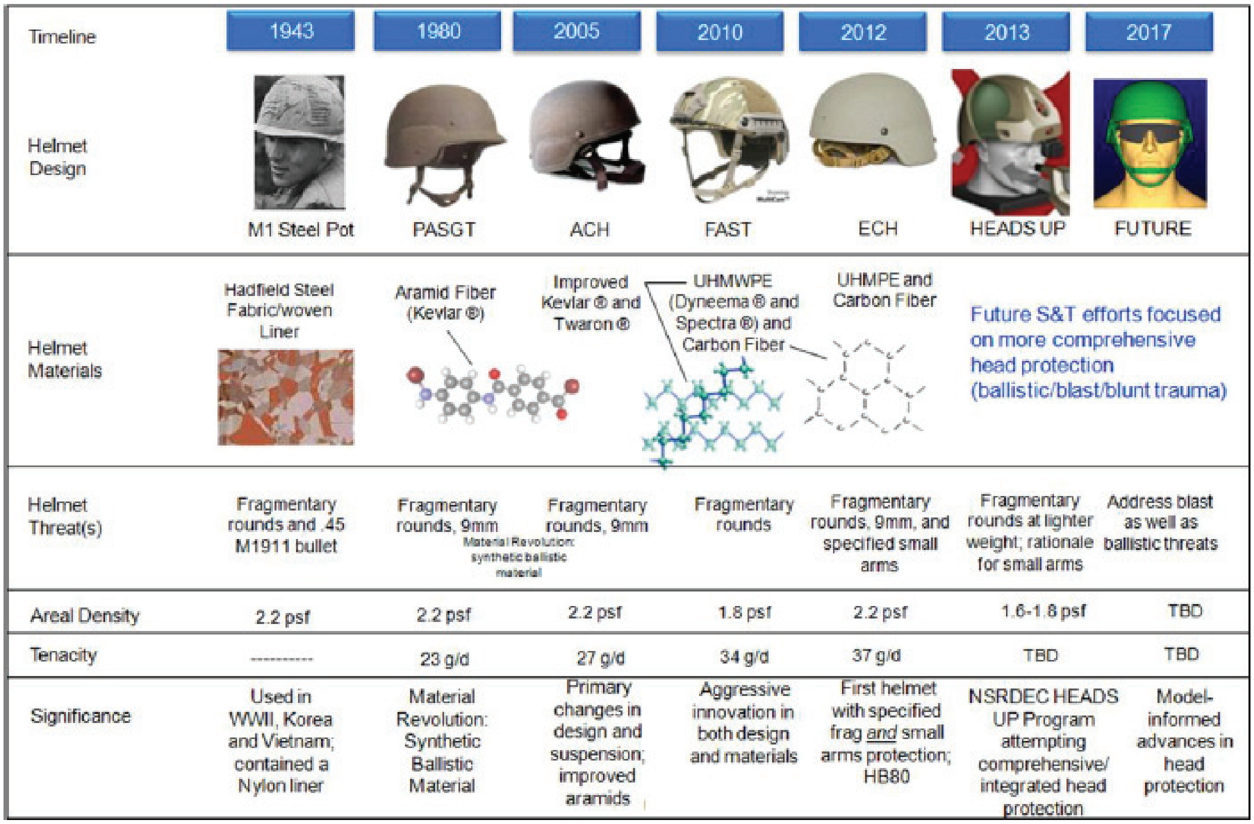

FIGURE 2-1 Evolution of helmets from World War I to present. SOURCE: Walsh et al. (2012).

the last decade. These helmets are still being used by some services but will be replaced in the future.

The U.S. Special Operations Command designed and developed the Modular Integrated Communications Helmet (MICH) as a replacement for PASGT. MICH had several changes, including improved Kevlar aramid-fiber reinforcement, leading to better protection. They also allowed better fit and integration of communication headsets. MICH was adopted by the U.S. Army in 2002 as its basic helmet and renamed the Advanced Combat Helmet. The Marine Corps decided to use a design profile that was similar to the PASGT and designated it the Light Weight Helmet (LWH).

There were also developments in helmet retention systems. The M1 "steel pot" used a nylon cord suspension system, sweatband, and chinstrap, and the PASGT helmet and its variants also used similar retention systems. The MICH, ACH, and LWH helmets switched to a multi-pad and four-point retention system (Figure 2-2) that had better impact protection while providing increased comfort.

The next major advance in helmet technology resulted from a combination of advances in materials and manufacturing processes. A new generation of ultra-high-molecular-weight polyethylene fibers (UHMWPE) was developed in industry. In parallel, the government funded efforts to address technology gaps that had previously precluded manufacture of thermoplastic-based fibers and matrices for affordable soldier protection systems. The programs focused on developing new technologies, tooling, and hybridization techniques to enable commercially available and emerging grades of thermoplastic ballistic composite materials to be formed into complex helmet shapes. There was participation from the Marine Corps, U.S. Special Operations Command, and the industrial sector. These efforts enabled the development of the Future Assault Shell Technology (FAST) helmet, the Maritime helmet, and, ultimately, the U.S. Marine Corps Enhanced Combat Helmet (ECH). The FAST helmet is significant for its early use of UHMWPE material and its novel design.

To improve ballistic protection, the Army has initiated several developmental programs over the last decade. These include the Scorpion, Objective Force Warrior, and Future Force Warrior programs. The goal of the Scorpion program was to improve protection and performance through an integrated system. It tried to address the continuing problem of protection while also providing the soldier with capability, such as communications, hearing protection, and displays, needed in an evolving battlefield environment. The program also explored the use of materials with better ballistic performance and processing concepts to deliver increased structural performance. In addition, the program examined how to provide more options in helmet shaping, compat-

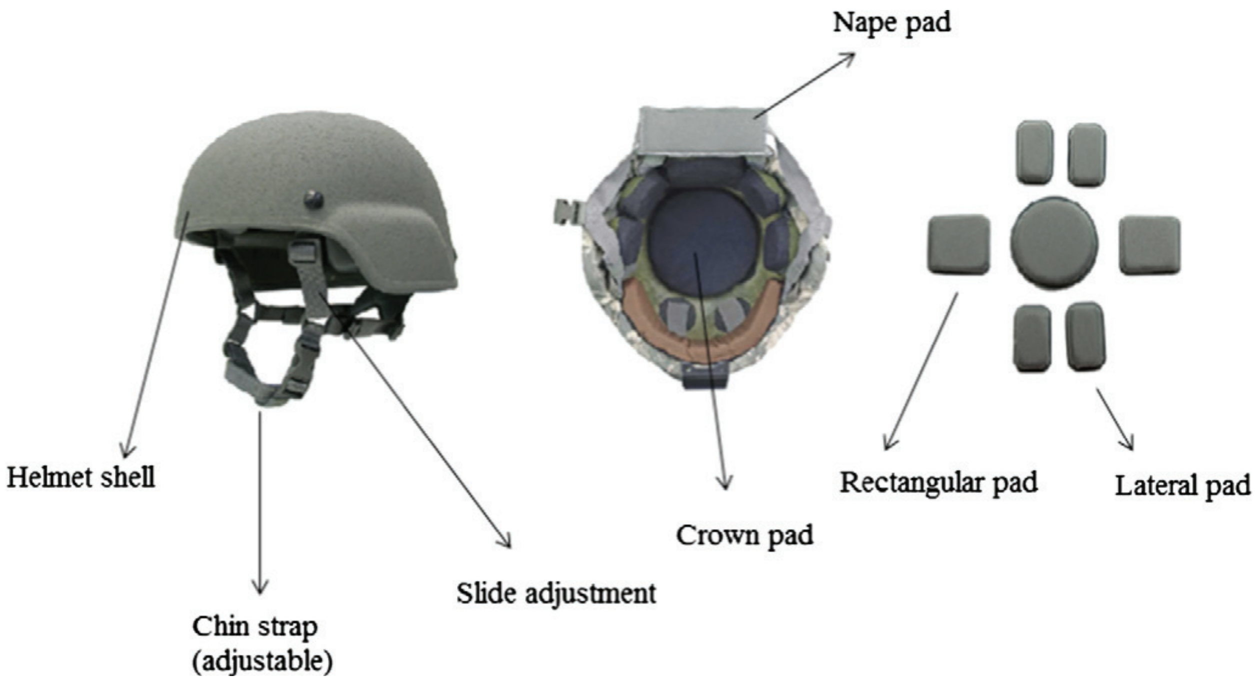

FIGURE 2-2 Helmet multi-pad and four-point retention systems. SOURCE: PEO Soldier, U.S. Army.

ibility, and ergonomics as well as device and accoutrement integration. These early efforts would ultimately result in an entirely new generation of helmet technologies, designs, and manufacturing processes.

2.3 RECENT DEVELOPMENTS AND DIRECTIONS

In 2009, the U.S. government launched the “Helmet Electronics and Display System–Upgradeable Protection” (HEaDS-UP) program, involving multiple organizations. As of 2012, it was the largest head-protection research and development project within the Army. It leverages multiple efforts—in the areas of ballistic materials (transparent and non-transparent), high-resolution miniature displays, and sensors—to design a modular-integrated headgear system that takes into account the relevant ergonomics considerations.

The HEaDS UP program is designed to include participation from a wide spectrum of Army organizations as well as other services and government agencies. The goal of the program is to provide two different and independently developed concepts of an integrated headgear system and packages of design options as well as guidelines based on manufacturing best practices, lessons learned, and technology maturation. The resulting insight will be used to develop an integrated head, face, and neck protection headgear system that incorporates modular, upgradeable protection.

The soldier-relevant goals are twofold: (1) reduced weight for equivalent protection and small increased weight for significantly increased capabilities; and (2) increased situational awareness in all environmental and obscurant conditions without sacrificing mobility and agility.

Unlike past considerations for fielded helmets, the HEaDS UP program also explicitly acknowledges that the helmet is no longer simply a device to prevent injury from fragments and blunt impact. It recognizes that the helmet has become a platform to provide the soldier with new capabilities to enhance their survivability. The consequence is further device integration and modularization of accoutrements in or attached to the helmet. It might mean even more ballistic protection from small arms threats and maxillofacial (mandible) systems that can be rapidly donned or doffed. But the advances are limited by the total amount of weight a soldier is able to carry for an extended period of time.

Continued improvement in materials is also leading to advances in helmet performance. For example, ECH delivers much better protection against fragments compared to ACH, due to a shift to unidirectional UHMWPE fiber in a thermoplastic matrix. The shift was also enabled by a new generation of preforms and manufacturing methods appropriate for UHMWPE. While other promising materials have been identified (e.g., copolymers, graphene, and high-tenacity UHMWPE), dramatic weight reduction without a significant loss in ballistic performance has been elusive.

Another factor in helmet protection is the way the constituent materials are assembled. Previous research results suggest that, in unidirectional UHMWPE panels, varying fiber orientation and fiber architecture can provide better balance between resistance-to-penetration and deformation mitigation. Vargas-Gonzalez et al. (2011) have explored this issue for panels that had more architectural complexity.

New materials are also under evaluation for mitigating the effect of impacts to the head. Both recoverable and non-recoverable energy-absorbing materials are being considered for use as helmet pads. Concepts for decoupling the helmet into a ballistic and impact shell (and using energy-absorbing materials between shells) are also being explored.

Novel manufacturing equipment and methodologies also have a role to play in improving performance. The first generation Helmet Preform Assembly Machine is an example of a process that exploited the ability of thermoplastic composites to be locally consolidated, leading to a rapid, automated method of stabilizing and building up helmet preforms. The underlying lesson is that processing should also be explicitly considered as an asset in pursuit of incremental performance gains in head protection materials and systems.

DoD has undertaken extensive efforts to improve combat helmet designs. The design goal is to reduce injuries and injury severity, while achieving operational needs. However, the goal of this report is to evaluate test protocols. In the following chapters, the extent to which the above goal—of reducing injuries and injury severity—is achieved by the test programs is discussed.

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Walsh, S.M., L.R. Vargas-Gonzalez, B.R. Scott, and D. Lee. 2012. Developing an Integrated Rationale for Future Head Protection in Materials and Design. U.S. Army Research Laboratory, Aberdeen Proving Ground, Md.

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.

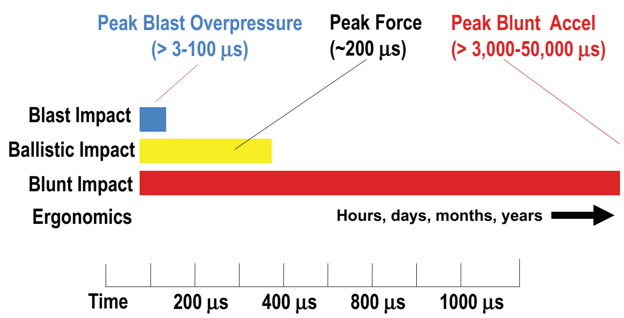

FIGURE 3-1 Typical timeline of blast, ballistic, blunt injuries compared to ergonomics-related injuries.

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.

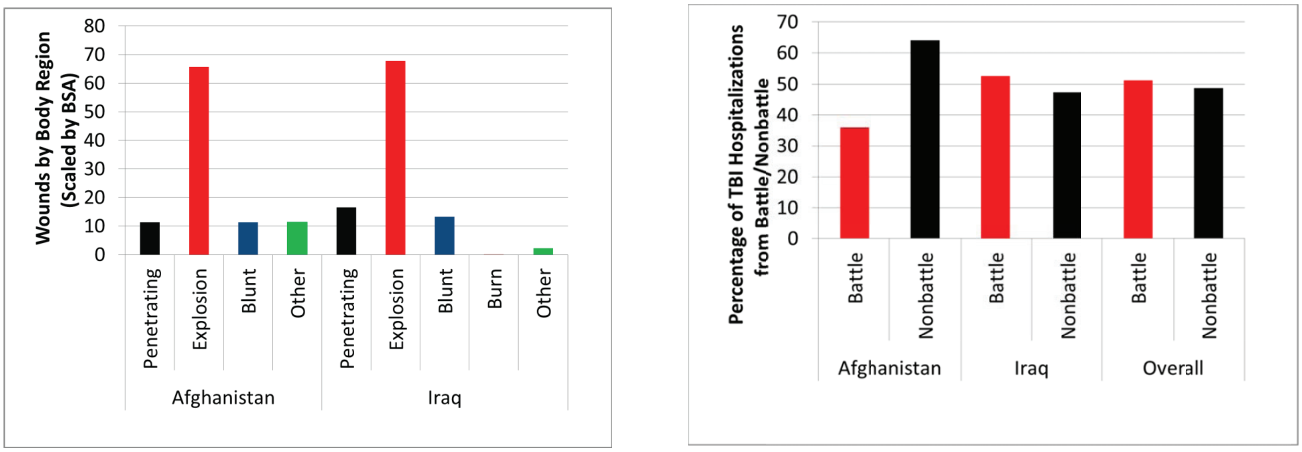

FIGURE 3-2 (a) Traumatic brain injury (TBI) hospitalizations by source for battle injuries categorized by regions in Operation Enduring Force/Operation Iraqi Freedom. (b) TBI hospitalizations by combat/noncombat source. NOTE: BSA, body surface area. SOURCE: Based on data from Wojcik et al. (2010).

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.

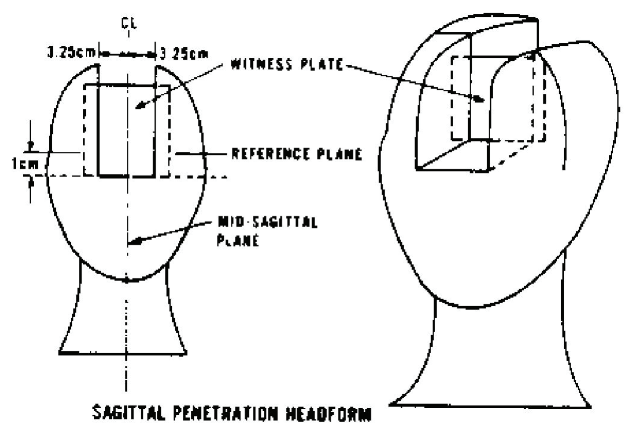

FIGURE 3-3 Sagittal headform specified in National Institute of Justice Penetration Standard, based on the Department of Transportation blunt impact headform. Two similar headforms are used for the helmet tests: A modified version of this headform provides the basis for the advanced combat helmet backface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

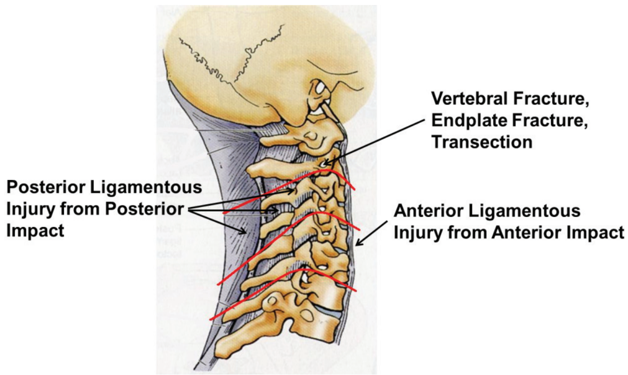

FIGURE 3-5 Typical potential neck injury locations in adults from impact loading. SOURCE: Courtesy of Dale Bass, Duke University.

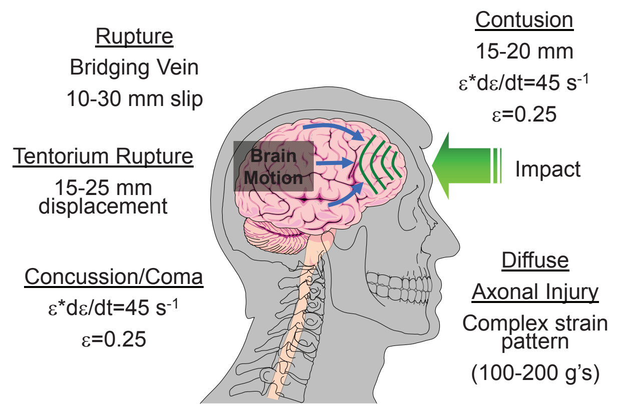

FIGURE 3-6 Typical blunt brain trauma diagram. SOURCE: Based on Ommaya et al. (1994).

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 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.

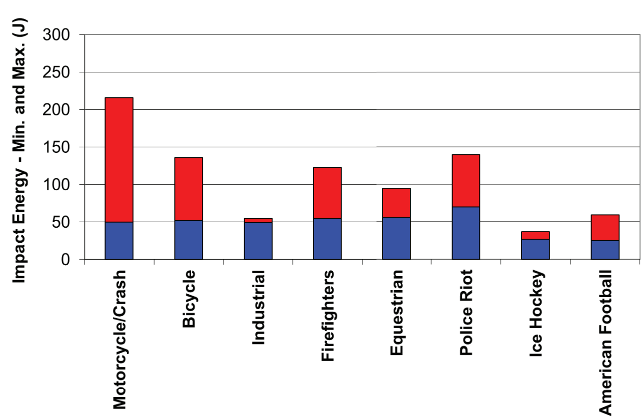

FIGURE 3-7 Energy limits for blunt impact injury assessment in AGARD AR-330. SOURCE: Based on data from AGARD (1996).

[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).

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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4

Combat Helmet Testing

4.0 SUMMARY

This chapter describes how combat helmets are tested. It includes a brief summary of the testing process, a description of the test threats, and a discussion of the various sources of variation in the testing process.

4.1 INTRODUCTION

Federal government departments and agencies are required to "develop and manage a systematic, cost-effective government contract quality assurance program to ensure that contract performance conforms to specified requirements" (Title 48 of the Code of Federal Regulations, subpart 246.1) (CFR, 2013). In particular, first article testing (FAT)[1] is conducted to ensure that "the contractor can furnish a product that conforms to all contract requirements for acceptance" (FAR, 2013). Once a contractor has passed FAT and begins production, lot acceptance tests (LAT)[2] are used to assess whether combat helmets continue to conform to contract requirements during regular production.

As part of FAT and LAT, combat helmets are subjected to a series of ballistic and nonballistic tests. Ballistic tests assess the helmet's ability to prevent penetration and limit helmet deformation to a given threshold. Nonballistic tests assess other helmet capabilities, including impact resistance, pad compression durability, coating adhesion durability, and helmet compression resistance testing. Helmets are also subjected to a series of inspections, such as whether the shell dimensions meet those specified in the purchase description. All of these tests and inspections are intended to assess whether a particular manufacturer's product conforms to the government's contract specifications as outlined in the purchase description (U.S. Army, 2012).

The goal of testing is to determine if the helmet is of acceptable quality based on a limited test sample. Not every helmet can be tested because the tested helmet is damaged in the testing process. Hence, decisions about the larger collection of helmets must be based on a limited test sample. Because only a sample of helmets can be tested, the resulting test conclusion is subject to uncertainty and unavoidable risks to both the Department of Defense and the manufacturer. Test protocol design requires making trade-offs between risks for both groups. The size of the risk for each group arises because of the test design and any limitation on resources.

4.2 BALLISTIC TESTING METHODOLOGY

The helmet ballistic testing methodology has been derived from existing body armor testing methods. The methodology for ballistic testing for body armor follows from testing done in the late 1970s by Prather et al. (1977) that, however tenuously, connects the current body armor methods and the test measures to some evidence of injury (NRC, 2010, 2012). For combat helmets, however, the current testing methods and measures have no connection to research on head and brain injury. The lack of connection between injury and current test methods and measures is a significant concern.

Test Processes

During a test, the helmet being tested is affixed to a headform packed with modeling clay, and a rifle-like device is used to fire various projectiles into the helmet. The clay is used as a recording medium for: (1) assessing penetration should the projectile or portions thereof pass through the helmet into the clay, and (2) measuring the deformation of the helmet, where an impression is left in the clay surface as a result of the ballistic impact pushing the helmet into the clay. Electronic instrumentation is used to measure projectile velocity before impact. Appendix E describes the ballistic testing process in more detail.

[1]The current DOT&E protocol for combat helmet first article testing is reprinted in Appendix B.

[2]The current DOT&E protocol for combat helmet lot acceptance testing is reprinted in Appendix B.

TABLE 4-1 DOT&E First Article Testing Helmet Test Matrix for the Advanced Combat Helmet

V_{50}	Ambient	Hot	Cold	Seawater	Weatherometer	Accelerated Aging
2-grain	1 V_{50} Size: Small	1 V_{50} Size: Medium	1 V_{50} Size: Large	1 V_{50} Size: XL		
4-grain	1 V_{50} Size: XL	1 V_{50} Size: Small	1 V_{50} Size: Medium	1 V_{50} Size: Large		
16-grain	1 V_{50} Size: Large	1 V_{50} Size: XL	1 V_{50} Size: Small	1 V_{50} Size: Medium		
17-grain	1 V_{50} Size: Medium	1 V_{50} Size: Large	1 V_{50} Size: XL	1 V_{50} Size: Small	1 V_{50} Size: Large	1 V_{50} Size: Medium
64-grain	1 V_{50} Size: Large	1 V_{50} Size: XL	1 V_{50} Size: Medium	1 V_{50} Size: Small		
Small arms	1 V_{50} Size: Medium	1 V_{50} Size: Small	1 V_{50} Size: XL	1 V_{50} Size: Large	1 V_{50} Size: Medium	
9-mm RTP/BTD shell	60 shots 12 helmets Sizes: Small: 3 Medium: 3 Large: 3 XL: 3	60 shots 12 helmets Sizes: Small: 3 Medium: 3 Large: 3 XL: 3	60 shots 12 helmets Sizes: Small: 3 Medium: 3 Large: 3 XL: 3	60 shots 12 helmets Sizes: Small: 3 Medium: 3 Large: 3 XL: 3		
9-mm RTP hardware	17 shots 9 helmets Sizes: Small: 2 Medium: 3 Large: 2 XL: 2	16 shots 8 helmets Sizes: Small: 2 Medium: 2 Large: 2 XL: 2	16 shots 8 helmets Sizes: Small: 2 Medium: 2 Large: 2 XL: 2	16 shots 8 helmets Sizes: Small: 2 Medium: 2 Large: 2 XL: 2		
Small arms RTP	17 shots 17 helmets Sizes: Small: 4 Medium: 5 Large: 4 XL: 4	16 shots 16 helmets Sizes: Small: 4 Medium: 4 Large: 4 XL: 4	16 shots 16 helmets Sizes: Small: 4 Medium: 4 Large: 4 XL: 4	16 shots 16 helmets Sizes: Small: 4 Medium: 4 Large: 4 XL: 4		

NOTE: BTD, ballistic transient deformation; RTP, resistance to penetration; V_{50}, velocity at which the probability of penetration is 0.5; XL, extra large.
SOURCE: DOT&E (2011).

There are two types of measurements that are made on the tested helmet: (1) whether the bullet penetrates the helmet or not (called resistance to penetration [RTP]); and (2) if there is no penetration, a surrogate measure of the deformation of the helmet referred to as the backface deformation (BFD). These measures are formally defined in Chapter 5.

Per the Director, Operational Test and Evaluation (DOT&E) protocol, the test is conducted as a sequence of five ballistic impacts: one each to the front, rear, left, and right sides of the helmet and to the helmet crown. Both penetration and BFD, a measure of the indent in the clay caused by the ballistic forces from the bullet, are measured. Current protocol also tests the V_{50} ballistic limit using a series of 6 to 14 shots to the five regions of the helmet at varying velocities per MIL-STD-622F (DoD, 1987). (See Chapter 9 for further discussion of the methodology for estimating V_{50}.)

For FAT, as shown in Table 4-1, 48 helmet shells are tested against the Remington 9-mm threat, and 35 helmets are tested for hardware. Another 65 helmets may be tested against a small arms threat (which is classified). In addition, 27 helmets are tested for V_{50}. Table 4-1 specifies both the size of the helmet (small, medium, large, and extra large) and whether the helmet is exposed to a particular environment, such as ambient, hot, cold, seawater,[3] weatherometer (accelerated test to mimic long-term exposure to weather), and other types of accelerated aging. Under the DOT&E protocol, within each set of tests (shell, hardware, and small

[3]The helmets the Army procures are used DoD wide, including both the Navy and the Coast Guard. Soldiers wearing helmets may also find themselves in a maritime environment while on Navy support troop-carrying vessels. The purpose of testing helmets that have been conditioned by seawater is to determine if the helmet material can withstand exposure in that environment without degraded ballistic performance.

arms), the results are combined across the helmet sizes and environments to assess whether FAT is passed or failed. The details are described in Chapters 5 and 6.

The current DOT&E testing methodology is based on a number of assumptions, including the following:

- *Shots are independent*. In FAT and LAT each helmet is shot five times in five separate locations. The resulting analyses treat these shots as independent, combining all the shots across the helmets to assess RTP performance. This practice minimizes the number of helmets tested so that, to the extent that RTP failure is a rare, helmet-level event, this practice decreases the chances of selecting a defective helmet to test. That said, to the extent that the shots are truly independent this is appropriate. On the other hand, to the extent that they are not, this practice introduces a bias in favor of soldier safety because helmets are stressed beyond what is likely to occur in the field.
- *Helmet performance is equivalent across testing environments.* In FAT, helmets are exposed to various environments that include temperature extremes and other potential helmet stressors. The goal in such testing is to ensure that the helmets perform up to specifications in a variety of environments. Because the helmets exposed to these environments respond differently to either RTP or BFD, combining the results across all the helmets is not precisely statistically correct. However, given the relatively small observed differences between environmental conditions, it does not appear that this is likely a major contributor to variability.
- *Data from predefined test locations sufficiently characterizes overall helmet performance.* As described in Appendix E, helmets are tested in five precise locations, and thus it is implicitly assumed that the results from these five locations adequately describe the performance of the helmet overall. From a process variation perspective, this approach potentially helps minimize testing variation. However, by definition, it also means that not all parts of the helmet are tested, some of which are known to be weaker. For example, the edges of the helmet are not tested, nor are the raised areas of the helmet around the ears. As such, the performance of the helmet in these regions is simply not observed during FAT and LAT.[4]

Test Threat Projectiles

For FAT, the helmet shell and hardware are tested against a Remington 9-mm, 124-grain full-metal-jacket (FMJ) projectile (DOT&E, 2011), and per the DOT&E protocol, it may be tested against an unspecified small arms threat.[5] The helmet is also tested for V_{50}, the velocity at which the helmet is equally likely to stop or not stop an object, such as the following:

- 2-grain right-circular-cylinder (RCC) fragment,
- 4-grain RCC fragment,
- 16-grain RCC fragment,
- 64-grain RCC fragment, and,
- 17-grain fragment simulating projectile (FSP) (DOT&E, 2011).[6]

The ACH purchase description further specifies minimum V_{50} velocities for the above RCC and FSP test projectiles (U.S. Army, 2012, p. 13).

As discussed in Chapter 3, there are three general categories of head injury threats: ballistic/fragmentation threats from rapidly moving bullets or fragments; blunt threats from impact into vehicle interiors, the ground, large slow fragments, or other sources of head impact; and blast threats from bombs, artillery, improvised explosive devices, and other explosive sources. Blast and fragmentation threats from explosions historically have been the source of a large majority of U.S. military wounding, while direct gunshot wounds have decreased 46 percent relative to injuries with an explosive source between Vietnam and Operation Enduring Freedom and Operation Iraqi Freedom.

For the DOT&E LAT protocol, the shell and hardware are required only to be tested against the Remington 9-mm, 124-grain FMJ projectile (DOT&E, 2012). The ACH purchase description further requires V_{50} testing for the 17-grain FSP (U.S. Army, 2012).

4.3 SOURCES OF TEST VARIATION

Variation in test measurement is an unavoidable part of testing. In the ideal testing process, all observed variation in test measures is related directly and perfectly to the items being tested. In industrial quality control parlance, this is referred to as "part-to-part" variation. However, in the real world, the testing process itself also introduces variation into the test measurements. In terms of assessing the quality of an item, this is the "noise" in the testing process. The goal of a good testing process is to minimize these process-related sources of noise. The National Research Council Phase I report (NRC, 2009, p. 12) noted that the "measurement system variance required for a test should be a factor of 10 or better than the total measured variation," in order to have confidence that differences in the observed measurements predominantly represent part-to-part (i.e., helmet-to-helmet) differences.

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[4]See Chapter 9 for a discussion of assessing helmet performance at other locations during characterization testing.

[5]Kyle Markwardt, Test Officer, Aberdeen Test Center, "Helmet IOP PED-003 Briefing to NRC Helmet Protocols Committee," presentation to the committee on March 22, 2013.

[6]Ibid.

Helmet-to-helmet variability includes both variation within and between helmet manufacturers. There are a number of additional sources of variation in the current test process, including the following:

- *Gauge-to-gauge (measurement) variability*, which arises when there are accuracy or precision differences within or between the gauges used to measure helmet performance. For helmet testing, the issue of gauge-to-gauge variation is largely associated with the laser used to measure BFD, although it may also arise in other test-range measures such as those related to measuring projectile velocity, yaw, and obliquity.
- *Operator-to-operator variability*, which arises when the individuals conducting the test either execute the test differently or interpret test or measurement outcomes differently (or both). For helmet testing, because V_0 RTP testing is assessed visually, the operator is the "gauge," and thus the two types of variation are synonymous in this particular case.
- *Lab-to-lab variability* arises when different laboratories conduct helmet ballistic testing. Currently, only the U.S. Army Aberdeen Test Center (ATC) conducts helmet testing, so this type of variation is not applicable at this time, but it could be in the future.
- *Environmental conditions variability* arises to the extent that the testing is dependent on environmental conditions such as ambient test range temperature and humidity. Although the current ATC test is conducted in a temperature- and humidity-controlled test range, the temperature and humidity can still vary within specified constraints around nominal values.
- *Projectile velocity and impact variability* arise from variation in individual shots. Much of this variability is controlled via the criteria that fair shots must be within certain constraints on velocity, obliquity, yaw, and location, but, as with the environmental conditions, some residual variation remains within the range of the specified constraints.
- *Test item configuration variability* could arise in V_0 helmet testing if helmet pads and other hardware differ if, for example, the helmet pads are installed in different configurations or if the construction or make-up of the pads themselves differs.
- *Helmet-to-headform stand-off variability* arises when one headform size is used to test multiple sizes of helmets. This can result in differential stand-off distances by helmet size, which can affect BFD.
- *Clay variability* arises because the clay formulation has changed over time and, as a result of this, the clay now has to be heated in order to achieve historical rheological properties. However, because the clay is now heated, its properties change over time during the test process as the clay cools, and this can affect BFD.
- *Impact location variability* arises to the extent that different locations on the helmet respond to the ballistic impacts differently and/or if the order in which the locations are shot affects the test outcome.
- *Environmental testing variability* arises when the various environmental conditions to which some of the helmets are exposed (high and low temperature, seawater, etc.) differentially affect the RTP and BFD performance of the helmets, and yet the helmets are combined together for analysis.

The current testing process seeks to control many of these sources of variation via the use of standardized testing procedures, accurate measurement instrumentation, and the like. To the extent physically, analytically, and economically possible, the more these sources of variation are controlled the easier it is to distinguish signal (i.e., differences in helmet performance) from noise (i.e., variation in the testing process).

Of course, testing costs time and money, and there are diminishing returns (and often increasing costs) in the pursuit of increasingly precise test measurements. Furthermore, the required level of measurement precision should be linked to and driven by the overall variation in the testing process where, for example, excessively precise measurements add little value to a testing process that is itself inherently highly variable. Conversely, in any testing process, there should be a precision threshold that any measurement device must meet—again based on the overall variation of the testing process—to ensure that the measurement process itself does not add excessive variability to the test (NRC, 2012). As noted earlier, the previous NRC body armor reports recommend that variance attributable to the test measurement process should be less than one-tenth of the total measured variation (see NRC, 2009, p. 12; NRC, 2012, Appendix G; McNeese and Klein, 1991).

Finding 4-1. Some sources of test variation are relevant to the current helmet testing process while others are not. For example, given that tests are currently conducted only at ATC, lab-to-lab variability is not currently applicable. Similarly, some sources of variation are directly observable with existing data, and some are not. For example, as discussed in Chapter 5, the test data show clear helmet size effects, impact location effects, and minor environmental effects.

Finding 4-2. In the absence of more formal gauge repeatability and reproducibility (R&R) studies, as well as other experimental studies, it is generally not possible to estimate the variation attributed to helmets that actually arises from the other sources of variation listed above, such as the clay, operators, and the laser.

The NRC Phase III report on body armor noted the need for a formal gauge R&R study to determine the sources and magnitudes of variation in the test process (NRC, 2012, p. 10). To the best of the committee's knowledge, such a study has not been done.

Recommendation 4-1. The Department of Defense should conduct a formal gauge repeatability and reproducibility study to determine the magnitudes of the sources of test variation, particularly the relative contributions of the various sources from the testing methodology versus the variation inherent in the helmets. The Army and the Office of the Director, Operational Test and Evaluation, should use the results of the gauge repeatability and reproducibility study to make informed decisions about whether and how to improve the testing process.

4.4 ADDITIONAL MEASUREMENT AND TESTING ISSUES

Without delving into the specific details of the DOT&E FAT and LAT protocols here (see Chapters 5-7), there are two additional BFD measurement and testing issues of note: the use of clay as a BFD recording medium, and headform impacts on the measurement of BFD.

Clay as a Recording Medium

As described in the Phase III report (NRC, 2012), there is not much that is known about the use of clay as an impact recording medium, including how accurately it records the backface signature of an impact and how much variation it adds to the testing process. Thus it is unclear if the use of clay is appropriate for helmet testing, particularly because "the mechanical backface response of the head surrogate may govern both penetration and impact tolerance portions of the test" (NRC, 2012, p. 152).

One of the critical issues with the current clay (Roma Plastilina #1), as first noted in the NRC Phase II report (NRC, 2010), is that the clay is time and temperature sensitive in that, as Figure 4-1 shows, its properties can change significantly over a 45-minute period as it cools. These effects are likely to affect BFD measurements.

The previous body armor committees studied many of the issues related to clay (NRC, 2012, 2010), and a detailed examination of these issues is beyond the scope of this committee's charge. But the committee notes that, purely from a testing process perspective, it is important to minimize this source of variation in the testing process. In particular, the Phase III body armor report recommended that DOT&E and the Army expedite the development of a replacement for the current Roma Plastilina #1 clay that can be used at room temperature (NRC, 2012). The committee notes that successful completion of this effort has the potential to remove a significant source of testing variation and thus greatly improve the testing process.

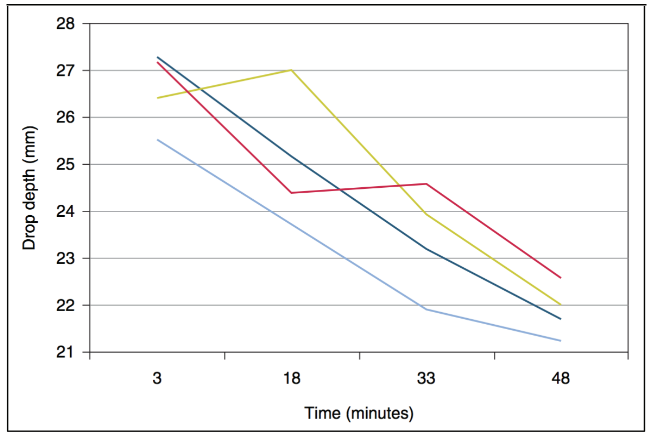

FIGURE 4-1 Clay time and temperature effects in the column drop test. Each line represents the results of repeated column drop tests on a standard clay box, each of which was subject to different environmental conditioning. Measurements were taken at times 3, 18, 33, and 48, and the lines on the graph are linear interpolations between the observed results at those time points. The graph shows that the depth of penetration systematically decreases over time as the clay cools. (See Appendix E for a description of the column drop test.) SOURCE: NRC (2010).

Headforms

Army helmet testing is currently based on the ATC headform—derived from the National Institute of Justice headform discussed in Chapter 3—with slots in the coronal and midsagittal directions (Figure 4-2). As more fully described in Appendix E, the slots in the headform are packed with clay as the recording medium for both penetration and BFD. There is currently one headform size, although there may be up to six helmet sizes (depending on the type of helmet).

Two major issues with the headform may compromise its ability to appropriately and consistently measure BFD. First, the petals may impede the BFD of the helmet, which could result in under-measurement of the actual ballistic transient deformation of the helmet. Second, as previously discussed, with only one headform size, the stand-off distances may vary by helmet. Large helmets likely have a larger stand-off distance, whereas small helmets likely have to be forced onto the headform with minimal stand-off.

The Army is developing five new "sized" headforms that will have a constant helmet shell-to-headform standoff distance for the Advanced Combat Helmet.[7] As illustrated in Figure 4-3, the motivation with the new sized headforms is to eliminate one source of variation in helmet testing that arises because different sizes of helmets interact with the current single-size headform in different ways.

[7]James Zheng, Chief Scientist, Soldier Protective and Individual Equipment, PEO Soldier, "Helmet Testing, Related Research & Development," presentation to the committee on March 22, 2013.

FIGURE 4-2 Aberdeen Test Center headform. SOURCE: NRC (2012).

Finding 4-3. The implementation of new "sized" headforms by the Army represent an improvement in the helmet testing process because the stand-off between helmet and headform will be the same for all helmet sizes.

The committee notes that these headforms were "reverse engineered" from the existing helmets so that the stand-off distances would all be exactly the same. It is not clear how anthropomorphically correct the new headforms are or how closely they reflect the actual needs of soldiers and marines.

Recommendation 4-2. For future helmet development and testing efforts, the Department of Defense should assess the importance of using anthropomorphically correct headforms (as well as any other ballistic test dummies) based on head sizes and proportions that appropriately characterize the population that will wear the helmet.

The "Peepsite"[8] headform (Figure 4-4) was developed by the U.S. Army Research Laboratory to avoid the drawbacks of the ATC headform, in particular, that the clay used to measure BFD is located in between four solid aluminum parts of the headform.

[8]The "Peepsite" headform was developed at the Army Research Experimental Facility Peep Site Range 20 at Aberdeen Proving Ground, Md.

As described NRC (2012), the ATC headform has three potential problems. The first is that the solid aluminum petals constrain the flow of the clay during impact, which may result in a smaller BFD than otherwise would have occurred. The Peepsite headform reduces this possibility by eliminating the metallic petals near the impact location.

The second potential problem is that helmet backface contact can span the aluminum petals, either preventing further impact or altering the BFD response and backface signature recorded in the clay. As with the first problem, the lack of petals in the Peepsite headform eliminates the potential for this type of helmet-headform interaction, which may alter helmet backface response.

The third potential problem arises because the clay and helmet have very different temperature characteristics. Using the current Roma Plastilina #1 clay, the clay is heated above room temperature to achieve the desired rheological behavior. Testing on the Peepsite headform, however, is done at room temperature, which means that the rate of cooling of the clay and the aluminum headform will be different, resulting in thermal gradients and residual strains and stresses in the clay that may affect the impact event (NRC, 2012).

NRC (2012) noted that the Peepsite headform reduces the potential for a number of problems with the existing ATC headform. It further recommended that the Army should investigate the use of the Peepsite headform for use with the new room-temperature clay. That report indicated that the headform has the potential to improve testing compared to the ATC clay headform using clay at elevated temperatures.

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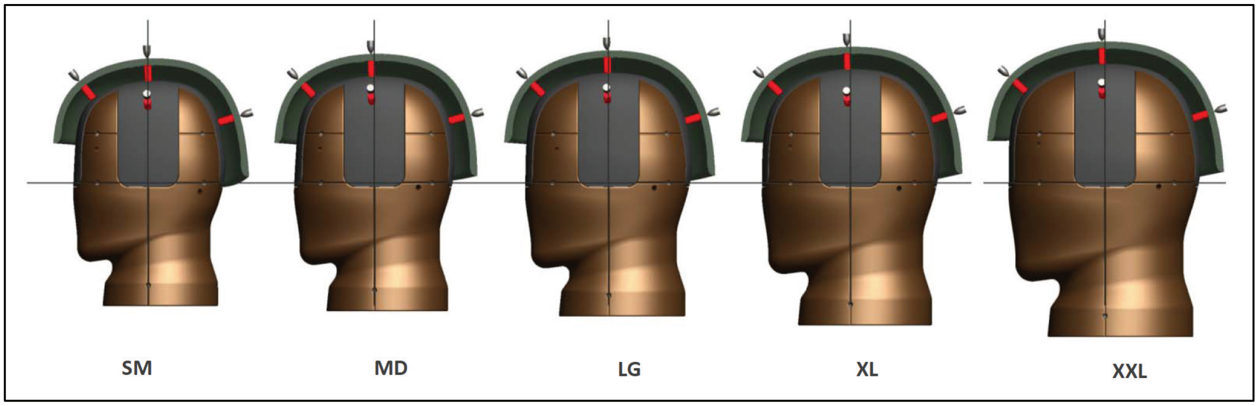

FIGURE 4-3 New Army "sized" headforms. SOURCE: James Zheng, Chief Scientist, Soldier Protective and Individual Equipment, PEO Soldier, "Helmet Testing, Related Research & Development," presentation to the committee on March 22, 2013.

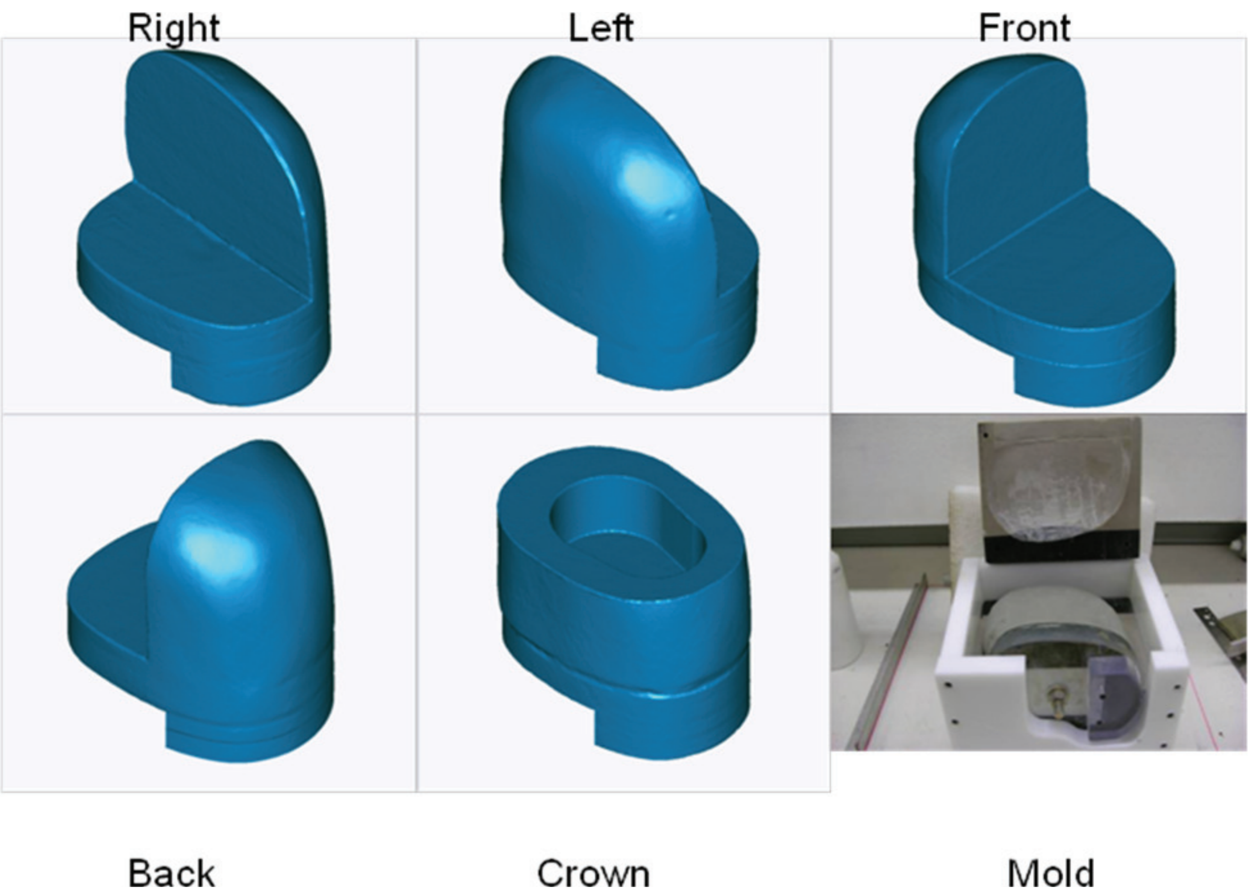

FIGURE 4-4 Peepsite headforms: five headforms, one for each shot direction. SOURCE: Robert Kinsler, Survivability/Lethality Analysis Directorate, Army Research Laboratory, "The Peepsite Headform," presentation to the committee on January 24, 2013.

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5

Helmet Performance Measures and Trends in Test Data

5.0 SUMMARY

A helmet's protective capabilities are evaluated on the basis of two primary test measures: resistance to penetration (RTP) and backface deformation (BFD). These are formally defined and their limitations are discussed in this chapter. RTP data available to the committee indicate that the probability of penetration of a helmet shell by a 9-mm bullet, fired under specified conditions, is on the order of 0.005 or less. Available BFD data show that the probability of exceeding the BFD thresholds is around 0.005 or less. The distributions of the BFD data also demonstrate significant differences among helmet sizes and shot locations. Some of the performance differences among helmet sizes may be attributed to the test process, such as headforms and stand-offs. Many others are likely to be due to the differences in the geometry of helmet shells, molds, manufacturing processes, and other factors. In fact, helmets of different sizes are intrinsically different products. Therefore, Recommendation 5-5 proposes changes to DoD's test protocols so that helmets of different sizes are treated separately. This is one of the major recommendations in the report.

5.1 INTRODUCTION

For the purpose of helmet testing, protective capabilities are measured by RTP and BFD. Section 5.2 defines these measures and discusses their limitations. Section 5.3 summarizes results from test data that were made available to the committee. The implications of these results for the Director of Operational Test and Evaluation's (DOT&E's) first article testing (FAT) and lot acceptance testing (LAT) protocols are discussed in Section 5.4.

Another measure, called V_{50},[1] is also used in FAT. However, the estimated value of V_{50} is not used in the decision process. Thus, the committee considers V_{50} estimation and testing to be an aspect of characterization analyses. This topic is discussed in Chapter 8.

5.2 PERFORMANCE MEASURES

Resistance to Penetration

RTP is measured by shooting a given ballistic projectile at a set of helmets and counting the number of complete penetrations. Most ballistic impacts penetrate the helmet to some degree, so the DOT&E FAT and LAT testing protocols distinguish between complete and partial penetrations. A *complete penetration* in RTP testing is defined as:

> Complete perforation of the shell by the projectile or fragment of the projectile as evidenced by the presence of that projectile, projectile fragment, or spall in the clay, or by a hole which passes through the shell. In the case of the fastener test, any evidence of the projectile, fragment of the projectile, or fastener in the clay shall be considered a complete penetration. Non-metallic material[s] such as paint, fibrous materials, edging, or edging adhesion resin that are emitted from the test specimen and rest on the outer surface of the clay impression are not considered a complete penetration.[2]

A *partial penetration* is defined as "any fair impact that is not a complete penetration."[3] In this report, the term *penetration* is used to refer to complete penetration. In DoD documents, the term "perforation" is used synonymously with "complete penetration."

According to personnel from the Army Test Center, there is currently no practical way to determine or measure the degree or depth of penetration, and thus helmet penetration testing is currently attribute-based: on a given (fair) shot, the result is recorded as either a complete penetration or a partial penetration. The intuitive notion is that a projectile

[1] V_{50} refers to "the velocity at which complete penetration and partial penetration are equally likely to occur" (DoD, 1997).

[2] The protocols for FAT and LAT testing are given in Appendix B.

[3] Ibid.

that penetrates the shell is apt to cause more serious head injuries than a projectile that does not, but there is no other linkage between what is measured and head injury.

Finding 5-1. It is not known whether partial penetrations might be reasonably and usefully measured in order to assess the degree to which a non-perforated helmet is penetrated.

V_{50} testing refers to estimating the bullet speed at which there is a 50 percent chance of penetration. This test uses a witness plate mounted inside the headform rather than packing the headform with clay as is done with RTP/BFD testing. (See Appendix D for details.) Because of this difference, the DOT&E FAT protocol defines a V_{50} complete penetration as a shot where

> Impacting projectile or any fragment thereof, or any fragment of the test specimen perforates the witness plate resulting in a crack or hole which permits light passage. A break in the witness plate by the helmet deformation is not scored as a complete penetration.[4]

Finding 5-2. The definition of what constitutes a penetration, and how such penetrations are measured, differs between RTP and V_{50} tests. V_{50} specifies a "hole which permits light passage" whereas RTP does not.

Recommendation 5-1. The Office of the Director, Operational Test and Evaluation, should revise the first article testing protocol for resistance to penetration and V_{50} testing to ensure that the two protocols are consistent.

Backface Deformation

Helmet BFD is measured on the non-perforating ballistic impacts from RTP testing. It is defined as the *maximum depth* in the post-impact clay surface at the intended impact location as measured from the original clay surface. It is measured as follows: After mounting the helmet on the headform and mounting the headform in the test fixture, the helmet is removed from the headform, and the clay surface is scanned with a laser. The helmet is then reattached to the headform and the shot taken. Finally, the helmet is again removed from the headform, inspected for penetration and perforation, and the clay is rescanned with the laser to calculate BFD. A typical BFD laser scan is shown in Figure 5-1.

The definition of BFD as the maximum depth of indentation left in the clay has a number of issues. First, as discussed in the Phase III report (NRC, 2012) report, clay is an imperfect recording medium. As that report said:

> The qualitative assertion that RP #1 exhibits little recovery has been interpreted to mean that the level of elastic recovery is small enough to be safely neglected. This has led to an assumption that the shape of the resultant cavity provides a record of the BFD. Since the relative degree of elastic and plastic deformation will vary as a function of strain rate, the backing material must be characterized under conditions that are relevant to those under which the tests will be performed. The cavity that results from live-fire ballistic testing is indeed related to the deformation on the back face of the armor, but it is not a true record of maximum deflection. It remains unknown how the dimensions of the cavity relate to the true BFD and how such a relationship may depend on the rate at which the cavity is formed (NRC, 2012, p. 5).

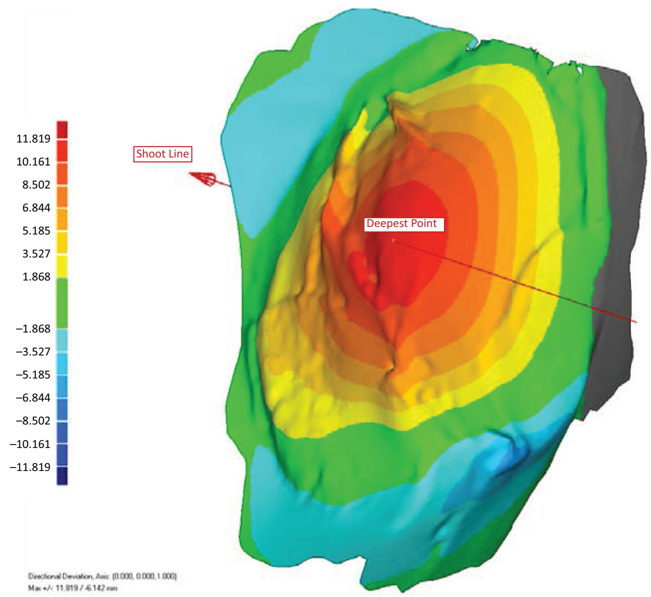

FIGURE 5-1 Illustrative backface deformation laser scan.
SOURCE: Courtesy of the Office of the Director of Operational Test and Evaluation.

Further, whether the appropriate measure is the depth of the BFD rather than BFD area, BFD volume, or some other measure such as total or instantaneous force imparted, is not known. It is also unclear how well BFD from ballistic impact characterizes the effect of blunt-force trauma, which is one of the main types of brain injury that the helmet is intended to protect against.

Finding 5-3. It is unknown whether the current definition of BFD is the most appropriate for assessing how well helmets protect soldiers and marines from the helmet deformation due to ballistic impact and other blunt-force trauma. It may be that some other measurement, such as the area or volume of the BFD, or perhaps some measure of force or acceleration imparted, is more appropriate for assessing the ability of the helmet to protect against brain injury. If such an alternative measurement is found, the protocols and thresholds would have to be changed appropriately.

[4]Ibid.

Recommendation 5-2. The Department of Defense should develop a better understanding of the relationship between backface deformation and brain damage, including the examination of alternative metrics to maximum depth.

In addition to the definition of BFD, the DOT&E protocol specifies BFD thresholds at 25.4 mm for front and back shots and 16 mm for side and crown shots. These appear to be based on historical helmet testing precedent and are not connected to the potential for brain injury. The analysis, however, appears to be based on the presumption that the larger the BFD, the greater the likelihood of serious head injury.

Finding 5-4. The choice of the helmet BFD threshold values—25.4 mm for front and back shots and 16 mm for side and crown shots—does not have a scientific basis. In contrast, the body armor BFD limit was derived from scientific studies.

As a result, the usefulness of the helmet FAT and LAT test data on BFD is limited. The data can be used for assessing helmet performance against the requirements in the purchase description and the DOT&E helmet testing protocol; the results can also be used to compare helmet performance within and between manufacturers and over time. But the data cannot be used to determine the level of protection provided by a new helmet that is designed and manufactured according to a different set of specifications. This becomes critical when assessing the protection offered by new helmets because there are trade-offs between penetration, BFD, and other helmet characteristics, such as weight, form, and fit.

Recommendation 5-3. The Department of Defense should examine the basis for backface deformation thresholds and develop appropriate ones based on scientific studies and data.

Recommendation 5-4. As research progresses, methods, measures, and thresholds should be continuously reviewed to determine whether the new knowledge warrants changes to any of them. The review team should include adequate expertise from a broad range of disciplines, including medical, engineering, and testing professionals**.**

5.3 SUMMARY OF RESULTS FROM AVAILABLE TEST DATA

The DOT&E FAT and LAT protocols, as well as any additional requirements included in service-specific contractual requirements, specify RTP and BFD pass or fail requirements. The particular details of these tests are described in detail in Chapters 6 and 7. This section summarizes how the Advanced Combat Helmet (ACH) performs in terms of these two measures using data made available to the committee.

Resistance to Penetration Data

Table 5-1 provides a summary of RTP test data for ACH helmets, provided to the committee, from FAT and LAT. There were two sources of FAT data: the first with 309 shots and the second one with 816 shots, and there were no penetrations. So, the estimate of the penetration probability from the combined data is 0, and a 90 percent upper confidence bound (UCB) is 0.002. The LAT data were from four different vendors (as shown at the bottom of Table 5-1), and there were only 7 penetrations out of 11,049 shots. This yields an estimated probability of penetration of 7/11,049 = 0.0006. The corresponding 90 percent UCB is 0.001. Hence, we see that a Remington 9-mm full-metal-jacket (FMJ) projectile shot at a randomly selected ACH, under test conditions, is unlikely—with only a 0.1 percent chance—of completely penetrating the helmet.

TABLE 5-1 Summary of Resistance to Penetration Test Data

Test Type	Penetrations	Number of Shots	Penetration Proportion (90% Upper Confidence Bound)
FAT—20-shot, five vendors	0	309	0
FAT—240- or 96-shot, four helmets	0	816	0
FAT—All	0	1,125	0.000 (0.002)
LAT—Four vendors (see below)	7	11,049	0.0006 (0.001)
Total	7	12,174	0.0006 (0.001)
			Penetration Proportion (90% Upper Confidence Bound)
LAT, Vendor A	5	5,422	0.0009 (0.002)
LAT, Vendor B	0	2,872	0.0000 (0.001)
LAT, Vendor C	2	1,285	0.0016 (0.004)
LAT, Vendor D	0	1,470	0.0000 (0.002)

NOTE: FAT, first article testing; LAT, lot acceptance testing.
SOURCE: Office of the Director, Operational Test and Evaluation.

During FAT and LAT, each helmet is subjected to five shots at different locations. So the 11,049 LAT shots correspond to roughly about 2,200 helmets. See Appendix D for additional details. (If a perforation is observed on a helmet, that helmet is not tested further, so the seven observed perforations were all on separate helmets.) One can estimate the probability of helmet failure (rather than penetration at any given location) to be approximately 7/2,200 = 0.003, which is also very low.

Finding 5-5. Available data indicate that there is very low probability of helmet perforation (less than 0.005) from a Remington 9-mm FMJ projectile shot under test conditions.

This level of penetration probability is considerably smaller than the 10 percent "standard" on which the DOT&E protocol is based. The implications of this result are discussed in Chapter 6.

Backface Deformation Data

This section summarizes relevant results from BFD data that were made available to the committee.

Data Set 1

Data Set 1 is from a test of 48 ACHs (referred to here as Helmet 1). Twelve helmets each are exposed to four different environments (ambient, cold, and hot temperatures and seawater) prior to testing. The test consisted of firing single shots at five locations on the helmet: front, back, left side, right side, and crown, leading to a total of 240 shots. The data are all from a single-sized helmet (size Large), so the effect of helmet size cannot be studied from this data set.

Figure 5-2 shows the BFD measurements by shot locations. DOT&E's tolerance limit analysis is based on pooling

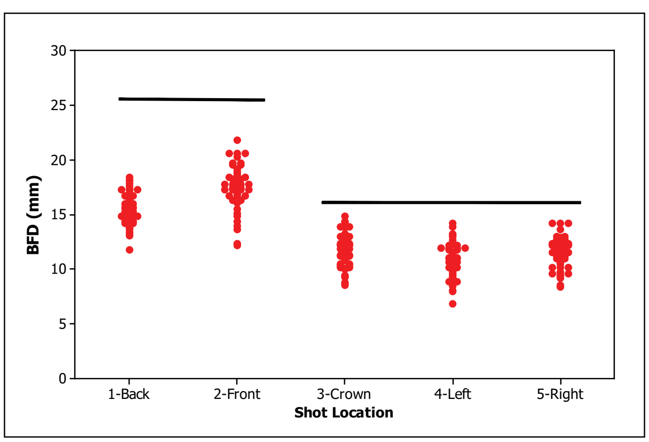

FIGURE 5-2 Backface deformation (BFD) measurements by location for Data Set 1. Specified limits of 25.4 mm and 16.0 mm are indicated by solid lines.

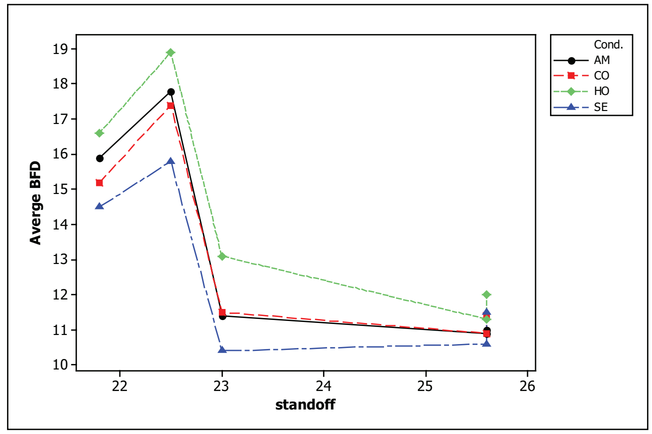

FIGURE 5-3 Average backface deformation (BFD) as a function of stand-off for Data Set 1. Colors represent different environments. NOTE: AM, ambient; CO, cold; HO, hot; SE, sea water.

the data across environments as well as across helmet sizes and shot locations in the two location groups. Therefore, the committee has also pooled the data across the environments. The horizontal solid lines in the figure are the BFD upper limits of 25.4-mm for back and front shot locations and 16-mm for left, right, and crown shot locations. The BFD measurements are below the thresholds at all locations, and in some cases considerably so. Note also that the distributions for the left, right, and crown locations are quite comparable, while the distribution for the front location is substantially higher than that of the back. This difference was consistent across the four different environments (figures not shown here), and similar effects were seen with other helmet test data as well.

The DOT&E protocol based on BFD is formally described in Chapter 7, and it requires that the upper 90/90 tolerance limit of the BFD distribution not exceed the threshold. Figure 5-2 shows that no BFD values exceeded their limits. Further, for the back/front group of data, the BFD values are considerably below their limit.

One possible reason for the differences in BFD measurements among location is stand-off: the distance between the inside of the helmet shell and the headform (see discussion in Chapter 4). For a large ACH, the stand-offs were as follows: back, 21.8 mm; front, 22.5 mm; crown, 23.0 mm; and left and right, 25.6 mm.[5] Figure 5-3 shows how the average of the BFD measurements differs with stand-off. The colors correspond to different environmental conditions. Note that the data are clearly separated by environment. The average BFDs are clearly different for different values of stand-off, but the relationship is not monotone, and hence not easy to

[5]Frank J. Lozano, Product Manager, Soldier Protective Equipment, "Setting the Specifications for Ballistic Helmets," presentation to the committee on April 25, 2013.

interpret. It may be expected that BFD would decrease as stand-off increases, but the average BFD for front and back have the opposite difference. The average BFDs for the crown, left, and right locations are quite close, even though the crown offset is considerably less than the side stand-offs. Perhaps other geometric aspects of the test and the shape of the helmet contribute to these patterns.

Data Set 2

Data Set 2 was from a test of the Marine helmet (MICH) (Helmet 2). Three helmets each corresponding to four sizes (small [S], medium [M], large [L], and extra large [XL]) were tested at four environmental conditions (ambient, cold, hot, seawater). Again, there were single shots at five locations (front, back, left side, right side, and crown) for a total of 240 shots. This is the suite of shots specified in the DOT&E protocol. Figure 5-4 shows the same sort of location differences for this helmet as for Helmet 1.

There is more spread in the Helmet 2 data than for Helmet 1 because the data are pooled over four helmet sizes as well as four environments. The BFD distributions for L and XL helmets were different, with the measurements for XL being generally smaller than those for L. Perhaps this is due to using a single headform for L and XL helmets. There were no appreciable differences among environments. Once again, the 10 percent standard is easily met by these data.

Data Set 3

Data Set 3 was from a test of Helmet 3, a repeat of the Helmet 2 tests, after a design change to the MICH. Figure 5-5 shows the BFD data by location, pooled over environments and helmet sizes.

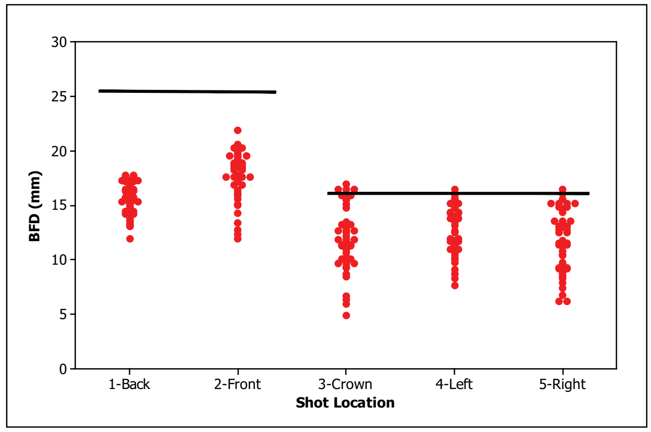

FIGURE 5-5 Backface deformation (BFD) measurements by location for Data Set 3. Specified limits of 25.4 mm and 16.0 mm are indicated by solid lines.

The Figure 5-5 plot shows that there is considerably less margin for the BFD data for the crown/left/right shot locations than there was for Helmet 2. Apparently, the design change increased the magnitude of the dents in the clay. Eight of the 144 BFDs in this group exceeded the 16.0-mm threshold. The upper 90 percent confidence limit on the probability of exceeding the limit, based on this outcome, is about 9 percent, so the 10 percent standard is met in this regard.

Figure 5-6 shows that the differences among shot locations for the XL helmet size have a pattern substantially different from those of the other three sizes.

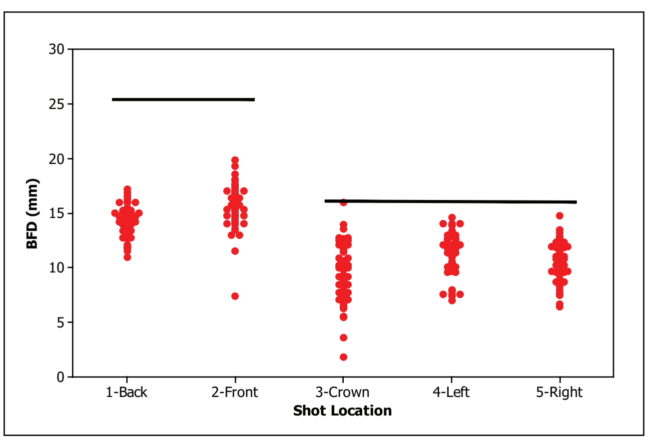

FIGURE 5-4 Backface deformation (BFD) measurements by location for Data Set 2. Specified limits of 25.4 mm and 16.0 mm are indicated by solid lines.

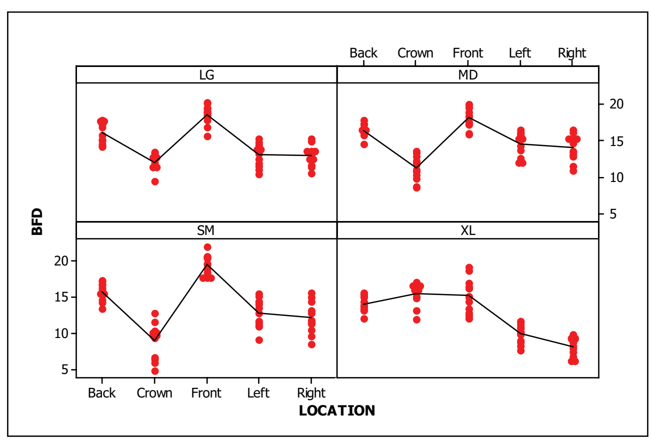

FIGURE 5-6 Backface deformation (BFD) measurements by location and helmet size for Data Set 3. NOTE: MD, medium; LG, large; SM, small; XL, extra large.

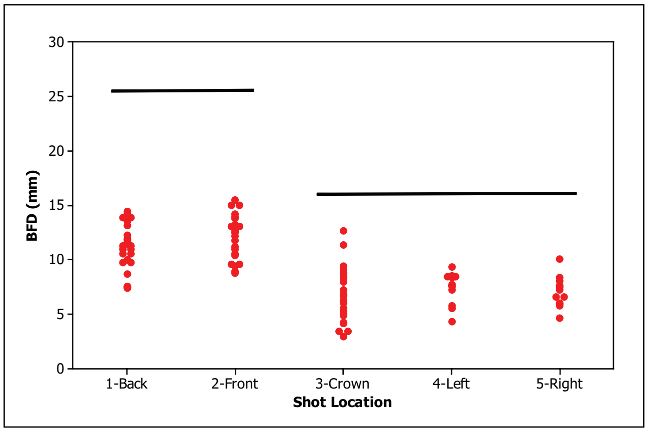

FIGURE 5-7 Backface deformation (BFD) measurements by location for Data Set 4. Solid lines are the specified limits of 25.4 mm and 16.0 mm.

Data Set 4

Data Set 4 was from a FAT for the enhanced combat helmet (Helmet 4). Three helmets, of each of four sizes, were tested at four different environments. However, because of excessive helmet damage, the DOT&E protocol was reduced to only two shots on each helmet.

Figure 5-7 shows the BFD data by shot location. There are 24 shots each in the back and front locations, 16 each in the crown, left, and right locations. Figure 5-7 shows that the BFD data for this helmet are well below their limits.

For the data sets analyzed by the committee, 8 of 816 BFD measurements exceeded their respective thresholds. All of these were for Helmet 3, which suggests something different about that helmet or the test procedure.

Finding 5-6. It is clear that manufacturers are capable of producing helmets for which the probability of failing the BFD protocol is very small.

Finding 5-7. Based on the available BFD data, one can make the following observations about heterogeneity:

- There are substantial differences in BFD data across helmet sizes.
- There is also a great deal of heterogeneity across locations. It was expected that there will be differences in BFD measurements between two shot-location groups: front and back versus crown, left, and right. This is reflected in the different BFD thresholds for the two groups. However, the data consistently indicate that BFD measurements at the front location are larger than those at the back, which is counter to the differences in stand-off at these locations. There is much less variability in the data among the other three locations: crown, back, and front.
- The effect of environments appears to be small. The same is also true for the effect of shot order.

5.4 IMPLICATIONS FOR FIRST ARTICLE TESTING PROTOCOLS

As shown in Table 4.1, the current DOT&E protocols involve testing 48 helmet shells: 12 each corresponding to sizes S, M, L, and XL. Of the 12 shells, 3 are conditioned in each of four different environments. Further, shots are taken at five different locations on the helmet. So, the committee looked at RTP and BFD data on a total of 240 shots. Chapters 6 and 7 describe in detail the pass-fail rules for FAT protocols for RTP and BFD, respectively. Briefly, the RTP protocol states that if there are 17 or fewer penetrations, the test is deemed to be successful. The BFD protocol is applied separately to the two groups of locations with different thresholds: back and front in one group and crown, left, and right in another. The specific approach involves computing 90/90 upper tolerance limits (UTLs), based on BFD measurements and the assumption that the data are normally distributed, and comparing the UTLs against their respective thresholds. If the UTL is smaller, the test is deemed successful; otherwise it is unsuccessful.

The plots of the BFD distributions in the previous section appear to be different across helmets and locations, and this raises the issue of pooling the data to implement the protocol. The differences in the two groups of locations (front and back versus crown, right, and left) are handled by implementing the protocols separately for the groups with different thresholds: 25.6-mm and 16-mm. Within the groups, differences noted at front and back locations indicate that the data should not be pooled and analyzed as a sample from a single normal distribution. DOT&E has proposed an analysis to check for differences in the mean and variances and pool the data only if the test is accepted. In addition to the complexity of the procedure, the statistical properties of the protocol are not valid when one applies a pre-test before implementing it.

In addition, the committee notes that helmets of different size are intrinsically different products: different-sized shells are manufactured from different molds and different manufacturing processes or settings (even if some of the equipment and process steps are common). Therefore, pooling the BFD data across different-sized helmets and treating the data as homogeneous does not seem appropriate. It also leads to the cumbersome process of pre-testing to see if the measurements have the same mean and variance before combining the data.

Recommendation 5-5. The Office of the Director, Operational Test and Evaluation, should revise the current protocols to implement them separately by helmet size.

This recommendation clearly involves a major change in the way helmets are currently tested. It will also require decisions on how the Department of Defense implements procurement decisions. For example, if a particular helmet size did not pass FAT and others did, DoD will need to decide whether the helmet sizes that passed FAT can be procured or not. The committee judges that such decisions should be left to the DoD and should be based on practical considerations rather than statistical properties of the protocol.

5.5 REFERENCES

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6

First Article Testing Protocols for Resistance to Penetration: Statistical Considerations and Evaluation of DoD Test Plans

6.0 SUMMARY

The test protocols for Army helmets were originally based on a requirement of zero penetrations in 20 shots (five shots on each of four helmets). The Director, Operational Test and Evaluation (DOT&E) protocol replaced this legacy plan with a requirement of 17 or fewer penetrations in 240 shots (five shots on each of 48 helmets). The helmets spanned four sizes and were tested in four different environments. The 0-out-of-20 (0, 20) plan and DOT&E's 17-out-of-240 (17, 240) plan have comparable performance if the probability of penetrating a helmet shell on a single shot is around 0.10. As noted in Chapter 5, available data indicate that penetration probabilities are around 0.005 or less. Near this value of penetration probability, both plans have a 90 percent or higher chance of passing the test, so the manufacturer's risk is small, as it should be. However, if there is a 10-fold increase in the penetration probability from the current level of 0.005 to 0.05, DOT&E's (17, 240) plan still has a 95 percent chance of acceptance. This may not provide sufficient incentive for the manufacturer to sustain current penetration-probability levels. Thus, the (17, 240) plan may have the unintended effect of leading to a reduction in helmet penetration resistance. In the absence of a link between penetration probability and human injury, there is no scientific basis for setting a limit on the penetration probability. In such a circumstance, the committee's view is that the objective of a new test plan should be to provide assurance that newly submitted helmets are at least as penetration-resistant as current helmets. This chapter proposes appropriate criteria for selecting test protocols and illustrates their use through several plans.

6.1 INTRODUCTION

The primary goal of this chapter is to evaluate DOT&E's protocol for testing a helmet's resistance to penetration (RTP). The committee compares its performance with that of the Army's legacy plan and a modified version of the DOT&E plan that has recently been adopted by the Army. A modification of the current protocol for the enhanced combat helmet (ECH) is also examined. These discussions are directly relevant to the issues raised in the correspondence between U.S. Representative Slaughter and the Department of Defense. To provide adequate background, the chapter begins with an overview of the statistical considerations in the design of test protocols for RTP. The chapter ends with a discussion of several topics: (1) robustness of the operating characteristic (OC) curves when the penetration probabilities vary across different test conditions; (2) examination of possible protocols for testing by helmet sizes; (3) post-test analysis of the RTP data to determine the achieved penetration probabilities of the tested helmets; and (4) a proposal to base future protocols with the helmets as the test unit rather than shots.

6.2 STATISTICAL CONSIDERATIONS IN DESIGNING TEST PLANS FOR RESISTANCE TO PENETRATION

As described in Chapter 4, the RTP test protocol specifies that helmets of different sizes be conditioned in selected environments and that shots be taken at different locations on the helmet. However, in this section, the committee starts with a simple setup—a single helmet size, a single shot location on the helmet, and a single environment—so that the test deals with a homogeneous population of units and a single test environment. (To be specific, one can think of a medium helmet, top location on the helmet, at ambient temperature.) It is then reasonable to view the penetration outcomes when n helmets are tested in this manner as being independent and identically distributed binary (pass/fail) random variables with *constant penetration probability* θ. Thus, the probability distribution of X, the (random) number of penetrations in n shots, is a binomial distribution with parameters (n, θ). The statistical properties of a test plan can be derived from this distribution.

c-out-of-n Test Plans

The test plans used by DOT&E for RTP are of the following form: take *n* shots, and if *c* or fewer penetrations are observed, the first article testing (FAT) passes; otherwise, it fails. In this study, the committee refers to such tests as (c, n)-plans. They are also called binomial reliability demonstrations plans or acceptance-sampling plans for attribute data.

The plan is defined by the value of two constants: *c* and *n*. Once these are specified, the protocol's properties are determined and can be studied through its operating characteristic (OC) curve. An OC curve is a plot of the probability (P) of acceptance (y axis) against the underlying failure (penetration) probability of the items under test (x axis). Figure 6-1 shows the OC curve for a ($c = 1$, $n = 40$) test plan; i.e., the FAT is successful if there are one or fewer penetrations in 40 shots.

In Figure 6-1 and subsequent plots of OC curves in this report, the x axis is the true (but unknown) penetration probability θ. This format is different from the OC curves that are currently used by the Army and DOT&E that plot the probability of *nonpenetration* in the x axis. One should focus on the penetration probability, because it is easier to interpret the curve as the penetration probability changes. For example, an increase in θ from 0.005 to 0.05 is easy to interpret as a 10-fold increase in penetration probability; it is hard to interpret this change in terms of $1 - \theta$, which decreases from 0.995 to 0.95.

Recommendation 6-1. The operating characteristic curves used by the Department of Defense should display penetration probabilities rather than non-penetration probabilities on the x axes.

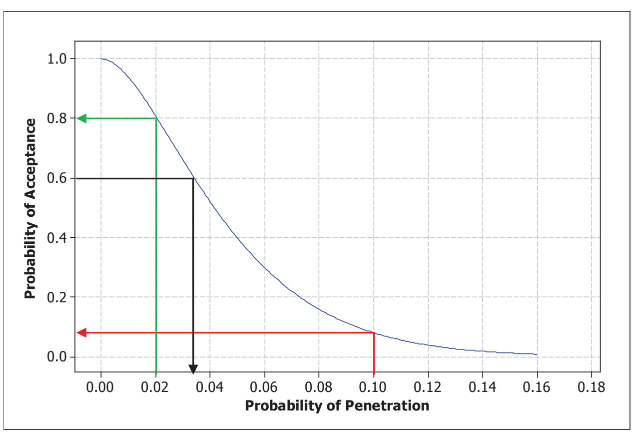

FIGURE 6-1 Operating characteristic curve for ($c = 1$, $n = 40$) test plan. The green and red lines show the probabilities of acceptance for the plan when the true probabilities of penetrations are, respectively, 0.02 and 0.10. The black line shows that, if we want the probability of acceptance to be 0.6, the true penetration probability has to be 0.38.

The y axis in Figure 6-1 shows the probability that a ($c = 1$, $n = 40$) test will be successful as a function of the underlying penetration probability θ. These acceptance probabilities are given by the cumulative distribution, $P(X \leq 1| \theta)$, where *X* has a binomial distribution with $n = 40$ and penetration probability equal to θ. For example, if θ, the underlying (unknown) penetration probability, equals 0.02 (green line), the probability of acceptance is 0.8 (80 percent chance of passing). If $\theta = 0.10$ (red line), the probability of acceptance is approximately 0.10. Conversely, in order to have a probability of acceptance of 0.6 (black line), the true penetration probability needs to be about 0.38. So the OC curve describes the relationship between the acceptance probabilities and the underlying penetration probability as θ ranges across values of interest.

Suppose the decision maker examined the OC curve for the 1-out-of-40 (1, 40) plan in Figure 6-1 and decided that the acceptance probability of 0.10 when $\theta = 0.10$ is too high. There are two options for reducing this value: decreasing *c* or increasing *n*.

Figure 6-2 provides a comparison with two alternatives: 0-out-of-40 (0, 40) and 1-out-of-70 (1, 70) plans. For both ($c = 0$, $n = 40$) and ($c = 1$, $n = 70$) plans, the acceptance probabilities are close to zero for $\theta = 0.10$. This may be acceptable to the decision maker who is the purchaser in this situation. But one cannot discriminate between the two plans at this value of θ.

Consider the case where the target penetration probability is $\theta = 0.01$. Figure 6-2 shows that, at this level, the (0, 40) plan has an acceptance probability of about 0.63, while the (1, 70) plan has an acceptance probability of about 0.83. Since this is the target penetration probability, the decision maker will want to accept helmets with a high probability and will choose the (1, 70) plan or another plan that provides an even higher acceptance probability at $\theta = 0.01$.

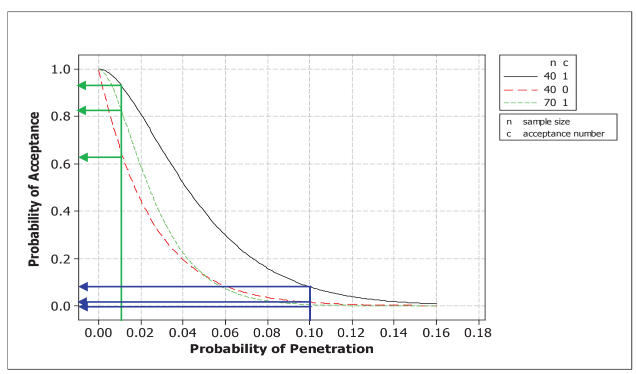

FIGURE 6-2 Operating characteristic curves comparing 1-out-of-40 test plan with 0-out-of-40 and 1-out-of-70 test plans. The blue lines show the probabilities of acceptance for the two plans when the true probability of penetration is 0.1; the green lines show the corresponding acceptance probabilities when the true penetration probability is 0.005.

Because manufacturers want to have a high probability of passing the test, their helmet design and manufacturing process should attain a penetration probability that achieves this goal. For example, to have a 90 percent chance of passing under the (0, 40) plan, the penetration probability will need to be about 0.003. To pass the (1, 70) test, penetration probability will need to be about 0.008, which is not as stringent a target as is set by the (0, 40) plan. These are the kinds of considerations and trade-offs that go into selecting a test plan. The next subsection provides a discussion of test designs that are derived by specifying two points on a plan's OC curve.

A few additional remarks on Figure 6-2:

- The OC curve for the (0, 40) plan is always below that of the (1, 40) plan. This is intuitively clear because the (0, 40) plan is more stringent (it has the same sample size but accepts fewer failures), so the probability of passing the test is lower.
- The OC curve for the (1, 70) plan is always below that of the (1, 40) plan. This is also obvious because the (1, 70) has a larger sample size but allows the same number of failures as the (1, 40) plan.
- More generally, consider two plans that have OC curves that cross, such as the (0, 40) and (1, 70) plans in Figure 6-2. The two plans cross at a penetration probability of 0.05. To the left of that point, the (1, 70) plan has the higher acceptance probability. To the right, the (0, 40) plan has the higher probability of acceptance (although the differences are quite small).

The different perspectives of manufacturer and purchaser could lead them to prefer different plans. Different plans could be considered and evaluated and a compromise plan could be negotiated. Alternatively, as described in the next subsection, plans can be derived from specifications of manufacturer's and purchaser's risks.

Statistical Approaches to Selecting (c, n)-Test Plans

The conventional statistical approach for choosing a test plan is to specify *two points* on the OC curve: (1) a low penetration-probability, θ_L, at which a high acceptance probability, denoted by $(1 - \alpha)$, is desired (a manufacturing process that produces good helmets has a high probability of being accepted), and (2) a high penetration-probability, θ_H, at which a low acceptance probability β is desired (a manufacturing process that produces poor helmets has a high probability of being rejected). Expressing these objectives algebraically leads to the following two equations:

$$P(X \leq c \mid n, \theta = \theta_L) \geq (1 - \alpha) \qquad \text{Equation 6.1}$$

and

$$P(X \leq c \mid n, \theta = \theta_H) \leq \beta \qquad \text{Equation 6.2}$$

In quality control terminology, θ_L is the "acceptable quality level" for the plan, and θ_H is the "rejectable quality level."

There are two kinds of errors that can occur in the (c, n) accept-reject decision. The first error is to reject the helmet (fail the acceptance test) when the underlying penetration probability is at the low (or desired) value (i.e., $\theta \leq \theta_L$); this is often referred to as producer's or manufacturer's risk. The term *manufacturer's risk* is used in this report. Equation 6.1 limits the probability of this error to at most α. The second error is to accept helmets when the penetration probability is too high (i.e., for values of $\theta \geq \theta_H$). These are usually called consumer's or customer's risk. The committee refers to this risk as *government's risk* in this report. As shown by Equation 6.2, the probability of this error is at most β. These are the Type I and Type II error probabilities in the corresponding statistical hypothesis testing formulation of the problem.

Equations 6.1 and 6.2 specify the cumulative binomial acceptance probabilities at two points. By setting the inequalities as equalities, one can solve them to get the values of test size, n, and acceptance limit, c, that satisfy these equations. Because the binomial distribution is discrete, one typically cannot achieve the equalities for α and β exactly. (There are catalogs of test plans and software that can be readily used to obtain the values of c and n to meet particular risks.)

As a concrete example, suppose the test should be designed to ensure that helmets with an underlying penetration probability of $\theta = 0.005$ have at least a 90 percent chance of passing the test. So $\theta_L = 0.005$ and $(1 - \alpha) = 0.90$, or $\alpha = 0.10$. Further, suppose it was decided that if the penetra-

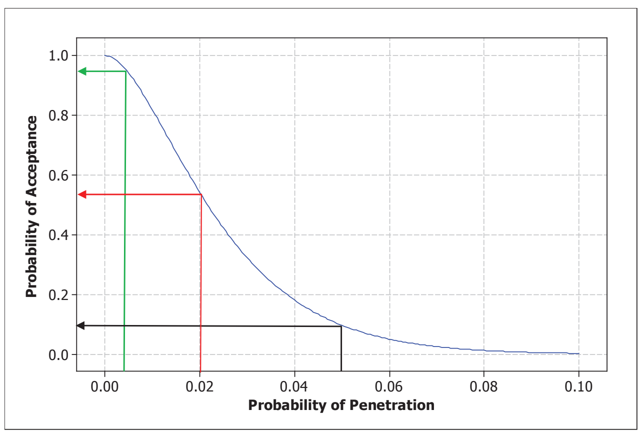

FIGURE 6-3 Operating characteristic curves of (c = 1, n = 77) plan with the desired risks. The black line shows the probability of acceptance for the plan when the true probability of penetration is 0.1; the green and red lines show the corresponding acceptance probabilities when the true penetration probabilities are, respectively, 0.005 and 0.02.

tion probability is $\theta = 0.05$, which is an order of magnitude higher, there must be at most a 10 percent chance of passing the test. So, $\theta_H = 0.05$, and $\beta = 0.10$. Therefore, the test is designed to discriminate between helmets with penetration probabilities of 0.005 and 0.05. In this example, both α and β are the same, but they do not have to be. These two risks are specified by the decision maker.

Figure 6-3 shows the OC curve for the 1-out-of-77 (1, 77) test plan that meets the above requirements. It has the desired properties at the specified penetration probabilities of 0.005 and 0.05. In practice, however, after a plan has been obtained, one should also examine its OC curve at other values of θ to see if it has reasonable (not too low or not too high) acceptance probabilities. In this case, if $\theta = 0.02$ (a four-fold increase from the desired penetration probability), the acceptance probability is about 0.55. One may decide that this is too high and look for a more stringent plan—say one with $c = 1$ but a larger value of n. That change, however, would increase the manufacturer's risk and decrease the government's risk. The OC curve of an acceptance plan conveys a variety of incentives and disincentives to stakeholders in the acceptance decision.

Zero-Failure Plans

A common class of test protocols is based on zero-failures (i.e., $c = 0$). One reason is that the lower the value of c, the smaller the number of units to be tested, n, in order to achieve a particular level of government's risk. However, there may be a false perception associated with zero-failure plans: Because it does not allow any failures, the quality of the products must be, in general, considerably higher than the government's threshold quality. It is clear but worth reiterating that a zero-failure plan does not imply that the penetration probability is zero! For example, if the penetration probability is 0.03, the probability of zero penetrations in 20 shots is 0.54. This means that, even though there is a 3 percent chance of penetration, the 0-out-of-20 failure plan will pass the test more than half of the time. Therefore, an outcome of 0/20 does not imply zero penetration probability.

Robustness to Deviations from the Binomial Distribution

The preceding subsection was based on a framework in which the penetration probability θ was constant across all shots. This assumption does not strictly hold in helmet testing: the helmets are of different sizes, they are tested at different environmental conditions, and the shots are taken at multiple locations on the helmet. It is possible that the penetration probability is different at different helmet locations. When the penetration probabilities vary across shots, the number of penetrations, X, in n shots would not have a binomial distribution. Therefore, the OC curves computed under this model would not apply exactly. The question of interest is whether the binomial calculations are still useful.

The committee performed numerical investigations to examine the differences between the true OC curves and the OC curves obtained by assuming that the penetration probabilities are the same across all shots. It examined a range of deviations for the penetration probabilities. Further, it took the constant penetration probability for comparison to be the average of the varying probabilities. The study shows that the differences in the OC curves are negligible for the range of penetration probabilities and deviations that are relevant to the helmet situation.

Finding 6-1. RTP data aggregated over helmet sizes, environments, and shot locations may not have a constant underlying penetration probability. An evaluation of operating characteristics for modest departures from this situation indicates that the actual acceptance probabilities are negligibly different from those calculated assuming a constant underlying penetration probability. This means that the OC curves computed under the assumption of constant probability provide very good approximations.

6.3 STATISTICAL EVALUATION OF DOD PROTOCOLS FOR RESISTANCE TO PENETRATION

"Legacy" Protocol for the Advanced Combat Helmet

The legacy protocol, first specified by the program manager for the Advanced Combat Helmet (DoD IG, 2013), was a (0, 20) test plan. It involved testing four helmets, one each at four test environments (ambient, hot, and cold temperatures and seawater). Only large-size helmets were tested. For each helmet, the protocol required shooting a 9-mm bullet at five different locations, for a total of 20 shots. The five shots on each helmet were in a fixed shot sequence and pattern. No penetrations were allowed (i.e., it was a zero-failure plan).

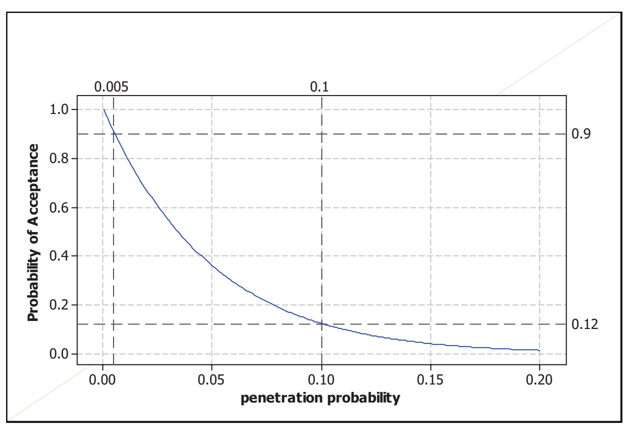

FIGURE 6-4 Operating characteristic curve for the legacy (0, 20) test plan. The darker dashed lines show the probabilities of acceptance for the plan when the true penetration probabilities are 0.10 and 0.005.

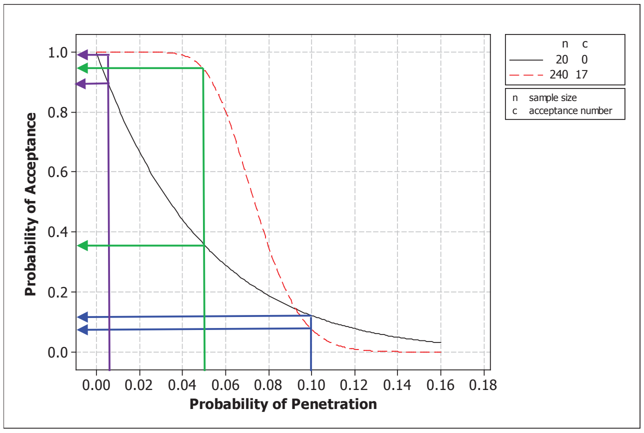

FIGURE 6-5 Comparison of the operating characteristic curves for (0, 20) and (17, 240) plans. The blue lines show the probabilities of acceptance for the two plans when the true probability of penetration is 0.1; the purple and green lines show the corresponding acceptance probabilities when the true penetration probabilities are, respectively, 0.005 and 0.05.

This legacy test plan was adapted from prior helmet protocols and was not designed to meet specified statistical risks. Nevertheless, one can study its properties through its OC curve in Figure 6-4. The acceptance probability is about 0.12 when the penetration probability is 0.10. In other words, if the underlying shot penetration probability is 0.10, the helmets will fail the demonstration test 88 percent of the time.

Consider the behavior of the curve to the left of $\theta = 0.10$ and the implications for manufacturers. If a manufacturer wants to have a 90 percent chance or higher of passing the (0, 20) test, the helmet design and production process would have to achieve a penetration probability of $\theta = 0.005$ or less.

Note that the manufacturer has to achieve a penetration probability considerably less than the government's standard of $\theta = 0.10$ to have a good chance of passing the (0, 20) test. While the government, by its specification of $\theta = 0.10$ as its limit on penetration probability, may be willing to purchase helmets with, say, $\theta = 0.075$, the manufacturer would not aim at that target because the chance of passing the (0, 20) test is too low for comfort—about 0.20 in Figure 6-5.

As noted earlier, the government's risk at $\theta = 0.10$ was 0.12. So, this plan does not strictly satisfy the 90/90 property (at most 10 percent government's risk at penetration probability 0.10 or, equivalently, at least 90 percent chance of failing the test if the nonpenetration probability is 0.90.) One needs a 0-out-of-22 (0, 22) plan to satisfy this requirement. The 90/90 criterion was explicitly adopted by DOT&E in its subsequent protocols.

DOT&E's ($c = 17$, $n = 240$) Protocol

In response to a Senate and House Armed Services Committee's request, the Secretary of Defense asked DOT&E in 2007 to take over the responsibility to prescribe policy and procedures for the conduct of live-fire test and evaluation of body armor and helmets (DoD IG, 2013).

DOT&E decided to increase the number of helmets tested to 48 in order to cover a range of conditions and to have adequate precision in comparing any differences in penetration probability, or BFD, due to environment, helmet size, and shot location. The new protocol called for testing 48 helmets, 12 each for Small, Medium, Large, and Extra Large sizes. Three helmets of each size were conditioned in the four environments before testing. There were five shots at different helmet locations, leading to a total of 240 shots.

There are good statistical reasons to justify DOT&E's increase in the number of helmets tested to 48 helmets from the Army's 5. One gets more precise estimates of the penetration probability from 240 shots than from 20 shots. In addition, DOT&E's plan allows better statistical comparison of possible differences between helmet sizes and environmental conditions.

To examine the properties of the ($c = 17$, $n = 240$)-plan, recall that if n is specified, one can control only one point on the OC curve, or one of the two risks, by the choice of c. With n chosen, the DOT&E approach was to specify that, for penetration probability of 0.10, the probability of acceptance (the government's risk) should be no more than 10 percent. This is referred to as the 90/90 plan (corresponding to a rejection probability of at least 0.90 at nonpenetration probability of 0.90). To summarize, DOT&E's (17, 240) plan was chosen by first increasing the sample size n to be 240 for statistical reasons. Then, the 90/90 standard was applied to get the maximum number of acceptable failures to be 17. Thus, there is a direct relationship between the 90/90 standard and the (17, 240) plan.

However, there is no scientific or empirical basis for specifying 0.10 as the acceptable limit for a helmet's penetration probability. It appears that the 90/90 standard was chosen because of its use in body armor protocols[1] and also because the legacy protocol approximately had this property. That specification led to the ($c = 17$, $n = 240$) test plan. The committee does not know if there was any attempt to control the manufacturer's risk.

Figure 6-5 provides a comparison of the OC curves for the (0, 20) and (17, 240) plans. The two OC curves cross at about $\theta = 0.092$. The (0, 20) plan has higher acceptance probabilities to the right of this penetration probability and has lower acceptance probabilities to the left. The two plans have about the same acceptance probabilities (government risks), in the neighborhood of $\theta = 0.10$, as intended.

When $\theta = 0.005$, near the region where the manufacturers are currently operating (see Chapter 5), the acceptance probability of the (0, 20) plan is about 0.9, while that of the (17, 240) plan is essentially 1.0. Thus, the (17, 240) plan has

[1]Personal communication between Christopher Moosmann, DOT&E, and Nancy Schulte, NRC, via e-mail on May 14, 2013.

lower manufacturer's risk. Director Gilmore's letter to Rep. Slaughter (see Appendix A) recognized that the DOT&E protocol would lessen the burden on manufacturers to pass the test with helmets with an underlying penetration probability less than the "standard" of 0.10. However, this is not necessarily an advantage.

Consider a comparison of the two plans when the penetration probability equals 0.05, which is a 10-fold increase in the penetration probability from the currently achieved level of around 0.005. For this value of $\theta = 0.05$, the acceptance probability is about 0.38 for the (0, 20) plan, while it is about 0.95 for the (17, 240) plan. Thus, even if there is a 10-fold degradation in the penetration resistance of helmets, there is a 95 percent chance of accepting the helmets under the DOT&E protocol. Similar comparisons can be made at other values of θ to the left of the point where the two curves cross. For example, for any values of penetration probability of $\theta \leq 0.04$—a five-fold increase—the helmets will almost certainly be accepted. To the right of the crossing point, however, the (0, 20) plan has a higher acceptance probability (and hence poorer performance in terms of screening out helmets with high penetration probabilities, but still less than a 12 percent chance of acceptance).

A decision on which of the two plans is better comes down to deciding what is the relevant range of values of the penetration probability. DOT&E's (17, 240) plan focuses around $\theta = 0.10$, and its main objective is to prevent helmets with a 0.10 penetration probability or more from being accepted. The (17, 240) plan has comparable performance to the (0, 20) plan at this point and has lower acceptance probabilities for $\theta \geq 0.10$. So if this is the region of interest, then the (17, 240) plan is superior to the (0, 20) plan. However, if the objective of the plan is to provide an incentive for manufacturers to produce helmets at least as good as current helmets ($\theta \leq 0.005$), the (0, 20) plan is better in that it has a lower probability of acceptance for helmets that are not as good as current helmets up to a penetration probability of 0.10.

To evaluate a plan, one needs to consider the whole OC curve, not just one point that may have been used to specify the plan. The DOT&E plan focuses on the point at which $\theta = 0.10$. Its main objective is to prevent helmets with a 0.10 penetration probability or more from being accepted. Available data show that the Department of Defense's design and production specifications have led to helmets with a much lower penetration probability. The committee considers it appropriate to replace the current (17, 240) plan, in light of the available RTP data, with a plan that has the objective of providing an incentive for manufacturers to produce helmets at least as penetration resistant as current helmets ($\theta \leq 0.005$). The (17, 240) plan does not have that property.

Finding 6-2. Helmet manufacturers are currently producing helmets with a penetration probability near $\theta = 0.005$, conservatively. If, as is the case for the (17, 240) plan, the manufacturers have a low risk of failing the test even when there is a 10-fold increase in the current penetration probability (from 0.005 to 0.05), this may provide a disincentive to maintain current levels of penetration resistance. In this sense, the (17, 240) plan is not as good as the legacy plan of (0, 20).

It is likely that manufacturers are more motivated by having a high probability of passing the test than they are in avoiding a penetration probability at the current DOT&E "standard" of 0.10, a value nearly two orders of magnitude higher than what current data indicate for a helmet penetration probability. If manufacturers have a very high probability of passing the test, even if there is a substantial increase in the penetration probability, the (17, 240) plan may have the unintended effect of leading to a reduction in helmet penetration resistance.

Recommendation 6-2. If there is a scientific basis to link brain injury with performance metrics (such as penetration frequency and backface deformation), the Director of Operational Test and Evaluation (DOT&E) should use this information to set the appropriate standard for performance metrics in the test protocols. In the absence of such a scientific basis, DOT&E should develop a plan that provides assurance that it leads to the production of helmets that are at least as penetration-resistant as currently fielded helmets.

Enhanced Combat Helmet Protocol: Modified DOT&E Protocol

The ECH protocol, a modification of the DOT&E protocol, is a 5-out-of-96 (5, 96) plan that involves taking two shots each at 48 helmets. The acceptance limit of $c = 5$ is based on the 90/90 criterion. Figure 6-6 provides a comparison of its OC curve with that of the (0, 20) plan. It shows that, if the penetration probability is 0.035, the manufacturer's risk

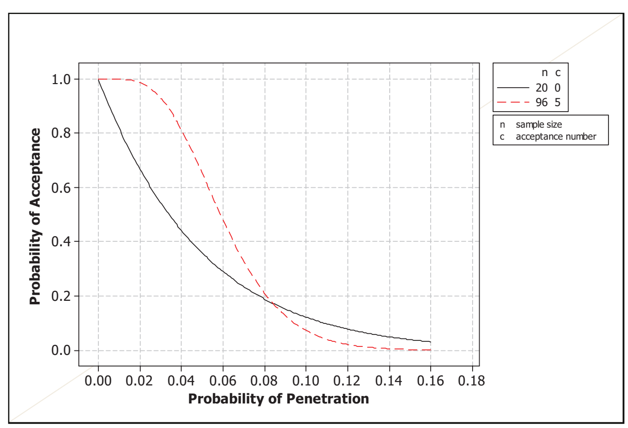

FIGURE 6-6 Comparison of the operating characteristic curves for (0, 20) and (5, 96) plans.

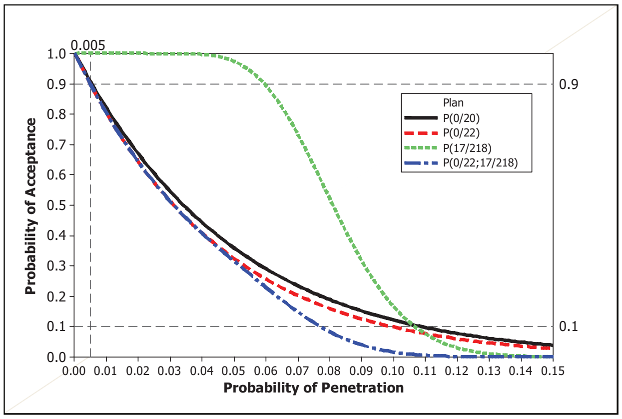

FIGURE 6-7 Operating characteristic curves for the hybrid plan and comparison to others.

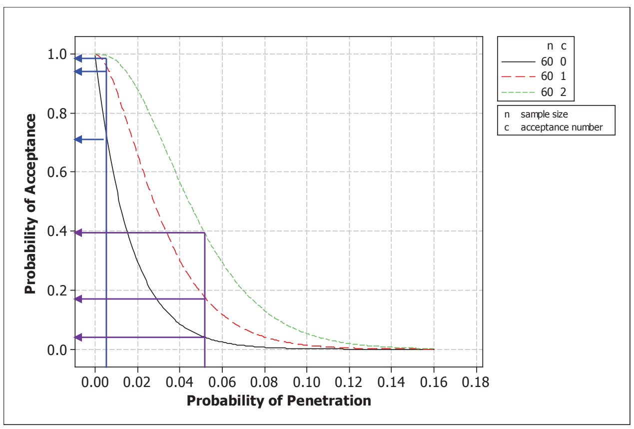

FIGURE 6-8 Operating characteristic curves for three plans with $n = 60$. The blue lines show the probabilities of acceptance for the three plans when the true probability of penetration is 0.05; the purple lines show the corresponding acceptance probabilities when the true penetration probability is 0.05.

is about 0.10 (i.e., there is a 90 percent probability of acceptance). Again, this is about an order of magnitude greater than the penetration probability that available data indicate. The above findings and recommendations pertaining to the full DOT&E protocol also apply here.

Army's Modification of the DOT&E Protocol

In 2012, with DOT&E's approval, the Army modified the (17, 240) plan to a hybrid (two-stage) protocol (U.S. Army, 2012). The two stages involve conducting a (0, 22) plan in the first stage; if the lot passes this test, then a second 17-out-of-218 (17, 218) plan is used, for a total of 240 shots.

Figure 6-7 provides a comparison of the OC curves of the hybrid plan with its component plans and also the legacy plan of (0, 20). It is intuitively clear that the OC curve of the hybrid plan should be below that of its two component plans—(0, 22) and (17, 218)—because it is more stringent than either one. Figure 6-8 confirms that this is indeed the case. The plan's government risk when $\theta = 0.005$ is around 0.10 (i.e., there is a 90 percent chance that helmets with penetration probability of 0.005 will be accepted). This is comparable to the (0, 20) legacy plan and also the first-stage (0, 22) plan. The government's risk when $\theta = 0.10$ is close to zero and much lower than the other three plans being compared.

Because of the first stage, the modified protocol maintains essentially the same incentive for a manufacturer to achieve a penetration probability in the 0.001 to 0.005 neighborhood, in order to have a high probability of passing the acceptance test. Further, thanks to the (0, 22) first-stage threshold, the protocol is considerably more stringent in rejecting submitted product with underlying penetration probability in the 0.05 to 0.10 range than is the (17, 240) plan in Figure 6-5. The (17, 218) criterion for Stage 2 would, by itself, give the impression that a penetration probability as high as 17/218 = 8 percent is acceptable, which is quite different from Stage 1 of the plan. Fortunately, if a product was submitted that had an underlying 0.08 probability of penetration, that helmet is unlikely to pass the (0, 22) first stage test.[2]

With this hybrid protocol, the Army has actually made this hybrid test plan more stringent than the earlier (0, 20) plan, particularly for penetration probabilities in the range of 0.05 to 0.12.

Finding 6-3. The Army's modified plan satisfies the criterion that it will provide an incentive for manufacturers to produce helmets that are at least as penetration resistant as current helmets.

6.4 EXAMINATION OF SEPARATE TEST PLANS BY HELMET SIZE

The committee made a recommendation in Chapter 5 related to testing by separate helmet sizes (Recommendation 5-3). It is neither the committee's intention nor its charge to recommend a specific alternative. Instead, the committee discusses the properties of several plans to indicate the considerations that DOT&E should take into account in making its decision.

If the current practice of 240 total shots is continued, there would be 60 9-mm shots for each helmet size. Figure 6-8 compares some possible acceptance plans. It shows that at the current operating level of around $\theta = 0.005$, the three plans have acceptance probabilities of about 0.76, 0.95, and almost 1, respectively, for $c = 0$, 1, and 2. One could decide

[2]The Army's hybrid plan essentially separates the procurement decision from the characterization analysis that is made possible by the complete set of 240 shots.

that the manufacturer's risk of 1 – 0.76 = 0.24 for the $c = 0$ plan is too stringent. One can compare the two remaining plans at θ = 0.05, which represents a 10-fold increase in penetration probability. The $c = 2$ plan has a 40 percent chance of acceptance, while the $c = 1$ plan has about a 19 percent chance of acceptance. One can then conclude that a 40 percent chance of accepting helmets with penetration probability of 0.05 is too high, in which case the $c = 2$ plan is not desirable. If the 19 percent is at an acceptable level, then one can go with the 1-out-of-60 (1, 60) plan.

An alternative approach to determining a plan for each helmet size is to specify the manufacturer's and government's risks and derive both the sample size and acceptance limit that would meet those criteria. Earlier in this chapter the committee derived a (1, 77) plan that had a 90 percent chance of acceptance probability at θ = 0.005 and a 10 percent chance of acceptance probability at θ = 0.05. This plan provided an incentive for manufacturers to achieve helmets with a penetration resistance that is at least as good as current helmets and protected against the acceptance of helmets that are 10 times worse than current helmets. By increasing the number of helmets tested in each environment to 4, the number of tests for each helmet size would be 80. A 1-out-of-80 (1, 80) plan would have an OC curve with comparable (slightly lower) acceptance probabilities as the (1, 77) plan.

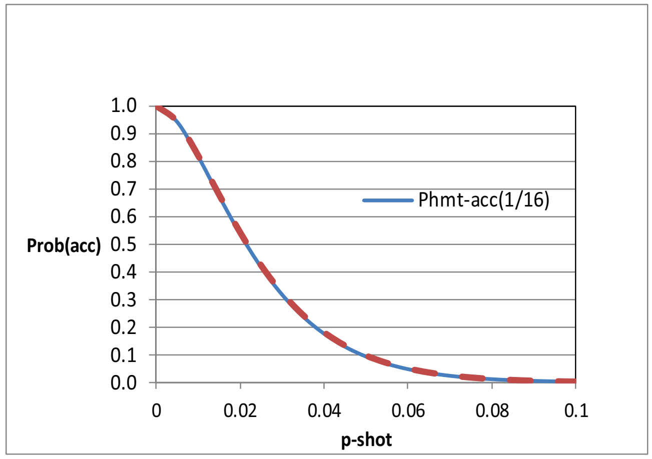

FIGURE 6-9 Comparison of helmet-level and shot-level test protocols. Blue line corresponds to a helmet-level plan; and dashed red line corresponds to the (1,77) shot-level plan.

Recommendation 6-3. The government's risk should be controlled at much lower penetration levels than the 0.10 value specified by the 90/90 standard.

6.5 POST-TEST ANALYSIS

It is important that the Army and DOT&E compute the upper confidence bounds for the penetration probability after the test is conducted. This confidence bound will provide additional information on the quality level of the helmets being tested.

As an example, consider the (17, 240) test plan. Suppose the test is conducted, and the result was one penetration. The estimated penetration probability of 1/240 = 0.004. The 90 percent upper confidence bound for the underlying penetration probability based on these data is 0.016. On the other hand, if there were 10 penetrations, and the estimated penetration probability is 0.04, an order of magnitude higher, the upper 90 percent confidence limit would be 0.06. The upper 95 percent confidence limit is exactly equal to the designed value of 0.10 only if there are 17 penetrations. In other words, the 90/90 conclusion is pertinent only if the maximum number of acceptable penetrations is observed during the test.

In these three examples, the observed number of failures differs substantially, so the data provide additional information on the underlying penetration probability and, hence, the quality of the helmets that will be manufactured. The only exception is with zero-failure plans where the observed number of failures is fixed up front and only a single outcome (zero failures) is allowed for a successful outcome.

6.6 FUTURE TEST PROTOCOLS: HELMET AS THE UNIT OF TEST

The current FAT protocols are based on a shot as the unit of test: The (17, 240) plan takes 240 shots, and FAT is successful if there are 17 or fewer penetrations. However, the basic unit of production is a helmet, not a shot location on a helmet. While it is important to test RTP at different locations, it seems desirable to make accept/reject decisions based on a helmet as the test unit. For example, observing five penetrations on a single helmet is quite different from a single penetration at the same location on five different helmets. A helmet-level test, one that scores a helmet as a failure if there is at least one penetration, would distinguish between these two cases: one failure in the former case, and five failures in the latter.

This section studies the properties of FAT plans defined at the helmet level. This option with respect to lot acceptance testing is discussed in Chapter 8.

Consider the rule where a helmet is scored a failure if there is at least one penetration among the five shots on that helmet.[3] Let the penetration probabilities for the five locations be denoted by $\theta_1, \theta_2, \theta_3, \theta_4$ and θ_5. Further, for the sake of illustration, suppose the penetrations at different locations

[3]In practice, one might declare a helmet failure at the first penetration and not complete the five shots, and thus reduce the cost of testing. However, for the sake of further characterization analyses, the protocol might require that each suite of five shots might be completed. Note that this is part of the test protocol to evaluate helmet performance. There is no assumption that this test plan represents a situation in which a soldier takes five helmet hits.

are independent events. Let θ(helmet) denote the probability of a helmet failure. Then,

$$1 - \theta(\text{helmet}) = (1-\theta_1) \times (1-\theta_2) \times (1-\theta_3) \times (1-\theta_4) \times (1-\theta_5)$$

Suppose one wants a helmet-level test plan with the properties that the probability of acceptance is at least 0.90 when θ(helmet) = 0.025 and at most 0.10 when θ(helmet) = 0.25. The blue solid line in Figure 6-9 shows the OC curve for this 1-out-of-16 (1, 16) plan: test n = 16 helmets, and the FAT is successful if no more than one helmet fails.

One can compare this helmet-level plan with a plan based on shots as the unit of test. When the θ_i's are all small, θ(helmet) can be approximated as the sum of the θ_i's, the individual shot-location probabilities. For illustrative purposes, it is assumed that all the θ_i's are the same and equal θ. Then, if θ(helmet) = 0.025, θ approximately equals 0.005; further, if θ(helmet) = 0.25, θ approximately equals 0.05. Earlier in this chapter, it was shown that a shot-level plan that satisfied these properties was a (1, 77) plan, shown in Figure 6-3. This OC curve is superimposed in Figure 6-9 as the dashed red line.

The two plans have virtually identical OC curves. This is not surprising. Two or more penetrations on any one helmet has a small probability for the range of θ values considered. So, one failure in 16 helmets means most likely that only one penetration occurred among the 80 shots in the 16 helmet tests. A (1, 80) plan is not much different from one of (1, 77).

Finding 6-4. Test plans with a helmet as the unit of test are more desirable and interpretable than those based on shots as the unit. When the penetration probability of a shot is small, the helmet-level test plans and the shot-level test plans will require about the same number of shots.

Recommendation 6-4. The Department of Defense should consider developing and using protocols with helmets as the unit of test for future generations of helmets.

6.7 REFERENCES

DoD IG (Department of Defense Inspector General). 2013. Advanced Combat Helmet Technical Assessment. DODIG-2013-079. Department of Defense, Washington, D.C.

U.S. Army. 2012. Advanced Combat Helmet (ACH) Purchase Description, Rev A with Change 4. AR/PD 10-02. Soldier Equipment, Program Executive Office—Soldier, Fort Belvoir, Va.

7

Test Protocols for Backface Deformation: Statistical Considerations and Assessment

7.0 SUMMARY

The original Army protocols for backface deformation (BFD) were based on binary (0-1) data. The BFD measurement at each location was compared against its specified threshold, and the outcome was scored as a "1" (failure) if it exceeded its threshold. This original plan was based on 20 shots; if no BFD measurements exceeded their limit, the demonstration was successful. In this sense, it was similar to Army's legacy protocol for resistance to penetration (RTP). The Director, Operational Test and Evaluation (DOT&E) protocol expanded the number of shots to 240 and used the continuous measurements together with an assumption that the data are normally distributed. Specifically, the plan compared the 90 percent "upper tolerance limits" computed at 90 percent confidence level (90/90 rule) with their thresholds for the corresponding location on the helmet. As noted in Chapter 5, available BFD test data show that the probability of BFD exceeding its limits is quite small—on the order of 0.005. As this chapter observes, DOT&E's BFD protocol has about a 90 percent chance of accepting the helmet design even if there is an order of magnitude increase in the exceedance probability (from 0.005 to 0.05). This weakens the incentive for manufacturers to produce helmets that are at least as good as current helmets with respect to BFD. In addition, the DOT&E protocols are based on an assumption of normality (a priori untestable) and the complex notion of an upper tolerance limit. Therefore, Recommendation 7-1 proposes that DOT&E's protocol be changed. This change has the advantage that the new BFD protocol would exactly parallel the RTP protocol and would be easy for designers and manufacturers to understand and interpret. It is important that, after testing, the continuous BFD measurements be analyzed to assess the actual BFD levels and monitor them for changes over time.

7.1 INTRODUCTION

This chapter evaluates the DOT&E's first article testing (FAT) protocol for BFD. For the sake of comparison, the committee also considers the Army's legacy test plan. As was the case for RTP (Chapter 6), the Army has modified the DOT&E protocol for application to the lightweight Advanced Combat Helmet, so the effect of that modification is also evaluated.

Recall from Chapter 4 that BFD is the maximum depth of the indentation in the clay headform resulting from a 9-mm-bullet impact on a mounted helmet. It is measured for each shot that does not penetrate the helmet. These BFD measurements are compared against corresponding thresholds (or limits) that depend on shot location: 25.4 mm for front and back and 16.0-mm for left, right, and crown. As discussed in Chapter 5, there appears to be no scientific basis for the choice of these thresholds. Without a scientific basis, the committee is limited to an assessment of whether the BFD distribution for a new helmet is at least as good as that of current helmets, in terms of the probability of exceeding the specified limits.

7.2 BACKFACE DEFORMATION FIRST ARTICLE ACCEPTANCE TESTING PROTOCOLS AND THEIR PROPERTIES

DOT&E Protocol

The DOT&E protocol is based on the suite of 240 shots discussed in Chapter 5. Data from the 240 shots are divided into two groups corresponding to shot location as follows:

1. 96 measurements from all the shots at front and back locations, combined across helmet sizes and environments; and

2. 144 measurements from all the shots at left, right, and crown locations, combined across helmet sizes and environments.

To accept the lot, the 90/90 UTLs calculated from the data for both groups must be less than their respective thresholds.

A 90/90 upper tolerance limit (UTL) is the upper 90 percent confidence bound on the 90th percentile of the underlying distribution. The statistical inference is that, with 90 percent confidence, 90 percent of the underlying BFD distribution is less than the UTL calculated from the data. The DOT&E protocol calculates the UTLs assuming the BFD measurements have a normal distribution (but different normal distributions for the two location groups).

For a normal distribution with mean μ and standard deviation σ, the upper 90th percentile is $\mu + 1.28\sigma$. Because the parameters are unknown, one has to estimate them and also incorporate the variability in the estimates. It turns out that UTL, based on the data, has the form

$$\text{UTL} = \bar{Y} + k\,S$$

Here, $\bar{Y}$ is the sample mean, S is the sample standard deviation, and k is a constant that depends on the sample size n (number of shots), the confidence level, and the distribution percentile of interest. The last two are both set at 90 percent by DOT&E, hence the 90/90 rule. The k-factors are derived from a non-central t distribution. They have been tabulated and can also be obtained using commercial software.

For the 90/90 criterion, it is clear that the k-factor has to be larger than 1.28 to account for the uncertainty in estimating the parameters μ and σ from the data using $\bar{Y}$ and S.

The 90/90 UTL is applied as follows in DOT&E's BFD protocol. UTL is a 90 percent upper confidence bound for the 90th percentile, so one can say with 90 percent confidence that at least 90 percent of the distribution is smaller than the UTL (or at most 10 percent of the distribution exceeds the UTL). Therefore, the FAT is successful if the UTL is *less than* the specified BFD limit B^* for each data group. The rationale is that if UTL < B^*, with 90 percent confidence, B^* exceeds more than 90 percent of the distribution, and there is less than 10 percent of the distribution exceeding B^*.

The same theory underlying the determination of normal distribution tolerance limits can be used to calculate a 90 percent upper confidence limit on the probability of exceeding a specified threshold. This exceedance probability is analogous to the penetration probability for RTP testing. The acceptance criterion would then be that this confidence limit on the exceedance probability be less than 0.10. This criterion is equivalent to the UTL criterion, but more in line with the 90/90 criterion underlying the DOT&E protocols.

The acceptance criterion, that $\bar{Y} + k\,S < B^*$, can be rewritten as

$$(B^* - \bar{Y})/S > k. \qquad \text{Equation 7.1}$$

The left-hand side of this inequality is the number of (sample) standard deviations, S, between B^* and the average BFD, $\bar{Y}$. The conventional term for this quantity is the estimated "margin" relative to a one-sided specification limit. If the estimated margin is greater than a specified k, the acceptance criterion is met.

In the statistical and quality control literature, the test plans are developed by controlling the probability of exceeding a one-sided specification limit directly from a margin calculation, rather than backing into this criterion from a UTL. If the calculated margin exceeds a threshold, k, the demonstration is successful.

Finding 7-1. Statistical tolerance limits, which are the basis of the DOT&E analyses, are complex, and one has to keep track of multiple probabilities and inequalities. An equivalent, and more conventional and transparent, analysis is to base the acceptance test on the margin (the standardized difference between the threshold and the sample mean, as in Equation 7-1).

The margin plan parameters (k, n) are analogous to the (c, n) parameters for binomial data. For a given plan, operating characteristic (OC) curves can be calculated that plot the probability of acceptance versus the underlying probability of exceeding the limit, B^*. By specifying two points on the OC curve, values of n and k can be derived that define a plan that satisfies those two requirements.

Operating Characteristics Curves of DOT&E Protocol

Figure 7-1 shows the OC curves for the two groups of shot locations: (1) red dashed line corresponds to back and front, and (2) black solid line corresponds to right, left, and crown.

At the right side of Figure 7-1, the green line shows that, if the underlying probability of a BFD "failure" is 0.10 for either location group, there is only a 10 percent chance of passing the test. This is the 90/90 criterion that was specified up front, and the plans have the intended property at this value. The manufacturer's risk, and incentive, is read from the left end of the curves. For example, for the extreme left (red) line where P(BFD > B^*) = 0.005, comparable to the proportion of available BFD data that exceed their thresholds, the probability of acceptance is close to one; that is, the manufacturer's risk is close to zero. The blue lines show that, to have at least a 90 percent chance of passing the acceptance test, the manufacturer must have a BFD exceedance probability of about 0.05 for the back and front locations and about 0.055 for the other group. Putting it another way, even if the exceedance probability is as high as 5 percent or 5.5 percent, manufacturers still have a 90 percent chance of passing the FAT requirement for BFD.

The DOT&E protocol specifies that the plans for both groups of locations must pass their acceptance tests in order for the overall BFD protocol to be successful. Thus,

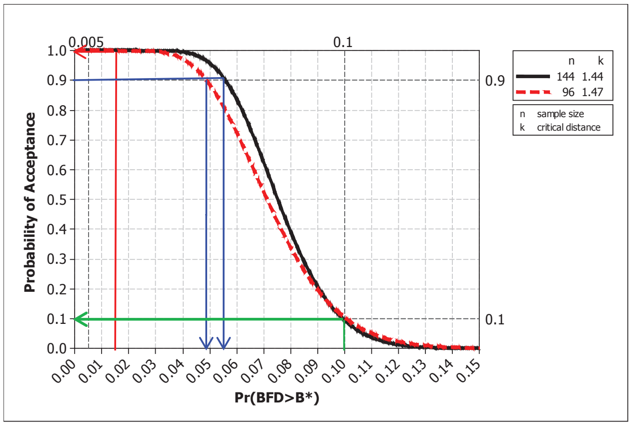

FIGURE 7-1 Operating characteristic curves for Director, Operational Test and Evaluation, backface deformation (BFD) protocol for the two groups of shot locations: red dashed line corresponds to back and front and black solid line corresponds to right, left, and crown. Green and red lines show the acceptance probabilities for the two groups when P(BFD > B*), the exceedance probabilities, are 0.10 and 0.005 respectively. Blue line shows the exceedance probabilities when the acceptance probability is fixed at 0.9.

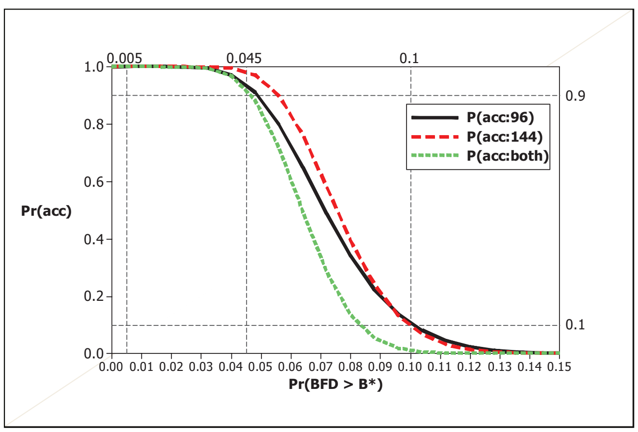

FIGURE 7-2 The two operating characteristic (OC) curves in Figure 7-1 overlaid with the overall OC curve of the backface deformation (BFD) protocol (assuming both BFD exceedance probabilities are the same).

if the underlying BFD failure probability was 0.10 for both subgroups of locations, the probability of passing both tests would be only 0.1 × 0.1 = 0.01, or 1 percent, as shown by the green curve in Figure 7-2. On the other hand, even when the underlying BFD failure probability is as high as 0.045, manufacturers have a 90 percent chance of passing both tests.

Finding 7-2. The use of two BFD tests, rather than a single test, has made the evaluation of the government's risk and the manufacturer's risk and incentive more complicated.

Comparison of DOT&E's Current Protocols to the Legacy Protocol

The legacy protocol was a ($c = 0$, $n = 20$) plan based on converting BFD failures to binary data. The OC curves of such plans were discussed in Chapter 5; in this case, P(BFD > B^*) is the probability of a BFD failure. Figure 7-3 overlays the OC curve for that plan on the OC curves in Figure 7-2.

To have at least a 90 percent chance of passing the legacy plan, the underlying BFD failure probability had to be 0.005 or less. The DOT&E protocol relaxes that incentive by about an order of magnitude (even considering that the tolerance limit acceptance test has to be passed by both data subgroups). Thus, as was the case for RTP, the DOT&E protocol is "easier" to pass than the legacy protocol for values of true BFD failure probabilities less than 0.075 (where the legacy and the green curves cross).

For the BFD data provided to the committee (see Chapter 5), there were 8 BFD failures in a total of 816 tests. All of those failures were in one test series, which could indicate a systematic problem with that helmet or that test series. The combined data for the other three helmet tests yield an upper 90 percent confidence limit on the BFD failure probability of 0.004. This should be the region of interest for BFD protocol.

Finding 7-3. Figure 7-3 shows that the DOT&E protocol has a 90 percent chance of accepting helmets even when the BFD failure probabilities are an order of magnitude larger than what has been achieved by current helmets. This reduces the incentive for manufacturers of future helmets to sustain BFD failure probabilities at current levels.

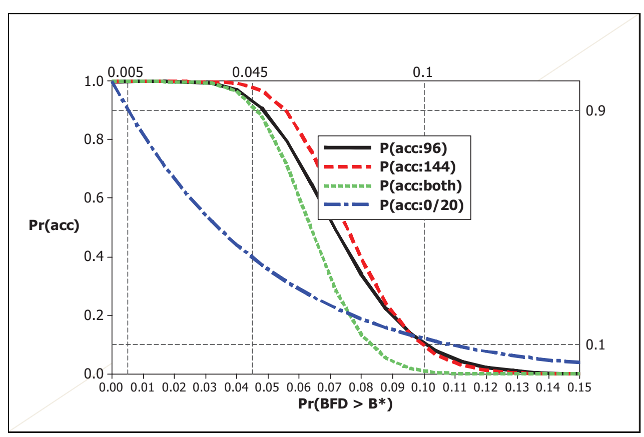

FIGURE 7-3 Comparison of the three operating characteristic curves in Figure 7-2 with that of the legacy (0, 20) plan.

Modified DOT&E Protocol for the Enhanced Combat Helmet

The Enhanced Combat Helmet (ECH) protocol is based on 48 helmets spanning four helmet sizes and four environments, with three helmets tested for each combination of helmet size and environment. There are 2 shots per helmet, totaling 96 shots. One shot is at one of the front/back locations; the other is at one of the left/crown/right locations. The same type of 90/90 UTLs are computed based on the assumption of normality; the k-factor for $n = 48$ and the 90/90 criterion is 1.57. The black curve in Figure 7-4 is the OC curve for the plan based on 48 shots. The red dashed curve is the OC curve for both tests passing. This curve shows that for a manufacturer to have a 90 percent chance of acceptance for both location groups, the helmets should have an underlying probability of exceeding the limit, B^*, at just less than 0.03. As was the case with the previous protocol, this is a substantially higher BFD failure probability than what current helmets have achieved.

Finding 7-4. The DOT&E protocol for the ECH has a 90 percent chance of accepting helmets that have an order of magnitude larger BFD failure probability than those achieved by current helmets.

Army's Modified DOT&E Protocol for the Lightweight Advanced Combat Helmet

This protocol changed the grouping of the shots in the subsection above as follows: (1) front only, (2) rear only, (3) crown only, and (4) right and left sides combined. Before combining right and left sides, a pre-test is done to test if the distributions (mean and variance) for the two sides are different; the data are combined only if there is not an indication of significant difference. This separation of the protocol into four or five subgroups is in line with the patterns of heterogeneity that were discussed in Chapter 5.

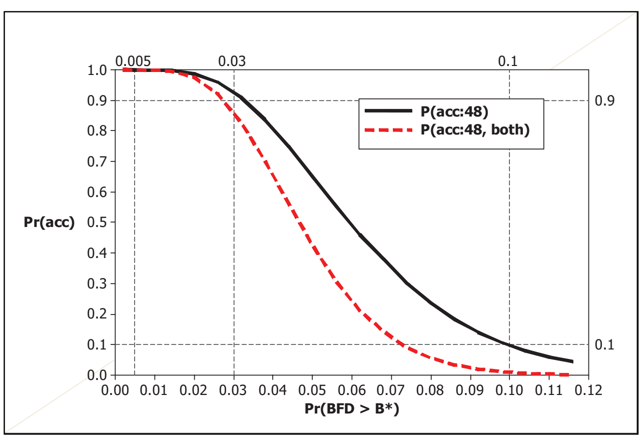

FIGURE 7-4 Operating characteristic curves for the two location groups for the Enhanced Combat Helmet. NOTE: BFD, backface deformation.

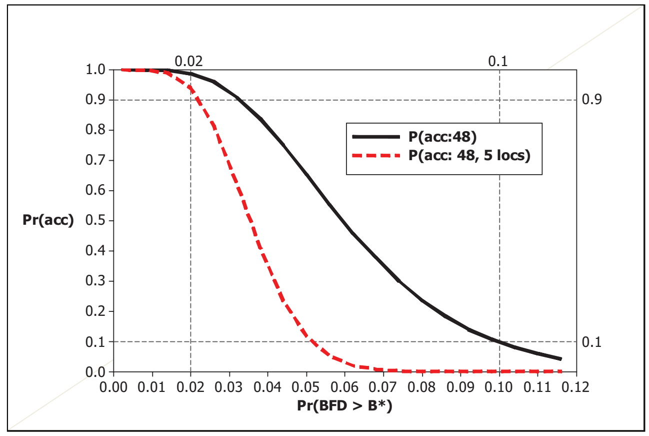

FIGURE 7-5 Operating characteristic curves for a single 48-shot plan and for five 48-shot plans. NOTE: BFD refers to backface deformation.

Under this protocol, the tolerance limit analysis is done on appropriate subsets of either 48 or 96 shots, depending on the location and whether the left and right distributions of BFD are consistent. Figure 7-5 shows the OC curves for the situation in which the protocol is applied to a single group of 48 shots, and the combined curve is for the situation of all five groups passing their individual margin tests.

Figure 7-5 shows that for a manufacturer to have a 90 percent chance of passing all five acceptance tests by location, the underlying BFD failure probability would have to be about 0.02. As was the case with RTP, the Army's modification of the DOT&E protocol is considerably more stringent than the DOT&E protocol (Figure 7-2).

7.3 DISCUSSION

Backface Deformation Protocol Based on Binary Data

Although the BFD tests are part of DOT&E's FAT protocols, the committee's impression is that they do not receive the same level of public scrutiny as the RTP protocols. For example, they were not mentioned in the communications between Rep. Slaughter and the Department of Defense. There are many possible reasons, some of which are stated in the following finding.

Finding 7-5. The rationale behind BFD protocols for FAT is difficult to understand for the following reasons:

- The lack of a scientific connection between BFD and brain injury dilutes the usefulness of BFD measurements;
- The choice of BFD thresholds is not based on data or scientific studies, so the notion of exceeding the

threshold has no practical or scientific meaning, and their use is limited to comparing a new design of helmets with existing ones; and

- BFD measures the deformation on clay, which is only an indirect measure of the actual deformation on helmets.

There are also several statistical issues related to the DOT&E protocols. The data in Chapter 5 indicate an appreciable difference between the BFD distributions for front and rear shots. To address this, DOT&E has recommended preliminary analyses to decide whether the BFD data can be pooled across groups before conducting the test. These added analyses will add substantial complexity to both the decision process and the properties of the test protocol. They also make ~~it~~ the protocols less transparent. These points are summarized in the following finding.

Finding 7-6.

- The current DOT&E protocols for BFD data are based on upper tolerance limits, which are more difficult to understand than the protocols for RTP based on binary data.
- These protocols are based on the assumption that the BFD data follow a normal distribution. The computed values of the upper tolerance limits are sensitive to this assumption.
- The graphical diagnostics that were shown to the committee indicate that the normality assumption is not unreasonable for the limited data sets that have been analyzed. However, one should be cautious in assuming that future BFD test measurements will always be normally distributed.
- The methodology for computing UTLs requires that the BFD data across environments, helmet sizes, and across locations (within the two groups) are homogeneous; that is, they have a normal distribution with the same mean and variance. DOT&E has proposed: (1) conducting preliminary hypotheses tests to determine if this assumption of homogeneity holds, and (2) pooling the data only for cases where the pre-test suggests the homogeneity assumption is valid. Such an approach will add substantial complexity to the decision process and, more importantly, to the properties of the test protocol.

The replacement of the legacy protocol, based on binary data, with variable BFD data was presumably driven by efficiency considerations. If the normal distribution assumption is correct, the resulting protocol is much more efficient from a statistical perspective. When the test sample is small, as was the case with the legacy protocol of 20 shots, statistical efficiency is indeed an important consideration.

However, if the test sample size is large (as is the case with 240 shots), the concern about efficiency is less critical. In this case, it is preferable to use protocols that do not require strong parametric assumptions. An additional consideration is the need for simplicity and transparency. The use of two very different protocols for RTP and BFD data makes it difficult for DoD test designers to develop plans with the same goals and for users to understand their properties.

DOT&E's legacy protocol was a simple and transparent plan that was based on binary data. Specifically, each BFD measurement is compared to its location-specific threshold, and the data are converted to 0-1 outcomes depending on whether the observation is below or above the threshold. A BFD measurement above the threshold leads to a "failure." The probability of interest is then the exceedance probability.

Recommendation 7-1. The Director, Operational Test and Evaluation, should revert to the more transparent and robust analysis of backface deformation data based on pass/fail scoring of each measurement.

With such conversion, one can use the same types of protocols as those for RTP. For the BFD data the committee has seen, the probability of exceedance is around 0.005, about the same levels as the penetration probabilities estimated from the data. So, if the same considerations in Chapter 5 are used to develop the BFD plan, the two protocols are likely to be the same.

A natural concern in converting continuous measurements to binary data is the loss of statistical efficiency. However, recall that the goal of the test protocols is to determine if the BFD measurements exceed their corresponding thresholds. The FAT BFD data provided to the committee indicate that these thresholds are well in the upper tails of the BFD measurements (see Figures 5-2 and 5-4). The data show that $P(BFD > B^*)$ is less than 0.005. The probability of rejecting helmets (manufacturer's risk) produced at this level of quality is essentially zero for the test, based on binary data (the same as that for protocols based on normal theory). In other words, the probability of acceptance is essentially 1 for both protocols. If $P(BFD > B^*)$ were to increase to 0.05 (an order of magnitude increase), the probability of rejection under a binary (17, 240) plan is about 0.10 (see Figure 6-5). This is very close to the combined normal-theory plan that is currently in use (see Figure 7-2).

The current DOT&E protocol is based on two different plans for the two different location subsets, because they have different thresholds and also differences in distributions within location subsets.

Recommendation 7-2. The binary data for the different location subgroups should be combined into a single backface deformation protocol.

Converting to a binary protocol and combining the data across the locations would mean that the exceedance probabilities may vary across locations. However, the numerical study described in Chapter 5 indicates that the OC curves are robust to the level of deviations in exceedance probabilities that are present with current BFD data.

Post-Test Analyses

As noted, the loss in efficiency is not a major concern in converting the continuous BFD measurements to 0-1 outcomes. It is, however, important for DOT&E and the Services to do post-test analyses of the continuous BFD data, compute the margins, and monitor them to see if there is any trend or increase or decrease in BFD values over time. Such monitoring is an important part of any test process.

Recommendation 7-3. The Office of the Director, Operational Test and Evaluation, and the Services should analyze the continuous backface deformation measurements, compute the margins, and track them over time to assess any changes over time.

Recommendation 7-4. Available backface deformation (BFD) data should be used to develop data-based limits against which to compare future BFD data, as a replacement for the current legacy ad hoc limits.

8

Lot Acceptance Testing

8.0 SUMMARY

Lot acceptance testing (LAT) is used to ensure that manufacturers continue to produce helmets that conform to contract specifications. A random sample of helmets is selected from the production lot, and the helmet shells as well as hardware are tested according to the LAT protocol. The number of helmets in the protocols is determined from an American National Standards Institute (ANSI) standard, and they vary by lot size. This chapter examines the operating characteristic (OC) curves for the Director, Operational Test and Evaluation's (DOT&E's) LAT plans and compares them with first article testing (FAT) protocols in the Army's legacy plans and DOT&E's plans. The OC curves for the LAT plans for the different lot sizes can vary a lot, indicating that the manufacturer's and government's risks can be quite different across lot sizes. This is primarily due to the different sample sizes (number of helmets and number of shots) as determined from ANSI standard. Further, DOT&E's FAT protocols are considerably less stringent (higher probabilities of acceptance for the OC curves) than their corresponding LAT protocols. This is counter to the philosophy that it should be more difficult for manufacturers to pass FAT than LAT. This issue can be addressed if DOT&E makes changes to the (17, 240) FAT protocol as discussed in Chapters 6 and 7. This chapter also proposes using binary data for backface deformation (BFD) LAT protocols, to make them consistent with the recommendations for FAT. Finally, the committee examines the properties of LAT protocols based on helmets as the unit of testing.

8.1 INTRODUCTION

After a helmet manufacturer has passed FAT and begins production, LAT is used to ensure that the helmets continue to meet contract specifications. This chapter describes the DOT&E's LAT protocol, which is based on the ANSI standard ASQ Z1.4-2008[1] for selecting lot sample sizes and acceptance limits (ASQ, 2008). The performance of the DOT&E's LAT protocol is compared to the Army's original FAT protocol and DOT&E's FAT protocol, both in terms of resistance to penetration (RTP) and BFD. This chapter also examines the feasibility of helmet-based LAT protocols.

8.2 LOT ACCEPTANCE TESTING PROTOCOLS

The Army's Original Lot Acceptance Testing Protocol

Table 8-1 shows the Army's original LAT protocol for RTP (DoD IG, 2013, p. 6). Note that the number of helmets, and thus the resulting number of shots, is small.

TABLE 8-1 Sample Sizes for the Army's Historical Lot Acceptance Testing Protocol for a 9-mm RTP Shell

Lot Size	Sample Size	Accept	Reject
4-150	5 shots, 1 helmet	0	1
151-1,200	5 shots, 1 helmet	0	1
1,201-3,200	10 shots, 2 helmets	0	1

SOURCE: DoD IG (2013).

DOT&E's Lot Acceptance Testing Protocol

For DOT&E's LAT, the sample sizes (numbers of helmets to be tested) are derived from the ANSI standard ASQ Z1.4-2008 (ASQ, 2008). Table 8-2 is the helmet LAT matrix from Appendix A of the DOT&E LAT protocol.[2] It provides the requirements in terms of the number of helmets to be tested,

[1]The committee notes that the DOT&E protocol does not mention or explicitly reference the ANSI standard. The Army purchase description does specify the ANSI standard (U.S. Army, 2012).

[2]The current DOT&E LAT and FAT protocols are found in Appendix B of this report.

TABLE 8-2 Helmet Lot Acceptance Testing Matrix

Lot Size	Sub-Test	Shots	Helmets	RTP Accept	RTP Reject
91-150	9-mm Hardware RTP	6	3	0	1
	9-mm Shell RTP/BTD	25	5	0	1
151-500	9-mm Hardware RTP	10	5	0	1
	9-mm Shell RTP/BTD	40	8	1	2
501-1,200	9-mm Hardware RTP	10	5	0	1
	9-mm Shell RTP/BTD	65	13	1	2
1,201-3,200	9-mm Hardware RTP	16	8	1	2
	9-mm Shell RTP/BTD	65	13	1	2

NOTE: BTD, ballistic transient deformation (synonymous with the term BFD used in this report); RTP, resistance to penetration.
SOURCE: DOT&E (2012).

the total number of shots, and the accept/reject criteria by lot size. The test plan in Table 8-2 involves a finer division of lot sizes and a larger number of helmets and shots than the Army's legacy protocol (Table 8-1).

The other aspects of DOT&E's LAT are similar to its FAT protocol, including range setup, the use of clay as a backing material and its calibration, the definitions of complete and partial penetrations, and the metrics (RTP and BFD). However, unlike FAT, all tests are conducted only under ambient conditions.

Note that the sample sizes for LAT are smaller than FAT sample sizes. Further, the protocol varies substantially by lot sizes: from a sample size of 5 helmet shells (and a total of 25 shots) for the smallest lot to a sample size of 13 helmet shells (and a total of 65 shots) for the largest lot. Similarly, for hardware testing, the sample sizes vary from 3 helmets (and 6 shots) to 8 helmets (and 16 shots).

As with FAT, the DOT&E LAT protocol specifies a helmet test matrix that defines the shot order for each helmet in the test sequence (Table 8-3).

The DOT&E LAT protocol makes no mention of helmet size. If lots consist of only one helmet size, then it is clear how to implement the protocol in Table 8-3. However, for situations where there are helmets of multiple sizes in a lot, Table 8-2 does not specify the order in which the different-sized helmets should be tested.

Finding 8-1. The DOT&E LAT protocol does not specify helmet size, while the FAT protocol specifies testing of four different helmet sizes.

The 1996 report *DoD Preferred Methods for Acceptance of Product*, MIL-STD-1916, states:

> The product shall be assembled into identifiable lots, sublots, or batches, or in such other manner as may be prescribed. Each lot or batch shall, as far as practicable, consist of units of product of a single type, grade, class, *size* [emphasis added], and composition, manufactured under essentially the same conditions, and at essentially the same time. (DoD, 1996, p. 9).

Recommendation 8-1. The protocol established by the Director, Operational Test and Evaluation, should be revised

TABLE 8-3 Helmet Shot Order Test Matrix for Aramid 9-mm

Helmet	Order				
LAT Helmet #1	B	L	Cr	F	R
LAT Helmet #2	Cr	R	B	L	F
LAT Helmet #3	R	B	Cr	L	F
LAT Helmet #4	B	F	L	R	Cr
LAT Helmet #5	B	R	F	L	Cr
LAT Helmet #6	Cr	B	L	F	R
LAT Helmet #7	L	B	Cr	F	R
LAT Helmet #8	Cr	B	R	F	L
LAT Helmet #9	L	F	R	B	Cr
LAT Helmet #10	F	Cr	B	L	R
LAT Helmet #11	Cr	L	R	B	F
LAT Helmet #12	R	F	B	L	Cr
LAT Helmet #13	Cr	F	L	B	R

NOTE: B, back; CR, crown; F, front; L, left; R, right; LAT, lot acceptance testing.
SOURCE: DOT&E, 2012.

to explicitly state that: (1) it will be applied separately to each helmet size; and (2) if the lot contains helmets of multiple sizes, the test requirements will be applied according to the number of helmets of each size in the lot.

The Army's Hybrid Protocols

As with FAT, the Army has recently introduced modified LAT protocols. For penetration, it is a hybrid of the Army's historical LAT protocol and DOT&E's LAT protocol (DOT&E, 2012).

- In Stage 1, either 5 or 10 shots are taken, depending on the lot size (as specified in Table 8-3). If there is any complete penetration, the test terminates in a failure. If there are no complete penetrations, the test continues to Stage 2.
- In Stage 2, passing the LAT RTP requirement is based on the accept/reject criterion specified in the DOT&E protocol (Table 8-2). As described in the DOT&E protocol, if a penetration is observed, then a new helmet is substituted and tested, and the data from both helmets are counted toward the final accept/reject determination.

Hardware testing is conducted strictly in accordance with the DOT&E protocol (DOT&E, 2012).

For BFD, the Army's LAT hybrid protocol is based on the same hybrid test for penetration (DOT&E, 2012). If the test continues as a result of successful completion of the first stage RTP test described above, then passing the LAT BFD requirement is based on all of the data collected and the accept/reject criterion specified for the lot size. As before, if a penetration is observed during the test, a new helmet is substituted and tested, and the BFD data from both helmets (excluding the shot that resulted in a penetration) are used in the BFD calculations. Thus, the Army's lightweight advanced combat helmet protocol is virtually the same as the DOT&E protocol. The only difference is that the lightweight protocol does not specify a two-stage procedure for lot sizes of 91 to 150 helmets; instead, it simply requires a 75 percent upper tolerance limit (UTL) at 90 percent confidence (DOT&E, 2012).

The committee does not study the properties of these hybrid protocols in this chapter because their properties are complex. Moreover, as noted in Chapters 6 and 7, the committee proposes that the DOT&E protocols be modified rather than addressing the issues through modified two-stage protocols.

8.3 EVALUATING PERFORMANCE: COMPARISON OF OPERATING CHARACTERISTIC CURVES

Resistance to Penetration

This section compares the OC curves of DOT&E's LAT protocol with DOT&E's FAT protocol and the Army's original FAT protocol. In comparing LAT and FAT, it is important to keep in mind that the manufacturer has already demonstrated the ability to meet specification requirements via FAT. The goal of LAT is to assess whether the manufacturer's helmets continue to conform, and thus the government is expected to assume greater risk at this stage.

Figure 8-1 shows the OC curves for the DOT&E LAT protocols for the three different lot sizes: 91 to 150 (black), 151 to 500 (red), and 501 to 3,200 (green). The interpretation of an OC curve here is the same as that in Chapter 6: It is a plot of the probability of acceptance (passing LAT in this case) on the y axis versus the true penetration probability on the x axis. In Figure 8-1, the OC curves for the different lot sizes vary considerably and hence can have quite different manufacturer's and government's risks. For example, the blue line corresponds to a penetration probability of 0.005 (current levels where manufacturers are operating), and the probabilities of acceptance for the three curves range from about 0.88 to about 0.99. Thus, the manufacturer's risks (which equal 1 – probability of acceptance) range from 0.01 to 0.12. Consider now the case where the probability of penetration is around 0.05—which is an order of magnitude higher. The purple lines indicate that the probabilities of acceptance, or government's risk, vary from about 0.18 to 0.4.

It is difficult to match the OC curves very closely if one wishes to vary the sample sizes for different lot sizes and, in particular, fix the sample sizes using the ANSI standard.

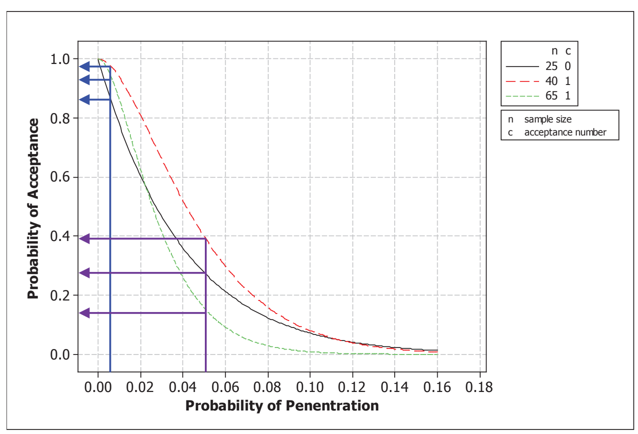

FIGURE 8-1 Operating characteristic curves for resistance to penetration for the three Director, Operational Test and Evaluation, protocols by lot sizes: 91 to 150 (black), 151 to 500 (red), and 501 to 3,200 (green).

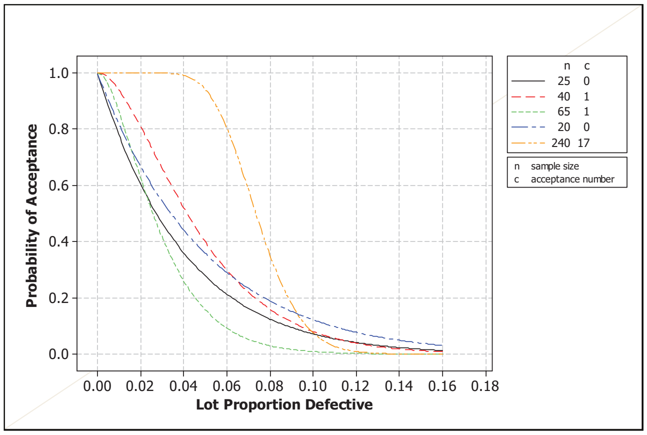

FIGURE 8-2 Comparison of operating characteristic curves for the three Director, Operational Test and Evaluation (DOT&E) lot acceptance testing protocols (black, red, and green) with the Army's Legacy first article testing (FAT) protocol (blue) and DOT&E's FAT protocol (orange).

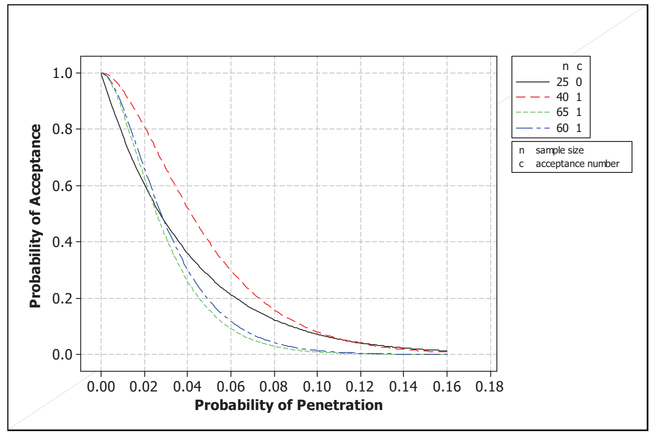

FIGURE 8-3 Comparison of operating characteristic curves for the three DOT&E lot acceptance testing protocols (black, red, and green) with an illustrative (1, 60) first article testing protocol (red).

Figure 8-2 provides a comparison of the DOT&E LAT protocols (black, red, and green OC curves) with the Army's legacy FAT protocol (blue) and DOT&E's FAT protocol (orange). The OC curve for the Army's legacy FAT protocol is within the range of the curves for DOT&E's LAT protocols. However, DOT&E's FAT protocol (17-out-of-240 penetrations) has a much higher probability of acceptance than the LAT protocols in the left end of Figure 8-2. This region corresponds to penetration probabilities of 0.08 or less, covering the current region where manufacturers operate as well as penetration levels more than an order of magnitude higher. So, the manufacturer's risk for the LAT protocols is higher than that for the DOT&E FAT protocol. This is counter to the philosophy that LAT should be easier for manufacturers to pass than FAT.

Finding 8-2. Some of the DOT&E LATs for penetration are more difficult for manufacturer's to pass than the FAT plans. This is contrary to the philosophy that LAT is intended to assess whether the manufacturers helmets continue to conform to specifications, and so it should be less stringent than FAT.

As discussed in Chapter 6, the problem illustrated in Figure 8-2 is with DOT&E's (17, 240) FAT protocol. For illustrative purposes, consider the situation in which the DOT&E FAT is changed to a 1-out-of-60 (1, 60) plan. Figure 8-3 shows a comparison of the OC curve of this plan with those of the current LAT OC curves. The blue curve corresponds to the (1, 60) FAT plan and, as to be expected, it is very close to the 1-out-of-65 (1, 65) LAT plan that corresponds to the largest lot size. If one wanted to insist that LAT plans be less stringent than the corresponding FAT plans, one could restrict the number of shots for the LAT plans to be 60 or fewer, rather than its current value of 65.

The committee emphasizes that these are just illustrative discussions and that the committee is not endorsing a particular FAT plan for RTP.

Backface Deformation

The Army's historical LAT BFD protocol was also based on the sample sizes in Table 8-1. For each of the shots, the BFD was measured and compared to a threshold: 25.4 mm for front and back shots and 16 mm for side and crown shots. If any of the BFDs exceeded its associated standard, then the lot failed. In other words, the BFD LAT protocol, like the BFD FAT protocol, was based on binary outcomes—whether the BFD measurement exceeded the threshold or not.

DOT&E's LAT protocol, like its FAT protocol, assesses helmet BFD performance using statistical tolerance limits (discussed in Chapter 7). The LAT procedures continue to fix the confidence levels at 90 percent. However, unlike FAT where the UTL was also fixed at 90 percent, the UTLs for LAT vary with lot size (and hence with sample size): 80 percent UTL for lot sizes of 501 to 3,200 helmets, 75 percent UTL for lot sizes of 151 to 500 helmets, and a more complicated two-stage procedure for lot sizes of 91 to 150 helmets.

The DOT&E LAT protocol states that the "UTL (at 90 percent confidence) will be calculated by combining the right and left shot locations if the data from the qualifying First Article Test indicates the data from the side locations can be combined for analysis."[3] This procedure is different from the DOT&E FAT protocol in which back and front

[3]DOT&E, 2012, pp. 5-6; reprinted in Appendix B

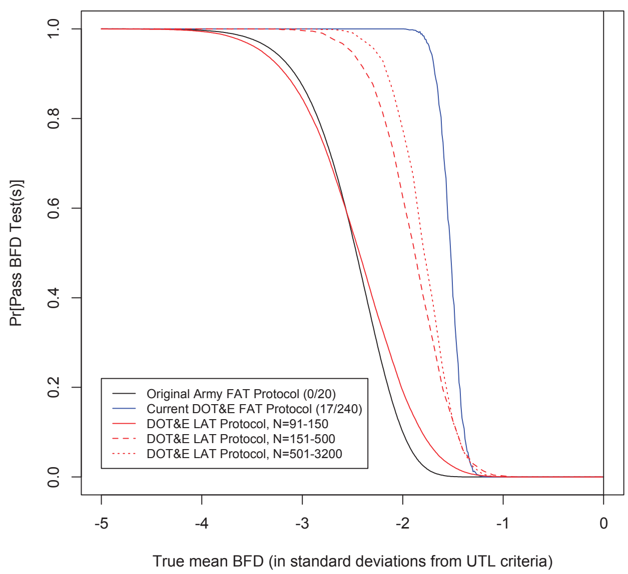

FIGURE 8-4 Backface deformation (BFD) operating characteristic curves for the Director, Operational Test and Evaluation (DOT&E) first article testing (FAT) protocol in blue, the original Army FAT protocol in black, and the DOT&E lot acceptance testing (LAT) protocols in red. NOTE: N is the lot size; UTL, upper tolerance limit.

are grouped into one category and left, right, and crown are grouped into another.

Figure 8-4 compares the performance of the various DOT&E LAT protocols (one for each lot size) against the Army's original (0, 20) FAT protocol and DOT&E's FAT protocol for BFD. These results are based on a simulation study conducted under the following scenario:

- The BFD measurements are normally distributed.
- The sample size is held constant in accordance with the lot size requirements of Table 8-1 (which occurs if there are no penetrations).
- The standard deviations are fixed as follows: 2.02-mm for the front and back locations and 1.58-mm for the side and crown locations. (These values were derived from actual BFD data).
- The means are varied. The x axis of Figure 8-4 shows the true mean in terms of standardized distance from the respective UTL thresholds. The standardized distance (true mean minus BFD*) is divided by the standard deviation. BFD* is the UTL threshold: 25.4-mm for front and back shots and 16-mm for side and crown shots. For example, if the true mean for the front location is set at 23.38-mm, the standardized distance on the x axis in Figure 8-4 will be (23.38-mm – 25.4-mm)/2.02-mm = –1.

Figure 8-4 shows the OC curves for the original Army FAT protocol (in black), the DOT&E FAT protocol (blue), and the three DOT&E LAT protocols (solid and dashed reds). As was the case with penetration, the curves for the three BFD LAT protocols vary considerably, indicating that they can have quite different manufacturer's and government's risks. In particular, the OC curves for the large two lot sizes (dashed reds) have much higher probabilities of acceptance (OC curves to the right) than that of the small lot size. Thus, it is easier to pass the LATs for the larger lot sizes.

Turning to a comparison with the FAT protocols (black and blue curves), one sees that the Army's legacy FAT protocol has a very similar performance to that of the LAT curve for the small lot size of 91 to 150. On the other hand, the OC curve for the DOT&E FAT protocol (blue curve) is much further to the right than the other curves, indicating that the FAT protocol for BFD is much easier to pass than the LAT protocols. This conclusion is similar to the one that can be made from Figure 8-2 for penetration.

Finding 8-3. The OC curves of the DOT&E LATs for BFD vary considerably, indicating that the protocols for the different lot sizes can have quite different manufacturer's and government's risks. The protocol for the small lot size is more stringent than the ones for the medium and large lot sizes.

Finding 8-4. DOT&E's LAT protocols for BFD are more difficult for manufacturers to pass than its FAT. This mirrors a similar finding for penetration. This result is contrary to the philosophy that LAT should be less stringent than FAT.

Backface Deformation Lot Acceptance Testing Protocols Based on Binary Data

As noted in Chapter 7, there are many difficulties with the use of tolerance limits for the BFD protocols. If DOT&E were to implement Recommendation 7-1 to revert to the use of binary data for BFD for FAT protocols, a similar change should necessarily be made to LAT protocols. This would simplify many of the additional complexities associated with LAT protocols and combine them across shot locations. It would also have the added advantage of using the same LAT protocols for penetration and BFD and make the BFD protocols easier to understand and more transparent to nonstatisticians.

8.4 ANSI STANDARD AND THE ACCEPTANCE QUALITY LIMIT

Comparison to the ANSI Standard

DOT&E'S LAT protocol attempts to be consistent with ANSI standard because it designates the helmet shell as both the unit of sampling and the unit of testing and analysis. However, the protocol also says:

TABLE 8-4 Subtest Acceptance Quality Limits (Approximate)

Lot Size	Subtest	Sample Size (Number of Helmets)	Accept/Reject Criteria (Number of Helmets)	Subtest AQL(%)
91-150	Hardware	3	0/1	4.0
	Shell	5	0/1	2.5
151-500	Hardware	5	0/1	2.5
	Shell	8	1/2	6.5
501-1,200	Hardware	5	0/1	2.5
	Shell	13	1/2	1.0
1,201-3,200	Hardware	8	1/2	6.5
	Shell	13	1/2	4.0

> If a perforation [complete penetration] occurs, no additional shots will be taken on the perforated helmet. The perforated helmet will count against the accept/reject criteria in Appendix A. To complete the test matrix,[4] a new (untested) helmet will be tested using the full 9mm V0 shot sequence for the helmet that was perforated. Valid penetration and BTD data from both helmets will be used for analysis (DOT&E, 2012, p. 5).[5]

The result of this requirement is that, if a penetration occurs, the number of helmets sampled will not match the sample size in Table 8-1 or the ANSI standard. Substituting for the penetrated helmet is a conservative approach, in the sense that additional data are collected when a perforation is observed. However, it introduces an additional level of complexity into the test, and it makes it difficult to quantify and compare test protocol performance in terms of OC curves.

A testing regime strictly implemented per the ANSI standard would simply fail any helmet that experienced a single penetration (out of five shots to the helmet). No additional helmets would be substituted in order to complete the total number of shots indicated in Table 8-1. Under this testing protocol, the helmet is the unit of testing and analysis. As such, the helmet is subject to a multi-shot test, and it either passes if no penetrations are observed, or it fails as soon as one penetration is observed. (Note that this is similar to the helmet-level test for FAT that was proposed at the end of Chapter 6.)

Finding 8-5. The DOT&E LAT protocol does not precisely follow the ANSI/ASQ Z1.4-2008 testing protocol that calls for sampling a fixed number of items out of a lot. It requires testing of additional helmets when penetrations occur. Further, the shot is the actual unit of testing, despite the fact that sample sizes are stated in terms of helmets.

[4]Here the term "test matrix" does not refer to Table 8-1. Rather it refers to a second matrix that specifies the shot order for each helmet.

[5]The committee notes that the DOT&E FAT protocol is silent on what should be done in the event that a helmet perforation occurs during testing. However, the lightweight ACH purchase description matches the DOT&E LAT requirement both to substitute a new helmet if a perforation occurs and to use all of the data (U.S. Army, 2012).

This lack of consistency in the current protocol—whether a shot or a helmet is the actual unit of test—makes it challenging to understand and interpret its properties. Further, as described below, it is difficult to connect the test sample sizes to the ANSI standard quality metrics.

Determining the Acceptance Quality Limit

The helmet sample sizes in Table 8-1 are derived from the ANSI standard special inspection level[6] S-2 for the hardware and special inspection level S-3 for the shell.[7,8] The DOT&E protocol alludes to this indirectly by saying, "Helmet testing is unique in that [it requires] two to three disparate destructive tests. . . . The total number of helmets allocated to . . . tests closely reflects the quantities required for . . . sampling at either the S-2 or S-3 levels" (DOT&E, 2012, p. 5). Table 8-4 provides the acceptance quality limit (AQL) for each of the sub-tests *assuming the tested helmets are not perforated*. As such, they are approximations of the actual AQLs for the LAT protocol.[9]

The DOT&E protocol goes on to say that the helmet sample sizes are based on a "4% acceptable quality level" or AQL[10] (DOT&E, 2012, p. 6), where "the total number of helmets allocated to penetration and BTD tests closely reflects the quantities required for the S-4 sampling level" (DOT&E, 2012, p. 5) of ANSI/ASQ Z1.4-2008 (ASQ, 2008). This is not correct, in the sense that the quality of shells in the

[6]Per the ANSI standard, special inspection levels "may be used where relatively small sample sizes are necessary and large sampling risks can or must be tolerated" (ASQ, 2008, p. 5).

[7]Using Table II-A of ANSI/ASQ Z1.4-2008, convert the helmet shell sample sizes in Table 8-1 to the sample size code letters and then use Table I to see that the lot size and letter combinations correspond to the S-2 and S-2 inspection levels.

[8]The "Shots" sample sizes in Table 8-1 do not correspond to any of the single sampling plan sample sizes in ANSI/ASQ Z1.4-2008. For example, see Table II-A in ASQ (2008).

[9]These AQLs are approximate because they are derived from the ANSI standard that assumes a fixed sample size, unlike the DOT&E protocol in which the sample size can vary if a perforation is observed.

[10]Note that ANSI/ASQ Z1.4-2008 defines AQL as the "Acceptance Quality Limit." It explicitly states, "the use of the abbreviation AQL to mean Acceptable Quality Level is no longer recommended" (ASQ, 2008, p. 8).

TABLE 8-5 Sample Sizes per ANSI Standard ASQ Z1.4-2008 to Achieve an AQL of 0.4 Percent

General Inspection Level	Lot Size	Sample Size (Number of Helmets)	Accept/Reject Criteria (Number of Helmets)
S-4	1,201-3,200	32	0/1
S-4	3,201-10,000	32	0/1
S-3	35,001-150,000	32	0/1
S-3	150,001-500,000	32	0/1
S-4	500,001+	125	1/2

SOURCE: Adapted from ASQ (2008).

helmets tested for hardware is unknown, and the hardware quality of the helmets whose shells are tested is unknown. Thus, while it is clear that for any lot the subtest AQLs are approximately those given in Table 8-4, the AQL of the helmets can be anywhere between the largest subtest AQL (because different types of defects tend to occur within the same helmets) and the sum of the AQLs for all the subtests (because different types of defects tend to occur on different helmets).

Finding 8-6. The AQL at the helmet level is unknown, despite the current DOT&E protocol that suggests helmets are being tested to a 4 percent AQL. Although the AQL for the helmet shell and hardware can be specified (see Table 8-4), it is not clear how these subsystem AQLs combine at the helmet level, and, further, the AQL associated with helmet BFD performance is not assessed.

The 2013 DoD Inspector General report *Advanced Combat Helmet Technical Assessment* found, "In selecting the LAT RTP requirement of 4 percent AQL . . . DOT&E did not consider selecting an AQL that was based on the safety criticality of the helmet" (DoD IG, 2013, p. 13). The report further notes that the Defense Contract Management Agency (DCMA) uses a 0.4 AQL for personal protective equipment and that manufacturers are currently working to a 0.4 percent AQL (DoD IG, 2013).

Table 8-5 provides the sample sizes necessary to achieve an AQL level of 0.4 percent. However, during presentations to the committee on June 17, 2013, DCMA stated that it would defer to Program Executive Office Soldier and DOT&E for setting the appropriate AQL for combat helmets.[11]

Finding 8-7. As Table 8-5 shows, the required sample size (in terms of helmet shells) to achieve an AQL of 0.4 is roughly three to six times larger than what is specified in the current DOT&E protocol. However, the sample size of 32 helmets for lots up to 500,000 helmets is generally smaller than the total number of helmets required for all the LAT tests as specified in the lightweight helmet purchase description (see the table on p. 76 of U.S. Army [2012], reproduced in Table 8-6 below). These values range from 28 for a lot of 500 helmets or less to 44 for lots of 1,201 to 3,200 helmets.

8.5 USING THE HELMET AS THE UNIT OF TESTING

Helmet-Based Lot Acceptance Testing Protocols

Chapter 6 (Section 6.6) proposed that protocols for future helmet designs be based on helmets as the units of test rather than shots. Such a test design has the advantage of following the ANSI standard more closely. In this section, the committee pursues this topic in the context of LAT.

Table 8-6 shows the number of lightweight Advanced Combat Helmets required for LAT under the current purchase description. Note that the total, including the contingency, is close to (or more than) the 32 helmets required for a 0.4 AQL test (cf. Table 8-4). Thus, if the various tests can be appropriately combined, then a helmet-based test at 0.4 AQL is feasible within the current contract requirements. Similarly, if two shots were required per helmet (say, consisting of a combination of two shell shots or one shell shot and one hardware shot)—rather than five shots per helmet shell and two per hardware test—then the total number of shots is 64, which is less than the combined number of shell and hardware shots currently required for lots greater than 500 helmets. This suggests that a helmet-based test is feasible within current resources.

To illustrate the concept, the committee studied the properties of a helmet-based LAT using simulation. The framework for the simulation study was as follows:

- 32 helmets are shot at three random locations, two of the standard five locations (front, back, right, and left sides, and the crown) and one on hardware.
- Each non-hardware shot is evaluated for whether it perforates and whether the resulting BFD is less than the required threshold and the hardware test is evaluated for perforation.
- Hence, in this illustrative test, each helmet is subject to five binary-outcome tests, and each helmet is scored as a pass if all five tests are passed or as a fail otherwise.

Making the BFD test a binary pass/fail is consistent with Recommendation 7-1 and consistent with past Army testing practice.

Figure 8-5 shows the OC curves for this illustrative helmet-based LAT protocol (red) compared to the DOT&E LAT protocol (blue). To do the comparison, the committee calcu-

[11]Clayton Maddio, Soldier Systems Sector Integrator, DCMA Operations Directorate, noted during an informal discussion with the committee on June, 17, 2013, that, while DCMA Critical Safety Items (CSI) policy is stated with an AQL of 0.4 percent, DCMA policy permits the customer to decide the AQL for CSI items, thus overriding DCMA Policy.

TABLE 8-6 Lot Acceptance Testing Helmet Sampling Rate as Specified in the Lightweight Advanced Combat Helmet Purchase Description

	Lot Acceptance Testing (Number of Helmets Required)										
Lot Size	9-mm RTP/ BTD (Shell)	9-mm RTP (Hardware)	17-grain FSP V50	Blunt Impact	Edging Adhesion	Paint Adhesion	Static Pull Test (Ref. System)	Pad Water Absorbancy	Barcode Label/ Marking	Contingency	Total
500	8	5	2	2	1	2	1	~	~	7	28
501-1,200	13	5	2	3	2	3	1	~	~	8	37
1,201-3,200	13	8	3	3	3	4	1	~	~	9	44

NOTE: BTD, ballistic transient deformation; FSP, fragment simulating projectile; RTP, resistance to penetration.
SOURCE: U.S. Army (2012).

lated a combined OC curve for the DOT&E LAT tests. This was accomplished by simulating the appropriate number of shell and hardware shots, each at the same probability of penetration, and also simulating the BFDs associated with the shell impacts. A helmet passed the LAT if the number of shell penetrations did not exceed their accept/reject requirements *and* the hardware penetrations did not exceed their accept/reject requirements *and* all of the BFD upper tolerance limits were within requirements. For example, for a manufacturer to pass the DOT&E Combined LAT protocol for lot sizes 1,201 to 3,200, there could be no more than 1 penetration out of 65 shots on 13 helmets *and* no hardware failures in 16 shots on 8 helmets, *and* the 80 percent upper tolerance limits in each of the five locations (where the assumption was made that the side shots could not be combined) had to be less than the required thresholds with 90 percent confidence. It is important to note that these combined OC curves are based on the assumption that, if there is a change in the x axis, that change is reflected in the probability of test failure across all tests in the LAT.

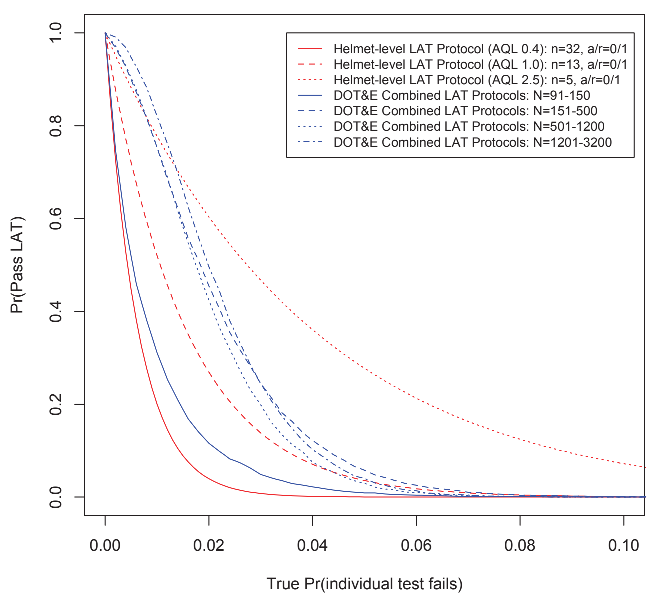

FIGURE 8-5 Operating characteristic (OC) curves for the illustrative helmet-based lot acceptance testing (LAT) protocol in red compared to the OC curve for the combined resistance to penetration and backface deformation for the Director, Operational Test and Evaluation (DOT&E) LAT protocol in blue. NOTE: AQL, acceptance quality limit.

The main points of Figure 8-5 are that (1) the curves for the illustrative helmet-based test are similar to the current DOT&E LAT in many respects, and (2) varying the AQL allows for tailoring the performance of the helmet-based test.

Finding 8-8. Implementing a helmet-based LAT in place of the current DOT&E protocol is feasible from the perspective of the required testing resources, and such a test can be appropriately tailored by setting the AQL.

Adding Switching Rules

According to ANSI/ASQ Z1.4-2008, “AQL is the quality level that is the worst tolerable process average when a continuing series of lots is submitted for acceptance sampling” (ASQ, 2008, p. 2). The standard goes on to say,

> The purpose of this standard is, through the economic and psychological pressure of lot non-acceptance, to induce a supplier to maintain a process average at least as good as the specified AQL while at the same time providing an upper limit on the consideration of the [government’s] risk of accepting occasional poor lots. The standard is not intended as a procedure for estimating lot quality or for segregating lots (p. 3).

Further, it is important to note that the ANSI standard specifically says,

> The concept of AQL only applies when an acceptance sampling scheme with rules for switching between normal, tightened and reduced inspection and discontinuance of sampling inspection is used. These rules are designed to encourage suppliers to have process averages consistently better than the AQL. If suppliers fail to do so, there is a

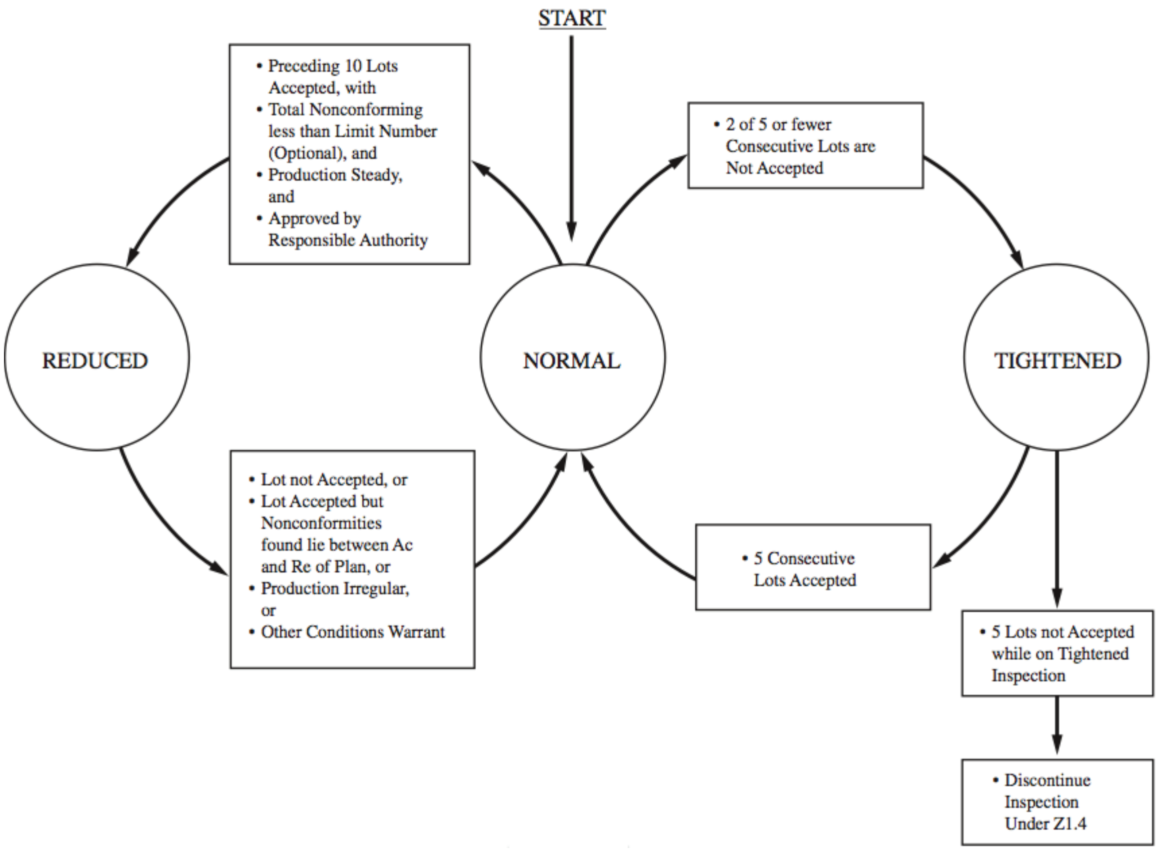

FIGURE 8-6 Switching rules from ANSI/ASQ Z1.4-2008. SOURCE: ASQ (2008).

> high probability of being switched from normal inspection to tightened inspection where lot acceptance becomes more difficult. Once on tightened inspection, unless corrective action is taken to improve product quality, it is very likely that the rule requiring discontinuance of sampling inspection will be invoked (p. 2).

Figure 8-6 illustrates how the switching rules work. A manufacturer starts under the normal regime. Should the manufacturer fail one or two of five consecutive lots, then it is switched to tightened rules, which make it more difficult to pass the LAT. If five consecutive lots are accepted under the tightened rules, then the manufacturer is switched back to the normal regime. On the other hand, if five consecutive lots are not accepted under the tightened regime, then the manufacturer must re-qualify via FAT.

If a manufacturer under the normal regime has 10 consecutive lots accepted, then it is switched to reduced rules that make it easier to pass the LAT. However, as soon as it fails a lot while under the reduced rules, the manufacturer is switched back to the normal regime.

For example, Table 8-7 shows the switching rules for lot sizes of 1,200 to 3,200 with an AQL of 0.4.

Finding 8-9. The DOT&E LAT protocol does not specify the use of switching procedures. Further, the lightweight ACH purchase description explicitly states that switching procedures will not be used (DOT&E, 2012). As a result, the motivation inherent in the ANSI standard for manufacturers to maintain a process average at least as good as the specified AQL is not incorporated into current LAT procedures.

With the current DOT&E LAT protocol, it is difficult to implement switching rules because they must be applied at the subtest level, which introduces a level of complexity in terms of record keeping that may be burdensome. However,

TABLE 8-7 Switching Rules for Lot Sizes of 1,200 to 3,200 with Acceptance Quality Limit of 0.4

Switching Rule	Lot Size	Sample Size (Number of Helmets)	Accept/Reject Criteria (Number of Helmets)
Normal	1,201-3,200	32	0/1
Tightened	3,201-10,000	50	0/1
Reduced	35,001-150,000	13	0/1

SOURCE: Adapted from ASQ (2008).

with the application of a helmet-based test, the implementation of switching rules is more feasible.

Recommendation 8-2. If the Director of Operational Test and Evaluation implements a helmet-based protocol, it should specify the use of switching procedures so that manufacturers are motivated to maintain a process average at least as good as the specified acceptance quality limit.

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9

Characterization Tests for the Advanced Combat Helmet and Future Helmets

9.0 SUMMARY

The statement of task to the committee includes the following: "Evaluate the scope of characterization testing relative to the benefit of the information obtained." The term "characterization" is broad and is used in different ways in different contexts. However, the Office of the Director, Operational Test and Evaluation (DOT&E) provided additional information to elaborate on this task. Most of the issues raised by DOT&E that are relevant to this portion of the statement of task are addressed in this chapter. The committee also describes additional characterization tests that are needed. Some of these are intended for future helmet designs. A number of these additional tests have been discussed in earlier chapters and are repeated here because they can be viewed as being related to characterization studies. These include the following: evaluating helmet performance across a broader range of, and more realistic, threats; assessing the effect of aging; understanding the relationship between helmet offsets and helmet protection; and conducting gauge repeatability and reproducibility (R&R) studies to understand the different sources of variation in the test process and possibly providing opportunities to reduce some of the variation. This chapter also includes a discussion of current V_{50} testing and an alternative methodology as well as a discussion of industrial practices in characterizing process capability.

9.1 INTRODUCTION

The committee's task to "evaluate the scope of characterization testing relative to the benefit of the information obtained" was added after the committee had started its deliberations, apparently in response to issues raised in the Department of Defense (DoD) Inspector General Report (DoD IG, 2013).

Chris Moosmann from DOT&E provided additional information on the task during a presentation to the committee on March 21-22, 2013. He said:

- ACH (Advanced Combat Helmet) characterization was not done prior to release of the helmet test protocol;
- DOT&E and PEO (Program Executive Office) Soldier have committed to characterize ACH helmets;
- DOT&E indicated that the ECH (Enhanced Combat Helmet) would also be characterized;
- DOT&E will use the results of characterization to determine whether any changes to current protocol standards are appropriate; and
- DOT&E/program offices will consider characterization of new future designs during developmental testing to assess any need for protocol changes.[1]

Mr. Moosmann's presentation noted that the following questions will be addressed as part of the above characterization testing:

1. What is the lower confidence limit (90% confidence) on P(nP) as measured with n shots?
2. What percent of the population (90% confidence) meets the backface deformation (BFD) requirement by location?
3. Do shot location, helmet size, environment, and shot sequence affect P(nP) or BFD?
4. What effect do shot location, helmet size, and shot sequence have on the slope of the ballistic characterization curve?
5. What are the V_0 and V_{50} velocities associated with the fragment simulating projectiles (FSPs) and right circular cylinders (RCCs) currently used during helmet testing?

[1] Chris Moosmann, Live Fire Test & Evaluation, DOT&E, "DOT&E Issues Update," presentation to the committee on March 21, 2013.

6. What BFDs are associated with FSPs/RCCs currently used during helmet testing?
7. How do helmets perform against foreign threats?[2] (slide 5)

The presentation requested that "the committee review and comment on the scope of characterization testing relative to the benefit of the information obtained and the resources required to do so." In particular,

I. Are there additional questions that should be addressed (threats, conditions, etc.)?
II. Should characterization address issues such as durability and aging ("shelf life")?
III. Should there be a common (minimum) set of questions all characterization efforts should address and what should those include?[3] (slide 6)

The rest of this chapter is aimed at identifying the relevant aspects of characterization, addressing the questions posed by DOT&E, and providing a general discussion of industrial practices involved in studying process capability.

9.2 CHARACTERIZATION OF THE ADVANCED COMBAT HELMET USING EXISTING TEST DATA

For the ACH, existing test data from first article testing (FAT), lot acceptance testing (LAT), and other sources can be used to answer most of the questions posed above by DOT&E. In fact, Question 1 was the subject of Recommendation 6-3 in Chapter 6. It notes that upper confidence bounds (UCBs) should be computed and reported based on the observed number of penetrations in FAT. In addition to characterizing the actual penetration probability, the UCBs can be used to monitor how the penetration levels vary over time and among manufacturers. The same kinds of analyses should also be done with LAT data to monitor a manufacturer's performance over time.

A similar recommendation was made in relation to Question 2 in Chapter 7. Recommendation 7-3 states that the BFD measurements (from FAT) should be analyzed to determine the margins (number of standard deviations between the mean BFD and its threshold) and tracked over time to assess changes. Since the BFD thresholds lack scientific basis, it is better to track changes in the margins or examine the exceedance probabilities at multiple thresholds. It is straightforward to compute the point estimates and associated confidence intervals (or upper bounds) for the exceedance probabilities. Again, similar analyses should be done with LAT data to track a manufacturer over time. Recommendation 7-4 suggests replacing the current ad hoc threshold for BFD (at different locations) using data-based limits obtained from historical BFD test data. Developing such limits can be viewed as a characterization study.

[2]Ibid.
[3]Ibid.

Similarly, existing data for ACH can be used to answer Questions 3 and 4 above. The suite of resistance-to-penetration (RTP)/BFD tests for FAT (see Table 4-1) consists of a designed "full factorial experiment" with three factors: helmet size (Small, Medium, Large, Extra Large), conditioning environment (ambient, hot, and cold temperatures, and seawater), and shot location (front, back, left, right, crown). While the procurement decision rules are based on aggregated data, the full data provide the necessary information to characterize differences among helmet size, shot location, and environment, as specified in Questions 3 and 4 above. In fact, Chapter 5 (Section 5.3) reports some answers to these questions from the committee's analyses of FAT and LAT data that were made available to it. Moreover, the "clustering" analysis already being done by DOT&E and the Institute for Defense Analysis is aimed at characterizing exactly these differences.[4,5]

The current goal of the clustering analysis is to do preliminary tests to see if the data can be pooled across the different factors (environment, locations, etc.), and the committee has noted in Chapter 7 that such preliminary tests are not to be recommended. However, the analyses to estimate the differences among the factors and to monitor them over time (Questions 3 and 4 above) are certainly important and should be continued.

V_{50} testing, raised in Question 5, is discussed in Section 9.4 in this chapter. Regarding Question 6, the committee does not know if data from fragment simulating projectiles (FSPs) and right circular cylinders (RCCs) are stored from past FAT studies for ACH. If they are, Question 6 can also be readily answered.

The issue of testing helmets against other threats has been discussed extensively in the report. The committee will return to this point in Section 9.3.

ACH test data can also be used to characterize many other aspects of helmet performance. For example, FAT and LAT data can be compared over time to find trends and patterns associated with the production process for an individual manufacturer. Data can also be compared across manufacturers to detect possible differences across manufacturers. Further, data from the drop-tests can be used to track performance of manufacturers over time in terms of blunt-force trauma.

9.3 EXPANDED CHARACTERIZATION REQUIRING ADDITIONAL DATA

DOT&E also asked if there were additional topics that should be part of its characterization studies. The committee describes selected topics here. This class of characterization

[4]Janice Hester, Research Staff Member, Institute for Defense Analysis, "DOT&E Helmet Test Protocols Overview: Statistical Considerations and Concerns," presentation to the committee on January 25, 2013.

[5]Laura Freeman, Research Staff Member, Institute for Defense Analysis, "Protocol Analyses and Statistical Issues Related to Testing Methodologies," presentation to the committee on March 21, 2013.

studies is intended to explore the properties of the helmet beyond the current DOT&E protocol. Several of these suggestions are of a longer-term nature and intended for the ECH and newer generations of helmets rather than the ACH.

- *Evaluate helmet performance for a variety of different threats.* As noted in Chapter 3, the primary focus of DOT&E's (and the Army's) test protocols is gunfire threats. Recommendations 3-1, 3-2, and 3-5 emphasize the importance of expanding the test profile to cover emerging threats as well as more realistic blunt-impact threats. For example, improvised explosive devices (IEDs) have dramatically different distributions of fragment sizes and velocities compared to those from artillery. Recommendation 3-3 asks DoD to reassess helmet requirements for current and potential future fragment threats, especially those energized by blast. Such a reassessment would include examining redundancy in the current profile of threats, such as the 2-grain versus 4-grain, and may lead to elimination of some tests. Resources can then be redistributed to cover a wider range of realistic ballistic threats, including larger mass artillery fragments, bullets other than 9-mm, and IED fragments. A comprehensive examination of threat profiles would involve considerable additional resources and consist of much more than characterization studies. Nevertheless, the committee believes that this is a very important direction for future efforts by DoD.
- *Evaluate the sources of variation in the test process.* As noted in Chapter 4, there are many sources of variation in the test process and test measurements. Recommendation 4-2 recommends that the DoD conduct formal gauge R&R studies to understand the different sources of variation (test methodology, helmets, use of clay, headforms, etc.) and use the results to improve the test process. The committee judges that this should be a high priority, given the high costs of testing and the benefits to be gained from such an R&R study.
- *Evaluate helmet performance at selected areas of the helmet not currently tested*. The test protocols do not assess the helmet in some regions, such as edges and around the ear covering. While it may be reasonable to exclude them in the formal test process, it is still of importance to understand the range of protection afforded at these helmet locations. Potential differences in manufacturing choices could be better understood and might lead to improvements in overall design.
- *Evaluate performance for different helmet pad configurations*. Current testing procedures test the five locations with padding directly in the line of fire of the shot (crown, front, and back) or in a gap between pads (left and right). Anecdotal evidence suggests that many soldiers change the padding locations or remove some of the pads from their helmets in the field. Understanding the differences between testing results and what would be experienced by the soldier would help quantify relevance of the testing. One option for such a characterization study would be to obtain samples of common pad configurations in the field and perform the standard RTP and BFD testing. This would allow better connection of results to soldier experience and may suggest additional recommendations or requirements for soldiers.
- *Evaluate the relationship between helmet offsets and helmet protection*. With the availability of 5 headform sizes, it should be straightforward to characterize differences in BFD by location as a function of helmet offset. It is widely assumed that increased offset provides improved protection through reduced BFD magnitude. (However, Figure 5-3 in Chapter 5 shows that this may not be the case.) Quantifying this improvement, if it exists, could lead to changes to helmet assignment or a reassessment of the trade-offs between functionality and protection.
- *Evaluate the aging characteristics of the helmets to determine if there is any meaningful degradation of the protection performance of the helmets over time.* An approach to this testing might be to store some of the helmets from a given lot and perform a test similar to FAT testing on helmets of different ages. For example, if helmets were generally thought to be used for 2 years before they were replaced, then a testing regimen could be established that tests helmets at ages 0, 6, 12, 18, 24, and 30 months to determine if there are changes in protection performance. An alternative would be to develop an accelerated testing program in which the helmets are exposed to stressful environmental or to use conditions that would simulate accelerated aging. This testing would provide reassurances that the helmets are not degrading over time.

Program and oversight personnel can identify other potentially important characterization tests that would provide additional information about a helmet's protective capabilities. DOT&E's charge to the committee specifically asked for an evaluation of "the scope of characterization testing relative to the information obtained." The committee does not have the necessary information or the expertise to do a cost-benefit analysis. On the other hand, the Department of Defense has the relevant expertise and information as to which information is important for soldier safety in the battlefield. DoD is better equipped to make the decision on which tests should be done, how to fund them, and whether funds should be redistributed from current test resources for important characterization tests.

Chris Moosmann's presentation to the committee[6] listed some possible studies that are being planned to characterize the ACH (from different vendors) and compare its performance with the lightweight ACH. If the ACH will no longer be procured (only current manufacturers who have passed FAT will produce them), then it is not wise to invest considerable additional resources to characterize the ACH. New tests and characterization studies should focus on new helmet designs.

When DoD adopts new helmets with changes to the design (such as lighter weight and added mobility), it will be necessary to reevaluate the test protocols. For example, it may not be possible for manufacturers to produce lighter helmets at current levels of penetration.

Recommendation 9-1. When combat helmets with new designs are introduced, the Department of Defense should conduct appropriate characterization studies and cost-benefit analyses to evaluate the design changes before making decisions. It is not advisable to automatically apply the same standard (such as the 90/90 rule or others) when these tests could potentially be across different protective equipment (body armor, helmets, etc.), different numbers of tests (e.g., 96 tests for the enhanced combat helmet, 240 tests for the advanced combat helmet), or over time.

9.4 V_{50} TESTING

Description

V_{50} refers to the "the velocity at which complete penetration and incomplete penetration are equally likely to occur" (DoD, 1997, p. 3). That is, V_{50} is the median of the velocity-penetration distribution or curve. (This is analogous to dose-response studies that arise in pharmaceutical studies.) This theoretical quantity is currently estimated from a series of ballistic tests using the methodology of Military Standard (MIL-STD) 662F (DoD, 1997).

V_{50} testing is an important component of the overall DOT&E protocol. The estimated value of V_{50} is used informally to track and compare helmet performance. The nature of the test suite and the subsequent data analysis are quite different from the RTP and BFD protocols. For these reasons, the committee considers V_{50} testing to be a part of characterization.

Table 4-1 (in Chapter 4) shows the test matrix and requirements for V_{50} testing under DOT&E's FAT protocol. It is performed for 2-, 4-, 16-, 17-, and 64-grain threats as well as a small arms threat (if required). The Army's lightweight ACH Purchase Description (which also specifies MIL-STD-622) further requires that helmets achieve a minimum V_{50} for each of the fragmentation threats (U.S. Army, 2012).

[6]Chris Moosmann, Live Fire Test & Evaluation, DOT&E, "DOT&E Issues Update," presentation to the committee on March 21, 2013.

The V_{50} testing procedure under MIL-STD 662F is as follows:

- A first round is shot with a striking velocity that is approximately 75 to l00 feet per second (ft/s) above the minimum V_{50} required per specification. (Previous V_{50} testing on comparable helmets could also provide a good starting velocity.)
- If the first round results in a complete penetration, the velocity of the second round is decreased by 50 to 100 ft/s from the velocity of the first round. If it results in no or partial penetration, the velocity is increased by 50 to 100 ft/s.
- In subsequent shots, the velocity is increased or decreased, as applicable, until one partial and one complete penetration is obtained.
- After obtaining at least one partial and one complete penetration, the velocity is increased or decreased in increments of 50 ft/s. Firing is continued until sufficient partial and complete penetrations are obtained to estimate V_{50} by taking the average of the velocities corresponding to an equal number of the highest partial and the lowest complete penetration, as specified in the contract (DoD, 1997, p. 10).[7] Typically 8-14 shots are used.

The committee notes that the protocol allows multiple shots per helmet, but it does not explicitly specify a maximum number of shots or shots per helmet: "If a valid V_{50} cannot be obtained with a single finished shell, the V_{50} will continue on an additional finished shell(s)" (IOP PED 003, Paragraph 5.2.1.1).

Finding 9-1. The current V_{50} testing protocol does not clearly specify the maximum number of shots per helmet.

During the committee's discussions with representatives of PEO Soldier[8] (Lozano, 2013) and DOT&E, the following reasons were given for collecting V_{50}-related data:

- It is a commonly understood metric that characterizes the performance of the helmet, both in the United States and in member countries of the North Atlantic Treaty Organization.
- It is easier to estimate than potentially more relevant velocity quantities such as V_0 or V_{10}.

[7]This estimation methodology is similar to the NATO Standardization Agreement (STANAG) 2920, Ballistic Test Method for Personal Armour Materials and Combat Clothing, promulgated 31 July 2003. STANAG 2920 requires an even number of at least six shots, half of which perforate and half of which do not, and all of which are have velocities of within 40 meters per second. Then the V_{50} is estimated as the mean velocity of the shots meeting these conditions (NSA, 2003).

[8]Frank J. Lozano, Product Manager, Soldier Protective Equipment, "Setting the Specifications for Ballistic Helmets," presentation to the committee on April 25, 2013.

- It can be useful for comparing helmet performance between manufacturers and over time.
- PEO Soldier uses V_{50} time series data as a leading indicator of manufacturer process degradation.

V_{50} values are used informally. More structured analyses could be done to compare V_{50} estimates among manufacturers, over time, and among environments. Another potential characterization analysis would be to investigate the relationship between V_{50} and fragment grain size.

Additional V_{50} Testing and Characterization Analyses

The current goal of V_{50} testing is to estimate a single point (the median) on the velocity-penetration curve. In the committee's view, it would be beneficial to expand V_{50} testing so that the whole curve can be estimated with reasonable precision, without expending a lot more additional resources in terms of number of shots.

This expanded testing would involve taking multiple shots at different (selected) velocities and fitting a parametric curve to the velocity-penetration response data. Typical choices for the curve are logistic or normal distributions, leading to logit and probit curves, respectively. This approach allows for estimation of any quantile of the velocity-penetration distribution, not just the median. One can also compute the standard error associated with the estimated quantile. There is extensive literature on the design and analysis of such studies (Ruburg, 1995; Prentice, 1976).

The curves are typically described by two parameters for location and shape. The shape parameter provides an indication of the spread in the velocity-penetration distribution. It measures how consistent the penetration velocity is from helmet to helmet or among shot locations within a helmet. Changes in a production process, for example, could either increase or decrease the variability of penetration velocities. Certain environments might not affect V_{50} but could increase the standard deviation and, thereby, degrade a helmet's protective capability.

Recommendation 9-2. The Department of Defense should consider alternative approaches to its current methodology for estimating V_{50}. One alternative is to estimate the entire velocity-penetration distribution by varying the shot velocities over a prescribed range. Given the limited test resources (number of shots), the estimation methodology has to be based on fitting parametric curves. The approach also allows computation of standard errors associated with V_{50} and other quantiles of interest.

9.5 COMPARISON WITH INDUSTRIAL PRACTICES

So far, this chapter has focused on specific issues on characterization related to helmet testing. This section provides a more general discussion of industrial best practices.

Understanding the ability of a current product to conform to production requirements is a common aspect of industrial practice and product improvement and is often called *capability analysis* (Bothe, 1997; Pyzdek and Keller, 2003). It encompasses characterization of process stability as well as margin on performance relative to product requirements (Hoerl and Snee, 2012). It is applicable to understanding product conformance internal to a company and for external suppliers, customers, and users. Typically, formal product requirements such as acceptable failure rates and specification limits are based on understanding customer needs. In the helmet procurement process, this would likely be based on data collected during developmental testing. Developing a stronger connection to what is possible, given current helmet manufacturing capability, would allow the opportunity to leverage this into improved helmets for the soldier. Using legacy measures to define the standard a helmet is required to meet for FAT and LAT represents a lost opportunity and potentially an important sacrifice in helmet protection.

Recommendation 9-3. To be consistent with the goal of continuous improvement, developmental testing results from helmet design should be used to allow better calibration of current helmet capability and to help define more meaningful thresholds for helmet protection.

A key difference in DoD's approach used in the procurement process for helmets from the more common practice of industry is the focus on performance specifications instead of design specifications. In much of industry, and indeed for some military procurement processes involving complex products and systems, when a product is being developed, design specifications for material, structure, and assembly are the basis for assessing its adequacy. In other words, the manufacturing process is closely monitored and checked to make sure that the product matches the details for what is required. This provides a direct and easily measurable means of checking new products as they are completed.

On the other hand, the current DoD helmet procurement process allows manufacturers to build the helmet with any design specifications, and the sole test of the adequacy of the helmet is through performance tests during FAT and LAT testing. An advantage of this approach is that it allows the manufacturers the flexibility to change the process and update their production methods as technology evolves. However, it has the disadvantage of placing all of the burden for evaluation at the end of the production process through rigorous and expensive testing.

A potentially beneficial alternative—one that would encourage improved process monitoring while still allowing manufacturers flexibility to improve their product as new technologies are developed—would be to combine the design and performance specification approaches. Manufacturers could develop their own design specifications, which would then be tracked with reports given to the DOT&E.

This information would then be used to complement the performance-based testing currently used, particularly at the LAT testing stage. This additional information would allow DOT&E to have better understanding of the stability of the process, while having the reassurances of the performance-based testing.

Once the design specification requirements have been determined by the manufacturer, then the capability of the currently available product can be quantified using one of the common process capability metrics (Montgomery, 2012). In the absence of formally specified requirements, matching or surpassing current production capability is a common alternative for capability analysis methods. Characterizing product performance is an established practice in industry and is used to quantify current performance as well as establish a baseline from which target future improvements can be assessed.

The standard approach to monitoring stability of production is through control charts based on manufacturing characteristics (Hoerl and Snee, 2012), that allow for continuous supervision and monitoring of standards as products are being produced. Supervision and monitoring involve active management and watching real-time results to see if there is a problem. Current FAT and LAT testing is based on a paradigm of inspection, in which during post-production the products are evaluated to assess conformance. Standard practice in industry has evolved away from primarily using inspection to a model in which monitoring is a key aspect of ensuring ongoing product quality. Monitoring has the advantages of ensuring that a production process operates at its full potential, reducing waste, and detecting changes in performance quickly.

Recommendation 9-4. Manufacturers should be required to provide some documentation of ongoing process monitoring of the helmet production as a beneficial enhancement to the lot acceptance testing protocol.

9.6 CONCLUDING REMARKS

It is for DoD to choose the appropriate characterization tests and analyses that should be done, based on its assessment of the benefits, in terms of improving the understanding of helmet protective properties and improving those capabilities, relative to the costs and resources they require. A number of the proposed characterization studies can be done using data that are collected as part of the FAT and LAT test process. Others will require different types of testing and the investment of additional resources.

Recommendation 9-5. For new generations of helmets, the scope of characterization studies should be broader than what is currently being done. They should include many of the activities described in Section 9.3.

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10

Linking Helmet Protection to Brain Injury

10.0 SUMMARY

The relationships between helmet deformation and brain injury are not well known. Most of the studies in biomechanical engineering and medicine are related to sports and vehicle collisions, and these investigations are based on a different range of stresses and stress rates from those encountered in the battlefield. The aim of this chapter is to present information on what is known, and the gaps, about the linkage between brain injury and current battlefield threats. The major finding is that helmet protection from penetration and backface deformation (BFD) greater than a particular value does not protect the brain from occurrence of many categories of tissue injury. Recommendations that can help focus research range from determination of the prevalence of reversible declines in hormonal function years after brain trauma to acceleration of research in computational modeling and simulation that can show shear stress fields associated with the known spectrum of threats and the protective capabilities of helmets.

10.1 INTRODUCTION

The transmission of stress to the brain from any substantial impact on the head can lead to traumatic brain injury (TBI). Acute brain injury, even mild injuries, may severely influence or restrict military operational capabilities, and long-term consequences will have an impact on individual quality of life.

The effects on brain function depend on the magnitude and direction of the force impacting the head. Therefore, it is important to understand linkages between blunt trauma and brain injury and how the helmet attenuates the effect of the impact (see Figure 10-1). For example, it is known that for lower severity ballistic or blunt inputs, the transfer of momentum and rate of change of momentum (force) from an impact can be sufficiently attenuated by the helmet to prevent brain tissue injuries. Thus, an understanding of brain tissue injury and brain physiological tolerance must be linked to the magnitude of the transfer of force or other mechanical parameters—from the impact to the helmet onto the head and into the brain.

For helmeted service personnel, nonpenetrating injuries may be caused by local contact of the deforming undefeated helmet onto the head/underlying skull or from more regional helmet/head contact with forces transmitted through the helmet webbing or padding to the skull (Bass et al., 2003). These forces may result in direct, local deformation of the skull and translation and/or rotation of the head, leading to brain injuries. Some mechanisms of brain injury, such as abrupt acceleration changes of the body due to an improvised explosive device (IED) blast or a paratrooper hard landing, are not necessarily attenuated by helmets, but the injury mechanisms are likely similar to injuries from blunt head trauma. Blast pressure stress from IEDs and artillery can directly or indirectly transmit pressure fields to the head that result in shear stresses in the brain (Panzer et al., 2012; Shridharani et al., 2012a).

The subject of this chapter is the right side of Figure 10-1. The committee presents what is known (and the gaps) about brain injury tolerances relative to current standards of helmet protection. This is an essential component in determining how much the helmet must attenuate the impact force to prevent brain trauma. Box 10-1 provides a glossary of terms used in this chapter.

10.2 BRAIN INJURIES

Types of Nonpenetrating Brain Injuries

Blunt trauma can lead to various types of brain injuries, ranging from concussion, hemorrhaging, hematoma (blood clots), skull fracture, anoxic injury (lack of oxygen), and diffuse axonal injury or DAI (damage to the brain neurons). Table 10-1 provides a listing of 13 major categories of brain injuries and potential causes.

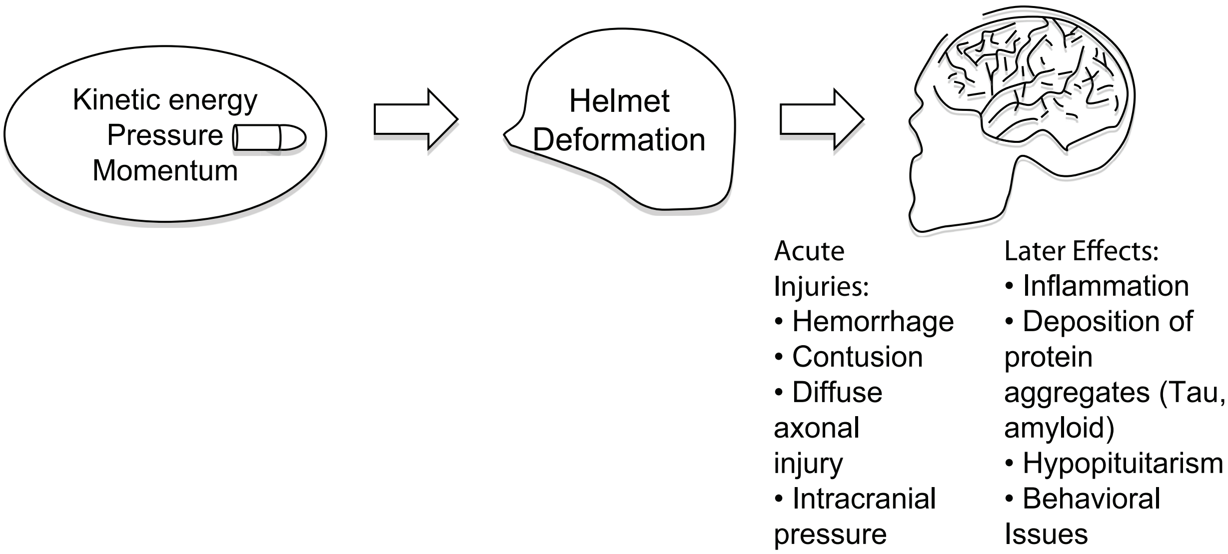

FIGURE 10-1 Linkages between the force of the impact, how the helmet attenuates it, and resulting brain injuries.

Many of these injuries are caused by differential motions/strains within the soft tissues of the brain. The motion of the surface of the brain against the bony structures of the head leads to tissue contusions, vascular tears, and hemorrhages. These initiating injuries may degrade brain function through various mechanisms such as the restriction of blood supply or damage to cells. It is thought that compression (hydrostatic) alone is not an initiating cause of tissue injury unless it results in shear stress. (See Panzer et al., 2012, for results with high rate blast impacts.)

TABLE 10-1 Categories of Brain Injuries

	Categories
1	Direct contusion of the brain from skull deformation or fracture
2	Brain contusion (including coup) from movement against interior surfaces of the skull
3	Indirect (countercoup) contusion from mechanical response of the brain opposite the side of the impact
4	Reduced blood flow due to infarction or pressure-based occlusion
5	Disruptive and non-disruptive diffuse axonal injury from shear stresses
6	Tissue stresses and strains produced by motion of the brain hemispheres relative to the skull
7	Subdural and epidural hematomas produced by rupture of bridging vessels between the brain and the dura mater
8	Pressure-based rupture of small blood vessels leading to petechial hemorrhages
9	Strains beyond material tolerances of nerves and blood vessels
10	Vasospasm resulting in diminished blood flow
11	Trauma induced hypopituitarism
12	Perturbations in brain biochemistry functioning with pathologic signs and symptoms long after the injury
13	Temporary or permanent changes in visual, verbal, and motor functioning

Quasistatic compression as high as 50 MPa (7300 psi) or more does not result in injury to mammalian cells (Grundfest, 1936). Nerves and blood vessels are susceptible to stresses with strain tolerances usually less than 10 to 20 percent for functional failure of neural tissues such as neurons/axons/glia and probably less for some arterial networks (Margulies and Thibault, 1992; Smith et al., 1999).

The susceptibility of the brain to shearing forces, and its very high incompressibility, may lead to contusions or hemorrhaging at the surface of the brain. Rotational acceleration and change in acceleration cause blood vessel ruptures leading to bleeding between the brain covering (dura mater) and the skull with the result of increased intracranial pressure. Bleeding may also arise in the space between the dura mater and the brain (subdural hemorrhage). Injuries associated with the rapid acceleration and deceleration of the head result in forces that produce stretching and tearing of axons (causing DAI). Such strains and potentially large pressure or stress waves in small blood vessels can lead to small hemorrhages (petechial hemorrhages) deep within the brain. Even when not life threatening, such injuries have the potential for delayed injury, including local brain swelling, as well as long-term consequences with symptoms persisting many years after the initial brain injury.

Important and frequently undiagnosed effects include alterations in microcirculation that can lead to hypoperfusion or regional vasospasm with the result of inadequate delivery of vital metabolites to neural tissue. These mechanisms are believed to contribute to the short-term as well as long-term effects from ballistic helmet hits, head collisions, and exposures to high-intensity blasts. Other long-term effects from brain trauma may include declines in hormonal function related to disruption of the pituitary gland (e.g., growth hor-

BOX 10-1
Glossary

Blast	Detonation of liquid or solid explosive material results in the generation of gaseous products in the pressure range of 150,000 atmospheres or 1.5 billion Pascals (1.5 GPa) and temperature of 3000 Kelvin.
DTI	Diffusion tensor imaging—a MRI method that maps the magnitude of water diffusion in different directions. The method gives a value of diffusion anisotropy (DA), which will decline if the normal orientation of fiber in white matter is disrupted by edema or tears, for example.
Epidural hematoma	Collection of blood from rupture of vessels between the brain dura mater and the skull.
FEM	Finite element modeling—a computational system that provides the means to simulate the effects of forces on structures such as the skull and brain tissues.
fMRI	functional magnetic resonance imaging—fMRI is similar to MRI, but the image gives information regarding blood flow changes in the brain after some stimulation.
G or ***g***	Symbol for the acceleration of gravity magnitude of 9.8 m s^{-2}.
Hypopituitarism	Dysfunction of the pituitary organ manifested by low secretion of hormones such as ACTH, growth hormone, thyroid stimulating hormone, oxytocin, vasopressin, etc.
J	Joule is energy or force times the distance over which force acts. It is the unit for kinetic energy defined as mass times velocity squared/2.
kPa	(kiloPascal) is a unit of pressure equal to a 1000 Pascals (10 kPa is 1 atmosphere of pressure).
Momentum	Defined as the product of mass and velocity. The rate of change of momentum is force.
MRI	Magnetic resonance imaging
N	Newton is the unit of force or the product of mass times acceleration.
NHTSA	National Highway Traffic Safety Administration.
National Institute of Justice Standard	This standard, designated “0101.04” stipulates the maximum deformation a soft armor vest can undergo without penetration is 44-mm as measured in a clay substrate after a live fire test of the armor.
PET	Positron emission tomography—an imaging method that uses radioactive tracers that specifically target proteins and other functions of the body. It differs from SPECT in the types of tracers used and the characteristics of the instrumentation.
Pituitary organ	A 7-mm diameter organ suspended on a stalk from the base of the brain into a well at the floor of the skull. It secretes 9 hormones into the bloodstream in response to stimuli from the hypothalamus also at the base of the brain. These hormones include growth hormone and thyroid stimulating hormone.
Shear modulus	The ratio of the tangential force per unit area to the angular deformation in radians.
Strain	The fractional change in a physical dimension of matter in response to stress. It is frequently given as a percentage (e.g., 5 percent) and can be over 100 percent.
Stress	The force per area or volume with dimensions of newtons per meter squared or Pascal.
Stress waves	Compression waves in a material due to an impulse or sudden load change.

mone and thyroid function deterioration) and the occurrence of abnormal proteins in the brain years after trauma.

Some data on injury thresholds exist for low-rate skull fracture, concussion, and diffuse axonal injury. But these have been derived from animal and human studies using experiences from vehicle collisions and laboratory experiments with stresses and rate of change of stress (i.e., strain rate) much lower than those associated with projectile and blast threats in the battlefield. Thus, a translation of these low-stress-rate data from animals, physical models, and mathematical simulations to the ballistic blunt trauma case is not expected to be reliable. As a consequence, design of protection from typical military threats is compromised because we do not know the injury thresholds.

A study by the Institute of Medicine found evidence for association between TBI and various disorders that included adverse social-functions, endocrine dysfunction, depression, aggressive behavior, and dementias for moderate or severe TBI (Ishibe et al., 2009). Further, concussion is no longer accepted as a threshold for diagnosis of potential brain trauma. Modern diagnostic methods reviewed in Appendix F show signatures of mild TBI (mTBI) unrelated to presence of concussion.

Once the acute medical events are treated, current clinical practice is not capable of effectively enhancing natural recovery or diminishing long-term effects after the blunt trauma (Giza et al., 2013). Thus, the best approach is protection from blunt brain trauma. This chapter presents relevant physiological and biomechanical aspects of blunt trauma, the state of knowledge regarding injury tolerances, and perspectives on detection of mTBI through noninvasive imaging. Current noninvasive methods of brain injury detection are in Appendix F. Aspects of helmet design and the threat characteristics are given in Chapters 2 and 3.

Historical Data

TBI can result from a number of events: falls, motor vehicle accidents, bicycle accidents, collisions, blast exposure, and blunt head trauma in the battlefield. More than 5 million Americans alive today have had a TBI, and the associated medical care cost is around $56 billion per year in the United States. Cognitive, communicative disabilities and social behavior abnormalities as well as medical complications, such as hormonal deficiencies that affect functioning of the brain, thyroid, and gonads, are prevalent in survivors of TBI.

Figure 10-2 shows the annual incidence of TBIs in warfighters during the period 2000-2011.[1] It is likely that the increasing numbers of mild and moderate TBI relative to severe TBI may be partly attributable to greater awareness of TBI risk among military clinicians (Okie, 2005; Warden,

[1]Armed Forces Surveillance Program information available at http://semanticommunity.info/Binary_at_LandWarNet_2011/Defense_and_Veterans_Brain_Injury_Center_Site_Map/DoD_Worldwide_Numbers_for_Traumatic_Brain_Injury. Last accessed on January 31, 2014.

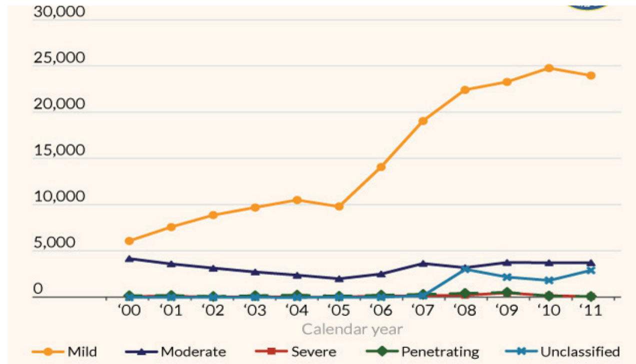

FIGURE 10-2 Incidence of traumatic brain injury classified by severity for warfighters. SOURCE: DoD Worldwide Numbers for Traumatic Brain Injury, http://semanticommunity.info/Binary_at_LandWarNet_2011/Defense_and_Veterans_Brain_Injury_Center_Site_Map/DoD_Worldwide_Numbers_for_Traumatic_Brain_Injury.

2006). During this period, 220,430 service members had sustained TBI, with 169,209 classified as concussion/mTBI (Kelly et al., 2012). In a study of 3,973 soldiers who served in Iraq, 23 percent percent had a clinician-confirmed history of TBI (Terrio et al., 2009). In a separate study, mTBI in soldiers deployed in Iraq was found to be strongly associated with posttraumatic stress disorder and depression (Hoge et al., 2008). The deployment of magnetic resonance imaging methods to the evaluation of brain injury related to blast exposure of warfighters (Mac Donald et al., 2011; Yeh et al., 2013) can potentially provide a refinement in diagnoses of brain injury in warfighters exposed to non-concussive blast and blunt trauma events. However, in one study white matter injuries were not revealed by magnetic resonance diffusion tensor imaging (DTI) on veterans with mTBI, despite their symptoms of compromised verbal memory (Levin et al., 2010).

10.3 HEAD AND BRAIN INJURY TOLERANCES

Brain response and brain injury tolerances are not well established for high-rate impacts such as those from BFD or blasts (Bass et al., 2003, 2012; Rafaels et al., 2012).

Head Injury Tolerance Standards for Vehicle Collisions

Early work on low-rate blunt trauma brain injury tolerance (Gurdjian et al., 1966; Ommaya and Hirsch, 1971; Ono et al., 1980) emphasized that acceleration of the head and the time duration of the acceleration are important parameters for assessing injury severity (Prasad and Mertz, 1985). Such criteria are in wide use in the automobile impact community (FMVSS-208, EuroNCAP), but the injury risk functions using these parameters have not been universally accepted. The most widely used criterion is known as the Head Injury

Criterion (HIC) severity index. Although it is widely used, it is recognized as inadequate to fully explain brain injury outcome (Versace, 1971). For military helmets, HIC and similar concepts incorporating global skull rotational parameters (e.g., Newman et al., 2000) assume rigid body motion of the head/brain system and do not incorporate local deformations that may be crucial for assessing the injury potential from ballistic impacts (Bass et al., 2003).

Some measures based on internal stresses and/or strains have been proposed as the injury criteria for the brain (e.g., Stalnaker et al., 1971; Takhounts et al., 2003). However, there is still no universally acknowledged criterion, and the situation today is much the same as that articulated by Goldsmith (1981):

> Thus, the state of knowledge concerning trauma of the human head is so scant that the community cannot agree on new and improved injury criteria even though it is generally admitted that present designations are not satisfactory. Minimally, there is an urgent need to differentiate skull fracture and mechanical and/or physiological damage to the central nervous system, with a replacement of a critical acceleration level for the former by a limiting stress value.

In the past 30 years, experimental data and models have been accumulating from animal, cadaver, physical models, and computational modeling and simulation studies (discussed later in this chapter). With further research, these data and models can lead to injury risk evaluations such as those done for the risk of a skull fracture for 9-mm bullet impacts to the helmet as detailed below. A goal is to determine the injury risk function for the major brain tissue injuries of Table 10-1 relevant to militarily relevant injuries such as those associated with BFD and blunt and blast neurotrauma.

Recommendation 10-1. There is an urgent need to establish stress and stress rate or other parameters as metrics for categories of brain tissue injuries from ballistic and blast-based head exposures.

Nonmilitary Helmet Protection Standards

There have been major advances in blunt head protection over the past 30 years. Some of these advances are be due to widespread use of helmets in athletics and the subsequent reduction in both frequency and severity of head and neck injuries. Many improvements in helmet technology have followed from the development of standardized test methodologies based on mechanical blunt impact injury criteria. The Advisory Group for Aerospace Research and Development (AGARD) Report AR-330 lists 29 blunt impact test standards (AGARD, 1996), and each of these standards has some form of translational impact acceleration limiting criterion. Of these standards, 19 are based on acceleration or force peaks alone, and 10 are based on acceleration/duration levels. The levels specified in these standards range from 150 to 400 *g*, with more recent standards tending to the 150 *g* peak limit.

Studies of football impacts suggest that an acceleration standard of approximately 80 *g* should be used to provide protection below the threshold for changes in mentation (Duma, et al., 2005). Other relevant results include: the Advanced Combat Helmet standard (CO/PD-05-04), which is based on the motorcycle helmet Federal Motor Vehicle Safety Standard-218 (49 CFR Sec. 571.218); and the National Operating Committee on Standards for Athletic Equipment and standards incorporating the International Standards Organization headforms. Virginia Polytechnic Institute's star rating system for helmets[2] involves extensive impact tests and risk analysis to establish a rating for commercial football helmets.

These criteria are based, in part, on underlying assumptions that are not realistic, especially for military use with ballistic protective helmets. The first is that the head acts as a rigid body so that acceleration or some derivative may be correlated with injury and that head injury of any type is associated with skull fracture (Hodgson and Thomas, 1973). Previous studies show a poor correlation between skull fracture and brain injury (Viano, 1988). For ballistic BFD injuries, local deformations invalidate the rigid body assumption, and injuries seen from BFD are not well correlated with acceleration-based measures.

10.4 BRAIN TISSUE INJURY: EXPERIMENTAL RESULTS

Over the past 70 years, researchers have attempted to understand the relationships between head, skull, and brain injury mechanisms and blunt trauma using cadavers, physical models, animals, and computer simulations. This has been stimulated largely by the automobile industry in an effort to improve vehicle occupant safety. More recently, sports injuries have triggered international efforts to improve helmet protection and to make measurements on human subjects involved in collision sports. Currently, there is no satisfactory experimental model that can produce the complete spectrum of brain injuries that are seen clinically while also being sufficiently well controlled and quantifiable for defining brain injury tolerances. Some data do exist for the stress associated with skull fracture, but this is only part of the spectrum of short- and long-term consequences of ballistic impacts to the helmeted soldier, and the low-rate tests generally available may not be applicable to ballistic impacts.

Early Investigations of Mechanisms

In the early 1940s, investigators proposed that brain injury from skull fractures was from intracranial pressure. However, physical studies using photoelastic models of the head dem-

[2] Additional information is available at http://www.sbes.vt.edu/nid.php.

onstrated that the likely cause of diffuse brain injury is from tissue strains induced by rotational acceleration of the head (Holbourn, 1943). This was confirmed by Gurdjian et al. (1955). The investigation of the relative roles of translational and rotational accelerations using more elaborate experimental models of the subhuman primate led to the conclusion that diffuse injuries to the brain occurred only in the presence of head rotational motion (Gennarelli et al., 1972; Gennarelli and Thibault, 1989; Ommaya and Gennarelli, 1974). Diffuse brain injuries occurred at lower angular deceleration levels as the pulse duration increased (Gennarelli and Thibault, 1989).

In coronal plane rotational acceleration, the critical shear strain associated with the onset of diffuse axonal injury was about 10 percent, and the rotational acceleration threshold for severe diffuse axonal injury was about 16,000 rad/sec^2 (Margulies et al., 1990). Inertial loading alone to the head can cause DAI, which is an important cause of fatality or late onset of disabilities due to head injury (Gennarelli et al., 1972).

Modern Experimental Investigations of Injury Criteria

To simulate the impact response of the human, the automotive industry developed the Hybrid III 50th Percentile Male anthropometric test device (ATD) in the early 1970s. Originally developed by General Motors, the ATD is now regulated by the National Highway Traffic Safety Administration (NHTSA) in conjunction with the committees from the Society of Automotive Engineers. It has become a validated tool for the evaluation of automotive impacts and can accommodate a wide range of instrumentation and transducers. It is also robust enough for repeated ballistic experiments (Bass et al., 2003).

A collaborative effort between Natick laboratories, DRDC-Valcartier, and the University of Virginia (UVA) led to the development of a ballistic version of the Hybrid III head augmented with impact pressure sensors (Bass et al., 2003). The UVA headform is shown in Figure 10-3a. Instrumentation for the Hybrid III head and neck region consisted of three linear accelerometers and angular rate sensors at the center of the ATD headform and six-axis upper and lower neck load cells. Using the Hybrid III headform modified to accept surface pressure sensors, the pressure measurements at various locations were recorded, analyzed, and compared to human cadaver results (e.g., Bass et al., 2003). Injury metrics assessed using this headform include force/pressure, the HIC injury criterion, and the National Institute of Justice Neck Injury Criteria. The force/pressure results correlated well with injury in the paired cadaver model, while HIC was poorly correlated with injury. This concept has been recently modified in a rigid headform with regional loadcell sensing under the ballistic impact by Biokinetics (Figure 10-3b).

a.

b.

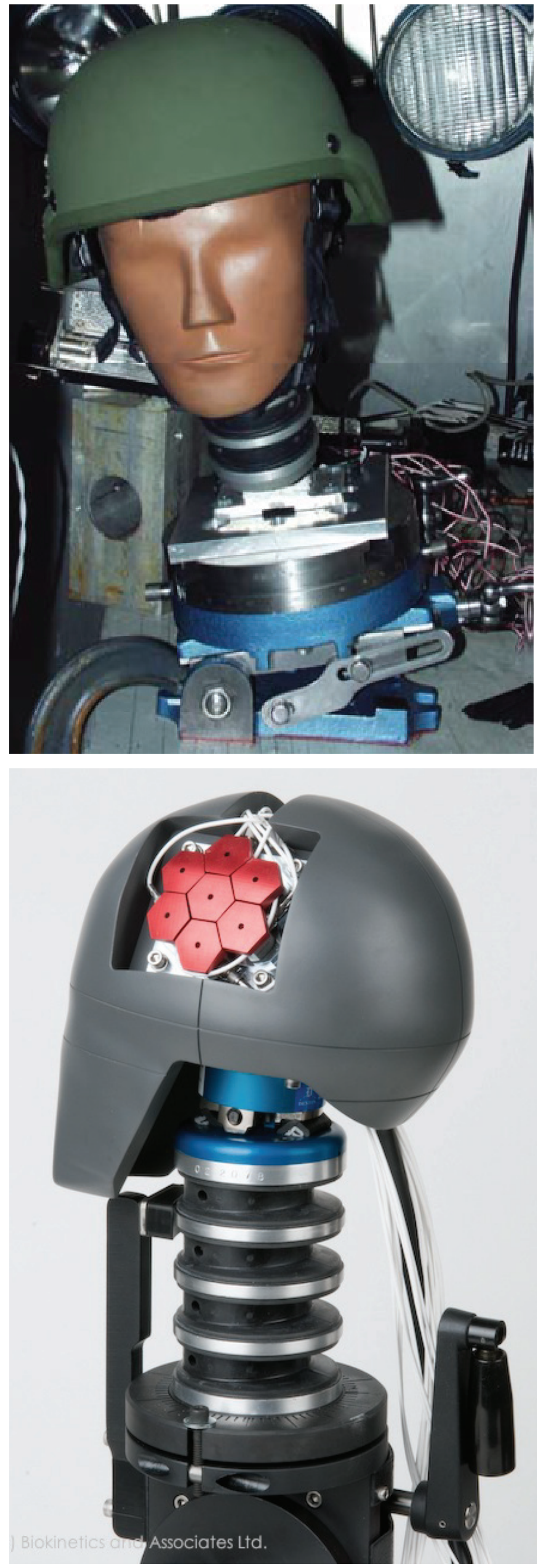

FIGURE 10-3 (a) The University of Virginia's Hybrid III head model used for laboratory simulations and measurements. (b) Biokinetics headform variant of the Hybrid III headform for ballistic impact. SOURCE: Courtesy of Biokinetics and Associates, Ltd.

Brain Injury/Concussion Risk/Thresholds

Concussion is a symptom of the state of awareness or consciousness and is not a category of pathological brain tissue injury. The linkage between a diagnosis of concussion and a specific brain injury has been the subject of controversy among neurologists and neurosurgeons since the mid-1920s (Saucier, 1955). For example, one cannot say to what extent structural damage, such as vascular ruptures or neuronal strains, cause loss of consciousness. What have been defined experimentally are the relations between stress and animal consciousness over a limited range of stress rates that have not included the rates associated with a high-velocity, ballistic, nonpenetrating hit to a helmet. The threshold for concussion increases as the duration of impact decreases (Guardjian et al., 1955). See Table 10-2 for the median concussion levels trauma given in dimensions of energy, power, and pressure.

The criteria for concussion in the animal laboratory studies reflected in most of the studies of Table 10-2 are much different from concussions diagnosed in sports, vehicle collisions, falls, and battlefield events. The majority of concussions do not result in a loss of consciousness. In particular, for sports injuries, a concussion is diagnosed if the athlete is confused, complains of dizziness, headaches, blurred vision, or sensitivity to light, sound, or odors or by the physical signs of motor coordination dysfunction (cf. Appendix F). Ninety-five percent of high school football concussions did not involve loss of consciousness (Meehan et al., 2010). In the battlefield, a diagnosis of mTBI or equivalently "concussion" involves a protocol called Military Acute Concussion Evaluation (MACE). This examination is given as soon as possible after a warfighter has been exposed to blast, projectile blunt trauma, or vehicle collision. It measures orientation, recent memory, concentration, and memory recall.

TABLE 10-2 Brain Injury Criteria and Median Values for Concussion for Low-Rate Blunt Impact

Brain Injury Criteria	Median Values for Concussion	Source
Energy	22-24 J	Denny-Brown and Russell (1941)
Power	13 kW	Newman et al. (2000)
Strain	0.2	Bain and Meaney (2000); Morrison et al. (2003)[a]
Strain x strain rate	30 s-1	Viano and Lövsund (1999)
Stress (von Mises)	6-11 kPa	Shreiber et al. (1997)
Cumulative strain damage measure	0.55	Takhounts et al. (2003)
Strain energy density	0.8-1.9 kJ/m^3	Shreiber et al. (1997)
Pressure	173 kPa	Ward et al. (1980)

[a] Strains less than 0.15 can cause diffuse axonal injury.

Modern Football Helmet Instrument Data versus Concussion Symptoms

In the early 1970s, head-bands of suspension-style football helmets were instrumented with an accelerometer and electroencephalogram system (Moon et al., 1971; Reid et al., 1974) that allowed records from a single player at a time. Around 2000, hockey and football helmets were instrumented with three-dimensional accelerometers, and these measurements gave an average of 29 g from 158 impacts from high school athletes with no observed symptoms of TBI. Addition of video analysis and dummy reenactments allowed laboratory simulations and measurements of head acceleration, although there are substantial limitations in inferring accelerations directly from video (Newman et al., 2005; Pellman et al., 2003). Velocities and changes in velocities were interpreted from video recordings, and threshold values for concussion were given based on analyses simulating the video impacts with the Hybrid III dummy headform. These studies did not clear up potential distinction between injuries from rotational and translational accelerations (Genarelli and Thibault, 1989; King et al., 2003). But it is important to note that: (1) purely translational or rotational accelerations of the head are not likely for a head tethered to the inertial mass of the body (King et al., 2003); and (2) even purely translational acceleration of the head produces rotational behavior in the brain tissue, and purely rotational excitation of the brain produces local translational behavior in the brain tissue. Thus, the debate regarding the severity of rotational acceleration versus translational acceleration brain trauma is largely artificial and is based on a rigid body view of the head.

Actual measurements of direction and magnitude of head accelerations football players receive became available when sensors and telemetry units were provided to multiple players using an in-helmet 6-accelerometer system that transmits data via radio frequency to a sideline receiver and laptop computer system (Duma et al., 2005). Using this commercial system, a risk of sustaining a concussion for a given impact was derived from data collected from 63,011 impacts including 244 concussions (Rowson and Duma, 2013). Both linear and rotational accelerations as well as the combination of linear and rotational accelerations were used in the derivation of a concussion risk function. The predictive capability of linear acceleration was about the same as that for the combined probability.

A study of the linkage of impact severity was done on high school football players using cognitive tests and magnetic resonance imaging (MRI) before and after two seasons of football while wearing accelerometer instrumented helmets (Breedlove et al., 2012). A relationship was found between the number of impacts and cognitive tests and the number of hits and functional MRI changes (see also Talavage et al., 2013). It is expected that an expansion of these types of study will improve the development of head injury criteria and clinical evaluation techniques as well as enhance return-to-play decision making.

Military helmet sensor instrumentation programs in the United States were initiated in 2008 in order to collect battlefield data that could then be used by medical epidemiologists as well as design and manufacturing communities to improve design. These data should help significantly in the quest to understand the linkages between stresses on the helmet and brain injuries.

Skull Fracture

Modern ballistic protective helmet materials (McManus et al., 1976; Carey et al., 2000) can deform sufficiently so that the backface of the helmet contacts the head, potentially causing head injuries (Bass et al., 2002). Potential injuries include both depressed and long-linear skull fractures and closed-head brain injuries. Substantial work has been done on skull fracture injury, especially at low rates, but most of it is not directly applicable to military helmet injury criteria.

Skull fracture is a measure of head injury that can be related to the forces applied and thus can provide one of the needed links between level of protection and threats. But most of the existing measurements are restricted to low velocities and large impact areas (Yoganandan et al., 1995; Bass and Yoganandan, 2013) and have limited relevance to the goal of linking battlefield threats to required protection for head and brain injury protection.

Whatever is known is based on cadaver measurements of skull fracture and recordings from internally placed pressure sensors and accelerometers. The mechanical properties of stiffness, force deflection, and energies to fracture were measured on 12 unembalmed cadaver skulls (Yoganandan et al., 1995) at low rates typical of blunt trauma from conventional falls and vehicle crashes. Impact loading at 7 to 8 m/s revealed failure loads of 6.4 kN (±1.1) and energies averaging 33.5 J (±8.5). Quasistatic loading at 2.5mm/s showed failure at 12 mm (±1.6). Variability was great in all parameters with, for example, a range of stiffness of 467 to 5,867 N/mm. Delye et al. (2007) found skull fracture energy level in the range of 22 to 24 J for dynamic loading of the cadaver head having one degree of freedom. A human cadaver study of fracture thresholds for 37-mm diameter projectiles of 25 to 35 *g* gave force values of 6 kN for the forehead, 1.9 kN for the mandible, and 1.6 kN for the zygoma (Viano et al., 2004). Impact stress values for the adult skull are given as 43 MPa (Ommaya et al., 2002) and are age and size related.

Two series of ballistic impact tests used human cadaver heads with protective helmets (Bass et al., 2003). These tests used UHMWPE helmets with 9-mm full-metal-jacket 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 correlation with existing blunt trauma injury models based on the Wayne State Concussive Tolerance Curve or similar concepts, including HIC. For the skull

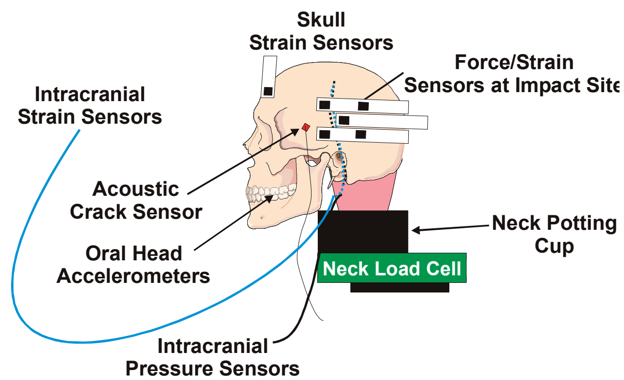

FIGURE 10-4 Instrumented cadaver head. SOURCE: NRC (2012).

fracture tests, the calculated injury assessment value was well below the usual low-rate blunt trauma injury reference value. Further, there was no obvious association of acceleration-based responses to the occurrence of BFD and fracture. This study developed injury criteria for both test round velocity and cadaver peak-impact pressure. For this injury risk function, there is a 50 percent risk of skull fracture for a peak impact pressure of 51 MPa as measured by the force/strain instrumentation (Figure 10-4). Using a simple velocity correlation between the dummy and cadaver, a dummy injury risk function is developed that has a 50 percent risk of skull fracture for dummy peak impact pressure of 15,220 kPa. This injury risk function may be used with a general helmet and the Hybrid III dummy discussed earlier in this section.

Automobile injury criteria, including the HIC, were not found to be a good predictor of cadaveric injury. Skull fracture from ballistic BFD is an intrinsically high rate event. Energy is deposited locally, and local skull deformations are significant. Use of HIC requires essentially rigid body motion of the head at relatively low rate compared to ballistic events.

Finding 10-1. Most of the experimental work that links brain injury to blunt trauma is related to vehicle collisions and football collisions. The data from these studies are not directly relevant to BFD and blast TBI because the rate of momentum change is higher and contact times shorter for military TBI situations.

Brain Intracranial Pressure and Edema

Symptoms from intracranial pressure (ICP) increases can be acute and an immediate consequence of the stress wave from blunt trauma to the brain or transmitted pressures from trauma delivered to remote parts of the body. The experimental data that link ICP elevations to blunt trauma to the surface of a helmet or surrogate protective material come from a limited number of experiments that used live animal models, cadavers, and physical models (Engelborghs et al., 1998;

Shridharani et al., 2012b; Rafaels et al., 2012; Sarron et al., 2004). The models differ in characteristics, and the ballistic trauma mechanism varies from dropping masses from varying heights in order to vary the velocities of projectiles (e.g., 9-mm rounds from 300 to 800 m/s). These types of data can be used to extrapolate a threshold for ICP elevation versus armor characteristics and threat velocity. Although there are limitations in animal model biofidelity with human skulls, these types of experimental data are needed to better assess brain injury tolerances and risk levels for defined threats. Some models, although illustrative of the sequence of events after brain trauma (e.g., occurrence of edema, blood brain barrier changes, ion concentration variations), are difficult to interpret relative to the ballistic threats and even collision impacts as they use impactors systems of low velocity (3m/s) and poorly or undefined energy or force metrics (e.g., Cernak et al., 2004).

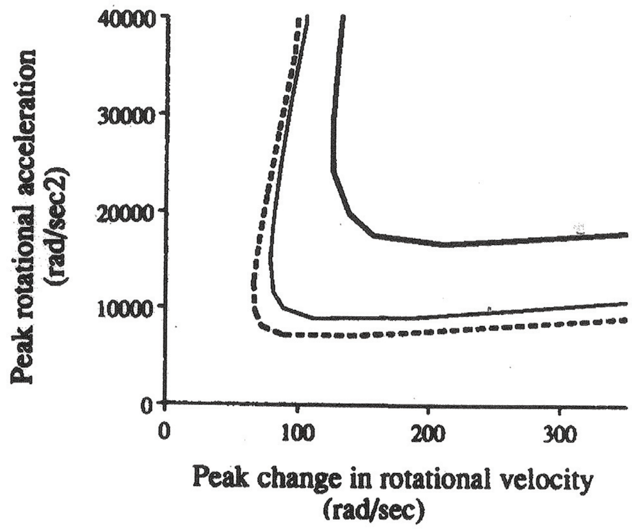

FIGURE 10-5 Thresholds for diffuse axonal injury based on non-human primate rotational acceleration experiments and scaling through computational modeling to human brain masses of 500 g (thick solid curve), 1,067 g (solid curve), and 1,400 g (dotted curve). Regions to the upper and right of each curve are regions of diffuse axonal injury. SOURCE: Reprinted from Margulies and Thibault (1992) with permission from Elsevier.

Brain Shear Stress and Diffuse Axonal Injury

Diffuse brain injury from low-rate traumatic impacts to the head results in both destructive and nondestructive axonal injury. Destructive axonal injury was first described for cases of collision-based injuries leading to limited periods of survival with autopsy findings of disrupted white matter tracks and normal grey matter (Strich, 1956, 1961). It is unknown whether such injuries can arise from ballistic BFD. Morphological studies of axonal injuries using non-human primates subjected to head acceleration have shown that shear forces create varying degrees of axonal damage, including fragmentation. Nondisruptive or reactive axonal injuries manifest over long time periods and are ascribed to axonal membrane damage. It is now recognized that animal models do not reflect the spatial and temporal patterns of axonal injury in human brains (Maxwell et al., 1997; Bain and Meaney, 2000).

Margulies and Thibault (1992) is one of the most detailed experimental and modeling studies relative to thresholds of brain injury, and it showed that a combination of a peak rotational acceleration of more than 10 krad/s^2 and a peak change in rotational velocity of more than 100 rad/s causes diffuse axonal injury. These criteria are proposed to be valid only for pure rotational accelerations, but the experimental model incorporates translational accelerations about the brain center of gravity and the effect of these accelerations is uncertain. Lower injurious risk levels for rotational acceleration were proposed by others (Ueno and Melvin, 1995; Meaney et al., 1995). Thresholds for human brain injuries from Margulies and Thibault (1992) are shown in Figure 10-5.

Animal studies, physical model experiments, and analytical model simulations have been employed to determine the critical tolerances in terms of strain (relative elongation) and deterioration in function (Gennarelli et al., 1972; Lewis et al., 1996; Bain et al., 2001). Based on animal studies, the strain tolerance for frank axonal injury that may lead to DAI occurs when neuronal axons are stretched by more than about 20 percent. The results from simulations presented in the discussion of modeling and simulations later in this chapter show maximum strain levels of 14 percent and lower (from 9-mm rounds) at 360 m/s striking helmets (Aare and Kleiven, 2007). However, it is not clear if these thresholds are safe for injury effects that might manifest years after the injury.

The threshold for nondisruptive axonal damage of 15 percent has been suggested by Maxwell and associates (Maxwell et al., 1997). But it is not clear that the 15 percent strain criterion should be an important benchmark, because tissue tolerance of the hippocampus and brainstem might be much lower, and the strain criteria are expected to be stress-rate dependent. Computational models and simulations can explore the structural strains of simulated brain tissues related to physical variables of a ballistic or blast impact (e.g., acceleration, stress rate, stress duration, etc.). But an important point is the understanding that nondestructive axonal damage can be the major cause of the high prevalence of posttraumatic stress syndrome months and years after brain trauma.

A summary of the current status of mechanisms, symptoms, and possible treatments of DAI is now available from the May 2011 workshop hosted by the National Institute of Neurological Disorders and Stroke (Smith et al., 2013).

Biological Response of Cells Exposed to Mechanical Forces

A key aspect of defining tissue tolerances is to describe the pathophysiological activation of cellular biochemical cascades that produce delayed cell damage and death. This can be accomplished by measurements of the consequences of mechanical injuries on living brain tissue through observations of cell viability and tissue biochemical changes using a tissue culture model of rapid stretch induced injury (Ahmed et al., 2000) or pulse pressure pulse exposure TBI (Morrison et al., 2003). Stretch-induced injuries associated with about 30 percent strains alter mitochondrial membrane potential and cellular bioenergetic molecules, as shown by chemical assay methods applied at various times after injury (Ahmed et al., 2000). Strains and strain rates can be precisely applied and responses measured by fluorescent imaging and immunostaining, including cell death quantification (Morrison et al., 2003). Cellular energy metabolism perturbations have been shown through standard molecular biology studies using in vitro and in vivo shock tube models of blast-induced TBI (Peethambaran et al., 2013). Blast exposures resulted in significant decreases in neuronal adenosine triphosphate levels at 6 h post-blast that returned towards normal levels by 24 h.

Finding 10-2. There are no data on axonal injuries from backface deformation. Also, currently there is no method to detect if diffuse axonal injury has occurred from head trauma in the battlefield.

Recommendation 10-2. Methods including blood sampling and brain imaging should be explored for feasibility of early detection of diffuse axonal injuries.

Evidence for Differential Motion of the Brain and Skull

A mechanism for many consequences of rapid accelerations and decelerations is the shearing caused by differential motion between the skull and local brain tissue. Typical injuries include contusions and meningeal hematomas seen in automobile accidents. The first definitive study of brain motion after a traumatic skull impact was done on live subhuman primates using a Lucite cover over the skull vertex. Blunt trauma was applied by a pneumatic impactor, and observations were made with cinephotography (Pudenz et al., 1946). These authors also provided a detailed review of theories and observations from the late 1800s regarding brain motion as well as contusion and hemorrhage mechanisms.

Although experimental studies demonstrate motion between brain and skull, little data exist regarding the base of the skull. Experiments on human subjects used MRI tagging techniques to show that the brain rotates relative to the skull (Kleiven and Hardy, 2002). Relative brain-skull displacements of 2 to 3 mm in some areas of the brain for induced linear and angular accelerations of 1.5 *g* and 120-140 rad s^{-2}, respectively. These accelerations are orders of magnitude less than those associated with concussions. Small displacements were found in regions having brain-skull connections. Strain fields seen in this study exhibited significant areas with maximal principal strains of 5 percent or greater at these low experimental accelerations. Simple head flexion causes cerebellum rotation of a few degrees and a downward motion of up to 1.6 mm of the brain stem (Ji et al., 2004).

Hemorrhage: Petechial Disruption, Subdural Hematoma, and Epidural Hemorrhage

There are three principal types of internal vascular disruptions from shear stresses and rotational accelerations that cause shear strain on small and large blood vessels and lymphatics: petechial, subdural, and epidural hemorrhages.

Petechial hemorrhages can occur throughout the brain and give evidence of shear strain as well as a pressure-based disruption of capillaries and arterioles. The pressure can be from a remote stress such as a blunt trauma to any part of the body and possibly from blast stresses of high intensities (NRC, 2012). These hemorrhages appear as blood extrusions of a millimeter or less in diameter in the midbrain, but they can be extensive throughout the brain. They are not recognized as a clinical entity unless they disrupt sensory or motor functions of the brain. But they can cause some compromise of brain function and perhaps play a role in progressive brain deterioration. They can be detected by high-field MRI if the proper MRI pulse sequence is used. Subdural hemorrhages leading to subdural hematomas occur in the space between the dura (the outer cover over the brain) and the arachnoid space.

Epidural hemorrhages are bleedings from ruptured vessels between the skull and the outer layer of dura. The build-up of blood causes an increase in pressure within the intracranial space, with subsequent compression of brain tissue and obstruction of the flow of blood and cerebral spinal fluid. This is associated with particularly serious brain injury because 15 to 31 percent of patients die of the injury (Leitgeb et al., 2013).

Pituitary/Hypothalamus Damage

The pituitary gland is a pea-sized gland suspended from a pedicle at the base of the brain. It is surrounded by a skull base bone structure whose saddle-shaped structure is known as the sella turcica (Figure 10-6). This gland secretes nine hormones, some of which control the secretion of other hormones that are vital to growth and metabolism and whose dysfunctions have been related to disorders beyond metabolism, including behavioral and affective disorders. Pituitary gland dysfunction has been inferred from the occurrence of hypopituitarism in victims of head injury from low-rate impact.

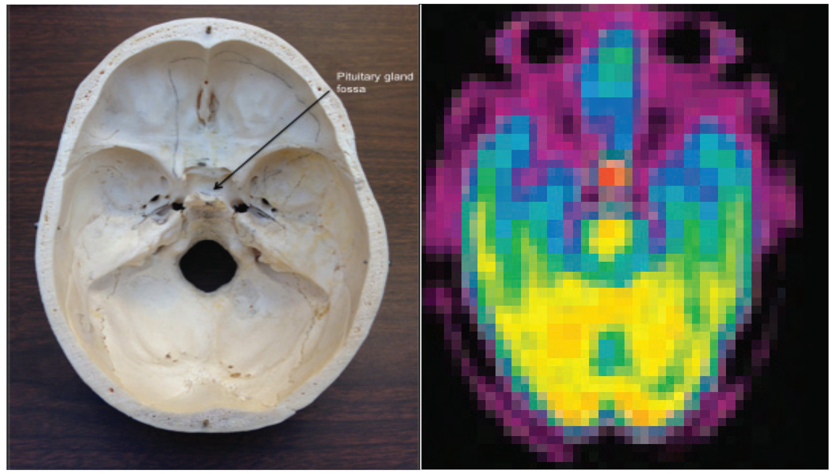

FIGURE 10-6 *Left*: The base of the human skull supports the bottom of the brain and the brain stem that descends through the large orifice in the center known as the foramen magnum. *Right*: Positron tomography of the uptake of ammonia-^{13}N in the normal pituitary. SOURCE: (Left) Image provided courtesy of member Tom Budinger. (Right) This research was originally published in JNM. Xiangsong, Z., Y. Dianchao, and T. Anwu. Dynamic ^{13}N-Ammonia PET: A new imaging method to diagnose Hypopituitarism. Journal of Nuclear Medicine. 2005;46:44-47. Copyright by the Society of Nuclear Medicine and Molecular Imaging, Inc.

Chronic hypopituitarism, defined as deficient production of one or more pituitary hormones at least 1year after injury, occurs in 40 percent of subjects who have sustained blunt brain trauma (Bondanelli et al., 2005). In contrast, the prevalence of hypopituitarism in the general population is estimated at 0.03 percent. As the hormones released from the pituitary are triggered by events in the hypothalamus, one cannot be certain of which tissue has been damaged. Growth hormone decreases develop in 15 to 20 percent of patients with complicated mild, moderate, or severe TBI and are associated with symptoms of posttraumatic stress disorder (Kelly et al., 2006; Powner et al., 2006). About 15 percent of TBI patients develop gonadal hormone deficiencies, and 10 to 30 percent of them develop hypothyroidism. After brain trauma, the short-term decline in hormones can recover in some cases, but there is a high prevalence of long-term deficiencies after severe TBI (Leal-Cerro et al., 2005; Agha et al., 2004). Chronic adrenal failure can occur because of low adrenocorticotropic hormone secretion from the pituitary in TBI patients.

Most studies found the occurrence of posttraumatic hypopituitarism to be unrelated to injury severity. In the past 2 years, researchers have found that about 42 percent of veterans with blast injuries showed abnormally low levels of at least one of the pituitary hormones (Wilkinson et al., 2012). Some veterans had abnormal levels of vasopressin and oxytocin, and these hormones are linked to psychological or behavioral abnormalities. It is not clear if this applies to ballistic BFD impacts.

Blood tests, some of which are complicated, can assess pituitary function. Positron emission tomography (PET) (Figure 10-6) and MRI, discussed in Appendix F, can noninvasively image metabolic function and structural abnormalities of the pituitary. MRI and PET can visualize anatomical and metabolic changes, respectively, as presented in Appendix F.

Recommendation 10-3. Modeling and simulation studies should incorporate the biomechanics of blunt brain trauma that affects the pituitary organ in the base of the brain in order to determine injury thresholds and tolerances for blunt trauma and for ballistic backface injuries.

Recommendation 10-4. The medical community should institute a data collection program to determine the prevalence of hypopituitarism in warfighters relevant to ballistic and blast blunt trauma with appropriate warfighter controls.

There is high prevalence of pituitary hypofunction in brain trauma from all causes. The recent discovery of low levels of pituitary hormones in TBI soldiers, coupled with the known replacement treatments for this disorder, mean that the medical community should launch a broad program of long-term periodic tests for veterans of head and blast injuries.

Neurobehavioral Effects from Traumatic Brain Injury

The linkages between the severity and frequency of blunt brain trauma to various physical injury classifications listed in Table 10-1 are the topics emphasized in this chapter. But there is another classification associated with brain trauma that has an association with TBI from all causes. Neurobehavioral changes include the specific neuropsychiatric syndromes of depression, mania, psychoses (e.g., paranoia and obsessive compulsive disease), aggressive behavior, and personality changes as well as cognitive decline. The causal associations have been debated for 100 years since the early papers on shell shock and also more recently because of the prevalence of psychiatric symptoms in veterans from wars of the past 70 years. Clear evidence of a causative relationship between negative neurobehavior and brain trauma has arisen in the past few years from pathological studies on athletes who have sustained TBI. Yet, despite some continuing skepticism about the lack of objective studies, there is compelling evidence for associations between both behavioral and cognitive disorders and TBI. From the vast literature of reports of psychiatric and cognitive evaluations of TBI subjects, two cited below have measures of the prevalence.

Depression, anxiety, and low self-esteem were the principal disabilities in half of 360 head-injured individuals evaluated from the group who had survived for 7 years after an initial head injury (Whitnall et al., 2006). Another study showed the prevalence of depression is 6 to 39 percent with mTBIs (Schoenhuber and Gentilini, 1988).

Cognitive impairments 10 years following TBI were found to be associated with injury severity using tests of attention, processing speed, memory, and executive function (Draper and Ponsford, 2008). Even mTBI patients may perform worse than controls on some tests of reasoning (Borgaro et al., 2003). Long-term effects of mild head injury approximately 8 years post injury included complex attention and working memory defects (Vanderploeg et al., 2005). Early-onset dementia in particular is frequently associated with head injury history (McMurtray et al., 2006). Repeated concussions have been linked to dementia (Guskiewicz et al., 2005) and chronic traumatic encephalopathy (McKee et al., 2009).

Finding 10-3. An increased prevalence of neurobehavioral abnormalities has been confirmed from many scientific evaluations of individuals involved in TBI incidents.

10.5 COMPUTATIONAL MODELING AND SIMULATION

Computational modeling and simulation (M&S) has long been considered an invaluable tool for analyzing engineering systems in a wide range of technology areas. Recently, M&S has also been used effectively in the broad field of injury biomechanics and to a limited extent in the evaluation and design of force protection systems.

M&S can provide a quantitative description of the relevant physical system response that can be used to assess system performance and inform potential improvements. Significant effort has been devoted in the past several decades to developing the basic science, algorithms, simulation software, and hardware infrastructure to meet this goal. However, owing to the unique complexities associated with the interplay between the physics and biology of injury, the full potential of M&S in understanding of injury biomechanics and the design of protection systems is yet to be realized.

Analytical and computational modeling of ballistic perforation of materials has been exhaustively reviewed up to 1978 (Backman and Goldsmith, 1978) with an update 10 years later (Anderson and Bodner, 1988). More recent reviews are provided by King et al. (1995). But the biomechanics of blunt trauma to tissues is a major added complexity to M&S because of the need to incorporate biophysical and biomedical parameters.

This section of the chapter, on linkages between a ballistic or blast threat and brain injury, is directed toward the important role of computational models, as it is through this tool that one can equate needed protection from brain injury to helmet design. One principal value of M&S in human injury biomechanics is its ability to obtain information in situations in which it is fundamentally impossible to conduct in vivo tests on the actual system (the human), although postmortem testing is possible using human cadaver tests. This approach may be supplemented by in vivo testing in animal surrogates to understand force effects on the human body and possible ways to mitigate them. There are cases in which this approach has provided useful insights into injury biomechanics such as blast lung injury criteria (Bass et al., 2008) and to develop test equipment for vehicle collision tests against tissue injury criteria. However, as discussed in this report, in the particular case of military helmets, evaluation and acceptance protocols are based exclusively on tests that use head surrogates with poor biofidelity.

It is therefore clear that M&S can play a significant role both in improving understanding of injury biomechanics and in guiding the design of protective systems with enhanced injury mitigation performance. Analytical approaches include mathematical modeling and computer simulations using advanced constitutive models and coupled fluid-solid mechanics. In the past, these approaches have been challenged as inadequate because of limitations in the fidelity of the computer simulations, realism of the tissue material properties, and the lack of validation.

Computational Simulations of Brain Injuries from Blunt Trauma

Ten years ago NHTSA developed a Simulated Injury Monitor (SIMon), based on a finite-element head model. This tool uses vehicle-dummy-head kinematics as an input and estimates the probability of three types of injuries: diffuse axonal injury, contusions, and subdural hematomas (Takhounts et al., 2003). This system is intended for vehicle crashes, and it is unclear how the results might apply to ballistic BFD injuries.

SIMon has been upgraded and recently did evaluations using input from instrumented helmets on professional football players (Takhounts et al., 2008) and vehicle collisions (von Holst and Li, 2013). A finite element model of the human head described the dynamic response of the brain during the first milliseconds after the impact with velocities of 10, 6, and 2 m/s, respectively. Their simulations show what is called a dynamic triple maxima sequence: (1) strain energy density, (2) intracranial pressure, (3) the first principal strain. Limitations of the NHTSA simulation system include limited spatial fidelity, uncertainty in brain material properties, and limited incorporation of potentially important brain structures such as the hippocampus and the amygdala. For example, the relative motion of the brain and skull is not modeled well with current computational model mesh sizes that do not provide the opportunity for insertion of the anatomy and material properties of vessels and tether points between the brain and the inner table of the skull. For example, the tensile strength of the dura material is much larger than brain tissues.

Simulations of Brain Strains from Ballistic Impacts on Helmeted Head

Finite element simulations to determine expected skull and brain tissue injuries from ballistic BFD trauma were performed in Sweden (Aare and Kleiven, 2007). These were performed using a validated human head and brain model as well as a model of the coupling between helmets of various stiffnesses and the head, so that tissue trauma parameters could be assessed based on the ballistic kinetic energy (ca. 518 J) of an 8 g, 9-mm bullet impact and angle of impact. The trauma parameters measured were stress in the cranial bone, strain in brain tissue, pressure in the brain, change in rotational velocity, and translational and rotational acceleration, as shown in Figure 10-7.

Computational Simulations of Brain Injury from Blast

Recent efforts in computational modeling of traumatic physical effects on the central nervous system have focused on blast-induced TBI. A reason for this effort is the need to resolve the controversy regarding the mechanism for brain injury dating from World War I when soldiers with neurological and neuropsychological symptoms were labeled "shell shocked" (cf. Bass et al., 2012). The linkage between symptoms and blast exposures is not the subject for this chapter, but the role of the helmet and face shield in mitigating the strain field is of great importance.

Several papers (including Moore et al., 2009; Chafi et al., 2010; Panzer et al., 2011; Przekwas et al., 2011; Nyein et al., 2010; and Sharma and Zhang, 2011) developed human head models from medical imaging data to study the interaction of blast waves with the head, including various anatomical structures resolved to various scales. Work still remains to be done on material properties, especially at blast-different stress rates (Panzer et al., 2012), but the body of this work suggests that blasts are a plausible cause of TBI, including the potential for axonal injury at various locations within the brain.

It has been clearly demonstrated that blasts can lead to the development of significant levels of pressure, volumetric tension, and shear stress in focal areas on a short time scale and that stress patterns are dependent on the orientation of the blast wave and the complex geometry of the skull, brain, and tissue interfaces (Taylor and Ford, 2009; Moore et al., 2009; Panzer et al., 2012).

A numerical and experimental investigation into the effects of low-level blast exposure on pigs used a two-dimensional pig head model that consisted of a skull model (Teland et al., 2010). They found that the blast wave propagates directly through the skull and that the orientation of

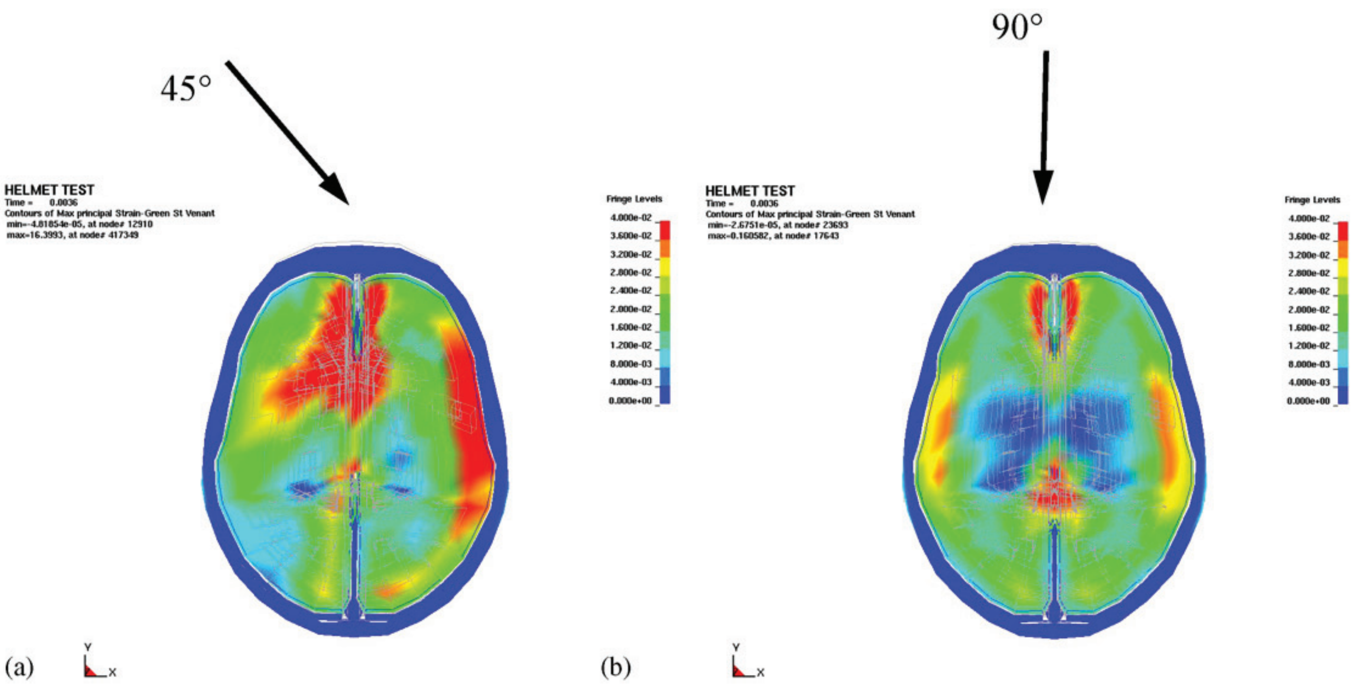

FIGURE 10-7 Principal strains in simulated brain material from projectile-induced kinetic energy striking a helmet at two angles. Blue is 0 percent, green is 2 percent, and red is >4 percent. SOURCE: Reprinted from Aare and Kleiven (2008), with permission from Elsevier.

the head is important. Another study constructed a better computational pig model consisting of skull, brain, cerebrospinal fluid, dura, and pia using computed tomography and MRI data (Zhu et al., 2013). The researchers found high pressures in the frontal and occipital regions, possibly due to wave reflection at the skull/brain interface. Examining strain, they found that the highest strains of 1.7 percent were in the brainstem, and the lowest strains of 0.2 percent were in the center of the brain. They also found that strains within the skull were two orders of magnitude lower than the strains within the brain and that the maximum deflection of the skull was less than 0.5 mm.

Very-high-resolution anisotropic models have been developed MRI T1 relaxation weighting and DTI with a three-dimensional, biofidelic finite-element volume mesh to conduct simulations of the stress and strain distributions after a frontal force of 7 kN impulse of 2.75 ms (Kraft et al., 2012). They then used a damage model based on data from rat experiments to predict cellular death based on axonal strain and strain rate. The temporal and occipital regions had the largest values of axonal strain and thus the highest amount of cellular death. Four days after injury, 19.7 percent of the network edges were fully degraded, but the network of axons remained intact. This type of analysis is new to blast-induced injury research and offers a promising route to connect biomechanical response to neurophysiological insight. It is unclear, however, what the brain material properties and detailed network behavior are in this basis, because the underlying experimental work has not been done.

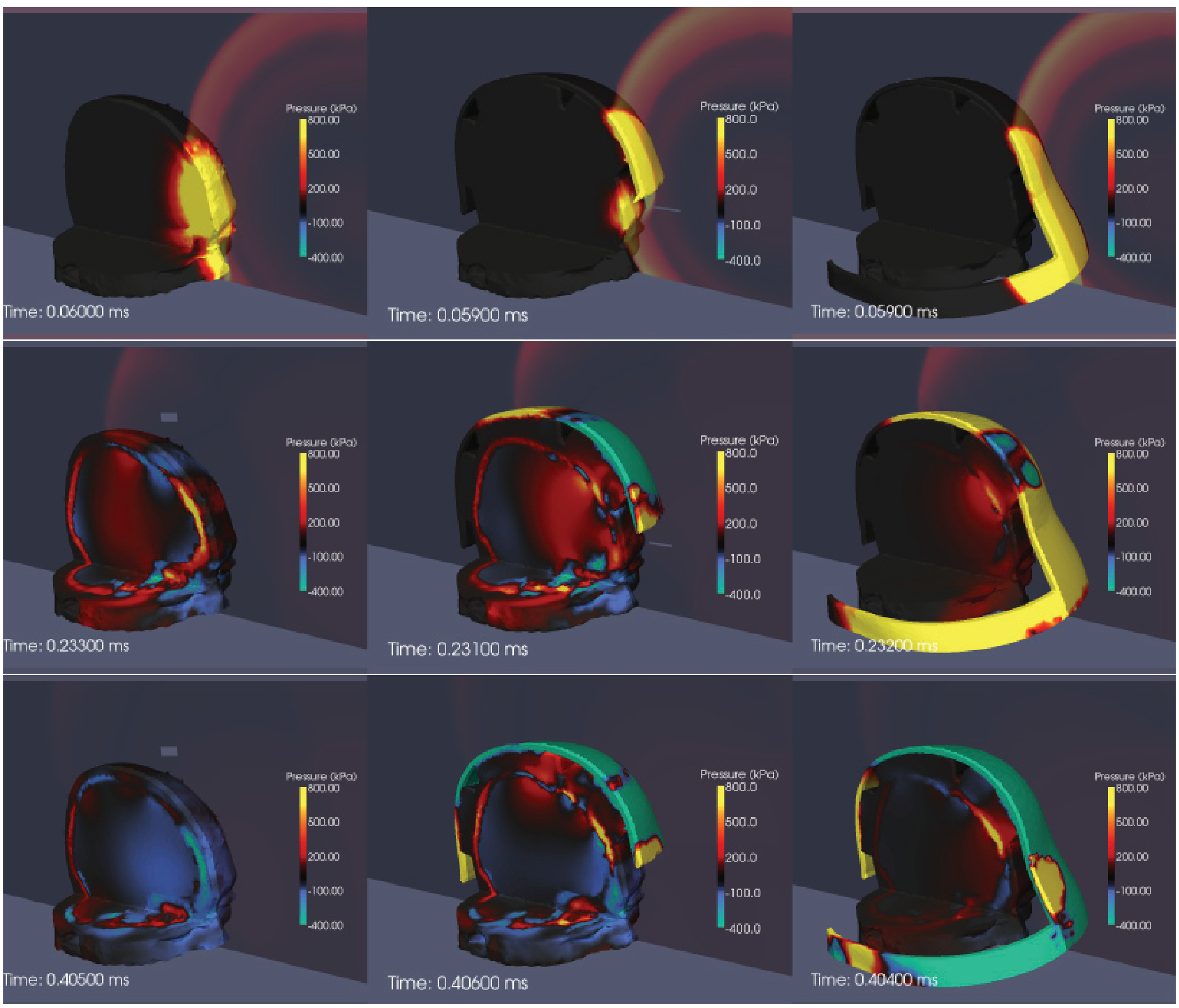

FIGURE 10-8 Computational simulations of the protective effect of the Advanced Combat Helmet (*center column*) and face shield (*right column*) show a significant attenuation of the transmitted pressure field when compared to the unprotected head (*left column*). SOURCE: Nyein et al. (2010).

Figure 10-8 shows results from large-scale computational simulations to compare the stress fields for blast exposures involving the head alone, head with helmet, and head with helmet and face shield (Nyein et al., 2010). Computer-aided design models of the actual ACH, including foam pads as well as a conceptual model of a mask protecting the face, were added to the detailed MRI-based model of the human head. For front blast conditions, the propagation of stress waves into the brain tissue is somewhat attenuated by the existing ACH and significantly attenuated by the addition of a face cover. This suggests a possible strategy to improve protection against blast-induced mTBI.

Other recent studies have considered the blast-mitigating effect of helmets (Panzer et al., 2010; Zhang et al., 2011; Shridharani et al., 2012a; Przekwas et al., 2011). These models and measurements have consistently shown strong mitigation of blast pressure behind the ACH.

Finding 10-4. Computational simulations of the protective effect of helmet and face shield show a significant attenuation of the transmitted pressure field.

In conclusion, M&S can prove a valuable tool in the analysis of the effects of mechanical threats (blast, impact) on brain tissue. Its main usefulness is in explaining mechanisms of momentum transfer from the external threat to the internal tissues, including the identification of areas of the brain that can be most vulnerable for particular threats. Simulations can also guide the design of protective gear and the assessment of the comparative effectiveness in mitigating the effect of the external threat on brain tissue. There is a clear opportunity to extend the existing use of M&S in the area of brain injury biomechanics and protective gear design, as in many other areas of science and engineering.

10.6 MECHANICAL AND CONSTITUTIVE PROPERTIES OF TISSUES

Characterization of the dynamic mechanical properties of brain tissue is important for developing a comprehensive knowledge of the mechanisms underlying brain injury and for developing computational models of potential ballistic and blunt neurotrauma. There are regional, directional, and age-dependent changes in the properties of the brain when it undergoes large deformations (Prange and Margulies, 2002). The frequency dependence of elastic properties must be included in comprehensive models, along with the frequency characteristics of the changing pressure field (Figure 10-9). Previous brain material characterizations at various stress rates suffer from wide experimental dispersion (Figure 10-9), nearly three orders of magnitude in the complex modulus. This has made comparison of computational results using these disparate data difficult (Panzer et al., 2012). Strain is dependent on the shear stress and stress rate, as shown in

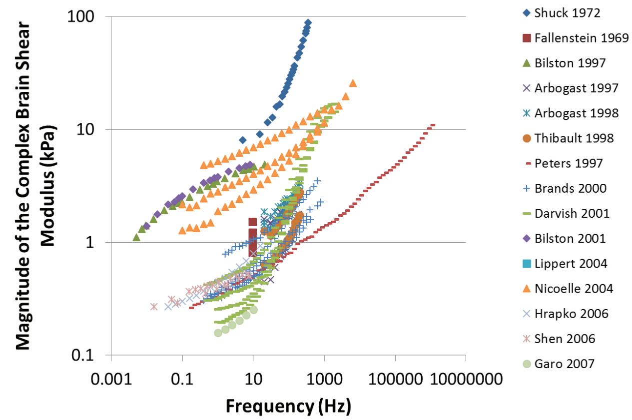

FIGURE 10-9 Experimental determination of brain shear modulus (magnitude of the complex shear modulus) showing wide variance of experimental results from different researchers.

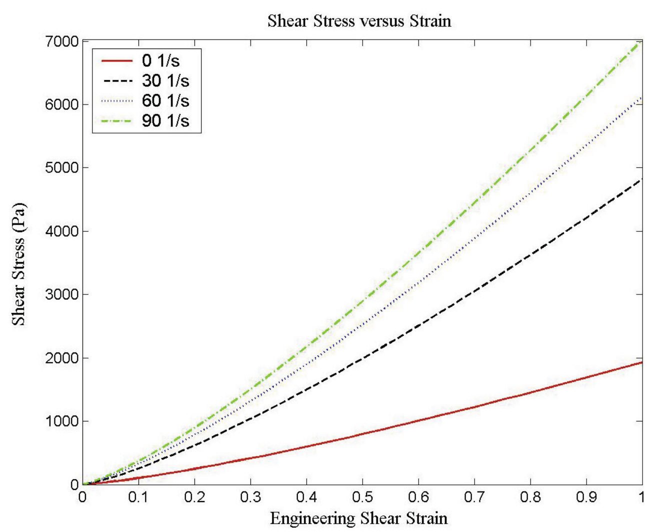

FIGURE 10-10 Dependence of shear strain on stress rate shows the importance of correct simulation of the shear stress rate in simulations. SOURCE: Adapted from Donelly and Medige (1997).

Figure 10-10. For a given shear stress, the strain on brain tissues is inversely related to the stress rate.

There has recently been significant progress in the experimental characterization and constitutive modeling of the mechanical response of brain tissue (Pervin and Chen, 2009; Prevost et al., 2011a, b). Tissue response exhibits moderate compressibility, substantial nonlinearity, hysteresis, conditioning, and rate dependence. A large-strain nonlinear viscoelastic model has been described that successfully captures the observed complexities of the material response in loading, unloading, and relaxation (Prevost et al., 2011a). This model covers strain rates—from quasistatic to dynamic rates—comparable or exceeding those in blast and ballistic events with stress rates from 0.01 to 3000 s^{-1}. But the low-strain-level behavior of brain tissue at high stress rates is not well known, and currently available results are not reliable because of the experimental methods employed to date. The results gathered to date on bovine and porcine tissue properties have been obtained mostly in vitro (Pervin and Chen, 2009; Prevost et al., 2011a). Previous studies on brain properties of note were on the juvenile pig (Gefen and Margulies, 2004). These results might differ quantitatively from those encountered in vivo, and this knowledge is critical for the development of biofidelic brain models. Further, different regions of the brain respond differently to identical mechanical stimuli, as shown in culture studies of the rat cortex and rat hippocampus. The cortex was less vulnerable to stretch-induced injury than the hippocampus (Elkin and Morrison, 2007).

Recently, Prevost et al. (2011b) measured the nonlinear dynamic response of the cerebral cortex to indentation of the exposed frontal and parietal lobes of anesthetized porcine subjects. Measurements included nonlinear, rate-dependent, hysteretic, and conditioning white and gray matter response in vivo, in situ, and in vitro. Results showed similar responses between in vivo and in vitro studies with respect to load versus indent and a "stiffening" with increase rate of stress. The data raise concerns regarding doing measurements in situ, wherein central circulation and cerebral spinal fluid pressures are much less than in vivo. Without the intact dura mater, whose tensile strength is much greater than other brain membranes, in vivo or in vitro measurements can be questioned, thus characterization of brain material properties might best be done by elastography using magnetic resonance techniques in vivo. But elastography does not have the spatial resolution to give region specific elastic properties and published values might be too low for studies of brain-surface-to-cortex relative motion or strains (cf. Coats et al., 2012).

Magnetic resonance elastography enables the visalization and measurement of mechanical waves propagating in three dimensions throughout a sample (Muthupillai et al., 1995; Manduca et al., 2001). From this information, the shear stiffness of the sample can be inferred. In MRE, oscillating shear displacements are generated by harmonic vibrations induced mechanically or acoustically on the skull or brain surface. The displacements are measured from phase images obtained by modulating the gradient field of the magnetic resonance scanner at the vibration frequency. These measurements have already shown the skull acts as a low-pass filter for frequencies of 45, 60, and 80 Hz. Skull transmission decreases, and shear-wave attenuation in the brain increases with increasing frequency (Clayton et al., 2012).

Further work is required to continue to improve and validate constitutive models—not just for brain but also for bone and other tissues. These models are essential for simulations of dynamic transients (impact from ballistic BFD/blunt trauma, blast/shock wave propagation) leading to TBI.

Finding 10-5. For models and simulations of brain trauma to be meaningful for injury assessments, they should include constitutive models of brain tissue response that account for nonlinear and rate-dependent viscoelastic effects. Viscoelastic brain properties for high rate, low strain levels necessary for ballistic BFD calculations are not established.

10.7 CONCLUSION

The protection of the warfighter afforded by helmets from threats ranging from bullets, shrapnel, blasts, vehicle collisions, and parachute landings has improved with improved helmet design and materials. However, the level of protection from nonfatal brain tissue injuries, which may have health consequences beyond the acute phase, is not known. This chapter and Chapter 3 give information regarding what is known about brain injury from blunt trauma and what is known about injury tolerances. In addition, this chapter defines the types of injuries that occur and most of the methods for diagnosis of both near- and long-term-onset medical conditions.

The principal finding is that there is not a known relationship between brain injury to the ballistic parameters of momentum, rate of change of momentum, acceleration, and time duration of the impact force. Findings in Chapter 3 emphasize that there is no known relationship between the measure of BFD by helmet evaluation protocols and skull fracture and brain trauma. This finding is known to the U.S. Army Medical Research and Materiel Command. Research is already underway on skull fracture injury criteria.[3] Linkage of the ballistic threats whose physical parameters are known to brain injury must include knowledge of the protective attenuation of the helmet. The degree to which the listed types of brain-injury parameters are moderated by the helmet is not known.

Vehicle and sports collisions have been studied and modeled with attendant animal experiments. But parameters for the rate of change of momentum (i.e., force) and duration of contact are orders of magnitude different from those for ballistic injuries. Therefore, considerations in the design of sports and vehicle head protective devices as well as the parameters of injury tolerance are not the same as those encountered by the warfighter. The committee notes a broad effort to define mechanisms, develop diagnostic methods for evaluating organic damage to the brain, and methods for treatment. But the current principal approach is protection from transfer of injurious forces afforded by the helmet.

[3] Karin Rafaels, Army Research Laboratory, Survivability/Lethality Analysis Directorate, "Joint Live Fire Test Program Behind Helmet Blunt Trauma Skull Injury," presentation to the committee on January 24, 2013.

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Appendix A

Study Origination Documents

LETTER FROM REPRESENTATIVE LOUISE M. SLAUGHTER TO SECRETARY OF DEFENSE LEON PANETTA, JUNE 26, 2012

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June 26, 2012

The Honorable Leon Panetta
Secretary of Defense
1000 Defense Pentagon
Washington, DC 20301-1300

Dear Secretary Panetta:

Since 2006, I have worked extensively with the Department and the Inspector General to ensure that our troops are being equipped with the best body armor available. Today, I write to you to express my concerns regarding new testing standards for Advanced Combat Helmets (ACH).

Our nation's servicemen and women deserve the highest quality protective armor and equipment when they are in harm's way for our country. As the Department has learned from past experience, safe armor and equipment in the field starts with comprehensive and effective testing procedures here at home.

However, government employees and contractors have shared concerns with my office that a recent modification to the standard for ballistic testing for ACHs would allow up to 17 penetrations during first article testing. While procurement standards have improved in recent years, the current standard poses an unacceptably high risk for equipment intended to protect the lives of Americans.

In 2010, the Department was forced to recall 44,000 ACHs after it was determined the helmets did not meet service standards due to questionable manufacturing processes. In the field, a penetration to a combat helmet could result in a fatality or extremely serious injury, which is why the Department should continue to take testing and performance concerns seriously.

Our goal should always be the most effective equipment possible and as such, I strongly urge you to modify the ballistics testing procedures currently in place to reduce the risk to military personnel.

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Thank you for your continued commitment to the men and woman of our Armed Forces. I am confident that you have our troops' best interests in mind and will continue do your very best to improve the quality standards of all protective body armor and equipment. I look forward to your response.

Sincerely,

Louise McIntosh Slaughter
Member of Congress

Cc: Honorable Lynne M. Halbrooks, Acting Inspector General for the U.S. Department of Defense

RESPONSE TO REP. SLAUGHTER FROM J. MICHAEL GILMORE, DIRECTOR, OPERATIONAL TEST AND EVALUATION, JULY 13, 2012

OFFICE OF THE SECRETARY OF DEFENSE
1700 DEFENSE PENTAGON
WASHINGTON, DC 20301-1700

OPERATIONAL TEST AND EVALUATION

JUL 13 2012

The Honorable Louise M. Slaughter
United States House of Representatives
Washington, D.C. 20515

Dear Representative Slaughter:

Thank you for your 26 June letter to Secretary Panetta expressing your concerns regarding the Department's protocols for testing the Advanced Combat Helmet (ACH). I am responding to you on behalf of the Secretary.

The Department insists—and I insist—on rigorous testing of soldier personal protective equipment, including combat helmets as well as body armor inserts. The protocols for ACH testing were developed to be analogous to the Department's revised, rigorous body armor test protocols. The revised body armor test protocols were developed in response to the January 2009 Department of Defense Inspector General (IG) report on Department of Defense Testing Requirements for Body Armor. In that report the IG recommended the Director, Operational Test & Evaluation (DOT&E) develop for Department-wide implementation a standard test operations procedure for body armor inserts. The IG further recommended that the protocol include statistical specification of probability of performance and associated confidence in that performance, two concepts discussed further below. As a result of this recommendation, DOT&E published on April 27, 2010 a statistically-based test protocol incorporating a 90/90 standard, as explained below, for hard armor inserts, and then published on December 7, 2010 a similar test protocol for combat helmets, including the ACH. The National Research Council (NRC), in its recent independent technical review of the Department's testing of body armor, indicated this approach to testing is scientifically defensible. The NRC also indicated the previously-used protocols for body armor testing were not scientifically defensible. I also note that you lauded all these actions in your September 7, 2011 letter to Secretary Panetta regarding body armor testing in which you stated: "I write to express my sincere appreciation to you and your staff for your work and cooperation in implementing the recommendations of the Inspector General (IG) of the Department of Defense concerning protective body armor equipment."

The standards in both the body armor and ACH test protocols require that combat helmets and the first shot for body armor inserts demonstrate at least a 90 percent probability of no perforation with 90 percent confidence (a 90/90 standard). The Services and the U.S. Special Operations Command have endorsed the 90/90 standard for no perforation. Probability and confidence are important statistical concepts for understanding the test protocols. A test, such as firing a round at a helmet, must be performed numerous times before the data obtained can be used with confidence to accurately assess performance. (A simple example illustrating this is that three flips of a coin will not accurately predict that the probability of heads (or tails) is 50 percent.) The revised ACH test protocol is better in several ways than the previously used protocol while being designed to demonstrate the same level of protection (probability of perforation) and also the same level of certainty of our knowledge of the level of protection (which is statistical confidence). While the revised protocol demonstrates the same probability of perforation and confidence, it provides better information in the context of multiple vendors and multiple helmets to be tested from each vendor. The previously used protocol for helmet testing allowed no perforations in 20 shots, equating to 89 percent probability of no perforation at 90 percent confidence. The difference between the old and revised protocol is in the level of knowledge they provide about differences in performance among and within vendors' helmets, not the level of protection helmets are required to provide. (The test protocol using the minimum number of shots—and therefore providing the least information about differences in helmet performance—while satisfying a 90/90 standard would use 22 shots and no perforations.) The revised protocol yields 90 percent probability of no perforation at 90 percent confidence, but allows 17 perforations in 240 shots. Again, this is the same level of protection: if 240 shots were fired at helmets that exactly met the 90/90 standard and had demonstrated the ability to withstand 22 shots with no perforations, about 17 perforations would occur. The revised protocol is not somehow flawed because it allows 17 perforations; rather, it is better because it requires 240 shots. The increase in number of helmets tested and shots taken reduces the risk of accepting a substandard helmet; it also reduces the risk of rejecting a helmet that meets standards. Additionally, because the revised protocol samples more helmets under more conditions, it provides the ability to distinguish if there are differences in performance associated with helmet size or environmental conditions.

Relative to the previously used protocol for helmet testing, the December 2010 protocol has the following specific advantages:

- By testing 48 helmets for perforation—versus four helmets under the previous protocol—to determine whether a contractor's "first articles" meet standards, the new protocol samples a large enough number of helmets for testing to demonstrate statistically significant differences in performance due to environmental conditions (such as hot and cold temperatures), among helmet sizes, and among different vendors' designs, enabling the Department to rigorously justify purchasing only the best-performing helmets.

- The revised protocol reduces the risk to the government of accepting a substandard helmet. The previous protocol sampled just four helmets, thus increasing the chances of accidently sampling unusually good helmets relative to the vendor's norms. With 48 helmets sampled (again, to the same 90/90 level of protection), the risk that the government will form an incorrect optimistic assessment of a vendor's performance is reduced.

- For similar reasons, the new protocol also reduces the risk of rejecting a helmet that meets standards (also called the manufacturer's risk). This feature is particularly important as the Military Services seek lighter weight helmets (and body armor) that provide needed protection. Soldiers and Marines fighting on the harsh terrain of Afghanistan care greatly about every ounce of weight they must carry. Because the previous protocol tested a relatively small sample of helmets, it incorporated greater risk that a lighter-weight helmet that actually met the 90/90 standard could fail testing. This is a key reason excessive risk of rejecting a good helmet is a concern—manufacturers' profits are not the reason it is a concern.

Therefore, the revised protocol does not pose "an unacceptably high risk for equipment intended to protect military personnel," as stated in your letter.

In conjunction with the revised protocol for first article testing, DOT&E has also published a scientifically defensible protocol for determining whether subsequent production lots of helmets purchased from a vendor whose helmets passed first article testing continue to meet standards. The previously-used lot acceptance protocol tested at most only two helmets from subsequent production lots to assess perforation and was, therefore, not defensible, having a high probability of passing a substandard production lot. This two-shot protocol was in effect when the concerns arose in 2010 regarding the quality of the ACH mentioned in your letter. In my view, that indefensible two-shot protocol did indeed pose "an unacceptably high risk for equipment intended to protect military personnel," which is why I insisted it be discarded.

I note that you have also communicated your concerns with the revised testing protocol for combat helmets to the Department's IG. DOT&E and the Services will, of course, cooperate fully with the Inspector General's office in any investigation it chooses to undertake. Consistent with its December 2009 request that the NRC undertake an independent review of body armor testing (which, as noted above, indicated the revised protocol for that testing is scientifically defensible), DOT&E is requesting that the NRC review the revised, similar protocol for testing combat helmets. This review will complement, and in no way interfere with, whatever action the IG decides to undertake. DOT&E has committed to continual improvement of the Department's revised test protocols for both body armor and combat helmets. I will use the results of the NRC reviews, whatever findings the IG makes, as well as our own ongoing analytical work and critical review to fulfill that commitment.

In closing, I want to assure you again that the Department remains committed to using rigorous test standards that ensure we provide our Service men and women with safe and effective personal protective equipment.

J. M. Gilmore

J. Michael Gilmore
Director

cc:
DoDIG

Appendix B

Protocols for First Article and Lot Acceptance Testing

PROTOCOL FOR FIRST ARTICLE TESTING, SEPTEMBER 20, 2011

OFFICE OF THE SECRETARY OF DEFENSE
1700 DEFENSE PENTAGON
WASHINGTON, DC 20301-1700

OPERATIONAL TEST AND EVALUATION

SEP 20 2011

MEMORANDUM FOR: SEE DISTRIBUTION

SUBJECT: Standardization of Combat Helmet Testing

All Department of Defense (DoD) combat helmet acquisition programs under DOT&E oversight will execute, at a minimum, the attached protocol for testing that results in a decision to qualify a design for full-rate production (i.e., First Article Testing). Likewise, First Article Testing conducted for sustainment contracts such as those executed for the Services by the Defense Supply Center Philadelphia will follow this protocol.

This protocol updates and supersedes the protocol for combat helmets published in December 2010. It includes changes necessary due to differences in the construction and material properties of aramid-based helmets such as the Advanced Combat Helmet (ACH) and Lightweight Helmet (LWH), and ultra-high molecular polyethylene-based helmets such as the Enhanced Combat Helmet (ECH). Specific changes include specifying, based on helmet material, the number of shots per helmet for penetration testing. In addition, the ballistic transient deformation upper tolerance limit will be calculated independently for each shot location; shot locations will not be combined as before. User input to this standard remains essential, not only in identifying the ballistic threats that combat helmets are expected to defeat, but especially as changes in helmet design and capabilities influence changes in test methods and procedures.

As testing of combat helmets continues and additional data are obtained, DOT&E will publish, as necessary, updates and changes to the attached protocol. Additionally, DOT&E will work with the Services, USSOCOM and Defense Agencies to incorporate this protocol, and future changes to it, into existing test operating procedures and military standards.

J. Michael Gilmore
Director

Attachment:
As stated

DISTRIBUTION:
ASSISTANT SECRETARY OF THE ARMY (ACQUISITION, LOGISTICS AND TECHNOLOGY)
ASSISTANT SECRETARY OF THE NAVY (RESEARCH, DEVELOPMENT, AND ACQUISITION)
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SPECIAL OPERATIONS ACQUISITION EXECUTIVE, UNITED STATES SPEICAL OPERATIONS COMMAND
DIRECTOR, DEFENSE LOGISTICS AGENCY
COMMANDER, DEFENSE SUPPLY CENTER PHILADELPHIA
COMMANDER, U.S. ARMY TEST AND EVALUATION COMMAND
COMMANDER, OPERATIONAL TEST AND EVALUATION FORCE
COMMANDER, AIR FORCE OPERATIONAL TEST AND EVALUATION CENTER
DIRECTOR, MARINE CORPS OPERATIONAL TEST AND EVALUATION ACTIVITY
COMMANDER, MARINE CORPS SYSTEMS COMMAND
DIRECTOR, OPERATIONAL TEST & EVALUATION, UNITED STATES SPECIAL OPERATIONS COMMAND
PROGRAM EXECUTIVE OFFICE SOLDIER
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COMMANDER, NAVAL SEA SYSTEMS COMMAND, SHIP INTEGRITY AND PERFORMANCE
FEDERAL BUREAU OF INVESTIGATION, BALLISTIC RESEARCH FACILITY, FBI ACADEMY (ATTN: SSA J. BUFORD BOONE III)
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, PROGRAM MANAGER WEAPONS AND PROTECTIVE SYSTEMS (ATTN: MR. KIRK RICE)

Military Combat Helmet
Standard for Ballistic Testing

The objective of this protocol is to establish DoD-wide, statistically-derived test methods for combat helmets that will provide increased confidence in the performance of personal protective equipment. This protocol also establishes standard testing references, protocols, procedures, and analytical processes for combat helmet testing.

As necessary, the Services will use the standards and information in this protocol to update or develop Test Operating Procedures (TOPs), Military-Standards (MIL-STDs), Purchase Descriptions (PDs), Internal Operating Procedures, and other documents relevant to this commodity area.

DOT&E will work in coordination with the Services, United States Special Operations Command (USSOCOM), and the Defense Logistics Agency to update this protocol at least annually. As this protocol is codified into the aforementioned documents, updates to this protocol may be directly addressed via updates to those documents.

Protocols established in this standard supplement those currently in practice across the DoD. However, this protocol does not address all issues associated with testing combat helmets. Test agencies, contracting officials, and material developers should therefore continue to use and reference TOPs, MIL-STDs, Internal Operating Procedures (IOPs), and other guiding documents currently in use to fully explain test setup and execution procedures. This protocol is not intended to be applied against already qualified designs.

Elements of Standardization

Table 1 establishes standard reference documents, precedence, and source information related to this standard. The list is not meant to be all encompassing. For elements referenced to this standard, those elements are found later in this document. Elements referenced to Service requirements documents reflect that this is a testing standard and not a requirements document. Service user representatives and the USSOCOM establish Service- and USSOCOM-unique requirements. This includes, for example the requirements of threat munitions and respective velocities to be applied against this testing protocol.

The Services have adopted a Ballistic Transient Deformation (BTD) standard that the BTD cannot exceed 16.0 mm for impacts by a 9 mm projectile on the right, left, and crown of the helmet, and 25.4 mm for impacts at either the front or back of the helmet. USSOCOM is developing a headform that may enable USSOCOM to achieve a BTD result that is better than the current Service BTD standard with the current headform. With the adoption of the laser scanning methodology for BTD measurement, and with the analysis completed by the National Institute of Standards and Technology[1], the DoD adopted the rounding methodology described in ASTM E29-08[2] for rounding the BTD measurement to 0.1 mm. Therefore, for uniformity with this standard, and unless changed by formal requirements documents (a Service-generated, Joint Capabilities Integration and Development System (JCIDS) compliant capability production document, for example), the DoD adopts as the BTD requirement a maximum of 16.0 mm for impacts by a 9 mm projectile on the right side, left side, and helmet crown, and a maximum of 25.4 mm

[1] National Institute of Standards and Technology, Dimensional Metrology Issues of Army Body Armor Testing, February 17, 2010.
[2] ASTM E29-08, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications.

for 9 mm projectile impacts at either the helmet front or back. The DoD requirement that these BTD standards are not exceeded is based on the specified upper tolerance limit calculated from the data set.

Table 1. Elements of Standardization

Element	Reference
Range Setup (physical layout of test range, instrumentation, measurement devices, recording devices, etc.) & Test Conduct	Service Requirements Documents IOP PED-003 MIL-STD 662 ITOP 4-2-805 NIJ 0106.01 This Standard
Backing Material/Clay Calibration	IOP PED-003 This Standard
Fair Hit/No Test Criteria	This Standard
Definition of Complete/Partial Penetrations	This Standard
Ballistic Transient Deformation (BTD) Measurement	IOP PED-003 w/current revisions IOP 002 Rev D This Standard
Shot Patterns/Shot Order/Distribution of Test Article Size in Test Matrix	Service Requirements Documents This Standard
Sample Size/Statistical Confidence in Test Results/Analysis Methodologies	This Standard
Threat Munitions	Service Requirements Documents This Standard

Range Setup and Test Conduct. Test range setup will be in accordance with Protective Equipment IOP PED-003, Procedures for Head Protection Testing. Test conduct will be in accordance with Service Requirements documents, IOP PED-003 (including revisions), and this standard. Testing will include both ballistic characterization testing (“V_{50}” testing) and resistance to penetration/ballistic transient deformation (RTP/BTD) testing (“V_0” testing). If these documents do not meet the needs of test agencies, test agencies may adopt procedures not defined within the documents. When such an event arises, DOT&E requests those agencies provide to the approving officials for those documents a written explanation of the deficiency and the range setup procedures used that were outside the scope of the documents. Subsequently, the approving officials should consider adoption of the provided information. Likewise, if a test agency deviates from these standards, they should provide a written explanation to the approving officials describing the necessity of doing so. Any changes to IOP PED-003 must be documented in individual test plans and concurred with by program offices prior to test execution. Revisions to IOP PED-003 must also be coordinated with the Services and USSOCOM prior to implementation. Any conflicts between Services and test organizations will be referred to the Integrated Product Team for resolution. Requirements or governing Service documents may specify the use of a headform other than the modified NIJ headform used in IOP PED-003. If a requirements document specifies a different (non-NIJ modified) headform, the responsible test agency will provide DOT&E with the range setup and test conduct procedures for use with the headform specified by the requirements document. Any Service, USSOCOM, or test organization that encounters helmet-related situations or circumstances not addressed in this protocol (e.g., first article testing of a single size) will coordinate the resolution of that situation with DOT&E.

Backing Material/Clay Calibration. Backing material (clay) preparation, cold working, temperature conditioning, monitoring, life-cycle management, and calibration will be in accordance with IOP PED-003.

Fair Hit/No Test Criteria. An impact is considered FAIR if:

(1) The yaw is within acceptable limits (less than or equal to 5.0 degrees for 9 mm full metal jacket projectiles and fragments or less than or equal to 3.0 degrees for rifle threats)

(2) The shot location is within acceptable limits (as specified in the requirements document or IOP PED-003)

(3) The obliquity is within acceptable limits

(4) The velocity is within acceptable limits. For RTP/BTD testing, a shot with a high velocity (except for the final shot), regardless of the results of the test (partial or complete penetration), will be declared "inconclusive" and repeated with a new (untested) helmet. For an impact with a low velocity that is not a complete penetration, the shot will be declared "inconclusive" and repeated with a new (untested) helmet. For an impact with a low velocity that is a complete penetration, the shot is valid and a retest is not required. If the final impact is a high velocity shot that generated a partial penetration, the shot is valid.

Complete Penetration (V_0 RTP/BTD). A complete penetration shall be defined as complete perforation of the shell by the projectile or fragment of the projectile as evidenced by the presence of that projectile, projectile fragment, or spall in the clay, or by a hole which passes thru the shell. In the case of the fastener test, any evidence of the projectile, fragment of the projectile, or fastener in the clay shall be considered a complete penetration. Non-metallic material such as paint, fibrous materials, edging, or edging adhesion resin that are emitted from the test specimen and rest on the outer surface of the clay impression are not considered a complete penetration.

Complete Penetration – Witness Headform (RTP). A complete penetration occurs when the impacting projectile or any fragment thereof, or any fragment of the retention system hardware perforates the witness plate resulting in a crack or hole which permits light passage.

Complete Penetration (V50). A complete penetration occurs when the impacting projectile or any fragment thereof, or any fragment of the test specimen perforates the witness plate resulting in a crack or hole which permits light passage. A break in the witness plate by the helmet deformation is not scored as a complete penetration.

Partial Penetration. A partial penetration is any fair impact that is not a complete penetration.

If these definitions do not meet the needs of the material developer, the material developer must document deviations from these definitions and provide them to DOT&E. DOT&E will coordinate such information with the Services and USSOCOM to determine if changes are warranted to this standard.

Ballistic Transient Deformation (BTD) Measurements. Transient deformation, or BTD, values shall be determined for each impact location. BTD values will be determined by comparing differences in the elevation of the pre-shot clay surface at the intended impact location to the surface of the clay after the impact has been made. For BTD measurements:

(1) The laser scanning device will be used in accordance with (IAW) IOP PED-003.

(2) The method used to determine BTD values shall be IAW IOP 002 Rev D (or updated revision), Measurement of Back-Face Deformation using Faro Quantum Laser Scan Arm and Geomagic Qualify for Helmets (RPS Alignment).

(3) The pre- and post-shot scans will then be analyzed using IAW IOP 002 Rev D (or updated revision) to determine the maximum BTD of depression made by the impact. In making this determination, any clay surrounding the impression that has been raised above the original level of the surface (cratering) will be ignored. The BTD value will be recorded as the number of digits reported out by the software, but reported in millimeters to the nearest tenth digit following standard ASTM E29 "Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications" (Rounding Method paragraph 6).

Shot Pattern/Shot Order/Distribution of Test Article Size. Appendix A defines the distribution of helmets in this protocol for V_{50}, V_0, and hardware testing. Shots against hardware are conducted against hardware on helmets separate from those helmets shot to determine resistance to penetration and ballistic transient deformation. For aramid-based helmets such as the Advanced Combat Helmet (ACH) and Lightweight Helmet (LWH), Appendix A provides five shots per helmet in each of the five impact locations described in IOP PED-003 for V_0 9 mm RTP/BTD testing, two shots per helmet for RTP hardware testing, and one shot per helmet for small arms RTP testing (if a requirements document calls for small arms testing). Shot sequence for 9 mm RTP/BTD testing is specified in Appendix A. For ultra-high molecular polyethylene-based helmets such as the Enhanced Combat Helmet (ECH), Appendix A provides two (instead of five) shots per helmet for V_0 9 mm RTP/BTD testing. For small arms RTP testing, test plans will ensure shots will be distributed between all helmet locations and will randomize shot sequence and sizes. All shots will be at 0° obliquity.

Sample Size/Statistical Confidence in Test Results. Table 2 displays the RTP/BTD statistical analysis required for this protocol. The standard is established to provide a high level of statistical confidence in the test results. For resistance to penetration tests (small arms, hardware, and 9 mm shell), the lower confidence level for the probability of no penetration, P(nP), is the statistic of interest and the result compared against a 90 percent probability of no penetration. For BTD, the Upper Tolerance Limit (UTL) will be computed and the result compared against the requirement.

Table 2. Statistical Analysis Methodologies

Resistance to Penetration	
Analysis Methodology	90% Lower Confidence Level
Ballistic Transient Deformation	
Analysis Methodology	90% Upper Tolerance Limit with 90% Confidence

Analysis Methodologies. The Lower Confidence Level (LCL) of the P(nP) is calculated using the Clopper-Pearson method. The LCL for P(nP) is calculated by combining shot locations, helmet sizes, and environmental conditions.

For BTD, the arithmetic mean of the BTD measurements is calculated as well as the indicated UTL. The 90 percent UTL at 90 percent confidence provides the estimated BTD measurement below which 90 percent of BTD measurements will occur, with 90 percent confidence. The BTD UTL will be calculated independently each for the crown, front, and back locations by combining all helmet sizes and environmental conditions at those locations. A fourth BTD UTL will be calculated by combining the right and left shot locations for all helmet sizes and environmental conditions after verifying the data from the side locations can be combined for analysis. If the BTD measurements from the side locations form two distinct distributions, then a separate BTD UTL must be calculated for each side location.

Threat Munitions. The Services and USSOCOM will generate requirements documents that identify the threat munitions and associated velocities that will be applied against this protocol. As noted previously, the BTD requirement of a maximum 16.0 mm for the 9 mm projectile on the right, left, and crown regions, and 25.4 mm for the 9 mm projectile on the front and back regions, will be the DoD standard until superseded by a validated capabilities document.

This protocol does not prevent the Services or USSOCOM from conducting testing with additional threats that may not be applied against this testing protocol.

Conclusion. The Services and USSOCOM will document adherence to this protocol in formal test plans and reports.

Appendix A

Helmet Test Matrix
(Advanced Combat Helmet and Lightweight Helmet)

V50	Ambient	Hot	Cold	Seawater	Weatherometer	Accelerated Aging
2-grain	1 V50 Size: Small	1 V50 Size: Medium	1 V50 Size: Large	1 V50 Size: XL		
4-grain	1 V50 Size: XL	1 V50 Size: Small	1 V50 Size: Medium	1 V50 Size: Large		
16-grain	1 V50 Size: Large	1 V50 Size: XL	1 V50 Size: Small	1 V50 Size: Medium		
17-grain	1 V50 Size: Medium	1 V50 Size: Large	1 V50 Size: XL	1 V50 Size: Small	1 V50 Size: Large	1 V50 Size: Medium
64-grain	1 V50 Size: Large	1 V50 Size: XL	1 V50 Size: Medium	1 V50 Size: Small		
Small Arms	1 V50 Size: Medium	1 V50 Size: Small	1 V50 Size: XL	1 V50 Size: Large	1 V50 Size: Medium	
9 mm RTP/BTD Shell	60 shots 12 helmets Sizes: Small: 3 Medium: 3 Large: 3 XL: 3	60 shots 12 helmets Sizes: Small: 3 Medium: 3 Large: 3 XL: 3	60 shots 12 helmets Sizes: Small: 3 Medium: 3 Large: 3 XL: 3	60 shots 12 helmets Sizes: Small: 3 Medium: 3 Large: 3 XL: 3		
9 mm RTP Hardware[1]	17 shots 9 helmets Sizes: Small: 2 Medium: 3 Large: 2 XL: 2	16 shots 8 helmets Sizes: Small: 2 Medium: 2 Large: 2 XL: 2	16 shots 8 helmets Sizes: Small: 2 Medium: 2 Large: 2 XL: 2	16 shots 8 helmets Sizes: Small: 2 Medium: 2 Large: 2 XL: 2		
Small Arms RTP[1,2]	17 shots 17 helmets Sizes: Small: 4 Medium: 5 Large: 4 XL: 4	16 shots 16 helmets Sizes: Small: 4 Medium: 4 Large: 4 XL: 4	16 shots 16 helmets Sizes: Small: 4 Medium: 4 Large: 4 XL: 4	16 shots 16 helmets Sizes: Small: 4 Medium: 4 Large: 4 XL: 4		

[1] This matrix provides for a total of 65 shots for both the 9 mm RTP hardware and the small arms RTP tests and allows up to three complete penetrations to achieve the lower limit of 0.90 for RTP with 90% confidence. For the 9 mm RTP hardware testing in ambient conditions, the third medium helmet will be shot once to obtain the 65th data point for this test.

[2] Applicable only if the requirements document specifies a small arms requirement.

Helmet Test Matrix

9 mm Resistance to Penetration/Ballistic Transient Deformation (Advanced Combat Helmet and Lightweight Helmet)

Ambient						
Size	Helmet	Order				
S	#1	F	B	Cr	R	L
	#2	L	R	Cr	B	F
	#3	B	R	F	L	Cr
M	#1	Cr	L	F	R	B
	#2	R	L	B	Cr	F
	#3	F	Cr	B	L	R
L	#1	L	Cr	R	F	B
	#2	B	F	R	Cr	L
	#3	Cr	F	L	B	R
XL	#1	R	B	L	F	Cr
	#2	B	L	Cr	F	R
	#3	R	F	Cr	L	B

Hot						
Size	Helmet	Order				
S	#1	L	F	B	R	Cr
	#2	Cr	R	B	F	L
	#3	F	R	L	Cr	B
M	#1	B	Cr	L	R	F
	#2	R	Cr	F	B	L
	#3	L	B	F	Cr	R
L	#1	Cr	B	R	L	F
	#2	F	L	R	B	Cr
	#3	R	L	Cr	F	B
XL	#1	B	F	Cr	L	R
	#2	L	Cr	F	B	R
	#3	R	B	F	Cr	L

Cold						
Size	Helmet	Order				
S	#1	Cr	F	B	R	L
	#2	L	R	B	F	Cr
	#3	F	B	R	L	Cr
M	#1	Cr	L	R	B	F
	#2	B	R	L	Cr	F
	#3	F	Cr	L	R	B
L	#1	F	R	Cr	B	L
	#2	L	B	Cr	R	F
	#3	R	Cr	B	L	F
XL	#1	F	L	B	Cr	R
	#2	Cr	B	L	F	R
	#3	R	F	L	B	Cr

Seawater						
Size	Helmet	Order				
S	#1	B	L	F	R	Cr
	#2	Cr	R	F	L	B
	#3	L	F	R	Cr	B
M	#1	B	Cr	R	F	L
	#2	R	B	Cr	L	F
	#3	F	L	Cr	B	R
L	#1	L	R	F	Cr	B
	#2	B	Cr	F	R	L
	#3	Cr	L	B	F	R
XL	#1	R	F	B	L	Cr
	#2	L	Cr	R	B	F
	#3	F	B	R	Cr	L

Key:
F=Front
B=Back
R=Right
L=Left
Cr=Crown
All shots at 0° obliquity

Helmet Test Matrix
(Enhanced Combat Helmet)

V50	Ambient	Hot	Cold	Seawater	Weatherometer	Accelerated Aging
2-grain	1 V50 Size: Small	1 V50 Size: Medium	1 V50 Size: Large	1 V50 Size: XL		
4-grain	1 V50 Size: XL	1 V50 Size: Small	1 V50 Size: Medium	1 V50 Size: Large		
16-grain	1 V50 Size: Large	1 V50 Size: XL	1 V50 Size: Small	1 V50 Size: Medium		
17-grain	1 V50 Size: Medium	1 V50 Size: Large	1 V50 Size: XL	1 V50 Size: Small	1 V50 Size: Large	1 V50 Size: Medium
64-grain	1 V50 Size: Large	1 V50 Size: XL	1 V50 Size: Medium	1 V50 Size: Small		
Small Arms	1 V50 Size: Medium	1 V50 Size: Small	1 V50 Size: XL	1 V50 Size: Large	1 V50 Size: Medium	
9 mm RTP/BTD Shell	24 shots 12 helmets Sizes: Small: 3 Medium: 3 Large: 3 XL: 3	24 shots 12 helmets Sizes: Small: 3 Medium: 3 Large: 3 XL: 3	24 shots 12 helmets Sizes: Small: 3 Medium: 3 Large: 3 XL: 3	24 shots 12 helmets Sizes: Small: 3 Medium: 3 Large: 3 XL: 3		
9 mm RTP Hardware[1]	17 shots 9 helmets Sizes: Small: 2 Medium: 3 Large: 2 XL: 2	16 shots 8 helmets Sizes: Small: 2 Medium: 2 Large: 2 XL: 2	16 shots 8 helmets Sizes: Small: 2 Medium: 2 Large: 2 XL: 2	16 shots 8 helmets Sizes: Small: 2 Medium: 2 Large: 2 XL: 2		
Small Arms RTP[1,2]	17 shots 17 helmets Sizes: Small: 4 Medium: 5 Large: 4 XL: 4	16 shots 16 helmets Sizes: Small: 4 Medium: 4 Large: 4 XL: 4	16 shots 16 helmets Sizes: Small: 4 Medium: 4 Large: 4 XL: 4	16 shots 16 helmets Sizes: Small: 4 Medium: 4 Large: 4 XL: 4		

[1] This matrix provides for a total of 65 shots for both the 9 mm RTP hardware and the small arms RTP tests and allows up to three complete penetrations to achieve the lower limit of 0.90 for RTP with 90% confidence. For the 9 mm RTP hardware testing in ambient conditions, the third medium helmet will be shot once to obtain the 65th data point for this test.

[2] Applicable only if the requirements document specifies a small arms requirement.

Helmet Test Matrix

9 mm Resistance to Penetration/Ballistic Transient Deformation (Enhanced Combat Helmet)

Size	Helmet	Ambient		Hot		Cold		Seawater	
		Shot 1	Shot 2	Shot 1	Shot 2	Shot 1	Shot 2	Shot 1	Shot 2
Small	#1	Cr	B	L	F	Cr	B	L	F
	#2	L	F	Cr	B	R	F	Cr	B
	#3	Cr	B	R	F	Cr	B	R	F
Medium	#1	R	F	Cr	B	R	F	Cr	B
	#2	Cr	B	R	F	Cr	B	L	F
	#3	L	F	Cr	B	L	F	Cr	B
Large	#1	Cr	B	R	F	Cr	B	R	F
	#2	R	F	Cr	B	L	F	Cr	B
	#3	Cr	B	L	F	Cr	B	L	F
X-Large	#1	L	F	Cr	B	L	F	Cr	B
	#2	Cr	B	L	F	Cr	B	R	F
	#3	R	F	Cr	B	R	F	Cr	B

Key:
F=Front
B=Back
R=Right
L=Left
Cr=Crown
All shots at 0° obliquity

PROTOCOL FOR LOT ACCEPTANCE TESTING, MAY 4, 2012

OPERATIONAL TEST AND EVALUATION

OFFICE OF THE SECRETARY OF DEFENSE
1700 DEFENSE PENTAGON
WASHINGTON, DC 20301-1700

MAY 04 2012

MEMORANDUM FOR: SEE DISTRIBUTION

SUBJECT: Standard for Lot Acceptance Ballistic Testing of Military Combat Helmets

Department of Defense (DoD) combat helmet acquisition programs under DOT&E oversight are required to execute, at a minimum, the attached protocol for testing that results in a decision to accept a production lot from a vendor (Lot Acceptance Testing). Lot Acceptance Testing conducted for sustainment contracts such as those executed for the Services by the Defense Supply Center Philadelphia must also follow this protocol.

This protocol updates and supersedes the combat helmet lot acceptance protocol published in January 2012. It revises the aramid-based LAT matrix in appendix A to conform with the acceptable quality level for resistance to penetration specified in the protocol. There is no change to the acceptable quality level for resistance to penetration.

As testing of combat helmets continues and additional data are obtained, DOT&E will publish, as necessary, updates and changes to the attached protocol. Additionally, DOT&E will work with the Services, USSOCOM, and Defense Agencies to incorporate this protocol, and future changes to it, into existing test operating procedures and military standards.

J. Michael Gilmore
Director

Attachment:
As stated

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Military Combat Helmet
Standard for Ballistic Lot Acceptance Testing

The objective of this protocol is to establish DoD-wide, statistically-derived test methods for combat helmet lot acceptance tests that will provide increased confidence in the ballistic performance of personal protective equipment. This protocol also establishes standard testing references, protocols, procedures, and analytical processes for combat helmet testing against ballistic requirements. This protocol will be used for testing conducted at government facilities and at commercial test facilities conducting lot acceptance testing (LAT) on behalf of the DoD.

As necessary, the Services will use the standards and information in this protocol to update or develop Test Operating Procedures (TOPs), Military-Standards (MIL-STDs), Purchase Descriptions (PDs), Internal Operating Procedures (IOPs), and other documents relevant to this commodity area.

DOT&E will work in coordination with the Services, United States Special Operations Command (USSOCOM), and the Defense Logistics Agency (DLA) to update this protocol at least annually. As this protocol is codified into the aforementioned documents, updates to this protocol may be directly addressed via updates to those documents.

Protocols established in this standard supplement those currently in practice across the DoD. However, this protocol does not address all issues associated with testing combat helmets. Test agencies, contracting officials, and material developers should therefore continue to use and reference TOPs, MIL-STDs, IOPs, and other guiding documents currently in use to fully explain test setup and execution procedures. This protocol is not intended to be applied against already accepted lots, or against lots produced from designs not qualified using the September 20, 2011, Military Combat Helmet test protocol for First Article Testing.

Elements of Standardization

Table 1 establishes standard reference documents, precedence, and source information related to this standard. The list is not meant to be all encompassing. The elements referenced to this standard are described later in this document. Elements referenced to Service requirements documents reflect that this is a testing standard and not a requirements document. Service user representatives and the USSOCOM establish Service- and USSOCOM-unique requirements. This includes, for example, the requirements of threat munitions and respective velocities to be applied against this testing protocol.

The Services have adopted a Ballistic Transient Deformation (BTD) standard that the BTD cannot exceed 16.0 mm for impacts by a 9 mm projectile (velocity 1400 +50 feet per second) on the right, left, and crown of the helmet, and 25.4 mm for impacts at either the front or back of the helmet. USSOCOM is developing an alternate headform that may enable USSOCOM to achieve a different BTD result as compared to the current Service BTD standard with the current headform. With the adoption of the laser scanning methodology for BTD measurement, and with the analysis completed by the National Institute of Standards and Technology, the DoD adopted the rounding methodology described in ASTM E29-08 for rounding the BTD measurement to 0.1 mm.[1,2] Therefore, for uniformity with this standard, and unless changed by formal requirements documents (a Service-generated, Joint Capabilities Integration and Development System (JCIDS) compliant capability production document, for example), the DoD adopts as the BTD requirement a maximum of 16.0 mm for impacts by a 9 mm projectile on the right side, left side, and helmet crown, and a maximum of 25.4 mm for 9 mm projectile impacts at either the helmet front or back. The DoD requirement that these BTD standards are not exceeded is based on the one-sided upper tolerance limit calculated from the data set.

Table 1. Elements of Standardization

Element	Reference
Range Setup (physical layout of test range, instrumentation, measurement devices, recording devices, etc.) and Test Conduct	Service Requirements Documents IOP PED-003 MIL-STD 662 ITOP 4-2-805 NIJ 0106.01 This Standard
Backing Material/Clay Calibration	IOP PED-003 w/current revisions This Standard
Fair Hit/No Test Criteria	This Standard
Definition of Complete/Partial Penetrations	This Standard
Ballistic Transient Deformation (BTD) Measurement	IOP PED-003 IOP 002 Rev D This Standard
Shot Patterns/Shot Order/Distribution of Test Article Size in Test Matrix	Service Requirements Documents This Standard
Sample Size/Statistical Confidence in Test Results	This Standard
Threat Munitions	Service Requirements Documents This Standard

Range Setup and Test Conduct. Test range setup will be in accordance with Protective Equipment IOP PED-003, Procedures for Head Protection Testing. Test conduct will be in accordance with Service Requirements documents, (Purchase Descriptions / Product Specifications), IOP PED-003 (including revisions), and this standard. Testing will include both ballistic characterization testing ("V_{50}" testing) and resistance to penetration/ballistic transient deformation (RTP/BTD) testing ("V_0" testing). If these documents do not meet the needs of test agencies, test agencies may adopt procedures not defined within the documents. When such an event arises, DOT&E requests those agencies provide to the approving officials for those documents (a specification owner, program office, etc) and the affected program offices a written explanation of the deficiency and the range setup procedures to be used that were outside the scope of the documents. Subsequently, the approving officials should consider adoption of the provided information. Likewise, if a test agency deviates from these standards, they should provide a written explanation to the approving officials describing the necessity of doing so.

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1 National Institute of Standards and Technology, Dimensional Metrology Issues of Army Body Armor Testing, February 17, 2010.

2 ASTM E29-08, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications.

Any proposed changes must be coordinated with program managers from the Services, USSOCOM, and DLA prior to implementation to preclude an adverse impact on existing contracts or specifications. Any changes to IOP PED-003 must be documented in individual test plans and concurred with by program offices prior to test execution. Revisions to IOP PED-003 must also be coordinated with the Services and USSOCOM prior to implementation. Any conflicts between Services and test organizations will be referred to the Integrated Product Team for resolution. Requirements or governing Service documents may specify the use of a headform other than the modified NIJ 0106.01 headform used in IOP PED-003. If a requirements document specifies a different (non-NIJ modified) headform, the responsible test agency will provide DOT&E with the range setup and test conduct procedures for use with the headform specified by the requirements document. Any Service, USSOCOM, or test organization that encounters helmet-related situations or circumstances not addressed in this protocol will coordinate the resolution of that situation with the responsible program office or specification owner and the Deputy for Live Fire Test and Evaluation, DOT&E.

Backing Material/Clay Calibration. Backing material (clay) preparation, cold working, temperature conditioning, monitoring, life-cycle management, and calibration will be in accordance with IOP PED-003; exceptions will be coordinated in the detailed test plan.

Fair Hit/No Test Criteria. An impact is considered FAIR if:

(1) The yaw is within acceptable limits (less than or equal to 5.0 degrees for handgun / pistol and fragment simulating projectiles or less than or equal to 3.0 degrees for rifle threats).

(2) The shot location is within acceptable limits (as specified in the requirements document or IOP PED-003).

(3) The obliquity is within acceptable limits.

(4) The velocity is within acceptable limits (as specified in the detailed test plan). For RTP/BTD testing, a shot with a high velocity (except for the final shot), regardless of the results of the test (partial or complete penetration), will be declared "inconclusive" and repeated with a new (untested) helmet. For an impact with a low velocity that is not a complete penetration, the shot will be declared "inconclusive" and repeated with a new (untested) helmet. For an impact with a low velocity that is a complete penetration, the shot is valid and a retest is not required. If the final impact is a high velocity shot that generated a partial penetration, the shot is valid for calculating penetration results but not for BTD. The shot sequence from that sub-test will be repeated on a new, untested helmet. All valid BTD and penetration data will be used for calculations.

(5) For RTP/BTD testing, a complete penetration on any shot that is otherwise fair is valid for calculating penetration results and a new (untested) helmet will be tested using the full 9 mm V_0 shot sequence to complete the test matrix. Valid penetration and BTD data from both helmets will be used for analysis.

Complete Penetration (V_0 RTP/BTD). A complete penetration shall be defined as complete perforation of the shell by the projectile or fragment of the projectile as evidenced by the presence of that projectile, projectile fragment, or spall in the clay, or by a hole which passes thru the shell. In the case of the fastener test (when specified in the detailed test plan), any evidence of the projectile, fragment of the projectile, or fastener in the clay shall be considered a complete penetration. Non-metallic material such as paint, fibrous materials, edging, or edging adhesion resin that are emitted from the test specimen and rests on the outer surface of the clay impression are not considered a complete penetration.

Complete Penetration – Witness Headform (RTP). A complete penetration occurs when the impacting projectile or any fragment thereof, or any fragment of the retention system hardware perforates the witness plate resulting in a crack or hole that permits light passage. This applies only when the use of this headform is required by the requirements document and specified in the detailed test plan.

Complete Penetration (V_{50}). A complete penetration occurs when the impacting projectile or any fragment thereof, or any fragment of the test specimen perforates the witness plate resulting in a crack or hole that permits light passage. A break in the witness plate by the helmet deformation is not scored as a complete penetration.

Partial Penetration. A partial penetration is any fair impact that is not a complete penetration.

If these definitions do not meet the needs of the material developer, the material developer must document deviations from these definitions and provide them to DOT&E. DOT&E will coordinate such information with the Services and USSOCOM to determine if changes are warranted to this standard.

Ballistic Transient Deformation (BTD) Measurements. Transient deformation, or BTD, values shall be determined for each impact location. BTD values will be determined by comparing differences in the elevation of the pre-shot clay surface at the intended impact location to the surface of the clay after the impact has been made. For BTD measurements:

(1) The laser scanning device will be used in accordance with (IAW) IOP PED-003.

(2) The method used to determine BTD values shall be IAW IOP 002 Rev D (or updated revision), Measurement of Back-Face Deformation using Faro Quantum Laser Scan Arm and Geomagic Qualify for Helmets (RPS Alignment).

(3) The pre- and post-shot scans will then be analyzed IAW IOP 002 Rev D (or updated revision) to determine the maximum BTD of depression made by the impact. In making this determination, any clay surrounding the impression that has been raised above the original level of the surface (cratering) will be ignored. The BTD value will be recorded as the number of digits reported out by the software, but reported in millimeters to the nearest tenth digit following standard ASTM E29 "Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications" (Rounding Method paragraph 6).

Shot Pattern/Shot Order/Distribution of Test Article Size. Appendix A defines the distribution of helmets in this protocol for V_0 and hardware testing. Shots against hardware are conducted against hardware on helmets separate from those helmets shot to determine resistance to penetration and ballistic transient deformation. For aramid-based helmets, such as the current Advanced Combat Helmet (ACH) and Lightweight Helmet (LWH), Appendix A provides five shots per helmet in each of the five impact locations described in IOP PED-003 for V_0 9 mm RTP/BTD testing, two shots per helmet for RTP hardware testing, and one shot per helmet for small arms RTP testing (if a requirements document calls for small arms testing). Shot sequence for 9 mm RTP/BTD testing is specified in Appendix B. For ultra-high molecular weight polyethylene-based (UHMWPE) helmets such as the Enhanced Combat Helmet (ECH), Appendix A provides two (instead of five) shots per helmet for V_0 9 mm RTP/BTD testing. For small arms RTP testing, test plans will ensure shots will be distributed between all helmet locations and will randomize shot sequence. For hardware RTP testing, test plans will ensure the first shot location alternates between the right and left sides. All shots will be at 0 degrees intended obliquity (checked prior to firing the test shot per IOP PED-003). Impacts within 5 degrees of intended obliquity are considered to meet the fair hit obliquity requirement (per IOP PED-003).

Helmet testing is unique in that two to three disparate destructive tests are required for each lot. Each test stresses the helmets in a particular way; presenting a challenging threat, exploiting a potential structural weakness, or imposing a BTD requirement; and each requires a different number of shots taken on an individual helmet. Each must therefore be treated as a distinct subtest. It is desirable to maintain reasonable LAT sampling levels (e.g. S-4); therefore, the total number of helmets allocated to penetration and BTD tests closely reflects the quantities required for the S-4 sampling level and consists of sub-tests sampled at either the S-2 or S-3 levels. The sampling levels reflect the perceived challenge imposed by each subtest, with more resources assigned to more challenging subtests.

For RTP/BTD testing, a complete penetration on any shot that is otherwise fair is valid for calculating penetration results. If a perforation occurs, no additional shots will be taken on the perforated helmet. The perforated helmet will count against the accept/reject criteria in Appendix A. To complete the test matrix, a new (untested) helmet will be tested using the full 9mm V_0 shot sequence for the helmet that was perforated. Valid penetration and BTD data from both helmets will be used for analysis. Testing is complete when a complete set of valid BTD measurements have been taken. It is not necessary to complete BTD testing if the helmet fails the RTP portion of the test.

Sample Size/Statistical Confidence in Test Results. Table 2 displays the resistance to penetration and ballistic transient deformation analysis required for this protocol. The standard is established to provide a high level of statistical confidence in the test results. It also is intended to indicate the vendor is consistently producing helmets capable of meeting the First Article Testing standards. For resistance to penetration tests (small arms, hardware, and 9 mm shell) the equivalent acceptable quality level is 4 percent; the corresponding accept/reject numbers are provided in Appendix A. Accept / reject numbers are in terms of helmets tested. For the BTD test (9 mm shell), the Upper Tolerance Limit (UTL) will be computed using BTD as a continuous variable and the result compared against the requirement. The BTD UTL (with 90 percent confidence) will be calculated independently each for the crown, front, and back locations. A fourth BTD UTL (at 90 percent confidence) will be calculated by combining the right and left shot locations if the data from the qualifying First Article Test indicates the data from the side locations can be combined for analysis. (Conduct both a t-test on the means and the Brown-Forsyth test for equal variances on the standard deviations using a significance level of 0.1 in both tests.) If the data from the side locations cannot be combined, the side locations must be calculated separately. Appendix A provides UTL proportions based on helmet type and number of 9 mm shell RTP/BTD subtests. Appendix C discusses UTL calculations. Lots that fail either the resistance to penetration or BTD criteria will be rejected.

Table 2. Statistical Analysis Methodologies

Resistance to Penetration	
Analysis Methodology	4% Acceptable Quality Level
Ballistic Transient Deformation	
Analysis Methodology	Upper Tolerance Limit with 90% Confidence

Threat Munitions. The Services and USSOCOM will identify the threat munitions and associated velocities that will be applied against this protocol. As noted previously, the BTD requirement of a maximum 16.0 mm for the 9 mm projectile on the right, left, and crown regions, and 25.4 mm for the 9 mm projectile on the front and back regions, will be the DoD standard until superseded by a validated capabilities document.

This protocol does not prevent the Services or USSOCOM from conducting testing with additional threats that may not be applied against this testing protocol.

Conclusion. The Services and USSOCOM will document adherence to this protocol in formal test plans and reports. This protocol does not preclude program offices from conducting additional testing of combat helmets to ensure compliance with other contractual requirements.

Appendix A

Helmet LAT Test Matrix

UHMWPE-based LAT Matrix

Lot Size	Sub-Test			RTP Accept	RTP Reject
91-150	Small Arms Shell RTP	Shots	3	0	1
		Helmets	3		
	9 mm Hardware RTP	Shots	6	0	1
		Helmets	3		
	9 mm Shell RTP/BTD	Shots	16	1	2
		Helmets	8		
151-500	Small Arms Shell RTP	Shots	5	0	1
		Helmets	5		
	9 mm Hardware RTP	Shots	10	0	1
		Helmets	5		
	9 mm Shell RTP/BTD	Shots	16	1	2
		Helmets	8		
501-1200	Small Arms Shell RTP	Shots	5	0	1
		Helmets	5		
	9 mm Hardware RTP	Shots	10	0	1
		Helmets	5		
	9 mm Shell RTP/BTD	Shots	26	1	2
		Helmets	13		
1201-3200	Small Arms Shell RTP	Shots	8	1	2
		Helmets	8		
	9 mm Hardware RTP	Shots	16	1	2
		Helmets	8		
	9 mm Shell RTP/BTD	Shots	26	1	2
		Helmets	13		

Aramid-based LAT Matrix*

Lot Size	Sub-Test			RTP Accept	RTP Reject
91-150	9 mm Hardware RTP	Shots	6	0	1
		Helmets	3		
	9 mm Shell RTP/BTD	Shots	25	0	1
		Helmets	5		
151-500	9 mm Hardware RTP	Shots	10	0	1
		Helmets	5		
	9 mm Shell RTP/BTD	Shots	40	1	2
		Helmets	8		
501-1200	9 mm Hardware RTP	Shots	10	0	1
		Helmets	5		
	9 mm Shell RTP/BTD	Shots	65	1	2
		Helmets	13		
1201-3200	9 mm Hardware RTP	Shots	16	1	2
		Helmets	8		
	9 mm Shell RTP/BTD	Shots	65	1	2
		Helmets	13		

*Current ACH and LWH have no small arms penetration requirement.

Appendix A

Helmet LAT Test Matrix Criteria

UHMWPE-Based Helmet:

For UHMWPE-based Lots Smaller Than 500 (only):

Calculate a 85/90 BTD UTL for every location using the four shots.
If the 85/90 UTL is below the limit for that location, the helmet passes for that location.
If all locations pass for BTD UTL, the lot passes.
If the location UTL is above the limit, calculate a 60/90 UTL using the four shots.
If the 60/90 UTL is above the limit, the helmet (and the lot) fails.
If the 60/90 UTL is below the limit, shoot an additional three helmets in that shot location. If the additional shots are needed from either the back or front, repeat the full 9 mm V_0 shot sequence (crown/back or side/front) on each of the three helmets. If the additional shots are needed from either the side or crown, shoot only those locations on each helmet. All valid BTD and penetration data will be used for calculations.
Calculate a 80/90 UTL using all seven shots for that location.
If the 80/90 UTL is below the limit, the helmet (and lot) passes. If it is above the limit, the helmet and lot fail.

For UHMWPE-based Lots Larger Than 500 (only):

Calculate a 80/90 BTD UTL for every location.
If the 80/90 UTL is below the limit for that location, the helmet passes for that location.
If all locations pass for BTD UTL, the lot passes; if not, the lot fails.

For UHMWPE-based Helmet Penetration Accept / Reject:
The accept / reject criteria for 9 mm shots are the number of helmets that fail to stop any of the hardware or the shell 9 mm shots. For 9 mm shell RTP/BTD shots, if a perforation occurs on the first shot, then no second shot will be taken on that helmet. Instead, a new helmet will be shot using the full 9 mm V_0 shot sequence (two shots) to measure the BTD to complete the test matrix. A complete perforation on any shot that is otherwise fair is valid for calculating penetration results and a new (untested) helmet will be tested using the full 9 mmV0 shot sequence to complete the test matrix. All valid BTD and penetration data will be used for calculations.

Aramid-based Helmets:

9 mm BTD UTL:

Helmets Tested	UTL
13	80/90
8	75/90
5	2-Stage (see below)

For Aramid-based Lots Smaller Than 150 (only):

Calculate a 85/90 BTD UTL for every location.
If the 85/90 UTL is below the limit for that location, the helmet passes for that location.
If all locations pass for BTD UTL, the lot passes.
If the location UTL is above the limit, calculate a 60/90 UTL for that location.
If the 60/90 UTL is above the limit, the helmet (and the lot) fails.
If the 60/90 UTL is below the limit, shoot an additional three helmets beginning with the shot sequence for LAT Helmet #6 (from the Aramid 9 mm shot order table on page B-1) to obtain the data for the required shot location(s) (for sides, shoot both sides for a total of 6 more side shots). All valid BTD and penetration data will be used for calculations.
Calculate a 75/90 UTL using shots from all 8 helmets.
If the 75/90 UTL is below the limit, the helmet (and lot) passes. If it is above the limit, the helmet and lot fail.

For Aramid-Based Helmet Penetration Accept / Reject:

The accept / reject criteria for 9 mm shots are the number of helmets that fail to stop any of the hardware or the shell 9 mm shots. For 9 mm shell RTP/BTD shots, if a perforation occurs then no following shots will be taken on that helmet. A complete perforation on any shot that is otherwise fair is valid for calculating penetration results and a new (untested) helmet will be tested using the full 9 mm V_0 shot sequence to complete the test matrix. All valid BTD and penetration data will be used for calculations.

Appendix B

Helmet Test Matrix

9 mm Resistance to Penetration / Ballistic Transient Deformation Shot Order

UHMWPE 9 mm Shot Order		
	Shot 1	Shot 2
LAT Helmet #1	Cr	B
LAT Helmet #2	R	F
LAT Helmet #3	Cr	B
LAT Helmet #4	L	F
LAT Helmet #5	Cr	B
LAT Helmet #6	R	F
LAT Helmet #7	Cr	B
LAT Helmet #8	L	F
LAT Helmet #9	Cr	B
LAT Helmet #10	R	F
LAT Helmet #11	Cr	B
LAT Helmet #12	L	F
LAT Helmet #13	Cr	B

Aramid 9 mm Shot Order					
Helmet	Order				
LAT Helmet #1	B	L	Cr	F	R
LAT Helmet #2	Cr	R	B	L	F
LAT Helmet #3	R	B	Cr	L	F
LAT Helmet #4	B	F	L	R	Cr
LAT Helmet #5	B	R	F	L	Cr
LAT Helmet #6	Cr	B	L	F	R
LAT Helmet #7	L	B	Cr	F	R
LAT Helmet #8	Cr	B	R	F	L
LAT Helmet #9	L	F	R	B	Cr
LAT Helmet #10	F	Cr	B	L	R
LAT Helmet #11	Cr	L	R	B	F
LAT Helmet #12	R	F	B	L	Cr
LAT Helmet #13	Cr	F	L	B	R

Key:
F=Front
B=Back
R=Right
L=Left
Cr=Crown

All shots at 0 degrees obliquity. Shooting should start at a random point (row) in this list. Test progression is row by row, so each row is one helmet.

Appendix C

Upper Tolerance Limit

The BTD Upper Tolerance Limit (UTL) will be calculated independently each for the crown, front, and back locations. A fourth BTD UTL will be calculated by combining the right and left shot locations for all helmet sizes (combining all helmet sizes if more than one size per lot is tested) after verifying the data from the side locations can be combined for analysis. If the BTD measurements from the side locations form two distinct distributions, then a separate BTD UTL must be calculated for each side location.

For BTD, the metric of merit is an UTL based on the assumption of normally distributed BFD data – a specified UTL at 90 percent confidence. Validated one-decimal place BTD measurements, for tested combat helmet articles that did not experience complete penetrations, are the basis for any UTL calculation. The UTL is defined as $Y_u = \bar{Y} + ks$, where $\bar{Y}$ is the mean of all valid BTD measurements, k is a look-up constant (varying with the sample size, UTL percentage, and confidence percentage), and s is the sample standard deviation.[1, 2] The UTL is reported to one decimal place accuracy after adjusting upwards via the "ceiling function" – ensuring that a conservative UTL is reported. For example, calculated results of 24.1349 mm and 24.1999 mm are each reported as 24.2 mm. Compliance with the BTD requirement is achieved only if the associated reported UTL is less than or equal to 16.0 mm (for left side, right side, and crown), and 25.4 mm (for front and back) (or a superseding threshold prescribed by a validated capabilities document).

1 http://www.itl.nist.gov/div898/handbook/prc/section2/prc263.htm

2 $k = \frac{z_{utl} + \sqrt{z_{utl}^2 - ab}}{a}$ where $a = 1 - \frac{z_{conf}^2}{2 \cdot (N-1)}$ $b = z_{utl}^2 - \frac{z_{conf}^2}{N}$ and z_{utl} is the critical value from the standard normal distribution associated with the UTL percentage. z_{conf} is the critical value from the standard normal distribution associated with the confidence percentage and N is the total sample size for the data of interest.

Appendix C

Committee Meetings and Data-Gathering Activities

FIRST COMMITTEE MEETING JANUARY 24–25, 2013, ABERDEEN, MARYLAND

Objective: To introduce National Research Council (administrative actions, including committee introductions and composition, balance, and bias discussions for committee members); review committee statement of task with sponsor; visit the Aberdeen Test Center, examine equipment, and receive detailed presentations; and discuss future meeting dates and next steps.

Briefings and Discussions

Body Armor Study and Helmet Testing. Cameron R. Bass, Thomas F. Budinger, and Ronald D. Fricker, Former members, Committee on Testing of Body Armor—Phase II, and members, Committee to Review Test Protocols Used by the DoD to Test Combat Helmets.

Army Perspectives on Helmet Protection and Performance Requirements and Specifications. Ian Rozansky, Project Engineer, Office of the Product Manager for Soldier Protective Equipment, U.S. Army.

Marine Corps Perspectives on Helmet Protection and Performance Requirements and Specifications. Deidre Hooks, ECH Project Officer, and Kathy Halo, Project Engineer, Office of the Product Manager for Soldier Protective Equipment, U.S. Marine Corps.

Special Operations Forces Perspectives on Helmet Protection and Performance Requirements and Specifications. David Colanto, Project Officer—Helmets Office of the Program Manager, Special Operations Forces—Survival, Support and Equipment Systems (PM SOF-SSES).

Medical Research on Skull Behind Armor Blunt Trauma (BABT) and Injury Criteria. Richard Shoge, Deputy Portfolio Manager, Blast Injury/Hearing and Vision Protection, Military Operational Medicine Research Program, U.S. Army Medical Research and Material Command.

The Peepsite Headform. Robert Kinsler, Survivability/Lethality Analysis Directorate, Army Research Laboratory.

Joint Live Fire Test Program Behind Helmet Blunt Trauma Skull Injury. Karin Rafaels, Survivability/Lethality Analysis Directorate, Army Research Laboratory.

Protocol Analyses and Statistical Issues Related to Testing Methodologies. Janice Hester, Research Staff Member, Institute for Defense Analysis.

SECOND COMMITTEE MEETING MARCH 21–22, 2013, WASHINGTON, D.C.

Objective: To review documents and data received; receive briefings on perspectives on the new protocol; review preliminary report outline and confirm committee writing assignments; and discuss information-gathering requests, and confirm next steps.

Briefings and Discussions

Perspectives of the PEO Chief Scientist. James Zheng, Chief Scientist, Soldier Protective and Individual Equipment, PEO Soldier, U.S. Army.

Protocol Analyses and Statistical Issues Related to Testing Methodologies. Laura Freeman, Research Staff Member, Institute for Defense Analysis.

Presentation on IOP PED-003. Kyle Markwardt, Test Officer, Aberdeen Test Center.

DOT&E Issues Update. Christopher Moosmann, Live Fire Test and Evaluation Office of the Director, Operational Test and Evaluation (DOT&E).

Perspectives on the New Protocol. Robby Young, Manager of Quality Engineering, Gentex Corporation; David Rogers, Vice President of Concept Development Ops-Core, Artisent LLC (a subsidiary of Gentex); with, by video and teleconference, Clayton Maddio, Sector Integrator, and Kenneth Williams, Lead Platform Command Defense Contract Management Agency.

Perspectives on the New Protocol. Marc A. King, President, Ceradyne Armor Systems, Inc.; Vasilios Brachos, General Manager, Diaphorm Division, and head of R&D for helmet products, Ceradyne, Inc.

THIRD COMMITTEE MEETING APRIL 25–26, 2013, WASHINGTON, D.C.

Objective: To review documents and data received; to receive briefings on perspectives on the new protocol; review the concept draft; confirm committee writing assignments; and discuss information-gathering requests, and confirm next steps.

Briefings and Discussions

Setting the Specifications for Ballistic Helmets. Frank J. Lozano, Product Manager, Soldier Protective Equipment, U.S. Army.

Blast Injury Research. Natalie Eberius, Predictive Analysis Team Leader, Survivability and Lethality Analysis Directorate, Army Research Laboratory, Aberdeen Proving Grounds.

Helmet Performance Testing with Respect to Head and Brain Injury Prevention. Carol Chancey, Injury Biomechanics Branch Chief, U.S. Army Aeromedical Research Laboratory (via video teleconference).

FOURTH COMMITTEE MEETING JUNE 17–18, 2013, WASHINGTON, D.C.

Objective: To review documents and data received; receive a briefing from the Office of the DoD Inspector General; review the first-full-message draft; confirm committee writing assignments; and discuss information-gathering requests, and confirm next steps.

Briefing

Advanced Combat Helmet Technical Assessment. Anna Ferre, Tom Bulk, Kandasamy Selvavel, and Rajesh Rajendrapillai, Office of the Inspector General.

FIFTH COMMITTEE MEETING JULY 29–30, 2013, WOODS HOLE, MASSACHUSETTS

Objective: To review documents and data received; review the concurrence draft; confirm committee writing assignments; and confirm next steps.

SIXTH COMMITTEE MEETING OCTOBER 10–12, 2013, WASHINGTON, D.C.

Objective: To review the concurrence draft and reach concurrence on findings and recommendations.

Appendix D

Test Range Description and the Ballistic Testing Process

The combat helmet test range at Aberdeen Test Center (ATC) is shown in Figures D-1a and D-1b. The ATC firing range uses a rifle-like test barrel to fire a projectile against a helmet. Electronic instrumentation is used to measure projectile velocity before impact. Tested helmets are affixed to headforms that are packed with modeling clay, where the clay serves as a recording medium.

Per the Director of Operational Test and Evaluation (DOT&E) test protocol, the test range is set up in accordance with a variety of ATC Test Operating Procedures; see Table 1 in the DOT&E FAT and LAT protocols (DOT&E, 2010, 2012). The test ranges are environmentally controlled at 68 ±10°F and a relative humidity of 50 ±20 percent (ATC, 2013).

Per ATC (2013), in the range set-up, the test barrels are mounted in a universal receiver, and the weapon is fired using a solenoid. A double base configuration of light screens is used to measure projectile velocity, and drag is applied to calculate strike velocity. A yaw card is used in conjunction with a go/no-go gauge to check the striking yaw of the projectile.

FIGURE D-1a The helmet test range at the U.S. Army Aberdeen Test Center. SOURCE: Kyle Markwardt, Test Officer, Aberdeen Test Center, “Helmet IOP PED-003 Briefing to NRC Helmet Protocols Committee,” presentation to the committee on March 22, 2013.

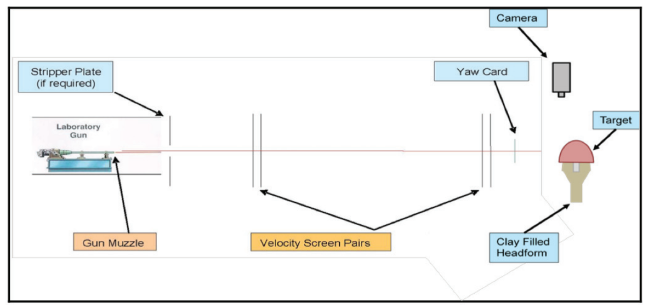

FIGURE D-1b Typical test range at set-up for helmet V_0 testing. SOURCE: ATC (2012).

In general, the test is conducted in accordance with National Institute of Justice (NIJ) Standard 0106.01 with the following four exceptions (NRC, 2012):

- Test items may be conditioned as required.
- Test distances may be altered.
- The ATC headform is modified from the NIJ headform with slots in both the coronal and midsagittal directions.
- Striking velocities are calculated according to the U.S. Army Test and Evaluation Command International Test Operating Procedure 4-2-805 in order to determine if a shot is fair (DOT&E, 2010).

Ballistic testing of combat helmets involves both the evaluation of resistance to penetration (RTP) and helmet backface deformation (BFD) as recorded in clay. With the exception of V_{50} testing, RTP and BFD are measured on a metal headform (Figure D-2) packed with Roma Plastilina #1

FIGURE D-2 U.S. Army Aberdeen Test Center headform. SOURCE: NRC (2012).

clay (as illustrated in Figure D-3), which ultimately results in a completed test headform such as that shown in Figure D-4.

Per the test methodology, a helmet is placed over the clay-filled headform. RTP (or V_0 testing) is then conducted as a sequence of five ballistic impacts, one each to the front, rear, left, and right sides of the helmet, and the helmet crown (Figure D-5). Internal Operating Procedure IOP PED-003 specifies the precise requirements for the five impact locations for V_0 9-mm RTP/BFD testing. In addition, the ballistic forces from the bullet cause an indent in the clay from which BFD is measured. Current protocol also tests the V_{50} ballistic limit using a series of 6 to 14 shots to the five regions of the helmet at varying velocities per MIL-STD-622F (DoD, 1997) . (See Chapter 6 for further discussion of the V_{50} calculation methodology.)

Appendix A of the DOT&E FAT protocol (DOT&E, 2010) specifies the distribution of helmet sizes and impact location order for V_0, V_{50}, and hardware testing. See Chapter 5 for additional discussion. The DOT&E LAT protocol does not specify helmet sizes, but impact location order for V_0 testing is contained in Appendix B. See Chapter 7 for additional discussion.

TEST ITEM CONFIGURATION AND IMPACT LOCATIONS

To allow positioning the headform in the required positions, the headform used is mounted on a test fixture capable of being rigidly fixed with six degrees of freedom. Prior to mounting, the helmet is marked to show the impact locations and the helmet pads are put into a standard configuration, as illustrated in Figure D-6.

For V_0 testing, the helmet is mounted on the headform in accordance with IOP PED-003 using the helmet's suspension/retention system to hold it on the headform (Figure D-7). Per IOP PED-003, "The finished helmet will be mounted on the headform such that it has the standoffs given in table from the inside of the crown shell to the top of the crown clay" (ATC, 2013).

The headform is mounted on the test frame shown in Figure D-8. The helmet is aligned to ensure the target location achieves the required obliquity. During the test, the velocity of the projectile is measured using Oehler Model 57 Ballistic Screens to verify that it was within the desired range (NRC, 2010). A fair hit is recorded if the shot location, obliquity, yaw, and shot velocity are within required limits as specified in the DOT&E protocol (and associated reference documents).

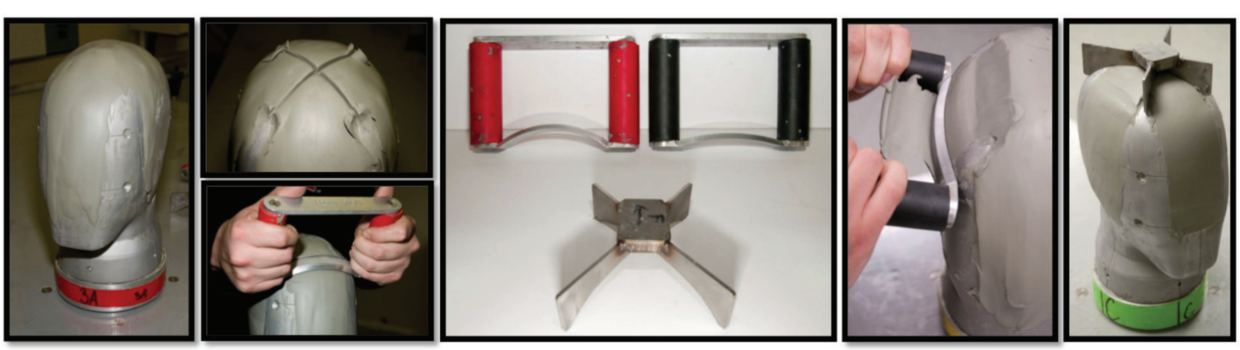

FIGURE D-3 Packing the headform with clay and shaping the clay. SOURCE: Kyle Markwardt, Test Officer, Aberdeen Test Center, "Helmet IOP PED-003 Briefing to NRC Helmet Protocols Committee," presentation to the committee on March 22, 2013.

FIGURE D-4 U.S. Army Aberdeen Test Center headform with clay. SOURCE: Kyle Markwardt, Test Officer, Aberdeen Test Center, "Helmet IOP PED-003 Briefing to NRC Helmet Protocols Committee," presentation to the committee on March 22, 2013.

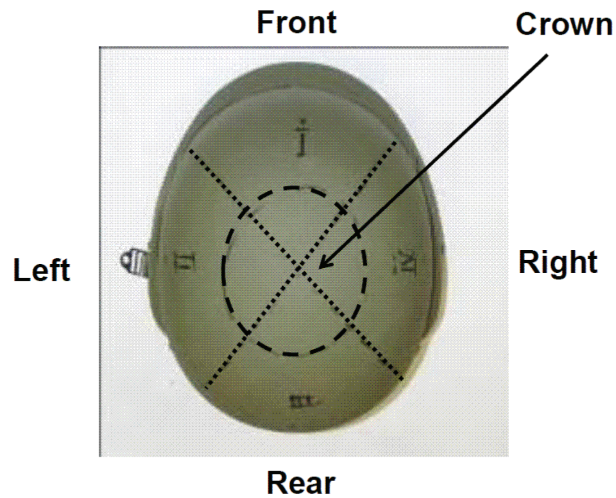

FIGURE D-5 Test impact locations. SOURCE: NRC (2012).

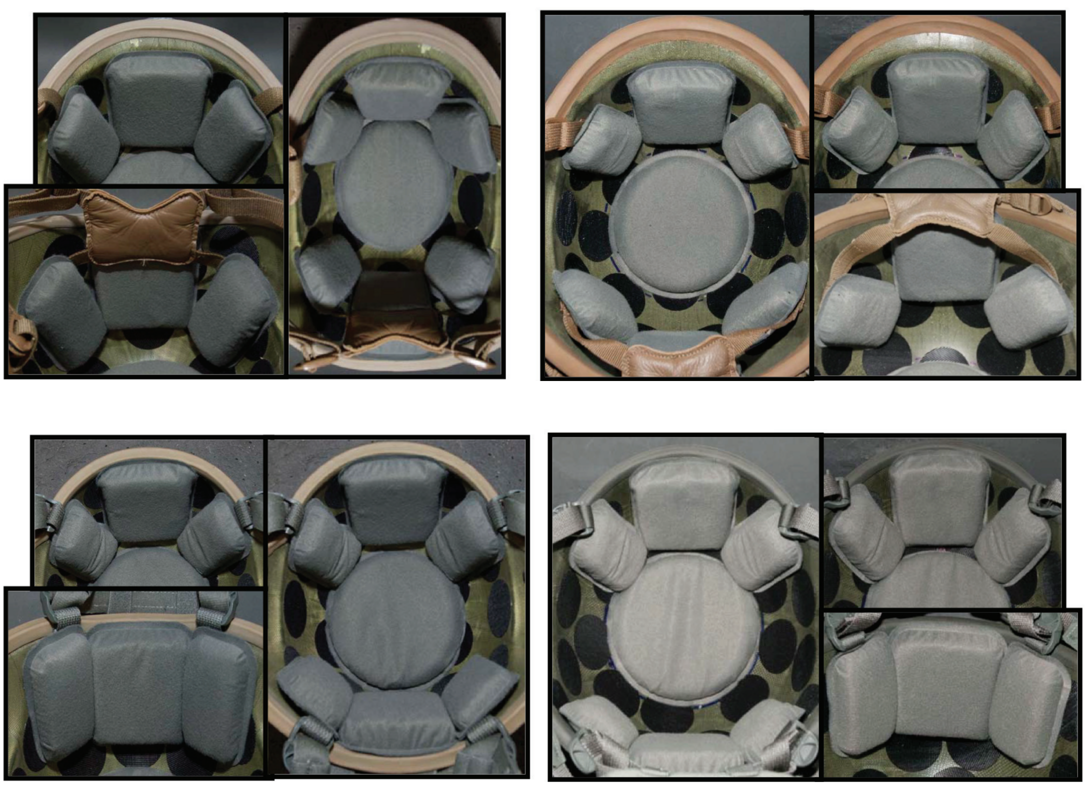

FIGURE D-6 Pad Configuration for V_0 resistance to penetration testing for full cut style helmet (*top*) or the tactical cut style helmet (*bottom*). SOURCE: Kyle Markwardt, Test Officer, Aberdeen Test Center, "Helmet IOP PED-003 Briefing to NRC Helmet Protocols Committee," presentation to the committee on March 22, 2013.

FIGURE D-7 Helmet mounted on a headform. SOURCE: ATC (2013).

Measuring Resistance to Penetration

In V_0 testing, resistance to penetration is measured by visual presence of either (1) the projectile or pieces or fragments of the projectile in the clay of the headform (Figure D-9) or (2) by a hole that passes thru the helmet shell. For hardware and V_{50} testing, penetration is recorded via a witness plate inserted in the headform. See Figure D-10 for hardware testing and Figure D-11 for V_{50} testing witness plates. V_0 testing is conducted with the helmet retention and pad systems in place, while V_{50} testing is conducted without the retention and pad systems.

Measuring Backface Deformation

Helmet BFD, defined as the maximum depth in clay as measured from the original clay surface at the intended impact location, is assessed using the nonperforating ballistic impacts from RTP testing. It is measured as follows. After mounting the headform in the test fixture and mounting the helmet on the headform, the helmet is removed from the headform, and the clay surface is scanned with a Faro® Quantum Laser Scan Arm laser. The helmet is then reattached to the headform, and the shot taken. The helmet is again removed from the headform and inspected for penetration and perforation. The clay is rescanned with the FARO laser to calculate BFD. Figure D-12 is an illustrative BFD indentation in the clay.

ATC IOP-002 revision E describes the BFD measurement process using a Faro scanning laser instrument scan

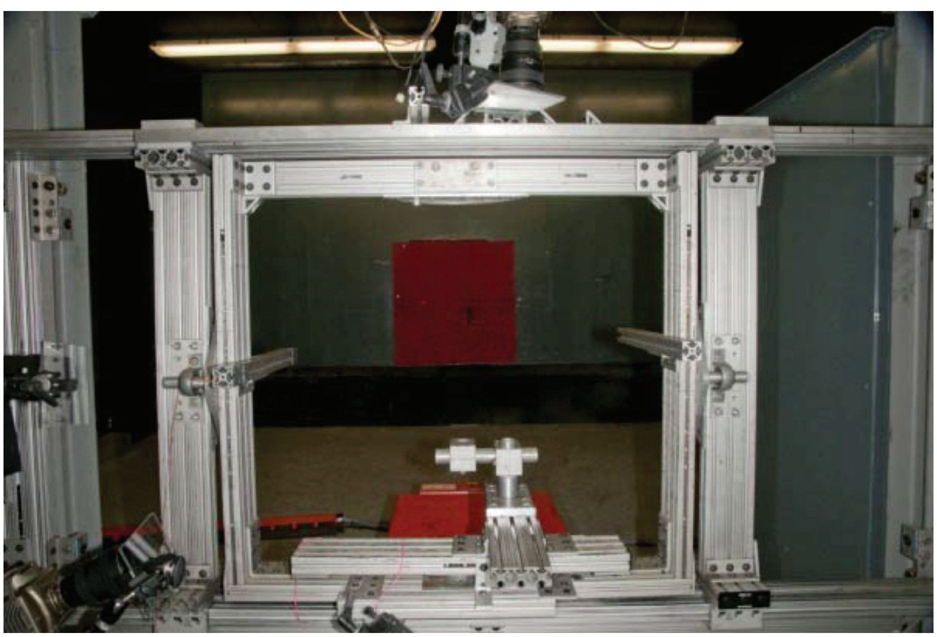

FIGURE D-8 Test frame and fixture. SOURCE: Kyle Markwardt, Test Officer, Aberdeen Test Center, “Helmet IOP PED-003 Briefing to NRC Helmet Protocols Committee,” presentation to the committee on March 22, 2013.

FIGURE D-9 Example of headform showing a penetration as evidenced by the presence of projectile fragments in the clay. SOURCE: ATC (2013).

arm (Figure D-13) and associated software. As described in *Testing of Body Armor Materials: Phase III*:

> Laser profilometry, as used by the Faro scanning laser instrument, employs the commonly used principle of optical triangulation. A laser generates a collimated beam, which is then focused and projected onto a target surface. A lens reimages the laser spot formed on the surface of the target onto a charge-coupled device, which generates a signal that is indicative of the spot's position on the detector. As the height of the target surface changes, the image of the laser spot shifts owing to parallax. To generate a three-dimensional image of the specimen's surface, the sensor scans in two dimensions, generating a set of noncontact measurements that represent the surface topography of the specimen under inspection. The data are then used to compute the three-dimensional geometrical profile of the surface, with readings essentially continuous over the scanned region. Thus, the laser scanner produces a series of measurements over the whole surface of the clay, as opposed to the single reading obtained with the digital caliper (NRC, 2010, pp. 97-98).

Clay Calibration

As described in the Phase II and Phase III body armor reports (NRC, 2010, 2012), the Roma Plastilina #1 clay currently being used to test helmets and body armor must be heated to achieve rheological properties consistent with past

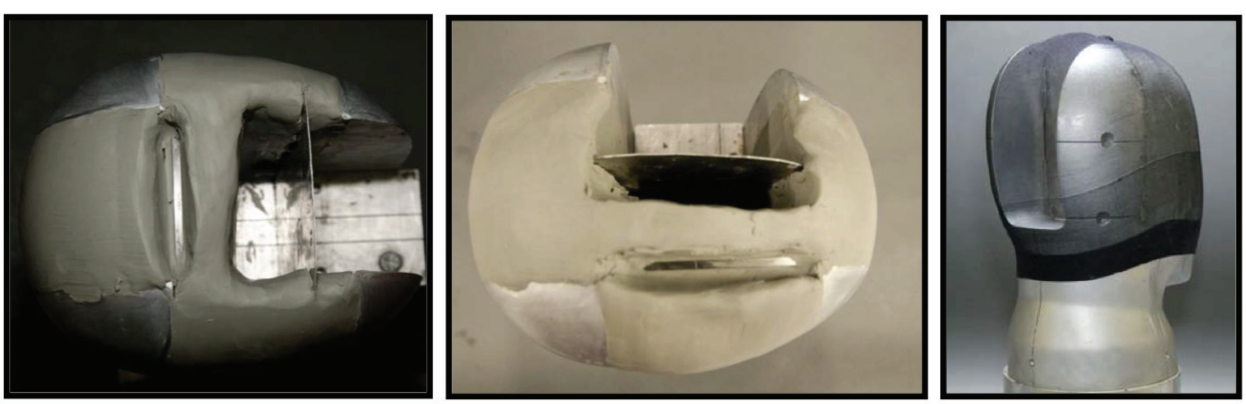

FIGURE D-10 Witness plate headforms for hardware testing. SOURCE: Kyle Markwardt, Test Officer, Aberdeen Test Center, "Helmet IOP PED-003 Briefing to NRC Helmet Protocols Committee," presentation to the committee on March 22, 2013.

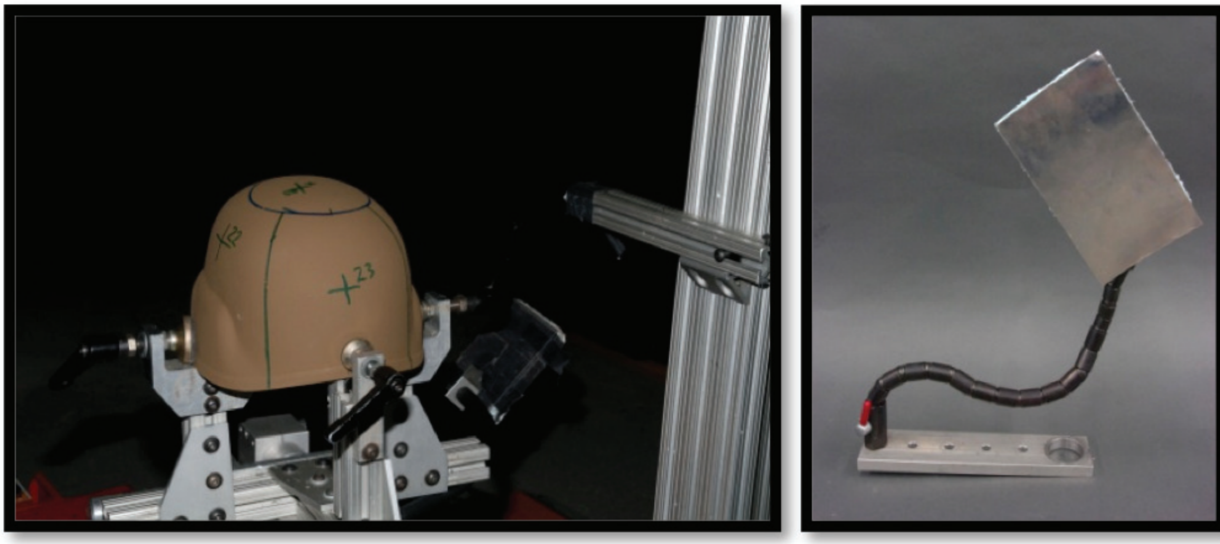

FIGURE D-11 V_{50} helmet test mount (*left*) and associated witness plate (*right*). SOURCE: ATC (2013).

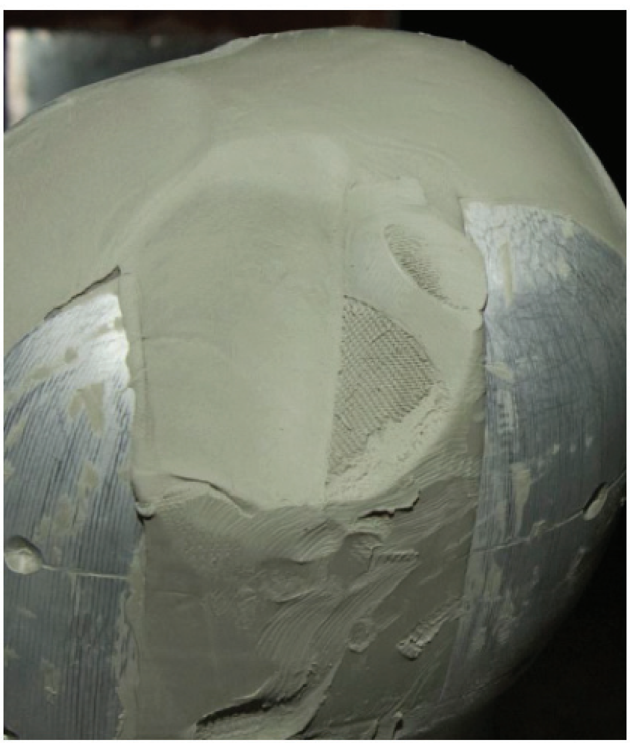

FIGURE D-12 Headform showing indent in the clay as a result of helmet backface deformation. SOURCE: Janice Hester, Research Staff Member, Institute for Defense Analysis, "DOT&E Helmet Test Protocols Overview: Statistical Considerations and Concerns," presentation to the committee on January 25, 2013.

FIGURE D-13 Faro® scanning laser instrument laser scan arm. SOURCE: NRC (2012).

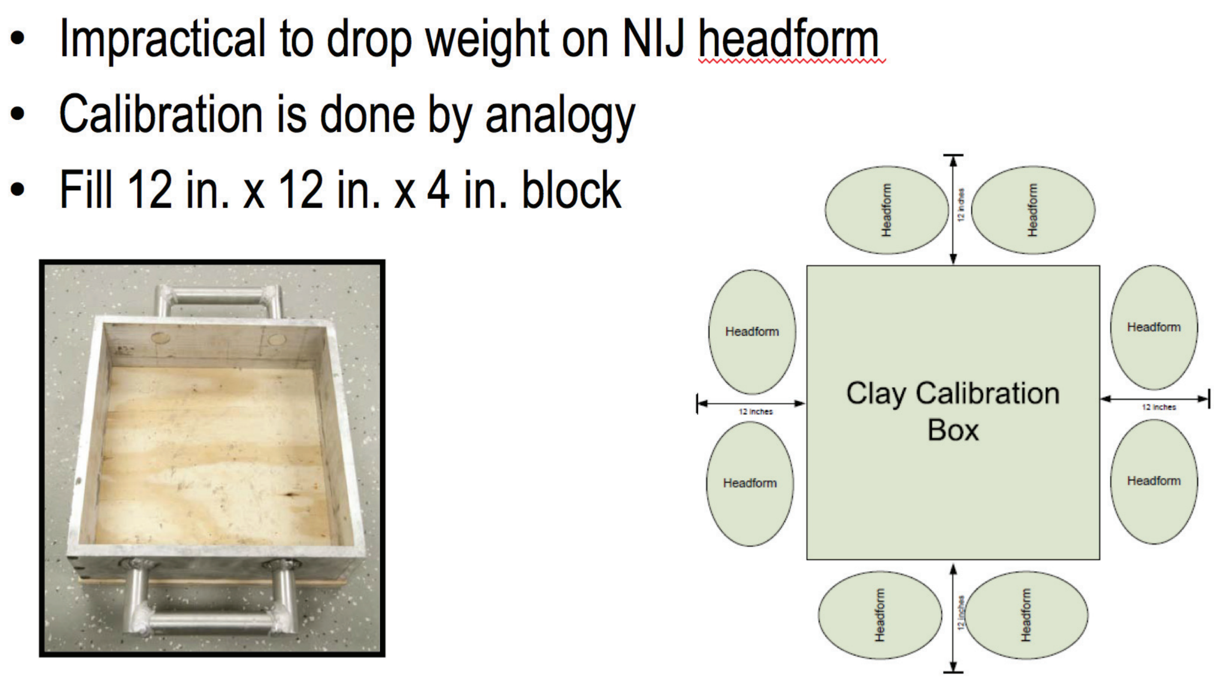

FIGURE D-14 Headform clay conditioning by analogy. SOURCE: Kyle Markwardt, Test Officer, Aberdeen Test Center, "Helmet IOP PED-003 Briefing to NRC Helmet Protocols Committee," presentation to the committee on March 22, 2013.

tests. This occurs because the manufacturer has changed the Roma Plastilina #1 clay composition over time for commercial reasons unrelated to armor and helmet testing.

For helmet testing, the clay in the headform is calibrated by analogy to a reference 12 inch × 12 inch × 4 inch plywood-backed box of clay.[1] Up to eight headforms may be conditioned with each box as long as the clay in the box and in the headforms come from the same lot and the headforms are conditioned within 12 inches of the box (Figure D-14).

Once conditioned, calibration of the box is performed via drop test in which 2.2-lb, 1.75-in.-diameter steel cylinders are dropped three times from a height of 78.7±0.8 in. into the clay box. The test rig is shown in Figure D-15. The clay is considered to be within calibration if the indentations made by the steel cylinders are all within 1.0±0.1 in. as measured by a digital caliper (NRC, 2012).

The first clay headform removed from the oven with the clay box may be used for up to 45 minutes after the third drop. The remaining headforms may be used for up to 4 hours from the time of the third drop and for up to 45 minutes after being removed from the oven (NRC, 2012).

FIGURE D-15 Clay calibration test rig. SOURCE: ATC (2013).

[1]Kyle Markwardt, Test Officer, Aberdeen Test Center, "Helmet IOP PED-003 Briefing to NRC Helmet Protocols Committee," presentation to the committee on March 22, 2013.

FIGURE D-16 Examples of helmet conditioning. SOURCE: Kyle Markwardt, Test Officer, Aberdeen Test Center, "Helmet IOP PED-003 Briefing to NRC Helmet Protocols Committee," presentation to the committee on March 22, 2013.

Helmet Conditioning

First article testing requires ballistic testing after the following conditioning:

- *Ambient*: conditioned at 68 ±10°F and a relative humidity of 50 ±20 percent;
- *High temperature*: conditioned at 160 ±10°F for minimum of 24 hours;
- *Low temperature*: conditioned at −60 ±10°F for minimum of 24 hours;
- *Seawater soak*: fully submersed in 3 ft. seawater for minimum of 3 hours;
- *Accelerated aging*: 30-lb weight on the apex of the shell, conditioned for 4 hours at a temperature of 104 ±2˚F followed by conditioning at a minimum ozone level of 50 +5 mPa partial ozone pressure for 72 hours; and
- *Weather resistance*: exposed to 100 kJ/m^2 of energy.

See Figure D-16 (ATC, 2013, slide 17; Marqwardt, 2013, slides 23-26) for examples of helmet conditioning.

For additional details and information about the testing process, see ATC (2013), the documents listed in Table 1 of the DOT&E FAT and LAT protocols (DOT&E, 2010, 2012), and particularly MIL-STD-3027 [Department of Defense Test Method for Performance Requirements and Testing of Body Armor (DoD, 1997)], ATC-IOP-PED-003 (Helmet Testing Procedures), ATC-MMTB-IOP-002 Rev. E (Measurement of Backface Deformation (BFD) Using FARO Quantum Laser Scan Arm and Geomagic Qualify for Helmets), and ATC-MMTB-IOP-004 (Ball Bar Laser Scanning, Rev. A).

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Appendix E

Synopsis of Brain Injury Detection Methods

SCOPE

Methods for detection of brain injury range from observation of the victim's behavior to advanced noninvasive imaging methods, including the following: report of symptoms and responses to questions that test awareness and memory; sophisticated computer-based neuropsychology computer tests; and advanced sensing methods of magnetic resonance, positron tomography, acoustic, electroencephalographic and impedance measurements that enable noninvasive sensing of blood flow, brain metabolism, brain inflammation, brain accumulation of markers of injury, and brain electrical properties.

The status of these methods relative to detection of traumatic brain injury (TBI) is reviewed here. Blood tests for biomarkers of nerve damage are not discussed because, despite extensive investigations in the search for definitive markers of TBI, none has emerged as specific, timely, and sufficiently sensitive for diagnosis within hours of the concussive incidents (Svetlov et al., 2009).

COGNITIVE TESTS

Detection of brain trauma in the battlefield is based on the signs and symptoms of mental status ranging from unconsciousness to symptoms such as confusion, memory loss, slurred speech, headaches, and dizziness. An assignment of concussion is based on these symptoms. The concept of concussion is imprecise and not related to a specific neurological mechanism, nor have methods of quantification of the severity of a concussive event been available until recently.

The most commonly used method for detection of concussion in combat zones and during sports events is neuropsychological testing. The assessment tool for concussion in the battlefield is the Neuropsychological Assessment Metrics (ANAM). The method is a 20-minute computer based evaluation that tests reflex times and some measures of memory and cognitive abilities. After development by the military more than 10 years ago, it has been used to assess sports injuries. Recently, ANAM was validated in the combat environment. Sixty-six cases and 146 controls were studied with the result that the simple reaction test, if applied within 72 hours of the injury, is a relatively sensitive method to differentiate concussed from non-concussed individuals in the combat environment (Kelly et al., 2012).

There are a multitutude of cognitive tests that neuropsychiatrists and psychologists use to assess and score mental capabilities. Before the computerization of cognitive tests, these were applied in controlled studies of cognitive abilities in old and young subjects years after experiencing TBI. For example, cognitive impairments 10 years following TBI were found to be associated with injury severity using tests of attention, mental processing speed, memory, and executive functions (Draper and Ponsford, 2008). An instrument that specifically assesses the quality of life in patients with TBI (Quality of Life after Brain Injury) has been developed (von Steinbüchel et al., 2010). The European Brain Injury Questionnaire (EBIQ) is a clinically reliable instrument to determine the subjective well-being of individuals with brain injury and to assess changes over time (Sopena et al., 2007).

MRI IMAGING

Of the major methods that have known efficacy in the examination of the brain in vivo (i.e., electroencephalogram [EEG], x-ray computer tomography [CT], emission tomography, magnetic resonance imaging [MRI]). MRI is the one that can provide noninvasive information specific to most of the pathologies (e.g., Gutierrez-Cadavid, 2005; Benson et al., 2012). MRI can provide a wealth of information regarding organ changes associated with ballistic trauma to the body, as has already been shown in studies of blast-injured veterans (Van Boven et al., 2009). Below is a synopsis of the specific capabilities for noninvasive measurements by MRI.

- *Brain contusion.* Edema is an expected early sign of contusion and will appear as a bright signal on T2-weighted or fluid-attenuated inversion recovery (FLAIR) MRI. The appearance of edema on MRI is variable (Gutiereex-Cadavid, 2005). T1-weighted protocols might give a sensitive diagnosis, as will other protocols.
- *Brain edema.* Edema resulting from vascular compromise (i.e., air emboli from lung damage), pressure impulse transmitted from the periphery to the brain, or ischemic damage from other causes can be detected by MRI diffusion-weighted imaging sequences, FLARE, and possibly by T1-weighted protocols.
- *Vasospasm.* Vasospasm is of major importance and perhaps the least understood. Vasospasm is a narrowing of the small arteries of the brain and frequently follows subdural hematoma, but also can occur as a consequence of blunt trauma without hematoma. The onset of vascular spasm can be a few days after trauma, and as vessel narrowing limits blood supply to parts of the brain, vasospasm is a major cause of morbidity. The importance of vasospasm has not been generally recognized (Ortell et al., 2005). It can be detected by magnetic resonance angiography (MRA) or Doppler ultrasound. The majority of cases of vasospasm reviewed at the National Naval Medical Center were blast trauma victims (Armonda et al., 2012).
- *Hemorrhage.* Early signs of hemorrhage usually occur due to tears in the tributary surface veins that bridge the brain surface to the dural venous sinus. T2-weighted MRI can show the accumulation of blood as a bright signal initially, with an evolution to a dark signal in 2 to 3 days and back again to a bright signal within the first 2 weeks (Taber et al., 2003, Tong et al., 2003). The choice of magnetic resonance (MR) protocol is important here as it has been shown that susceptibility-weighted MR imaging depicts significantly more small hemorrhagic lesions than does conventional gradient echo (GRE) MR imaging and, therefore, has the potential to improve the diagnosis of small hemorrhagic lesions as well as diffuse axonal injury (Tong et al., 2003).

Neuronal Architecture Imaging Methods

Neural axon injury might be the most subtle, yet the most important, pathology that requires early imaging for diagnosis (Mayorga, 1997). Experience has shown that this pathology occurs in the corpus callosum and brain stem. Diffusion-weighted imaging (Huisman et al., 2003) and T1-weighted protocols have been replaced by diffusion tensor imaging (DTI) because DTI has been found to be a sensitive indicator of white matter defects. DTI is able to detect damage to axonal tracts using a measure of directional water diffusion (fractional anisotropy). Fractional anisotropy metric varies from 0 to 1. Low values indicate less directional diffusion and relatively less fiber orientation suggestive of damage. This MRI method has been found to delineate white matter defects in TBI, and these defects were correlated with neuro-cognitive function (Lipton et al., 2008, Kumar et al., 2009; Jorge et al., 2012). Some caution should be exercised in making inferences from the MRI studies as being directly related to organic nerve injury. A recent study found DTI abnormalities in combat-exposed soldiers that normalized after 1.5 years, but the soldiers had neither posttraumatic stress disorder (PTSD) nor TBI (van Wingen et al., 2012).

As discussed in Chapter 10, a number of clinical imaging studies with MRI have shown associations between white matter neuronal track disruptions inferred from images and symptoms associated with blunt trauma and blast injuries in veterans months and years after return from the battlefield (Mac Donald et al., 2011; Yeh et al., 2013). However, in one study, white matter injuries were not revealed by magnetic resonance DTI on veterans with mild TBI, despite their symptoms of compromised verbal memory (Levin et al., 2010).

Functional MRI

Functional MRI (fMRI) involves evaluation of the changes in local blood flow and volume due to an external stimulus such as a visual challenge or memory test (Figure E-1). It is also known as blood oxygen level dependent (BOLD) MRI. This is an objective test of brain functioning and has been found to correlate with some post-concussion symptom metrics such as visual memory (Talavage et al., 2013).

Instrumentation availability and costs vary widely—from a permanent magnet system for small animals at less than $0.5 million to elaborate systems that combine magnetic resonance with PET at over $2 million. Most studies can be enabled through collaboration with medical clinics.

Magnetoencephalography

Mapping the origin of ionic current densities in the brain by detection of the induced magnetic fields at the surface of the human head has been employed in neurophysiological investigations and surgical applications to treat epilepsy as well as to identify functioning tissues in tumor surgery. The principal attribute of magnetoencephalography is its ability to provide high temporal fidelity information of the activity of parts of the brain with limited spatial resolution. The combination of magnetoencephalography with MRI methods, including MRI tractography (a method of displaying major nerve bundles in the brain through detection of proton diffusion principal tensor component), has promise for identification of late manifestions of neuronal dysfunction in TBI patients (Larson-Prior et al., 2013).

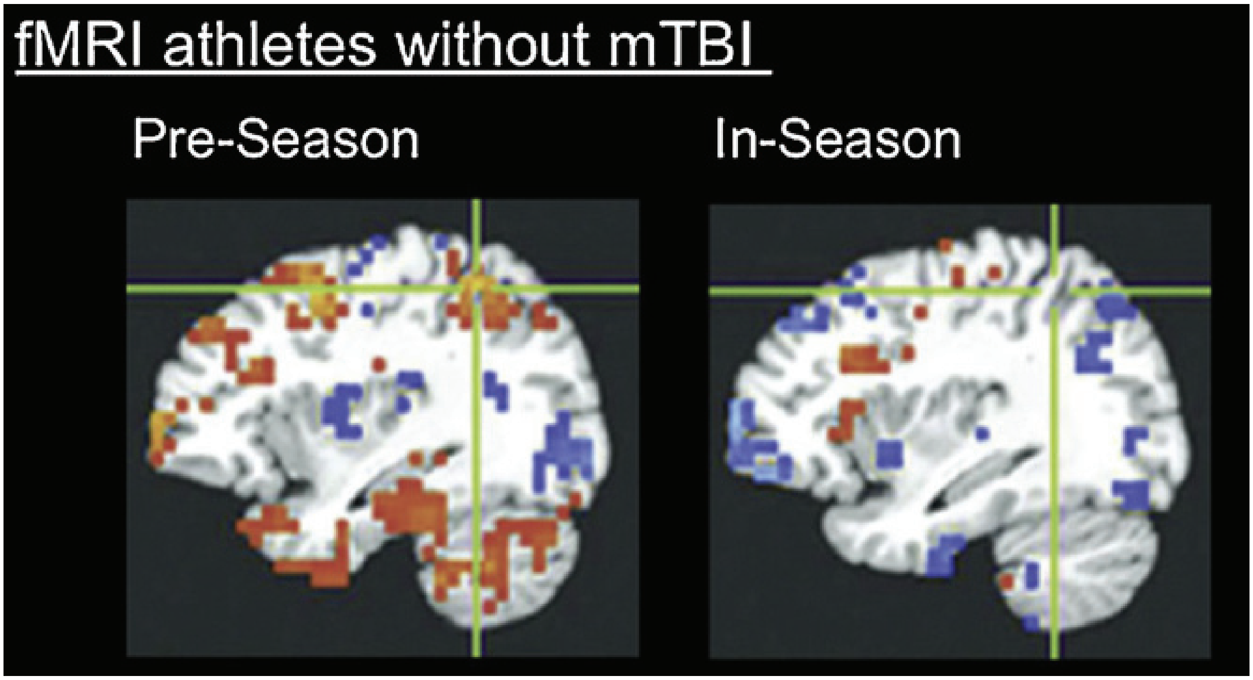

FIGURE E-1 Brain alterations shown on functional imaging without behavioral changes. fMRI image of highschool football players without clinically diagnosed concussion, performing neurocognitive testing before football season and during football season: Even in the absence of concussion (in 8 out of 21 athletes), fMRI shows changes in stimulated blood flow that are correlated with a poorer performance in neurocognitive testing. SOURCE: Talavage et al. (2013). The publisher of this copyrighted material is Mary nn Liebert, Inc., publishers.

PET AND SPECT IMAGING

Whereas magnetic resonance spectroscopy of specific volumes of the brain can define the chemical status of, for example, bioenergetic molecules (e.g., adenosine triphosphate [ATP], creatine phosphate, etc.) for most studies of brain metabolism and neuroreceoptor concentrations, emission tomography (single photon emission tomography [SPECT] and positron tomography [PET]) is the sensitive measurement method. Pathophysiological perturbations in the following parameters can be imaged by PET:

- Oxygen utilization,
- Regional glucose metabolism,
- Regional blood flow and vasospasm detection,
- Permeability,
- Neuroreceptor concentrations,
- Inflammation,
- Beta amyloid deposits associated with dementia, and
- Tau protein associated with brain trauma and dementia.

The methods are noninvasive and can be repeated over the course of hours or days. Whereas PET and SPECT are readily available in medical centers, not all experimentalists will have these instruments and the required radioisotopes available, particularly for small animal studies. The spatial resolution in instruments designed for animal studies can be 2 mm or less. Normally, the spatial resolution for large animals and human subjects is 4 to 6 mm. The tracers available allow studies of blood flow, glucose uptake (commonly interpreted as cerebral metabolism), dopamine transporters and receptors, muscarinic system activity, and blood brain permeability. PET and SPECT instrumentation for small animal studies is available from a number of vendors. Large animal studies can be accomplished through collaborators at medical institutions where the requisite approvals for use of radionuclides are already in place.

Metabolism Imaging

Since the early 1980s, cerebral glucose metabolism associated with dementia has been quantitatively imaged in patients using ^{18}F-fluoro-deoxyglucose and positron tomography. Recent human studies in boxers showed patterns of hypometabolism using the accumulation of ^{18}F-deoxy-glucose (Provenzano et al., 2010), but one must be careful not to interpret hypometabolism when the reason for less apparent tracer uptake is tissue atrophy or decreases in blood flow rather than a decrease in the metabolic uptake mechanism. An important application of PET evaluation of brain glucose uptake is to study the effects of low growth hormone associated with trauma-induced hypopituitarism because brain glucose metabolism increases after growth hormone stimulation in patients with hypopituitarism. PET using ^{13}N-labeled ammonia was shown to be an important method for detection of pituitary dysfunction in a limited study (Zang et al., 2005).

Inflammation Imaging

Detection of inflammation in the brain is facilitated by PET compounds that localize in the receptors on the surface of brain cells that are part of the inflammation response (Cagnin et al., 2001; Figure E-2). Amyloid depositions seen in nontrauma-based dementia (e.g., Alzheimer's disease) can be quantified by a ^{11}C- PET agent (Klunk et al., 2001) and recently a ^{18}F agent. Because autopsy and spinal fluid assays have demonstrated that a biomarker for dementias and blunt brain trauma is phosphorylated tau protein, a quest for a suitable ligand that would specifically accumulate in regions of the brain having excesses of tau protein has led to some successes. Tau protein is the main component in neurofibrillary tangles seen in Alzheimer's disease and the pathologic protein associated with dementias such as Pick's disease, corticobasal degeneration, and progressive supranuclear palsy.

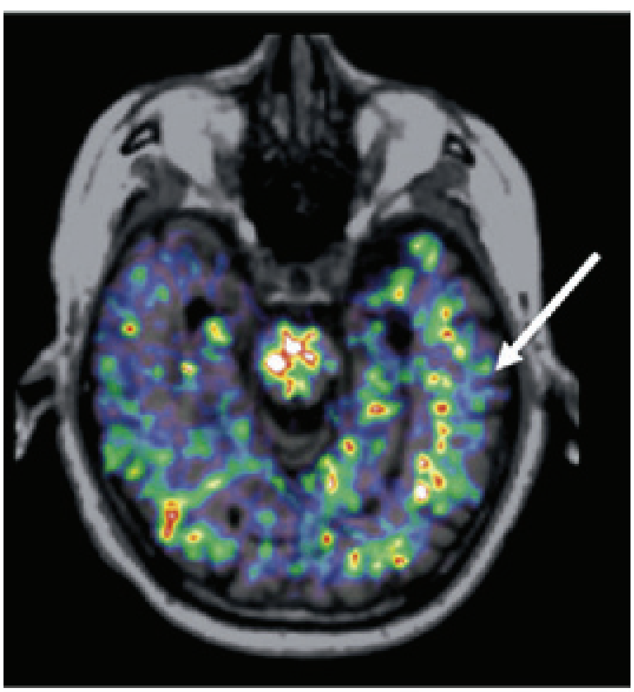

FIGURE E-2 Positron tomography image showing sites of inflammation using the tracer ^{11}C-PK11195 with superposition of the positron emission tomography emission on a magnetic resonance imaging anatomical image. SOURCE: Cagnin et al. (2007), with kind permission from Springer Science & Business Media.

Tau Protein Imaging

Studies at autopsy have shown the occurrence of tissue responses to trauma, including tau (T-tau) hyperphosphorylated protein (Blennow et al., 1995; Zetterberg et al., 2001), c-Fos and c-Myc expression, deposition of β-APP (Säljö et al., 2002), glial fibrillar acidic protein (GFAP), and fibrillar light protein (FL-P). The most recent and promising noninvasive detection method for neurochemistry of the brain in mild cognitive impairments (MCIs) and behavioral disorders subsequent to multiple episodes of blunt trauma is ^{18}F-ligands for aggregates of the protein tau known to accumulate in injured brain tissue. A few years ago, a successful study in vitro and in small animals revealed the potential of PET to visualize tau protein using a fluoroethoxyquinoline compound and the positron emitter ^{18}F (Fodero-Tavoletti et al., 2011). The first human studies with another agent for amyloid and tau protein, called FDDPN, was associated with the pattern of glucose accumulation deficits in Alzheimer's disease patients (Barrio et al., 2008) and shortly thereafter, the accumulation in the brains of symptomatic pro-football veterans was demonstrated (Small et al., 2013).

ULTRASOUND FOR BRAIN BLOOD FLOW

Measurements of blood flow in the brain basal arteries and the carotids by transcranial Doppler (Jaffres et al., 2005; Visocchi et al., 2007) are surrogates for estimating cerebral vascular resistance and are effective methods for detection of vasospasm associated with abnormally high velocities. These measurements rely on the skill of the operator. Vascular spasm can occur late after brain injury (Armonda et al., 2012) and will result in a change in the flow characteristics (Jaffres et al., 2005; Kochanowicz et al., 2006; Oertel et al., 2005) with eventual change in electrical impedance (Fritz et al., 2005). Ultrasound instrumentation is generally more available than the other radiological imaging systems for human studies. Specialized small animal systems are now available to the researcher.

ELECTROENCEPHALOGRAPHY AND ELECTRICAL IMPEDANCE

Electroencephalography and electrical impedance tomography are two techniques that might be used to assess parenchymal integrity through measurement of electrical properties both during the acute phase of ballistic trauma and during posttrauma intervals up to years. Both approaches require sensitive instruments and are plagued with electrode coupling noise. However, in previously successful large and small animal experiments, EEG measurements (Drobin et al., 2007) and impedance measurements (Klein et al., 1993; Olsson et al., 2006; Harting et al., 2010) have shown the kinetics of brain physiologic response to blunt trauma. Methods for field measurements of brain electrical potentials and impedance are available, and their development has promise using modern electrode systems and signal processing (Budinger, 1996).

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Appendix F

Biographical Sketches of Committee Members

Vijayan N. Nair, *Chair,* is the Donald A. Darling professor of statistics and professor of industrial and operations engineering at the University of Michigan, Ann Arbor. Previously, he was a research scientist at Bell Laboratories in New Jersey for 15 years. His areas of expertise include quality improvement and system development, particularly in industrial applications. Dr. Nair has done extensive consulting work with the automotive and telecommunications industries. He is a fellow of the American Association for the Advancement of Science, the American Statistical Association (ASA), the American Society for Quality (ASQ), and the Institute of Mathematical Statistics (IMS). Dr. Nair is currently president of the International Statistical Institute (ISI) and is past-president of the International Society for Business and Industrial Statistics. He served as editor of *Technometrics* and is currently co-editor-in-chief of the *International Statistical Review*. He was a member of the National Research Council (NRC) Committee on National Statistics, the NRC Board on Mathematical Sciences and their Applications, and has served on several NRC panels on statistics and testing in defense acquisition. He holds a Bachelor's degree in Economics from the University of Malaya and a Ph.D. in statistics from the University of California, Berkeley.

Christine M. Anderson-Cook has been a research scientist in the Statistical Sciences Group at Los Alamos National Laboratory since 2004. Her current research areas include design of experiments, response surface methodology, system reliability, and multiple criteria optimization. She was a faculty member in the Department of Statistics at the Virginia Polytechnic and State University from 1996 to 2004. Dr. Anderson-Cook is a fellow of the ASA as well as the ASQ. She has more than 100 peer-reviewed publications in professional statistics and interdisciplinary journals and is currently serving on the editorial boards of *Technometrics*, the *Journal of Quality Technology*, *Quality and Reliability Engineering International,* and *Quality Engineering*. She has served as the Chair of the ASQ Statistics Division (2010-2011) and the ASA Section on Quality and Productivity (2006). Dr. Anderson-Cook holds a Ph.D. in statistics from the University of Waterloo, Waterloo, Ontario, Canada, as well as an M.S. in statistics (University of Toronto, Toronto, Ontario, Canada).

Cameron R. Bass is director of the Injury Biomechanics Laboratory in the Biomedical Engineering Department at Duke University. He is a recognized expert in blast and ballistic injury risk modeling with more than 15 years of experience in biomechanics. This includes substantial experience in developing biomechanical injury models of blast, ballistic, and blunt trauma. Following postdoctoral experience (on an a National Science Foundation fellowship) developing injury biomechanics models for blunt impact at the University of Virginia, Dr. Bass established a military and high-rate biomechanics program at the University of Virginia Center for Applied Biomechanics, which he ran from 1995 to 2008. Since 2008, he has led efforts in biomechanics at Duke University in the Injury Biomechanics Laboratory. One initial focus of the program was cranial, thoracic, and spinal injuries from behind-armor blunt trauma and other biomechanically based injury risk functions. In recent years, Dr. Bass's program has focused on the assessment of brain and thoracic trauma from primary blast and high-rate blunt trauma. He has developed animal and human cadaver models for assessing blast injuries, including the first large animal model, which demonstrated diffuse injury to axons from short-duration blasts that do not cause fatality from pulmonary trauma. Dr. Bass has more than 80 peer-reviewed publications in biomechanics, including blast and blunt injury biomechanics and tissue biomechanics. He received a Ph.D. from the University of Virginia.

Thomas F. Budinger (NAE/IOM) holds concurrent positions with the University of California, Berkeley (UCB), where he is a professor of the Graduate School, and Lawrence Berkeley National Laboratory (LBNL) where he is senior scientist. He is professor emeritus at University of California, San Francisco, where he was a professor of radiology from 1984 to 2008 and previously served as director of the Magnetic Resonance Science Center and Research PET [Positron Emission Tomography] (1993-1997). At UCB, he has been a professor of bioinstrumentation, electrical engineering, and computer sciences since 1976 and is the founding chair of the Department of Bioengineering. Dr. Budinger was elected to the National Academy of Engineering in 1996 and to the Institute of Medicine in 1990. He has authored numerous papers on biomedical electronics, aging, cardiovascular physiology, bioastronautics, image processing and reconstruction, nuclear magnetic resonance, positron emission tomography, reconstruction tomography, and inverse problem mathematics. Dr. Budinger received a B.S. in chemistry from Regis College, an M.S. degree in physical oceanography from the University of Washington, Seattle, an M.D. in medicine from the University of Colorado, Denver, and a Ph.D. in medical physics from UCB. He served in the Arctic and Antarctica as a U.S. Coast Guard officer.

Michael J. Cushing recently retired as director of the U.S. Army Evaluation Center s Reliability and Maintainability Directorate. In this position he directed the evaluation of 550 active Army and Department of Defense (DoD) systems with respect to their reliability and maintainability characteristics. Dr. Cushing earned a B.S. degree in electronic engineering and computer science from Johns Hopkins University and M.S. and Ph.D. degrees in reliability engineering from the University of Maryland, College Park. During 30 years in military reliability, he authored numerous publications, helped formulate and implement a variety of Army and DoD reliability policies, and contributed towards several reliability standards.

Robert G. Easterling is retired from Sandia National Laboratories where he was a statistical consultant, manager, and senior scientist. He spent the majority of his career investigating and promoting the application of statistical methods to various engineering issues, with emphasis on statistical methods for reliability evaluation. He is a fellow of the ASA, a former editor of *Technometrics*, and a recipient of the ASQ's Brumbaugh Award. Since retirement from Sandia, he has been an itinerant visiting professor at various universities and has taught an introductory statistics short course at Sandia. He holds a Ph.D. in statistics from Oklahoma State University.

Ronald D. Fricker, Jr., is a professor at the Naval Postgraduate School. His current research is focused on the performance of various statistical methods for use in biosurveillance, particularly epidemiologic surveillance, and statistical process control methodologies more generally. Dr. Fricker holds a Ph.D. and an M.A. in statistics from Yale University, an M.S. in operations research from George Washington University, and a bachelor's degree from the U.S. Naval Academy. Upon graduation from the Naval Academy, he served as a surface warfare officer in the U.S. Navy. Dr. Fricker is a fellow of the ASA and an elected member of the International Statistical Institute. He has published widely in professional journals and is on the editorial boards of *Statistics, Politics and Policy,* and the *International Journal of Quality Technology and Engineering.* He has served as the chair of the section on Statistics in Defense and National Security (SDNS) of the ASA and, prior to the creation of SDNS, he was a member of the Committee on Statisticians in Defense and National Security, serving as both chair and vice chair.

Peter N. Fuller (Major General, U.S. Army retired) is the president and chief operating officer at Cypress International, a business development and acquisition management consulting firm operating for over 36 years. Previously, he was the deputy commander for programs, NATO Training Mission—Afghanistan, and was responsible for planning and executing resources in order to generate and sustain the Afghan security forces. He integrated and synchronized all processes to include requirements generation, acquisition, funding, construction, logistics, and contract management for a yearly program valued at over $10 billion dollars comprised of infrastructure, equipment, training, and sustainment efforts. He also coordinated with external organizations such as the Defense Contract Management Agency, Corps of Engineers, Joint Task Force-435, NATO International Security Assistance Force, ISAF Joint Command, Combined Air Power Transition Force, Office of the Secretary of Defense, and the Joint Staff. Prior to his assignment in Afghanistan, he was Program Executive Officer—Soldier. In his capacity as PEO Soldier, General Fuller was responsible for ensuring all Soldiers were lethal, survivable and able to operate in any environment. He was commissioned a second lieutenant in 1980 after graduating from the University of Vermont with a B.A. in history and political science. He also holds an M.S. in public administration from Shippensburg University, an M.S. in military arts and sciences from the U.S. Army Command and General Staff College, Fort Leavenworth, Kansas, and an M.S. in resourcing of the national security strategy from the Industrial College of the Armed Forces, Fort McNair, Washington, D.C. General Fuller's assignments include assistant director for acquisition (PATRIOT), Ballistic Missile Defense Organization, Washington, D.C.; systems coordinator, U.S. Army Staff for Anti-Armor Missiles; project manager, Stryker Brigade Combat Team; deputy commanding general of the U.S. Army Research, Development and Engineering Command, Fort Belvoir, Virginia; and Program Executive Officer—Soldier, Fort Belvoir, Virginia.

Raúl Radovitzky is the associate director, Institute for Soldier Nanotechnologies, and a professor of aeronautics and astronautics, Massachusetts Institute of Technology (MIT). Dr. Radovitzky was born in Argentina and educated at the

University of Buenos Aires, where he obtained his civil engineering degree. He received his S.M. in applied mathematics from Brown University and his Ph.D. in aeronautical engineering from the California Institute of Technology. He joined MIT's Department of Aeronautics and Astronautics in 2001 as the Charles Stark Draper Assistant Professor. Dr. Radovitzky's research interests are in the development of advanced concepts and material systems for blast, ballistic, and impact protection. To this end, his research group develops theoretical and computational descriptions of the physical event and its effects on structures and humans, including advanced computational methods and algorithms for large-scale simulation. The resulting models help to improve the understanding of the various physical components of the problem and thus to design protective systems. Dr. Radovitzky's educational interests include computational mechanics, continuum mechanics, aerospace structures, mechanics of materials, numerical methods, and high-performance computing. He is a member of the American Institute of Aeronautics and Astronautics, International Association of Computational Mechanics, American Academy of Mechanics, Materials Research Society, U.S. Association of Computational Mechanics, and American Society of Mechanical Engineers.

Ernest Seglie is retired from the position of science advisor of the Office of the Secretary of Defense, Operational Test and Evaluation. His responsibilities included providing scientific and technical guidance on the overall approach to DoD evaluation of the operational effectiveness and suitability of major DoD weapons systems. He received a B.S. in physics from Cooper Union and a Ph.D. in theoretical nuclear physics from University of Massachusetts. He taught at Rensselaer Polytechnic Institute and Yale University before joining the Institute for Defense Analyses in 1979. He received the Andrew J. Goodpaster Award for Excellence in Research in 1987, the International Test and Evaluation Association 2009 Allen R. Matthews Award for "leadership and technical contributions to the evaluation of operational effectiveness and suitability," and the National Defense Industrial Association Walter W. Hollis Award in 2009. In addition, he received the President of the United States' Rank Conferral of Meritorious Senior Professional in 2003 and the Secretary of Defense Medal for Meritorious Civilian Service in 2010, which included mention that he "led the drive to apply statistical methods to test design and evaluation." Recent areas of interest include test and evaluation policy in DoD, and reliability.