



Final Report: Eye Injury Risk Functions for Humand and FOCUS Eyes: Hyphema, Lens Dislocation, and Retinal Damage

Stefan Duma & Eric Kennedy

Notice

Qualified Requesters

Qualified requesters may obtain copies from the Defense Technical Information Center (DTIC), Fort Belvoir, Virginia 22060. Orders will be expedited if placed through the librarian or other person designated to request documents from DTIC.

Change of Address

Organizations receiving reports from the U.S. Army Aeromedical Research Laboratory on automatic mailing lists should confirm correct address when corresponding about laboratory reports.

Disposition

Destroy this document when it is no longer needed. Do not return it to the originator.

Disclaimer

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Citation of trade names in this report does not constitute an official Department of the Army endorsement or approval of the use of such commercial items.

REPORT DOCUMENTATION PAGE

*Form Approved
OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 08-07-2011		2. REPORT TYPE Contract Report		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Final Report: Eye Injury Risk Functions for Human and FOCUS Eyes: Hyphema, Lens Dislocation, and Retinal Damage				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER W81XWH-05-2-0055	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Stefan Duma, PhD Eric Kennedy, PhD				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Virginia Tech - Wake Forest University, Center for Injury Biomechanics 439 ICTAS Building, Stanger Street Blacksburg, VA 24061				8. PERFORMING ORGANIZATION REPORT NUMBER USAARL-TECH-CR--2020-046	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Medical Research and Development Command U.S. Army Aeromedical Research Laboratory P.O. Box 620577 Fort Rucker, AL 36362				10. SPONSOR/MONITOR'S ACRONYM(S) USAMRDC/USAARL	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES This work was performed under Cooperative Agreement W81XWH-05-2-0055 by the Virginia Tech - Wake Forest University, Center for Injury Biomechanics with Bucknell University for the U.S. Army Aeromedical Research Laboratory,					
14. ABSTRACT The following report presents the results from all tasks from the study "Eye Injury Risk Functions for Human and FOCUS Eyes: Hyphema, Lens Dislocation, and Retinal Damage." The study was a subtask of continued efforts under the research program "Head-Neck Injury Prevention: Biomechanical Analysis of the Eye, Face, Brain, and Neck," which was a Cooperative Agreement with the U.S. Army Aeromedical Research Laboratory, Warfighter Protection Division (now the Injury Biomechanics and Protection Group). This study had two main primary objectives. The first objective was to develop injury criteria and confidence intervals for closed globe eye injuries such as hyphema, lens dislocation, and retinal damage. The second objective of this study was to develop injury criteria for these same injuries that apply to the FOCUS (Facial and Ocular Countermeasures Safety) headform. These two objectives would enhance the ability of the FOCUS to predict and in turn prevent eye injuries from occurring in military combat.					
15. SUBJECT TERMS Impact, Closed globe eye injury, FOCUS, Hyphema, Lens dislocation, Retinal damage, Injury criteria, Survival analysis					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 74	19a. NAME OF RESPONSIBLE PERSON Loraine St. Onge, PhD
a. REPORT UNCLAS	b. ABSTRACT UNCLAS	c. THIS PAGE UNCLAS			19b. TELEPHONE NUMBER (Include area code) 334-255-6906

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

13. Supplementary Notes (continued)

a laboratory of the U.S. Army Medical Research and Development Command. Report contains the updated content after review of Government sponsors and corrections by university performers.

14. Abstract (continued)

Additionally, the injury risk functions for both humans and the FOCUS can be used in civilian applications as well, such as for evaluation of sports and recreation, automotive, and industrial eye injury risk. For the development of the closed globe eye injury criteria, a database of more than 250 eye impacts from the literature was used to develop injury criteria for hyphema, lens damage, and retinal damage. In contrast to earlier efforts to develop eye injury criteria, where logistical regression was used to develop injury risk functions, the final risk functions were generated using the more robust survival analysis methodology. The final recommended risk functions employed survival analysis, using the maximum likelihood method to estimate parameters. A weibull distribution was assumed for all injury types. Using this methodology, final risk functions and 5%-95% confidence intervals are presented for hyphema, lens damage, retinal damage, as well as globe rupture. The closed globe eye injury criteria established in Part I served as the basis for the FOCUS headform injury risk criteria developed in Part II. Eye impact testing using projectiles of six different sizes, ranging from 3.2 mm to 17.5 mm in diameter was conducted and compared to previously conducted tests that used a 4.5 mm diameter projectile. Using the peak load reported by the FOCUS headform for each impact, injury risk functions were then developed. FOCUS injury risk functions are presented for each size projectile, a total of seven projectile sizes, and four different injury outcomes for each projectile size are given (hyphema, lens damage, retinal damage, and globe rupture). These risk functions will dramatically enhance the usefulness of the FOCUS headform for evaluation of blunt impacts.

AD _____
(Leave blank)

Award Number:
W81XWH-05-2-0055

TITLE:
Final Report: Eye Injury Risk Functions for Human and FOCUS Eyes:
Hyphema, Lens Dislocation, and Retinal Damage

PRINCIPAL INVESTIGATOR:
Stefan Duma, PhD
Eric Kennedy, PhD

CONTRACTING ORGANIZATION:
Center for Injury Biomechanics
439 ICTAS Building, Stanger Street
Blacksburg, VA 24061

REPORT DATE:
August 2010 (Updated: July 2011)

TYPE OF REPORT:
Final

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: (Check one)

- Approved for public release; distribution unlimited
- Distribution limited to U.S. Government agencies only;
Report contains proprietary information

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.

FINAL REPORT
***Eye Injury Risk Functions for Human and FOCUS Eyes:
Hyphema, Lens Dislocation, and Retinal Damage***

Prepared For:

*U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012*

*Frederick Brozoski
United States Army Aeromedical Research Laboratory
Warfighter Protection Division
6901 Andrews Road
Fort Rucker, Alabama 36362-0577
Frederick.Brozoski@us.army.mil*

Prepared By:

*Eric Kennedy, PhD
Biomedical Engineering Department
Bucknell University
Lewisburg, PA 17837
eric.kennedy@bucknell.edu*

*Stefan Duma, PhD
Virginia Tech – Wake Forest University, Center for Injury Biomechanics
313 ICTAS Building
Stanger Street (MC 0298)
Blacksburg, VA 24061
duma@vt.edu*

Submitted: July 21st, 2010
Update: July 8th, 2011

REVISION NOTICE

July 8th, 2011

This version of the report includes typographical corrections for risk function coefficients given in Table 6 and Table 9. In the previous report, the alpha (α) coefficients listed in these tables were expressed in units of J/m^2 while the equations presented were written for an alpha (α) coefficient with units of kJ/m^2 . In all cases, the typographical error did not affect the risk functions presented in the related figures, nor did it impact the associated discussions within the report. Within the report itself, the text accompanying each risk function equation and tabulation of risk function coefficients has been further clarified to reduce the possibility of misinterpretation or misapplication of these data.

Several additional minor editorial revisions were also made. The asterick (*) callout below Table 4 was updated, as the text was cut-off in the previous version of the report. Additionally, along with the aforementioned clarification of text describing the use of risk functions, Equation 4 was simplified for this current update of the report, while an intermediate step in the derivation of FOCUS eye injury risk function was added (shown as Equation 5). The reduced form of the FOCUS eye injury risk function is now given as Equation 6.

ABSTRACT

The following report presents the results from all tasks from the study “Eye Injury Risk Functions for Human and FOCUS Eyes: Hyphema, Lens Dislocation, and Retinal Damage.” The study was a subtask of continued efforts under the research program “Head-Neck Injury Prevention: Biomechanical Analysis of the Eye, Face, Brain, and Neck,” which is sponsored by the US Army Aeromedical Research Laboratory, Warfighter Protection Division and funded by the US Army Medical Research and Materiel Command. This study had two main primary objectives. The first objective was to develop injury criteria and confidence intervals for closed globe eye injuries such as hyphema, lens dislocation, and retinal damage. The second objective of this study was to develop injury criteria for these same injuries that apply to the FOCUS headform. These two objectives would enhance the ability of the FOCUS to predict and in turn prevent eye injuries from occurring in military combat. Additionally, the injury risk functions for both humans and the FOCUS can be used in civilian applications as well, such as for evaluation of sports and recreation, automotive, and industrial eye injury risk.

For the development of the closed globe eye injury criteria, a database of more than 250 eye impacts from the literature was used to develop injury criteria for hyphema, lens damage, and retinal damage. In contrast to earlier efforts to develop eye injury criteria, where logistical regression was used to develop injury risk functions, the final risk functions were generated using the more robust survival analysis methodology. The final recommended risk functions employed survival analysis, using the maximum likelihood method to estimate parameters. A weibull distribution was assumed for all injury types. Using this methodology, final risk functions and 5%-95% confidence intervals are presented for hyphema, lens damage, retinal damage, as well as globe rupture.

The closed globe eye injury criteria established in Part I served as the basis for the FOCUS headform injury risk criteria developed in Part II. Eye impact testing using projectiles of six different sizes, ranging from 3.2 mm to 17.5 mm in diameter was conducted and compared to previously conducted tests that used a 4.5 mm diameter projectile. Using the peak load reported by the FOCUS headform for each impact, injury risk functions were then developed. FOCUS injury risk functions are presented for each size projectile, a total of seven projectile sizes, and four different injury outcomes for each projectile size are given (hyphema, lens damage, retinal damage, and globe rupture). These risk functions will dramatically enhance the usefulness of the FOCUS headform for evaluation of blunt impacts.

TABLE OF CONTENTS

Revision Notice.....	2
Abstract.....	3
I. Introduction.....	5
II. Review of Eye Injury Tests and Injury Criteria.....	7
III. Closed Globe Injury Criteria Development.....	10
Background:.....	10
Methods:.....	10
Part I: Eye Injury Database.....	10
Part II: Initial Logistic Regression Analysis.....	11
Part III: Data Pooling and Survival Analysis.....	11
Results:.....	12
Part I: Eye Injury Database.....	12
Part II: Initial Logistic Regression Analysis.....	12
Part III: Injury Pooling and Survival Analysis.....	15
Discussion:.....	19
Distribution Model: Weibull Distribution.....	19
Final Recommendation: Survival Analysis Risk Function (Maximum Likelihood).....	20
Comparison to Previously Published Globe Rupture Criteria.....	22
IV. FOCUS Eye Injury Criteria.....	23
Background:.....	23
Methods:.....	23
Results:.....	24
Discussion:.....	30
FOCUS Sensitivity to Projectile Kinetic and Normalized Energy.....	30
Alternative Injury Risk Function Determination.....	31
V. Task Summary from Statement of Work.....	32
VI. Publication Plan.....	35
VII. Conclusion.....	36
VIII. Acknowledgements.....	37
IX. References.....	38
X. Appendix A: Tabulation of Human Risk Function Corridors.....	41
XI. Appendix B: FOCUS Injury Risk Functions by Projectile Size.....	45
XII. Appendix C: FOCUS Injury Risk Functions by Injury Type.....	49
XIII. Appendix D: Eye Injury Database.....	51
XIV. Appendix E: Eye Injury Database With Injury Data Pooled.....	56
XV. Appendix F: FOCUS Eye Impact Test Results.....	61

I. INTRODUCTION

Eye injuries in modern warfare are an increasing concern with studies showing that the rate of injury to the eyes has dramatically increased to between 17%-26% in the current conflict (OIF/OEF) (Thomas 2009). Numerous studies have investigated eye injuries in the current conflict and show that approximately 80% of severe eye injuries are the result of debris from fragmentation, while ballistic eyewear demonstrated potential to both reduce the severity and occurrence of these injuries (Mader 2006, Thach 2008, Thomas 2009). The FOCUS Headform was developed to serve as an evaluative tool for protective equipment for the face and eyes to help mitigate some of this injury risk (Figure 1). The headform is segmented into left and right segments of all facial bones, and has instrumented eyes that can assess the severity of eye impact (Figure 2). Due to the high percentage of open-globe/penetrating eye injuries, the initial injury criterion for the headform was developed for the prediction of globe rupture and corneal penetration (Kennedy 2006A, Kennedy 2007, Bisplinghoff 2008). This initial criteria was also based on a small 4.5 mm (0.177 inch) diameter projectile size, which represented a conservative injury risk assessment for larger projectiles.



Figure 1: The FOCUS headform is designed to predict the risk of eye and facial injuries, and was particularly designed to help evaluate facial and ocular protection.

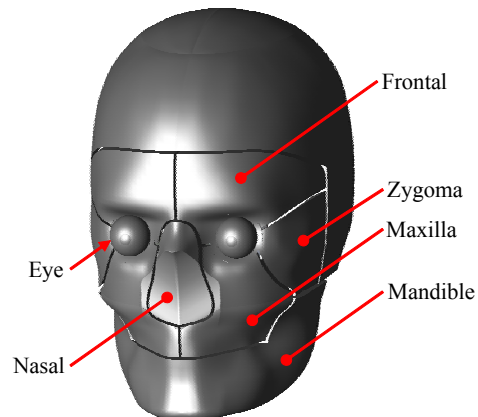


Figure 2: Segmentation of the instrumented FOCUS headform, all facial bone segments, as well as both eyes, are instrumented.

While penetrating eye injuries are experienced at extremely high rates in combat, recent studies have shown that a large minority (~ 45%) of the severe eye injuries experienced in-theater are closed-globe injuries (Thach 2008). The purpose of the current research effort has focused on expanding the available eye injury criteria for the FOCUS headform to include closed-globe injuries such as hyphema, lens- and retinal- damage. The effort is two-fold: 1) to develop eye injury criteria based on projectile normalized energy levels, and 2) using the injury criteria from Part I, to develop risk functions suitable for the FOCUS headform, which are based on headform sensor measurements.

In Part I, a database of all eye impact tests conducted and reported in the literature was created and supplemented with data from impact tests conducted at the Virginia Tech – Wake Forest University Center for Injury Biomechanics and at Bucknell University. These tests were sorted by eye injury group and analyzed to determine injury risk functions and confidence intervals for the risk functions for both closed globe injuries (hyphema, lens- and retinal- damage), while existing risk functions for open globe injuries (perforations and globe rupture) were reassessed using the same survival analysis methodology. All injuries were evaluated based on projectile normalized energy (Equation 1), which has been previously shown to have the highest predictive capability for eye injury (Duma 2005A, Kennedy 2006B).

$$\text{Normalized Energy } \left(\frac{kJ}{m^2} \right) = \frac{\text{Kinetic Energy (J)}}{\text{Projectile Area (m}^2\text{)}} \cdot \frac{1 kJ}{1000 J} \quad (\text{Equation 1})$$

In Part II, experimental eye impact tests were performed using the FOCUS headform. These impact tests corresponded to a range of impact severities and were correlated to the injury risk from Part I. Projectiles of various sizes were used to simulate the broad range of potential impacting objects that lead to eye injury. For each of the closed and open globe eye injuries (hyphema, lens damage, retinal damage, and globe rupture), risk functions were developed based on each of the various projectile sizes evaluated. In total, seven different sets of eye injury criteria were developed ranging from 3.2 mm (0.125 inches) to 17.5 mm (0.687 inches) in diameter. For each of these seven sets of projectile sizes, four injury risk functions are presented, representing risk of hyphema, lens damage, retinal damage, and globe rupture. These FOCUS headform specific criteria can now be used to evaluate a much broader spectrum of eye injuries across a broader size range of objects, which further enhances the capability of the headform.

The increased capabilities of the FOCUS headform also enhance its usefulness to the civilian sector in addition to its application in a military environment. Eye and facial injuries remain a serious threat in sports, automotive, and industrial accidents (Duma 1996, Vinger 1997, Fleischhauer 1999, Vinger 1999, Endo 2000, Kuhn 2000, Endo 2001, Duma 2002, Hansen 2003, Rodriguez 2003, Duma 2005B, Kennedy 2006C).

II. REVIEW OF EYE INJURY TESTS AND INJURY CRITERIA

Numerous previous researchers have performed eye impact tests to determine the injury tolerance of eyes to a variety of blunt objects (Weidenthal 1964, Weidenthal 1966, Delori 1969, Berger 1978, McKnight 1988, Green 1990, Galler 1995, Duma 2000, Scott 2000, Stitzel 2002, Kennedy 2006B). Additionally, other studies have performed experimental testing to determine the tolerance of the eye to injury by determining the failure threshold of the eye to an increase in internal eye pressure, as well as determining the material properties of the eye under high-rate loading conditions (Kennedy 2004, Bisplinghoff 2009). These experimental studies are used primarily for comparison and validation of computational models of the eye, where internal pressure and peak stresses are the main criteria used to infer injury (Power 2002, Stitzel 2002, Hansen 2003, Stitzel 2005).

These previously reported eye impact tests can be extremely useful for further analysis and interpretation if results are reported that can associate each unique test and testing condition with injury outcome. Previous research has shown that particular test parameters of concern are the size or diameter of a projectile, the projectile mass, projectile velocity and the injury outcome associated with each test. While not all previous studies have reported data in this much detail, many previous studies report all, or a portion of their data, that can be reassessed in more detail or utilized for further metaanalysis.

Weidenthal et al. performed two series of eye impact tests in 1964 and 1966. In the study conducted in 1964, Weidenthal et al. report on eye impact tests conducted on rhesus monkeys using a blunt, brass rod tested at various energy levels. Hyphema, lens dislocation, and globe rupture are reported. It should be noted that hyphema was the predominant injury outcome, and lens dislocation was not found in any specimens; however, several sustained a more serious injury of globe rupture which may have rendered assessment of hyphema or lens damage difficult if not impossible. Weidenthal et al. also reported a study in 1966 on BB impacts to 235 porcine eyes, as well as a compression test to rupture. Unfortunately, most of this data was insufficient to account for specific test conditions and injury pathologies with exception to two tests noted as examples within the manuscript.

Similarly, over 75 BB impacts with porcine eyes and one set of human eyes were conducted by Delori et al. (1969). Unfortunately, insufficient data is presented to account for the specific injury pathologies and the frequency at which these injuries occurred, with exception of the single test on the human eye which resulted in globe rupture.

McKnight et al. (1988) performed testing to observe the effects of radial keratotomy on globe rupture, by subjecting adult cats to eye impacts with BBs. In addition to testing on cat eyes that underwent surgery, 17 eyes were tested as controls without surgery. None of the unoperated eyes ruptured, while all suffered a hyphema.

Testing performed and reported by Green et al. (1990) was conducted on macaca fascicularis monkeys to observe fracture of the orbital floor. Additionally, these tests, conducted by dropping a brass cylinder down a tube to directly impact the globe, also resulted in 5 globe ruptures out of 16 total reported tests.

In 2000, Scott et al. reported on testing performed on pig eyes impacted with a three different blunt steel rods. These tests presented injury results for corneal abrasion, hyphema, lens damage, retinal damage and globe rupture. Perhaps most interesting is the observation that injury outcomes suggested that hyphema occurred 80% of the time with lens damage, and that lens damage was present in 100% of cases of retinal injury. However, the reciprocal was not true, where retinal injury does not always occur if lens damage is present. An injury risk function was developed to predict the likelihood of various severity injuries, such as lens damage, lens dislocation, and retinal damage.

Duma et al. (2000) performed a series of foam particle tests on 21 porcine eyes specifically looking into the incidence of corneal abrasion. This study also presented an injury risk function based on kinetic energy to predict the risk of corneal abrasion.

Stitzel et al. (2002) performed a series of 22 eye impact tests on enucleated human eyes using foam projectiles, BBs, and baseballs. The results of these tests were used to validate a failure stress level for a computational eye model. In the experimental tests, globe rupture was observed to occur from both BB impacts and baseball impacts. Data available from those tests also suggests that corneal abrasion was inspected for and not observed in three low-speed foam tests.

A study presented as part of the development of risk functions for globe rupture, Kennedy et al. (2006B) presented globe rupture tests performed on 61 human eyes and 65 porcine eyes. No other injury pathologies were noted from the testing of these fresh, post-mortem eyes.

In order to develop a comprehensive set of meaningful eye injury criteria, several previous studies have been performed that presented injury risk models for various types of eye injury. Each of these studies investigated various methods of developing injury risk models, looking into the effects of different parameters and their relationship to injury outcome. Additionally, a previous study presented a technique used for the development of eye injury criteria for the FOCUS headform.

The study by Duma et al. (2005A) presented a metaanalysis of eye injury data reported in the literature, and identified '*normalized energy*' as the most highly significant predictor of eye injury. In that study, logistic regression analysis was performed on data from multiple studies to develop eye injury risk functions; however, the combination of analysis type and available data precluded the study from obtaining confidence intervals for hyphema or retinal damage.

The study by Kennedy et al. (2006B) took a similar approach to the Duma et al. (2005) study, by expanding the dataset available for globe rupture injuries and applying the same logistic regression analysis technique to develop an injury risk function and associated confidence intervals. This study not only presents the current standard for blunt impact globe rupture injury prediction, but also serves as the foundation for the current injury risk functions for the FOCUS headform. At present, the only injury criteria for the FOCUS headform is for globe rupture and penetrating injuries due to blunt impact with projectiles 4.5 mm or larger (Kennedy 2007).

III. CLOSED GLOBE INJURY CRITERIA DEVELOPMENT

Background:

As discussed in Section II, 'Review of Eye Injury Tests and Injury Criteria,' several previous studies have been conducted where injury criteria was developed in order to predict the possibility of various types of eye injuries from blunt object impacts (Duma 2005A, Kennedy 2006B). However, the previous studies were limited in that they were unable to present a complete set of eye injury risk functions with associated confidence intervals for each injury type.

The purpose of the current research effort was to develop a comprehensive set of injury criteria for the prediction of closed globe eye injuries, specifically hyphema, lens dislocation (lens damage), and retinal damage. These injury criteria would not only provide the ability to predict risk of eye injury from a blunt projectile impact, but they would serve as the basis for the development of a more comprehensive set of injury criteria for the FOCUS headform, which will be discussed in Section IV, 'FOCUS Eye Injury Criteria.'

Methods:

The human eye injury risk functions were conducted in essentially three parts. In part I, a database was developed to include eye injury data from the literature. In Part II, a logistic regression analysis was conducted to evaluate the data in the database, and the statistical significance of its findings. In Part III, data was pooled into larger datasets based on the principle of an increasing threshold for injury for increasing severity eye injury, similar to those used by Scott et al. (2000) and Duma et al. (2002).

Part I: Eye Injury Database

In order to develop the closed globe injury criteria, a database of all blunt eye impact/injury tests conducted and reported in the literature was updated. The database was similar, but expanded in scope, to the original metaanalysis conducted by Duma (2005A) and Kennedy (2006B); including the addition of more impact tests from the literature or test results from independent studies at Virginia Tech and Bucknell University. Details of blunt impact experiments such as projectile type, mass, diameter, velocity, species of animal subjected to impact, and injury outcome (corneal abrasion, hyphema, lens damage, retinal damage, or penetrating injury/globe rupture) were recorded. Although developing a risk function for corneal abrasion was not within the specific scope of the study, it was included in the database and initial analysis, as it was considered to be the eye injury with the lowest injury threshold or tolerance. Additional parameters of kinetic energy and normalized energy were calculated based on reported projectile characteristics.

Part II: Initial Logistic Regression Analysis

Using the initial database, a first analysis was conducted on the individual data for corneal abrasion, hyphema, lens damage, retinal damage, and globe rupture. A logistic regression analysis was performed on this data to develop a parametric risk function for each injury type (corneal abrasion, hyphema, lens damage, retinal damage, and globe rupture) using normalized energy as the predictor. The logistic regression was initially used, assuming a logistic distribution, to be consistent with the methodologies used in the Duma et al. (2005A) and Kennedy et al. (2006B) studies and due to the fact that all data in this dataset was doubly-censored (Kent 2004).

Additionally, p-values and Goodman-Kruskal Gamma values were used to establish the statistical significance and goodness of fit of the risk function model to the specific injury data. The statistical software package Minitab (Minitab 15.1.0.0, Minitab Inc., State College, PA) was used for all statistical analysis.

Part III: Data Pooling and Survival Analysis

Using the results from the initial analysis, data was evaluated and pooled based on information regarding the onset of each injury type. For example, if a non-injury datapoint existed for an injury type that occurred at a lower threshold than a more severe injury, it was assumed a priori that this would therefore result in a non-injury for a more severe injury type. Similarly, for an injury datapoint of an injury outcome that was found to occur at higher thresholds of normalized energy, this it was assumed that an impact of that severity would have led to other lesser severity injuries as was included as an injury datapoint for the lower-level normalized energy injuries as well. This methodology is supported by injury outcome data from the database, and is also consistent with injury classification methodologies developed by Scott et al. (2000) and Duma et al. (2002).

It is significant to note, that although a risk function for corneal abrasion is not presented as a part of this study, impact tests that evaluated for corneal abrasion and observed no injury are included as part of the dataset for many of the test scenarios. Additionally, although only human globe rupture data was used for the globe rupture risk curve itself, globe rupture data from tests conducted on primates were included as part of the pooled injury dataset for hyphema, lens damage, and retinal damage.

Data was excluded from analysis if the projectile was larger than 25 mm in diameter. This eliminated several datapoints from the initial database that tested objects such as a cork, baseball, or squashball. These datapoints were excluded because they were larger than the eye itself, and would lead to unrealistically low estimates of normalized energy, because the contact area between the projectile and eye would be less than the overall cross-sectional area of the projectile.

Using the data pooled for each injury scenario, two distinct statistical methodologies were utilized to develop injury risk functions for each of the injury types. Both logistic regression and survival analysis for censored data were employed.

First, a logistic regression analysis was performed on the pooled data. Additionally, a probit analysis was used in conjunction with the logistic regression analysis in order to estimate confidence intervals for the injury risk model (Collett 1991, Allison 1999). Confidence intervals from 5% to 95% were calculated assuming a logistic distribution.

Second, a survival analysis for arbitrarily censored data was performed on the data to generate parametric risk functions and confidence intervals from 5% to 95%. Prior to running the survival analysis, a distribution analysis was conducted on each dataset to evaluate the goodness of fit for various distribution models used to represent the data in survival analysis. Models evaluated were the weibull, lognormal, normal, and logistic distribution. The survival analysis was conducted using both least squares and maximum likelihood estimation functions.

Results:

The results are presented in three separate sections. Part I will discuss the data contained in the eye injury database. Part II will present results from the initial logistic regression analysis. Part III will present the results of the final analysis, using survival analysis and injury pooling.

Part I: Eye Injury Database

Overall, the eye injury database contains approximately 251 individual eye impact tests reported in the literature from nine different studies (Weidenthal 1964, Weidenthal 1966, Delori 1969, McKnight 1988, Green 1990, Duma 2000, Scott 2000, Stitzel 2002, and Kennedy 2006B). An additional 296 tests from testing conducted at Virginia Tech and at Bucknell University in parallel studies are included in the database for future work, such as the development of a pressure or area-sensitive FOCUS eye.

In these studies, three animal species (cat, monkey, and porcine) as well as human eyes are used for experimental testing to determine the threshold of inducing injuries ranging from corneal abrasion, hyphema, lens damage, retinal damage, and globe rupture.

Part II: Initial Logistic Regression Analysis

Initial logistic regression analysis used a total of 162 unique tests to establish initial logistic regression curves. The quantity of injury and non-injury tests from the literature, as well as the studies where data was obtained are shown in Table 1. The complete dataset is shown in Appendix D (Table 14).

Table 1: Initial dataset from literature review.

Injury Type	Injury	Non-Injury	Species (Injury/Non-injury)	Studies
Corneal Abrasion <i>Total: 21</i>	13 Total	8 Total	Cat (0/0) Monkey (0/0) Pig (13/5) Human (0/3)	Duma (2000), Scott (2000), Stitzel (2002)
HypHEMA <i>Total: 55</i>	36 Total	19 Total	Cat (17/0) Monkey (14/14) Pig (5/5) Human (0/0)	Weidenthal (1964), McKnight (1988), Scott (2000)
Lens Damage <i>Total: 60</i>	13 Total	47 Total	Cat (0/0) Monkey (0/28) Pig (13/19) Human (0/0)	Weidenthal (1964), Weidenthal (1966), Duma (2000), Scott (2000)
Retinal Damage <i>Total: 26</i>	7 Total	19 Total	Cat (0/0) Monkey (0/0) Pig (7/19) Human (0/0)	Weidenthal (1966), Scott (2000)
Globe Rupture* <i>Total: 83</i>	27 Total	56 Total	Cat (0/0) Monkey (0/0) Pig (0/0) Human (27/56)	Delori (1969), Stitzel (2002), Kennedy (2006)

* Globe rupture dataset from Kennedy et. al (2006B) is included for completeness.

The general equation of injury risk based on a logistic regression analysis is given in Equation 2.

$$Injury\ Risk = \left[\frac{1}{1+e^{(a-b \cdot x)}} \right] \cdot 100\% \quad (Equation\ 2)$$

In Equation 2, ‘a’ and ‘b’ are parameters obtained from the logistic regression analysis for each specific injury type. While the ‘a’ term is unitless, the ‘b’ term is expressed in terms of m²/kJ, requiring an input of ‘x’, or projectile normalized energy, in units of kJ/m². Parameters are shown in Table 2, which also shows Goodman Kruskal Gamma values and p-values for each injury type. Goodman Kruskal Gamma values indicated strong fits for all injury types, with all injury types showing a fit of 0.96 or above, except for hypHEMA with a moderately high correlation of 0.79. Injury risk functions for all injury types found normalized energy to be a statistically significant predictor of injury. Unfortunately, insufficient data existed to estimate confidence intervals for retinal damage. The complete set of risk functions is shown in Figure 3.

Table 2: Risk function parameters from logistic regression using a logistic distribution. Note that these parameter values are to be used with input parameters in the form of kJ/m^2 as described by Eq. 2.

Injury Type	Logistic Regression Analysis			
	Parameter 'a' (unitless)	Parameter 'b' (m^2/kJ)	Goodman Kruskal Gamma	P-Value
Corneal Abrasion	4.87190	3.25640	0.96	< 0.001
Hyphema	2.37610	0.18960	0.79	< 0.001
Lens Damage	13.54890	0.63480	0.99	< 0.001
Retinal Damage*	71.48190	2.34190	1.00	< 0.001
Globe Rupture**	9.12274	0.25680	0.98	< 0.001

* Insufficient data for solution to converge and generate confidence intervals.

** Globe rupture dataset from Kennedy et. al (2006B) is included for completeness.

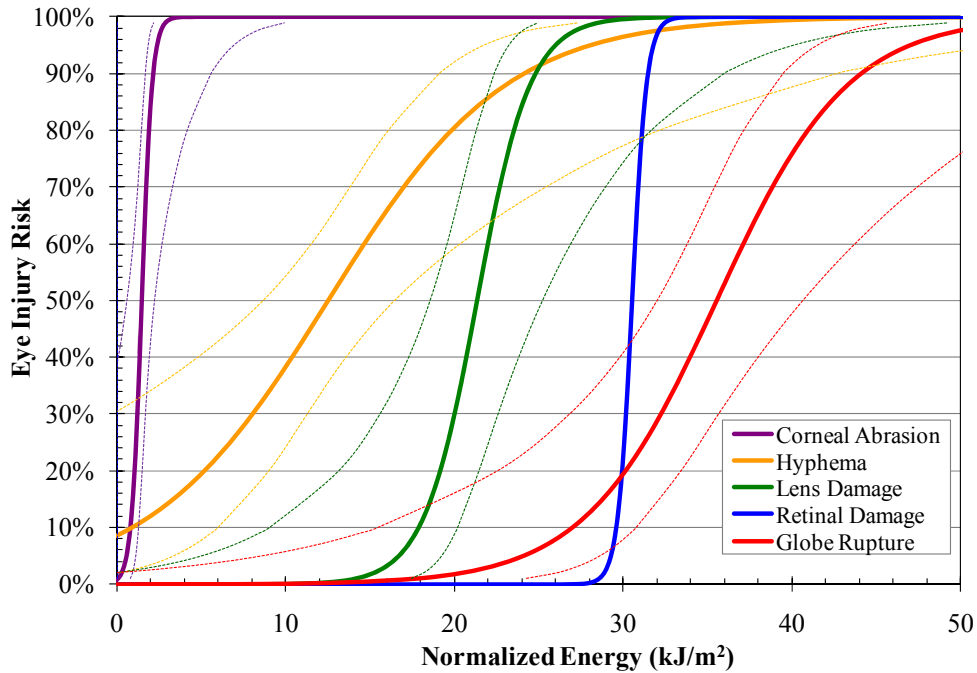


Figure 3: Risk functions for corneal abrasion, hyphema, lens damage, retinal damage and globe rupture based on initial logistic regression analysis. Confidence intervals are shown as dashed lines, although no confidence intervals could be determined for retinal damage with the original dataset.

Part III: Injury Pooling and Survival Analysis

Supplementing non-injury data with non-injury datapoints from lower-level-onset injuries and injury data with higher-level-onset injuries yielded a total of 165 individual tests from eight different studies which were used to create the injury risk functions (Table 3). A total of 104 datapoints were used to create the risk function for hyphema, 95 datapoints for lens damage, 90 datapoints for retinal damage, and the 81 datapoints were used for globe rupture. The complete dataset is shown in Appendix E (Table 15).

Table 3: Summary of total number of tests used, injury outcome, and study where data was reported. This data was used to create the risk functions for each injury type.

Injury Type	Injury	Non-Injury	Species (Injury/Non-injury)	Studies
Hyphema Total: 104	77 Total: 36 Hyphema 9 Lens Damage 0 Retinal Damage 32 Globe Rupture	27 Total: 19 Hyphema 8 Corneal Abrasion	Cat (17/0) Monkey (19/14) Pig (14/10) Human (27/3)	Weidenthal (1964), Weidenthal (1966), Delori (1969), McKnight (1988), Green (1990), Duma (2000), Scott (2000), Stitzel (2002), Kennedy (2006)
Lens Damage Total: 95	50 Total: 13 Lens Damage 0 Retinal Damage* 37 Globe Rupture	45 Total: 42 Lens Damage 0 Hyphema** 3 Corneal Abrasion	Cat (0/0) Monkey (10/23) Pig (13/19) Human (27/3)	Weidenthal (1964), Weidenthal (1966), Delori (1969), Green (1990), Duma (2000), Scott (2000), Stitzel (2002), Kennedy (2006)
Retinal Damage Total: 90	44 Total: 7 Retinal Damage 37 Globe Rupture	46 Total: 19 Retinal Damage 24 Lens Damage 0 Hyphema 3 Corneal	Cat (0/0) Monkey (10/23) Pig (7/20) Human (27/3)	Weidenthal (1964), Weidenthal (1966), Delori (1969), Green (1990), Duma (2000), Scott (2000), Stitzel (2002), Kennedy (2006)
Globe Rupture*** Total: 81	27 Total: 27 Globe Rupture	54 Total: 54 Globe Rupture	Cat (0/0) Monkey (0/0) Pig (0/0) Human (27/54)	Delori (1969), Stitzel (2002), Kennedy (2006)

* There 7 cases of retinal damage noted in the dataset, but they were observed only when lens damage was also noted (Weidenthal 1966, Scott 2000).

** There were no cases of non-injury hyphema data noted that were not also noted as incurring no lens damage (Weidenthal 1964, Scott 2000).

*** Globe rupture dataset from Kennedy et. al (2006B) was reprocessed using current survival analysis technique, projectiles larger than 25mm

The general equation of injury risk based on a logistic regression is given, again, as Equation 2.

$$Injury Risk = \left[\frac{1}{1+e^{(a-b \cdot x)}} \right] \cdot 100\% \quad (Equation 2)$$

In Equation 2, 'a' and 'b' are parameters obtained from the logistic regression analysis for each specific injury type. While the 'a' term is unitless, the 'b' term is expressed in terms of m²/kJ, requiring an input of 'x', or projectile normalized energy, in units of kJ/m². Individual parameters for the logistic regression risk function each of the various injury outcomes are given in Table 4. Goodman Kruskal Gamma values for hyphema, lens damage, retinal damage, and globe rupture are 0.93 and above. Normalized energy was determined to be a statistically significant variable for all cases, with a p-value of < 0.001.

Table 4: Risk function parameters from logistic regression using a logistic distribution. Note that these parameter values are to be used with input parameters in the form of kJ/m^2 as described by Eq. 2.

Injury Type	Logistic Regression Analysis			
	Parameter 'a' (unitless)	Parameter 'b' (m^2/kJ)	Goodman Kruskal Gamma	P-Value
Hyphema	3.16096	0.25780	0.93	< 0.001
Lens Damage	6.45795	0.38050	0.98	< 0.001
Retinal Damage	6.02105	0.34300	0.98	< 0.001
Globe Rupture*	9.09379	0.25600	0.98	< 0.001

* Globe rupture dataset from Kennedy et. al (2006B) was reprocessed using current survival analysis technique, projectiles larger than 25mm excluded.

The results of the survival analysis distribution identification are shown below in Table 5. The correlation coefficient is only calculated when using a least squares estimation function, a value closer to 1.0 indicates a better fit. The Anderson-Darling, adj. statistic is specific to each dataset, a lower number for a specific dataset indicates a better fit; however, the statistic cannot be compared between different datasets. All four distributions yielded similarly good fits to the dataset, with very little overall difference between adjusted Anderson-Darling statistics, with no one distribution type consistently demonstrating a better fit than other distributions. Because of its widespread use in developing injury risk functions within the field of injury biomechanics, all analysis was conducted assuming a weibull distribution. This distribution is commonly used for injury risk models within the field of injury biomechanics and it has been shown that other parametric distributions typically fall within the overall confidence intervals; this will be visited as well in the discussion to this section.

Table 5: Goodness of fit statistics for various distribution models evaluated for survival analysis.

Analysis Type	Distribution Model	Least Squares		Maximum Likelihood
		Correlation Coefficient	Anderson-Darling, adj.	Anderson-Darling, adj.
Hyphema	Weibull	0.978	2.715	2.506
	Lognormal	0.965	2.655	2.514
	Logistic	0.982	2.728	2.503
	Normal	0.982	2.741	2.495
Lens Damage	Weibull	0.804	4.987	4.338
	Lognormal	0.835	4.455	4.305
	Logistic	0.803	4.496	4.344
	Normal	0.803	4.530	4.337
Retinal Damage	Weibull	0.801	7.087	6.552
	Lognormal	0.829	6.656	6.521
	Logistic	0.794	6.709	6.559
	Normal	0.795	6.724	6.552
Globe Rupture	Weibull	0.930	5.018	4.923
	Lognormal	0.930	5.092	4.902
	Logistic	0.914	5.053	4.901
	Normal	0.914	5.053	4.906

The general equation of injury risk based on survival analysis, using a weibull distribution is given in Equation 3.

$$Injury Risk = \left[1 - e^{-(x/\alpha)^\beta} \right] \cdot 100\% \quad (\text{Equation 3})$$

In Equation 3, ‘ α ’ is expressed in units of kJ/m^2 , requiring an input of ‘ x ’, or projectile normalized energy, in units of kJ/m^2 . The ‘ β ’ term is unitless. The values of ‘ α ’ and ‘ β ’ are the scale and the shape parameters, respectively, and are given in Table 6, for both least squares and maximum likelihood parameter estimation techniques.

Table 6: Risk function coefficients from survival analysis using a weibull distribution. Coefficients were determined using both least squares and maximum likelihood estimation techniques. The final recommendation from this report is to use the coefficients determined from the maximum likelihood approach. Note that these parameter values are to be used with input parameters in the form of kJ/m^2 as described by Eq. 3.

Analysis Type	Hyphema		Lens Damage		Retinal Damage		Globe Rupture	
	Scale ‘ α ’ (kJ/m^2)	Shape ‘ β ’ (unitless)	Scale ‘ α ’ (kJ/m^2)	Shape ‘ β ’ (unitless)	Scale ‘ α ’ (kJ/m^2)	Shape ‘ β ’ (unitless)	Scale ‘ α ’ (kJ/m^2)	Shape ‘ β ’ (unitless)
Survival Analysis: Least Squares	13.26540	1.60484	17.03770	7.56980	17.30610	7.19171	35.15170	8.25638
Survival Analysis: Maximum Likelihood	14.23320	1.94012	19.01200	4.03800	19.82630	3.73625	38.52490	5.73194

A complete set of risk functions for each injury type was generated for comparison. The risk functions for hyphema are given in Figure 4, showing the logistic regression risk function compared to the two risk functions generated using survival analysis, both least squares and maximum likelihood estimation methods. The comparative set of risk functions also show each

injury and non-injury datapoint that was used in the analysis. Similar plots of risk functions were created for lens damage (Figure 5), retinal damage (Figure 6), and globe rupture (Figure 7). Tables giving confidence interval limits for the risk functions are provided in Appendix A.

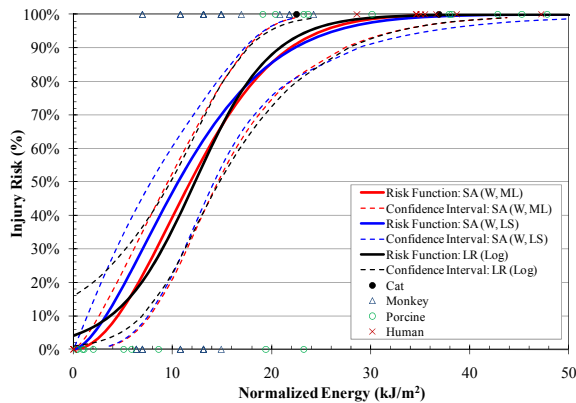


Figure 4: Comparison of risk functions generated for hyphema developed from pooling of eye injury data from database. Three risk functions are shown: a risk function developed using a survival analysis, assumed weibull distribution using maximum likelihood to estimate parameters, a risk function developed using a survival analysis, assumed weibull distribution using least squares to estimate parameters, and a risk function developed by logistic regression technique. Injury and non-injury datapoints are shown along the axis.

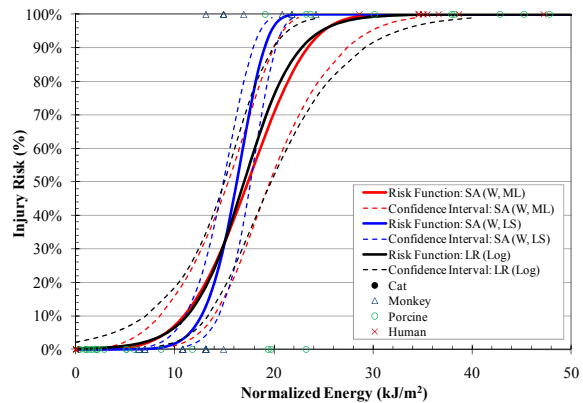


Figure 5: Comparison of risk functions generated for lens damage developed from pooling of eye injury data from database. Three risk functions are shown: a risk function developed using a survival analysis, assumed weibull distribution using maximum likelihood to estimate parameters, a risk function developed using a survival analysis, assumed weibull distribution using least squares to estimate parameters, and a risk function developed by logistic regression technique. Injury and non-injury datapoints are shown along the axis.

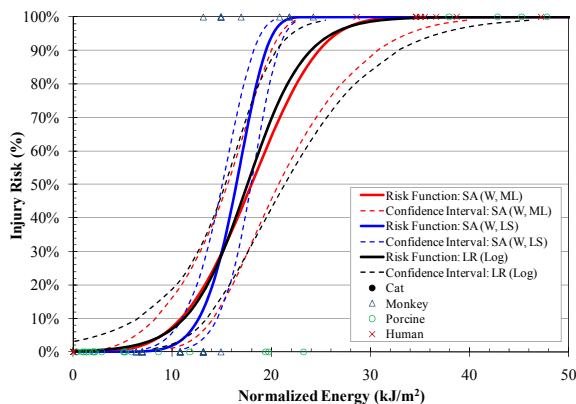


Figure 6: Comparison of risk functions generated for retinal damage developed from pooling of eye injury data from database. Three risk functions are shown: a risk function developed using a survival analysis, assumed weibull distribution using maximum likelihood to estimate parameters, a risk function developed using a survival analysis, assumed weibull distribution using least squares to estimate parameters, and a risk function developed by logistic regression technique. Injury and non-injury datapoints are shown along the axis.

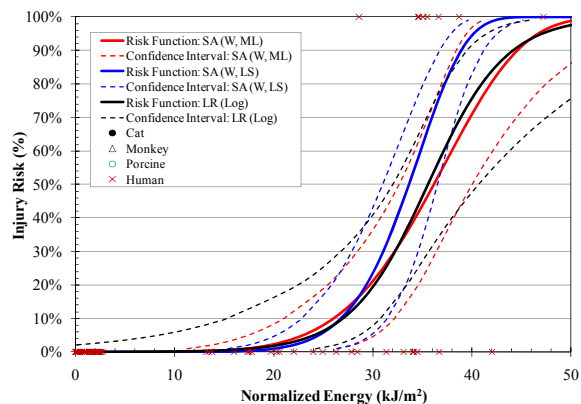


Figure 7: Comparison of risk functions generated for globe rupture developed from pooling of eye injury data from database. Three risk functions are shown: a risk function developed using a survival analysis, assumed weibull distribution using maximum likelihood to estimate parameters, a risk function developed using a survival analysis, assumed weibull distribution using least squares to estimate parameters, and a risk function developed by logistic regression technique. Injury and non-injury datapoints are shown along the axis.

Discussion:

Distribution Model: Weibull Distribution

Within the survival analysis model, there are multiple possible distributions from which an injury risk function could be generated. The weibull distribution was selected as the preferred model for the development of the eye injury risk functions for several reasons. First, across the various injury types, no distribution type was consistently the best fit, making it difficult to select one model as clearly the best-fit. A study by Kent et al. (2004) looked into the effects of various distributions on the outcome of injury risk functions based on biomechanical data and concluded that the effects of distribution type were inconsequential to the final form of risk function, with each function falling within the overall confidence intervals and the limited amount of data used to generate risk functions in the injury biomechanics community. The weibull model is often cited as the preferred distribution type for biomechanical injury data, so this distribution was selected as the preferred distribution for the current analysis

In order to demonstrate the effect of the selection of this distribution type on the final risk function model, a comparison plot was generated to show the relationship of the injury risk functions to the globe rupture risk function presented by Kennedy et al. (2006B) for globe rupture (Figure 8). In this comparison plot, the consistency between the two sets of risk functions for globe rupture can be observed. The maximum difference for any given globe rupture risk level is 1.1 kJ/m² up to a 98% risk.

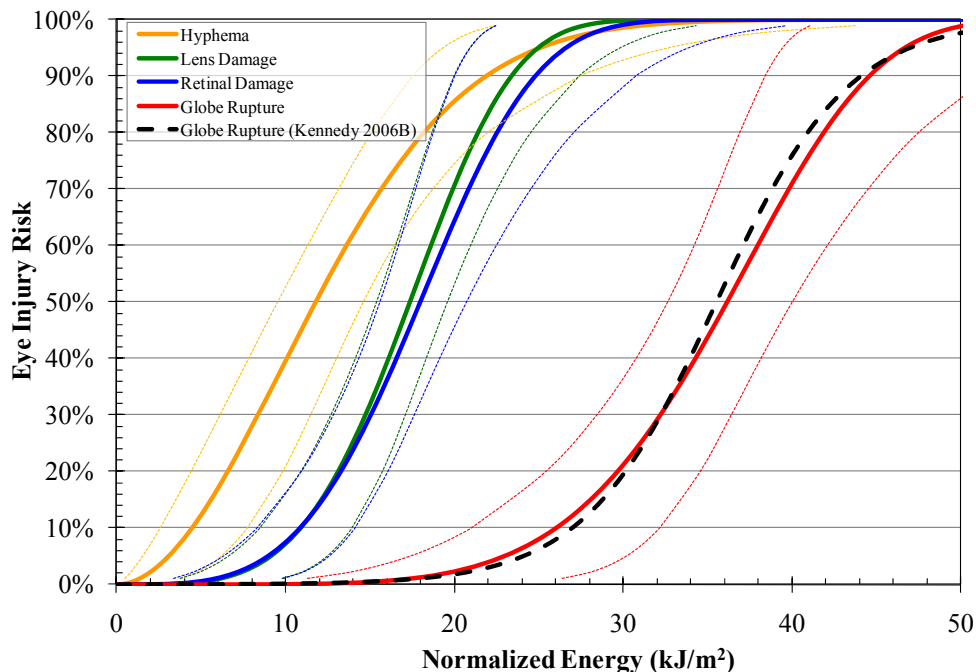


Figure 8: Comparison plot showing the relationship between the risk functions developed as part of this study and the risk function for globe rupture presented by Kennedy et al. (2006B). The risk functions shown in this plot are generated using survival analysis, with a weibull distribution, parameters estimated by maximum likelihood method.

Final Recommendation: Survival Analysis Risk Function (Maximum Likelihood)

A study of the literature yields a tremendous number of possibilities and recommendations for potential injury risk function models, such as the consistent threshold (CT) technique, modified median rank, certainty method, logistic regression, survival analysis (Mertz 1996, Eppinger 1999, DiDomenico 2003, Kent 2004). Even disregarding all potential models with exception to survival analysis, a tremendous number of potential models exist based on assumed distribution type and parameter estimation methods.

Overall, for these eye injury criteria, the recommended version of the risk functions for hyphema, lens damage, retinal damage, and globe rupture is survival analysis, assuming a weibull distribution model and employing the maximum likelihood method for establishing parameter estimates. This is for several reasons.

Survival analysis is recommended because it is widely considered to be an excellent parametric failure modeling technique, offering a robust analysis of injury data. Survival analysis is possible on datasets that include right-censored non-injury data, as well as non-censored and left-censored injury datapoints (Kent 2004). Additionally, the parametric models are recommended over non-parametric models because they account for the possibility of injury probability at toe regions of the curve, with the assumption that the lowest level injury point used within a test series does not account for the potential for injury at an even lower impact level. A non-parametric model, such as CT, will show a 0% risk of injury up to the first injury datapoint (Kent 2004).

This study used two different approaches to estimate the parameters used for the survival analysis risk functions, a least squares approach, as well as a maximum likelihood approach. It is suggested that the most appropriate estimation approach for this analysis is maximum likelihood. This is recommended due to the fact that for censored data, such as in this study, the maximum likelihood estimation method will theoretically yield the most precise estimate of risk function parameters as compared to the least squares estimation method (Abernathy 1996).

It should also be noted from Figure 4, Figure 5, Figure 6, and Figure 7 that the survival analysis risk functions generated using least squares (as well as the logistic regression) may sometimes present a more conservative risk function, generally with regard to risk levels above 30%. The variation between each of these risk functions lie within the confidence intervals of each technique, which suggests that these are extremely minor variations; however, where it is warranted, it may be desirable to calculate or determine injury risk with each of the presented risk functions for comparison. Because the target of most evaluative testing is to ensure that moderate levels of risk are not exceeded, such as verifying that risk is less than 20% for a given impact scenario, the differences between various models will often be inconsequential.

Ultimately, taking the aforementioned points under consideration, the risk functions developed using a survival analysis technique, with the weibull distribution, and estimating parameters with

the maximum likelihood estimation technique generates the recommended final form of eye injury risk functions. The final recommended curve (shown independent from the other forms of the risk functions depicted in the Results) for hyphema is given in Figure 9, for lens damage in Figure 10, retinal damage in Figure 11, and globe rupture in Figure 12. The combined set of injury risk functions is given in Figure 13.

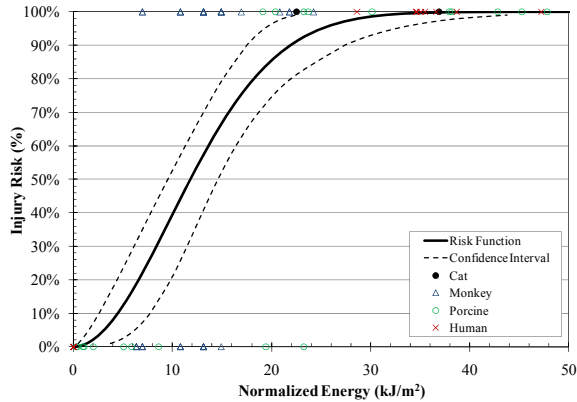


Figure 9: Final form of the risk function recommended for hyphema. The risk function is developed using survival analysis, with a weibull distribution. The scale and shape parameter estimates are obtained using the maximum likelihood method.

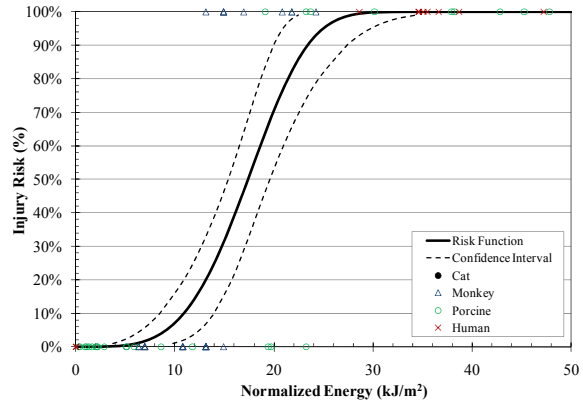


Figure 10: Final form of the risk function recommended for lens damage. The risk function is developed using survival analysis, with a weibull distribution. The scale and shape parameter estimates are obtained using the maximum likelihood method.

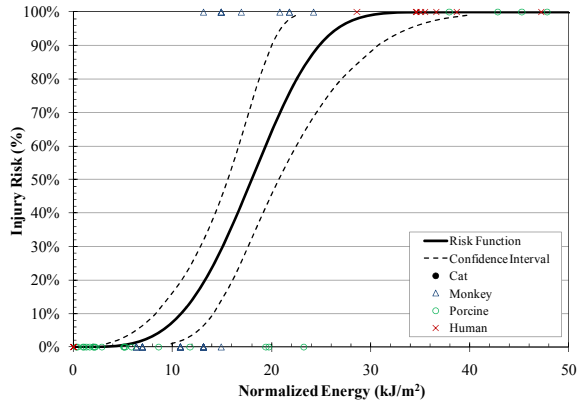


Figure 11: Final form of the risk function recommended for retinal damage. The risk function is developed using survival analysis, with a weibull distribution. The scale and shape parameter estimates are obtained using the maximum likelihood method.

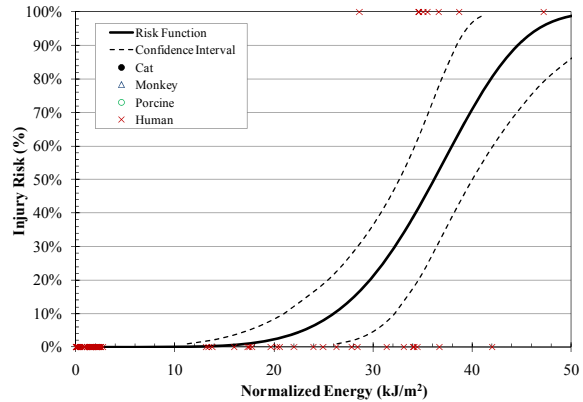


Figure 12: Final form of the risk function recommended for globe rupture. The risk function is developed using survival analysis, with a weibull distribution. The scale and shape parameter estimates are obtained using the maximum likelihood method.

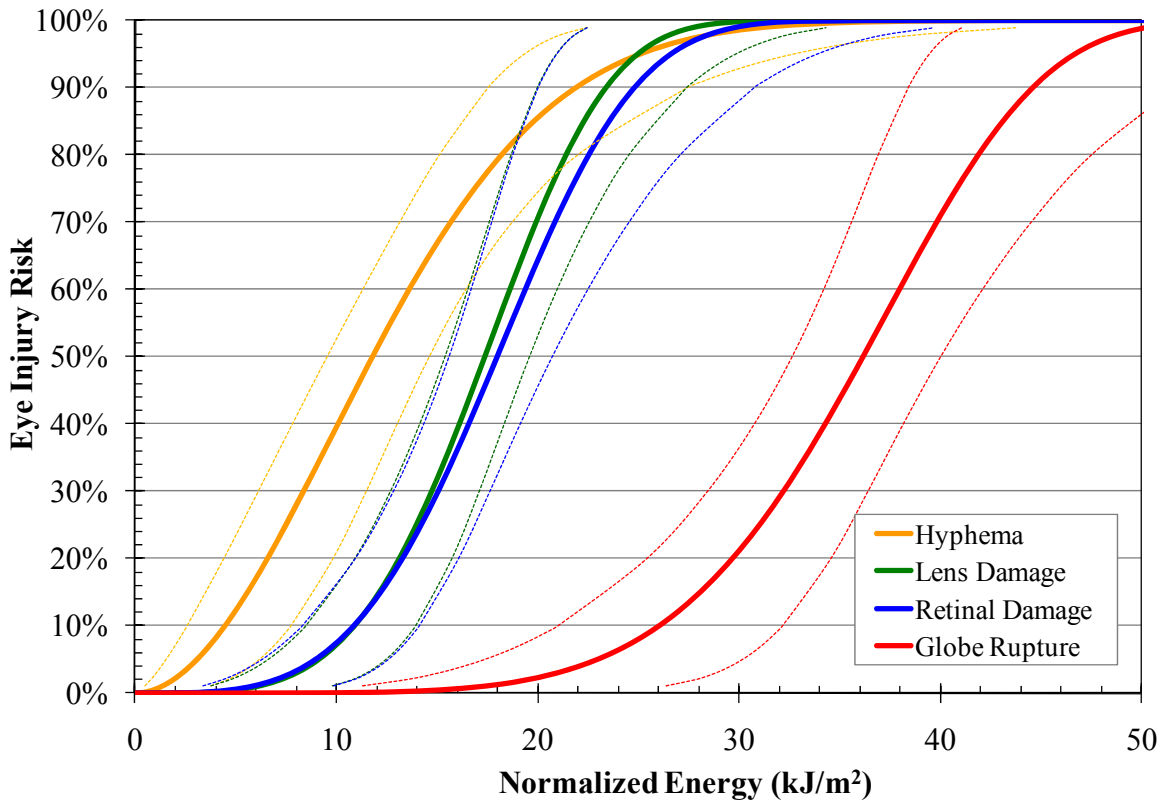


Figure 13: Injury risk function generated from survival analysis using a weibull distribution and estimates based on maximum likelihood method. Confidence intervals for each injury type from 5%-95% are shown as dashed lines.

Comparison to Previously Published Globe Rupture Criteria

Given that within the survival analysis model, there are multiple possible distributions from which an injury risk function could be generated. The weibull distribution was selected as the preferred model for the development of the eye injury risk functions for several reasons. First, across the various injury types, no distribution type was consistently the best fit, making it difficult to select one model as clearly the best-fit. A study by Kent et al. (2004) looked into the effects of various distributions on the outcome of injury risk functions based on biomechanical data and concluded that the effects of distribution type were inconsequential to the final form of risk function, with each function falling within the overall confidence intervals and the limited amount of data used to generate risk functions in the injury biomechanics community. The weibull model is often cited as the preferred distribution type for biomechanical injury data, so this distribution was selected as the preferred distribution for the current analysis.

IV. FOCUS EYE INJURY CRITERIA

Background:

The eyes of the FOCUS headform were initially developed and validated in a three-part study by Kennedy et al. (2007). In that study, force-deflection corridors for human eyes were developed, then the force-deflection response of the FOCUS eyes were validated to fall within the human response corridors. Finally, initial injury criteria were developed for the FOCUS headform to predict the risk of globe rupture, based on existing globe rupture injury criteria.

The initial globe rupture risk functions developed by Kennedy et al (2007) were developed by using a 4.5 mm projectile and correlating the risk of injury based on projectile normalized energy to the response of the FOCUS eye load cell. In performing these initial tests it was observed that the FOCUS eye load cell measurement was highly correlated to the kinetic energy of impacting objects ($R^2=0.996$), but not sensitive to variation in size, or cross-sectional area of the projectile. This finding meant that for objects larger than 4.5 mm the developed injury risk functions would be conservative. Therefore, in addition to developing injury risk functions for other closed-globe injuries, it was desirable to develop risk functions across broad size range of projectiles, for more accurate and less-conservative injury risk determination when projectile size is known or can be obtained by other means.

The purpose of this portion of the study was to develop injury criteria for the FOCUS headform for closed globe injuries of hyphema, lens damage, and retinal damage. Additionally, risk functions were generated for a broad size range of projectiles ranging from 3.2 mm to 17.5 mm in diameter. Globe rupture risk functions were also generated for each scenario for completeness.

Methods:

In order to generate the injury risk functions for the FOCUS, impact tests were conducted on both left and right eyes of the FOCUS headform using spherical steel projectiles. All tests were conducted using a pneumatic cannon to fire the projectiles from approximately 0.5 m from the headform.

A uni-axial load cell (8060JFL, Robert A. Denton, Inc., Rochester Hills, MI) at the aft-end of the modular orbit measured impact loads transmitted through the eye and surrounding soft tissue. Data was collected from the load cell at 50 kHz and was filtered to 3500 Hz using a Butterworth 4-pole phaseless digital filter.

High-speed video (Motion Scope M3, Integrated Design Tools, Inc., Tallahassee, FL) at 4000 frames/second was used to visualize the response of the eye as it was impacted by oncoming projectiles, as well as to calculate the velocity of the projectile when it was approximately 10 mm to 30 mm from striking the eye. The velocity of the projectile, the kinetic energy, and the normalized energy (kJ/m^2) were calculated for each impact.

A regression analysis was performed to establish the best model to relate the peak FOCUS eye load cell measurement with the kinetic energy and normalized energy of the projectile. Using the relationship between peak FOCUS eye impact force and normalized energy, an equation was developed to calculate the risk of eye injury based on FOCUS eye impact force. Risk functions were based on the results from Section III: Closed Globe Eye Injury Criteria Development, using the final risk functions from survival analysis methodology with weibull distribution and parameters estimated using the maximum likelihood approach. Overall, risk functions for use with the FOCUS headform were created for a total of seven projectile sizes. For each size projectile, risk functions to predict the risk of hyphema, lens damage, retinal damage, and globe rupture were determined.

Results:

Overall, a total of 296 impact tests were conducted on the FOCUS headform using six different spherical projectiles ranging in size from 3.2 mm to 17.5 mm in diameter. A total of 12 FOCUS eyes were used for all testing, their use randomized between each of the six barrel sizes used. A summary of the impact tests conducted is contained in Table 7 below. Additionally, the dataset from the 82 4.5 mm projectile FOCUS impact tests conducted by Kennedy et al. (2007) were combined with this dataset for analysis. All impact tests results are given in Appendix F (Table 16 - Table 21).

Table 7: Summary of experimental impact tests conducted on FOCUS headform for development of closed globe injury criteria and development of projectile size-dependent injury criteria.

Projectile Diameter (mm)	Total Tests	Eyes Tested	Peak Force (N)		Velocity (m/s)		Energy (J)		Normalized Energy (kJ/m ²)	
			Min	Max	Min	Max	Min	Max	Min	Max
3.2 mm	59	6	5.0	156.4	38.5	108.8	0.09	0.75	12.0	95.6
4.5 mm*	82	2	11.5	153.1	12.0	73.8	0.02	0.93	1.6	59.8
6.4 mm	59	8	135.9	702.5	25.5	101.1	0.34	5.27	10.6	165.9
9.5 mm	39	8	32.2	775.3	4.6	47.5	0.04	3.89	0.5	54.6
12.7 mm	41	7	5.0	882.1	2.2	30.7	0.02	3.91	0.2	30.8
15.9 mm	57	6	39.5	917.0	2.6	22.8	0.06	4.18	0.3	21.1
17.5 mm	41	5	69.2	846.3	3.3	21.7	0.13	5.47	0.5	22.9

* Data from FOCUS eye impact tests reported by Kennedy et. al (2007)

The response of the FOCUS eye load cell was found to be proportional to the kinetic energy of each projectile tested. Equation 4 presents a generalized form of the equation that can be used to determine the kinetic energy of the projectile based on the peak load of the FOCUS eye load cell. In this equation, 'F' is the peak force of the load cell in newtons, 'a' is given in newtons to normalize the force, while 'n' is unitless. Terms 'a' and 'n' are specific to the projectile size and yield the kinetic energy, or 'E,' of the projectile in joules (Table 8).

$$Kinetic\ Energy\ ('E',\ in\ Joules) = 1\ Joule \cdot \left(\frac{F}{a}\right)^{\frac{1}{n}} \quad (Equation\ 4)$$

Table 8: Parameters for predicting the kinetic energy of the projectile based on FOCUS eye load force, as given in Equation 4.

Projectile Size (mm)	a (N)	n (unitless)	Correlation Coefficient
> 3.2 mm	162.16	0.8188	0.95
> 4.5 mm*	164.15	0.7295	1.00
> 6.4 mm	234.49	0.5654	0.95
> 9.5 mm	318.82	0.6929	0.97
> 12.7 mm	290.60	0.7735	0.96
> 15.9 mm	291.19	0.6525	0.99
> 17.5 mm	279.49	0.6411	0.99

* Data from FOCUS eye impact tests reported by Kennedy et al. (2007)

A graphical representation of the relationship between projectile kinetic energy and the FOCUS eye peak impact force is created from Equation 4 and parameters listed in Table 8 (Figure 14). It should be noted that the aperture of the opening in the FOCUS eye is approximately 13 mm in height, and less impact force is transmitted to the eye load cell for objects exceeding this diameter (at the same energy level).

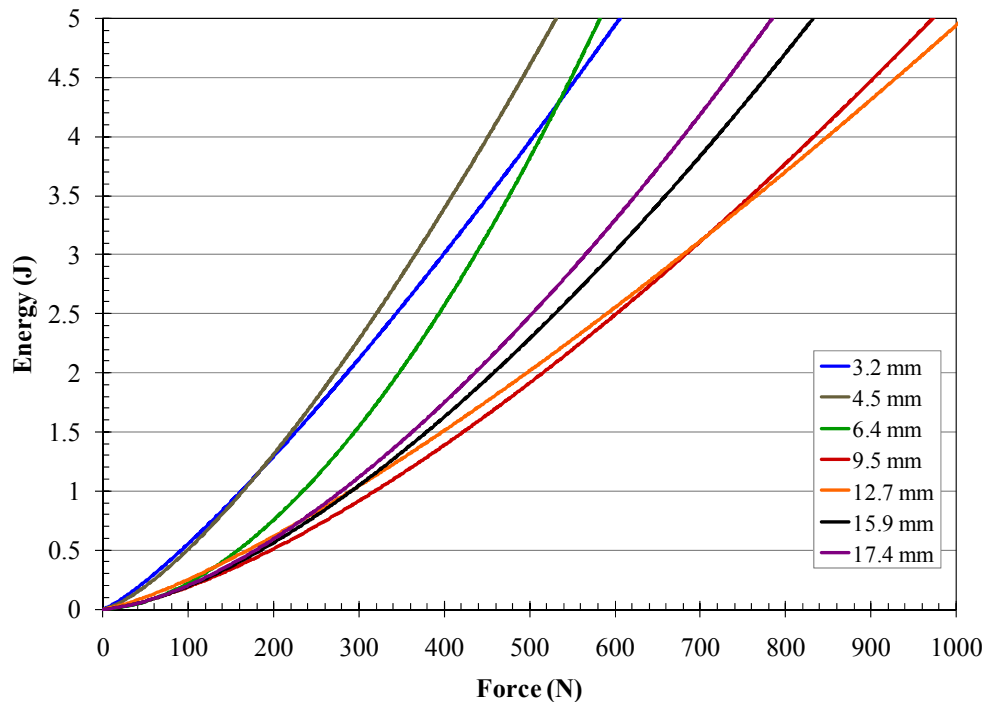


Figure 14: Projectile kinetic energy can be determined from the peak force recorded by the FOCUS eye load cell and knowledge of the diameter of the projectile. Note that projectiles larger than 12.7 mm transfer lower peak impact forces for the same energy level. This is due to some impact force being absorbed by the FOCUS eyelids on the external skin, where the opening for the eyes is roughly 13 mm tall. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

Taking into account the individual projectile size and dividing the kinetic energy shown in Figure 14 by projectile cross-sectional area yields the normalized energy of each projectile tested, shown again as Equation 1. This normalized energy can then be plotted relative to the peak impact force reported by the FOCUS headform (Figure 15). Using this normalized energy vs. force relationship, risk functions for each projectile size were then developed.

$$\text{Normalized Energy} \left(\frac{\text{kJ}}{\text{m}^2} \right) = \frac{\text{Kinetic Energy (J)}}{\text{Projectile Area (m}^2\text{)}} \cdot \frac{1 \text{ kJ}}{1000 \text{ J}} \quad (\text{Equation 1})$$

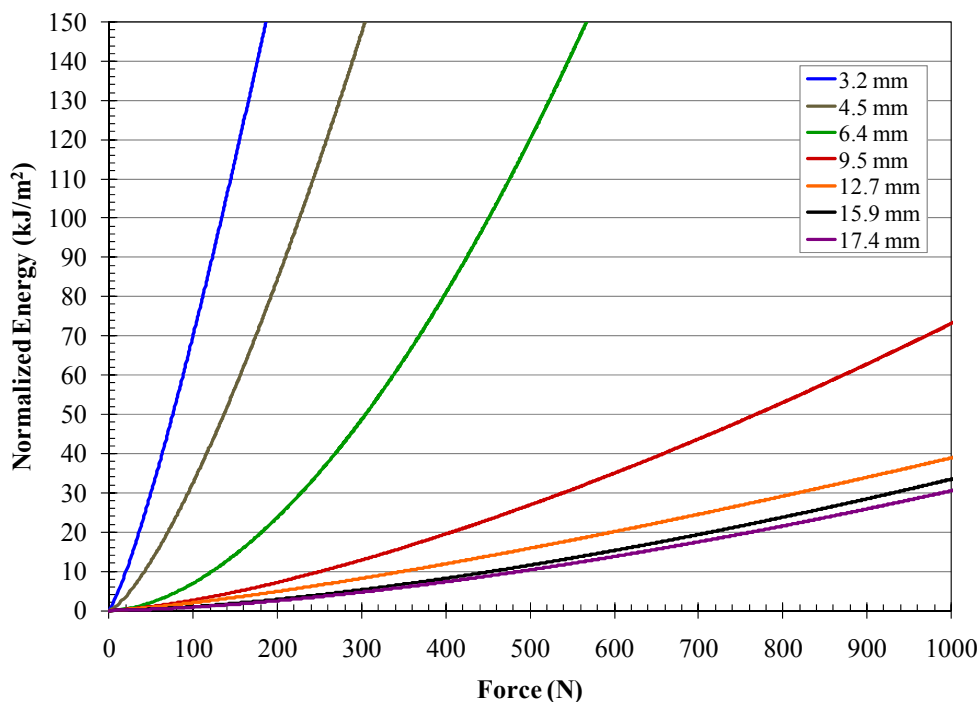


Figure 15: Dividing the projectile kinetic energy by the projectile diameter, the normalized energy from a FOCUS impact test can be determined. It is from this relationship that FOCUS injury risk functions are developed, based on the human eye injury criteria presented in Section III. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

In order to calculate eye injury risk based on ballistic projectile tests on the FOCUS headform, three separate mathematical calculations are required. First, the kinetic energy of the eye impact must be calculated, based on the force recorded by the eye load cells. This calculation was previously detailed using Equation 4 and the parameters given in Table 8. Second, with knowledge of the kinetic energy of the impact, 'E,' and the projectile size, it is possible to calculate the projectile's area-normalized energy, using Equation 1. Third, the area-normalized energy can then be used to calculate injury risk based on the recommended survival analysis using a weibull distribution (Equation 3), where 'x' is the area-normalized energy of the projectile.

$$Injury Risk = \left[1 - e^{-(x/\alpha)^\beta}\right] \cdot 100\% \quad (\text{Equation 3})$$

To simplify the number of steps from this calculation, the given risk function (Equation 3) is combined with the result, 'E', of the kinetic energy calculation (Equation 4) and the normalized energy calculation (Equation 1) to create an eye injury risk function for the FOCUS headform. The FOCUS eye injury risk function is given as Equation 5.

$$Injury Risk = 1 - e^{-\left[\frac{E \cdot \left(\frac{1 \text{ kJ}}{10^3 \text{ J}}\right)}{\alpha \cdot \left(\frac{\pi \cdot d^2}{4}\right) \cdot \left(\frac{1 \text{ m}^2}{10^6 \text{ mm}^2}\right)}\right]^\beta} \cdot 100\% \quad (\text{Equation 5})$$

In Equation 5, 'α' and 'β' are the scale and shape parameters of the injury risk function, given in Table 9. Additionally, 'E' is the kinetic energy of the projectile that is calculated based on the impact force recorded by the FOCUS, from Equation 4. The units of 'E' should be entered in joules (J), and are converted to kJ by multiplying by 1 kJ per 1000 J. Finally, 'd' is the diameter of the projectile that struck the eye, given in terms of millimeters (mm). After the cross-sectional area of the projectile is calculated it is converted to square meters (m²) by multiplying by 1 m² per 10⁶ mm².

Reducing terms from Equation 5 yields a simplified version of the equation, given as Equation 6. In Equation 6, 'α' is expressed in units of kJ/m², while the 'β' term is unitless, both parameters are given in Table 9. The units of 'E,' for kinetic energy are entered in joules (J) while 'd,' the diameter, is entered in terms of millimeters (mm).

$$Injury Risk = 1 - e^{-\left[\frac{4 \cdot 10^3 \cdot E}{\alpha \cdot \pi \cdot d^2}\right]^\beta} \cdot 100\% \quad (\text{Equation 6})$$

Table 9: Risk function coefficients for FOCUS eye injury risk functions. The FOCUS headform utilizes the same scale and shape parameters from the survival analysis using a weibull distribution given in Section III, the maximum likelihood method for parameter estimation is recommended.

Analysis Type	Hyphema		Lens Damage		Retinal Damage		Globe Rupture	
	Scale 'α' (kJ/m ²)	Shape 'β' (unitless)	Scale 'α' (kJ/m ²)	Shape 'β' (unitless)	Scale 'α' (kJ/m ²)	Shape 'β' (unitless)	Scale 'α' (kJ/m ²)	Shape 'β' (unitless)
Survival Analysis: Maximum Likelihood	14.23320	1.94012	19.01200	4.03800	19.82630	3.73625	38.52490	5.73194

Risk functions for the FOCUS headform eye injury can be plotted in two ways. First, for a given projectile diameter, the complete set of risk functions for hyphema, lens damage, retinal damage, and globe rupture can be presented. An example is given for a 9.5 mm projectile (Figure 16), while a complete set of risk functions for 3.2 mm, 4.5 mm, 6.4 mm, 9.5 mm, 12.7 mm, 15.9 mm, and 17.5 mm projectiles are given in Appendix B (Figure 18 - Figure 24).

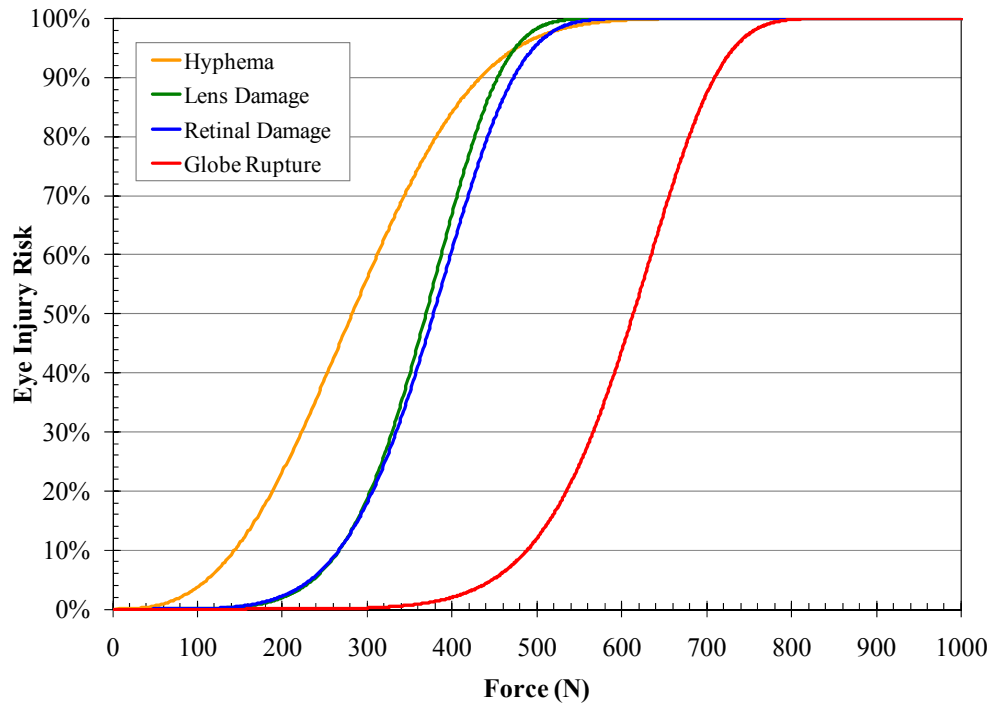


Figure 16: Eye injury risk curves for FOCUS headform subjected to an impact using a 9.5 mm projectile. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

Additionally, risk functions across the full range of projectile sizes can be plotted for each of the four eye injury outcomes, hyphema, lens damage, retinal damage, and globe rupture. An example risk function for hyphema is shown (Figure 17). In this risk function, the risk of hyphema is shown for a range of projectile sizes. The full set of risk functions for each eye injury outcome are given in Appendix B (Figure 25 - Figure 28).

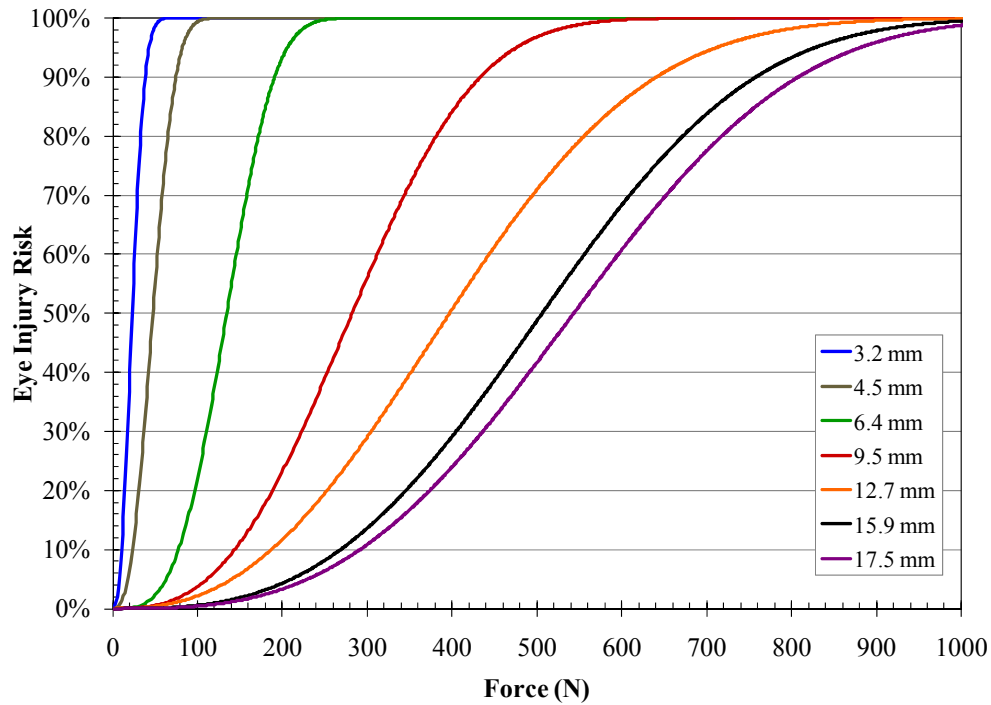


Figure 17: Eye injury risk curves for hyphema when using the FOCUS headform to assess impact severity. Risk curves are shown for projectiles ranging in size from 3.2 mm to 17.5 mm in diameter. Note that the maximum force limit for the FOCUS eye load cell is 1000 N

Discussion:

FOCUS Sensitivity to Projectile Kinetic and Normalized Energy

Overall, nearly 300 impact tests were conducted using the FOCUS headform in order to correlate FOCUS response to various eye impact scenarios. A total of six different projectile sizes were used during this testing, and data from impact tests reported by Kennedy et al. (2007) with a seventh projectile size were also analyzed. Consistent with observations made in the 2007 study, test results from the current study were that peak eye impact force was correlated with kinetic energy but not the normalized energy of the projectile.

In order to most accurately predict the risk of eye injury, the size of the projectile that impacts the eye must be known. If the size of the projectile is not known, it is recommended that a conservative estimate of projectile size be used to evaluate injury risk (i.e. the smallest possible projectile size is assumed); however, this can lead to extreme overestimations of eye injury risk. For example, while a 300 N peak impact force with a 17.5 mm projectile leads to a 10.8% estimated risk of hyphema, a 300 N impact with a 6.4 mm or smaller projectile will have a nearly 100% estimated risk of hyphema. This example is not intended to diminish the effectiveness of the FOCUS in evaluating the severity of eye impacts, a correlation coefficient of 0.95 or better for all projectile sizes indicates that it is highly sensitive to both the mass and velocity of projectiles; however, the FOCUS will have diminished usefulness if the size of the projectile that hits the eye cannot be accurately determined. Further development effort to obtain projectile area via FOCUS headform instrumentation measurement is recommended and should be pursued to make the FOCUS a more versatile testing instrument.

Currently, several potential solutions to this problem are being looked into. One potential solution is the use of a pressure sensitive eye. This instrumented synthetic eye would obtain internal pressure information from inside the eye, possibly in conjunction with the force measurements. This pressure response could then be linked to deformation of the eye, or deformation rate, which can then be correlated to projectile area.

Another potential solution includes an area-sensitive load cell with the synthetic eye, which would be sensitive to the exact area of the eye that was impacted by an object. Additional development on a next-generation FOCUS eye should also consider a more comprehensive investigation into the response of FOCUS instrumentation, to investigate if loading rate, impulse, impact duration, etc. can be used to more accurately predict projectile size. The ability to predict projectile size based on FOCUS instrumentation response will yield a significant improvement for the overall usefulness of the advanced headform.

Alternative Injury Risk Function Determination

The risk functions were developed for the FOCUS headform were developed using the recommended approach from Section III: Closed Globe Injury Criteria Development, that is to say that the risk functions for the FOCUS are based on risk functions for eye injury based on a survival analysis, assuming a weibull distribution, and using the maximum likelihood approach to estimate risk function parameters.

Although the maximum likelihood approach is recommended because it minimizes the variance and lowers the associated error for scales and shape parameters of the risk function, it has been shown to have less conservative nominal injury risk values than a risk function developed using the least squares approach. Therefore, it may be desirable to compare injury risk values determined from the maximum likelihood and least squares estimation methods. In these scenarios, the scale and the shape parameters given in Table 9 can be replaced with the respective scale and shape parameters from Table 6.

V. TASK SUMMARY FROM STATEMENT OF WORK

Overall, there were five main objectives from the original project statement of work. These five objectives were correlated with a total of ten sub-tasks for the overall project. Project objectives were:

1. Develop a statistical methodology for the development of closed-globe eye injury risk functions.
2. Reduce the incidence of closed globe eye injuries from blunt trauma by establishing injury risk functions for hyphema.
3. Reduce the incidence of closed globe eye injuries from blunt trauma by establishing injury risk functions for lens dislocation.
4. Reduce the incidence of closed globe eye injuries from blunt trauma by establishing injury risk functions for retinal damage.
5. Develop and perform experimental impact tests with the FOCUS headform to determine projectile characteristics and force data.

As has been detailed in this report, each of the project objectives have been met. A depiction of each project sub-task and the section of this report that details its completion and findings is detailed below.

Task 1.1 Collection and Analysis of Previous Eye Injury Tests

Develop a database of all previously reported eye injury tests from the literature. Develop a methodology for metaanalysis of existing eye injury impact tests on human cadavers and animal surrogates. Analysis technique will be focused on determining injury criteria for hyphema, lens dislocation, and retinal damage.

Status: Complete

Section of Final Report: Section III: Closed Globe Injury Criteria Development

Task 1.2 Develop and Build Experimental FOCUS Testing Configuration

Develop a methodology for experimental impact tests utilizing the FOCUS headform to determine injury criteria for hyphema, lens dislocation, and retinal damage. Build a test configuration that will aid in the measurement of projectile characteristics including energy and normalized energy, as well as, the force data measured by the FOCUS headform.

Status: Complete

Section of Final Report: Section IV: FOCUS Eye Injury Criteria

Task 2.1 Analysis and Comparison of FOCUS Tests to Previous Eye Injury Tests

Collaborate with other researchers and materiel developers to determine a suitable test-plan for development of closed-globe eye injury criteria for the FOCUS headform. In order to assess the sensitivity of various impact measurements (normalized energy, kinetic energy, force, pressure) as they relate to eye injury, some reported human cadaver and animal impact tests will be replicated using a synthetic eye to assess these parameters and fill in missing data from published impact experiments.

Status: Complete

Section of Final Report: Section III: Closed Globe Injury Criteria Development

Task 2.2 Perform Experimental FOCUS Tests

Perform experimental impact tests on the FOCUS headform to determine projectile characteristics and force measurements. The goal of this test series will be to combine the collected experimental data with published tests to develop eye injury criteria to be used with the FOCUS headform.

Status: Complete

Section of Final Report: Section IV: FOCUS Eye Injury Criteria

Task 3.1 Development of Eye Injury Criteria for Hyphema

Analyze reported experimental eye impact test results and compare to the injury response of the available published tests. Using statistical analysis, develop injury criteria for hyphema based on the injury risk functions of the published tests. Report the results of the development of human eye injury criteria for hyphema.

Status: Complete

Section of Final Report: Section III: Closed Globe Injury Criteria Development

Task 3.2 Development of Eye Injury Criteria for Lens Dislocation

Analyze reported experimental eye impact test results and compare to the injury response of the available published tests. Using statistical analysis, develop injury criteria for lens dislocation based on the injury risk functions of the published tests. Report the results of the development of human eye injury criteria for lens dislocation.

Status: Complete

Section of Final Report: Section III: Closed Globe Injury Criteria Development

Task 3.3 Development of Eye Injury Criteria for Retinal Damage

Analyze reported experimental eye impact test results and compare to the injury response of the available published tests. Using statistical analysis, develop injury criteria for retinal damage based on the injury risk functions of the published tests. Report the results of the development of eye injury criteria for retinal damage.

Status: Complete

Section of Final Report: Section III: Closed Globe Injury Criteria Development

Task 3.4 Development of FOCUS Injury Criteria for Hyphema

Analyze experimental FOCUS headform impact test results and compare to the injury response of the available published tests. Using statistical analysis, develop injury criteria for hyphema based on the injury risk functions of the published tests and the matched experimental data for the FOCUS tests. Report the results of the development of FOCUS injury criteria for hyphema.

Status: Complete

Section of Final Report: Section IV: FOCUS Eye Injury Criteria

Task 3.5 Development of FOCUS Injury Criteria for Lens Dislocation

Analyze experimental FOCUS headform impact test results and compare to the injury response of the available published tests. Using statistical analysis, develop injury criteria for lens dislocation based on the injury risk functions of the published tests and the matched experimental data for the FOCUS tests. Report the results of the development of FOCUS injury criteria for lens dislocation.

Status: Complete

Section of Final Report: Section IV: FOCUS Eye Injury Criteria

Task 3.6 Development of FOCUS Injury Criteria for Retinal Damage

Analyze experimental FOCUS headform impact test results and compare to the injury response of the available published tests. Using statistical analysis, develop injury criteria for retinal damage based on the injury risk functions of the published tests and the matched experimental data for the FOCUS tests. Report the results of the development of FOCUS injury criteria for retinal damage.

Status: Complete

Section of Final Report: Section IV: FOCUS Eye Injury Criteria

VI. PUBLICATION PLAN

In order to disseminate information to the rest of the scientific community, two publications are planned as the result of this research. Both manuscripts will be prepared beginning with the completion of this report and are planned for submission for review before the end of the year.

First, the comprehensive set of eye injury risk functions will be submitted for publication. The planned publication venue is the Journal of Trauma in order to supplement the original publication “Determination of significant parameters for eye injury risk from projectiles” by Duma et al. (2005). The submitted publication will provide final, up-to-date risk functions for the prediction of closed and open globe eye injuries, based on normalized energy. These risk functions will serve as an excellent resource for material developers and consumer product engineers, where the risk of eye injury can be evaluated based on knowledge of objects likely to strike the eye. In the military arena, this could be used for analysis of debris fields from helicopter rotorwash, or from debris kicked up in a blast field. In the civilian sector, these risk functions may be used for toy design, as well as identification of injury potential from various sports or recreational activities, and automotive or industrial accidents.

Second, the FOCUS eye injury criteria is planned for submission to Aviation, Space, and Environmental Medicine, a journal which has a history of presenting research relevant to the military community. Not only will this publication present a complete set of injury risk curves for the FOCUS headform, but it will circulate to a readership that will have a keen interest in staying abreast of current technology available for research in military and injury prevention applications.

VII. CONCLUSION

The parallel efforts discussed in this report provide two different types of meaningful injury criteria. For the normalized energy risk functions presented in Section III, the criteria are useful from a design perspective, providing a useful tool for material developers to identify safe and unsafe limits for military equipment. An example is to determine safe landing zone perimeters for both current and future military rotorcraft, particularly with respect to civilians (who lack protective eyewear) who are susceptible to eye injury due to rotorwash. There are also numerous applications in the civilian sector as well, notably in the design of children's toys, amusement park ride risk assessment analysis, and sports and automotive safety.

The applications of the FOCUS headform are numerous, but a primary purpose is as a primary evaluative tool for the effectiveness of goggles and faceshields from material developers. In conjunction with the new injury risk functions, the FOCUS headform can be used to evaluate the level of interaction the goggles have with the eye and face as they attenuate various impacts. This will yield new information on the relative effectiveness of various goggle designs, not only to protect from penetrating injuries, but from closed globe injuries as well.

VIII. ACKNOWLEDGEMENTS

The authors would like to acknowledge the United States Army Medical Research and Materiel Command for their support of this research and development program. Additionally, the authors wish to acknowledge the sponsoring agency, the United States Army Aeromedical Research Laboratory, for their technical and logistical support of this project.

Many students and staff from both Bucknell University and the Virginia Tech – Wake Forest University Center for Injury Biomechanics made substantial contributions to this project throughout the past year. From Bucknell University, the authors wish to thank Samantha Clark, Emily Thiel, Kelly Desharnais, and Rushtin Chaklader for their assistance in experimental testing and data analysis for this project. George Waltman and Tim Baker provided exceptional support for test equipment fabrication and modification.

From the Center for Injury Biomechanics, Craig McNally and Steve Rowson provided technical support of this project, from design details of the FOCUS headform slider cart design, to support and sharing of experimental testing data from FOCUS and results from eye impact tests in parallel studies. Vanessa Alphonse and Steve Rowson continue to be instrumental in development of a next-generation design for the FOCUS synthetic eye.

Finally, the authors would like to acknowledge the support of Dr. Pang Du, of Virginia Tech's Department of Statistics for his feedback and advice on statistical methodologies employed in this study.

IX. REFERENCES

- Abernathy R (1996). The new weibull handbook, 2nd edition. Dr. Robert B. Abernethy
- Allison PD (1999) Logistic regression using the SAS system: Theory and Application, Cary, NC, SAS Institute Inc.
- Berger RE (1978) A model for evaluating the ocular contusion injury potential of propelled objects. *Journal of Bioengineering* 2: 345-358.
- Bisplinghoff J, Kennedy E, Cormier J, Depinet P, Brozoski F, Duma S (2008) Development and validation of eye injury and facial fracture criteria for the FOCUS headform. 26th Army Science Conference, Orlando, Florida.
- Bisplinghoff JA, McNally C, Duma SM (2009) High-rate internal pressurization of human eyes to predict globe rupture. *Archives of Ophthalmology* 127(4): 520-523.
- Collett D (1991) Modeling binary data, Chapman and Hall, London.
- Delori F, Pomerantzeff O, Cox MS (1969) Deformation of the globe under high speed impact: its relation to contusion injuries. *Investigative Ophthalmology and Visual Science* 8:290-301.
- DiDomenico L, Nusholtz G (2003) Comparison of parametric and non-parametric methods for determining injury risk. *Society of Automotive Engineers*. 2003-01-1362.
- Duma SM, Kress TA, Porta DJ, Woods CD, Snider JN, Fuller PM, Simmons RJ (1996) Air bag induced eye injuries: a report of 25 cases. *Journal of Trauma*. 41(1):114-119.
- Duma SM, Crandall JR (2000) Eye injuries from airbags with seamless module covers. *Journal of Trauma*. 48(4):786-789.
- Duma SM, Jernigan MV, Stitzel JD, Herring IP, Crowley JS, Brozoski FT, Bass CR (2002) The effect of frontal air bags on eye injury patterns in automobile crashes. *Archives of Ophthalmology* 120:1517-1522.
- Duma SM, Jernigan MV (2003) The effects of airbags on orbital fracture patterns in frontal automobile crashes. *Ophthalmic Plastic and Reconstructive Surgery* 19(2): 107-111.
- Duma SM, Ng TP, Kennedy EA, Stitzel JD, Herring IP, Kuhn F (2005A) Determination of significant parameters for eye injury risk from projectiles. *Journal of Trauma* 59(4): 960-964.
- Duma S, Rath A, Jernigan M, Stitzel J, Herring I (2005B) The effects of depowered airbags on eye injuries in frontal automobile crashes. *American Journal of Emergency Medicine* 23(1): 13-19.
- Endo S, Ishida N, Yamaguchi T (2000) The BB gun is equivalent to the airsoft gun in the japanese literature. *Archives of Ophthalmology* 118: 732.
- Endo S, Ishida N, Yamaguchi T (2001) Tear in the trabecular meshwork caused by an airsoft gun. *American Journal of Ophthalmology* 131: 656-657.
- Eppinger R, Sun E, Bandak F, Haffner M, Khaewpong N, Maltese M, Kuppa S, Nguyen T, Takhounts E, Tannous R, Zhang A, Saul R (1999) Development of improved injury criteria for the assessment of advanced automotive restraint systems - II. NHTSA, USA.
- Fleischhauer JC, Goldblum D, Frueh BE, Koerner F (1999) Ocular injuries caused by airsoft guns. *Archives of Ophthalmology* 117: 1437-1439.
- Galler EL, Umlas JW, Vinger PF, Wu HK (1995) Ocular integrity after quantitated trauma following photorefractive keratectomy and automated lamellar keratectomy. *Investigative Ophthalmology and Visual Science* 36(4):S580.
- Green RP, Peters DR, Shore JW, Fanton JW, Davis H (1990) Force necessary to fracture the orbital floor. *Ophthalmic Plastic and Reconstructive Surgery* 6(3): 211-217.

- Hansen GA, Stitzel JD, Duma SM (2003) The incidence of elderly eye injuries in automobile crashes: the effects of lens stiffness as a function of age. Association for the Advancement of Automotive Medicine 47.
- Kennedy EA, Voorhies KD, Herring IP, Rath AL, Duma SM (2004) Prediction of severe eye injuries in automobile accidents: static and dynamic rupture pressure of the eye. Association for the Advancement of Automotive Medicine 48.
- Kennedy EA, Duma SM, Depinet P, Morgan C, Beebe M, Roller R, Crowley J, Brozoski F (2006A) Design of an advanced headform for the prediction of eye and facial injuries. 25th Army Science Conference, Orlando, Florida.
- Kennedy EA, Ng TP, McNally C, Stitzel JD, Duma SM (2006B) Risk functions for human and porcine eye rupture based on projectile characteristics of blunt objects. Stapp Car Crash Journal 50: 651-671.
- Kennedy EA, Ng TP, Duma SM (2006C) Evaluating eye injury risk of airsoft pellet guns by parametric risk functions. Biomedical Sciences Instrumentation 42: 7-12.
- Kennedy EA, Inzana JA, McNally C, Depinet P, Sullenberger KH, Morgan CR, Brozoski FT, Duma SM (2007) Development and validation of a synthetic eye and orbit for estimating the potential for globe rupture due to specific impact conditions. Stapp Car Crash Journal 51: 381-400.
- Kennedy EA, Duma SM (2008) The effects of the extraocular muscles on eye impact force-deflection and globe rupture response. Journal of Biomechanics 41(16): 3297-3302.
- Kent RW, Funk JR (2004) Data censoring and parametric distribution assignment in the development of injury risk functions from biomechanical data. Society of Automotive Engineers. 2004-01-0317.
- Kuhn F, Morris R, Witherspoon CD, Mann L, Mester V, Modis L, Berta A, Bearden W (2000) Serious fireworks-related eye injuries. Ophthalmic Epidemiology 7: 139-148.
- Mader TH ; Carroll RD ; Slade CS ; George RK ; Ritchey JP ; Neville SP (2006) Ocular war injuries of the Iraqi Insurgency, January-September 2004. Ophthalmology 113(1): 97-104
- McKnight SJ, Fitz J, Giangiacomo J (1988) Corneal rupture following keratotomy in cats subjected to BB gun injury. Ophthalmic Surgery 19(3):165-167.
- Mertz HJ, Prasad P, Nusholtz G. (1996) Head injury risk assessment for forehead impacts. SAE Transactions 960099: 26-46.
- Power ED, Stitzel JD, Duma SM, Herring IP, West RL (2002) Investigation of ocular injuries from high velocity objects in an automobile collision. Society of Automotive Engineers. 2002-01-0027.
- Rodriguez JO, Lavina AM (2003) Prevention and treatment of common eye injuries in sports. American Family Physician 67: 1481-1488.
- Scott WR, Lloyd WC, Benedict JV, Meredith R (2000) Ocular injuries due to projectile impacts. Association for the Advancement of Automotive Medicine 44: 205-217.
- Stitzel JD, Duma SM, Cormier JM, Herring IP (2002) A nonlinear finite element model of the eye with experimental validation for the prediction of globe rupture. Stapp Car Crash Journal. 46:81-102.
- Stitzel JD, Hansen GA, Herring IP, Duma SM (2005) Blunt trauma of the aging eye: injury mechanisms and increasing lens stiffness. Archives of Ophthalmology 123: 789-794.
- Thach AB, Johnson AJ, Carroll RB, Huchun A, Ainbinder DJ, Stutzman RD, Blaydon SM, Demartelaere SL, Mader TH, Slade CS, George RK, Ritchey JP, Barnes SD, Fannin LA (2008) Severe eye injuries in the war in Iraq, 2003-2005. Ophthalmology 115(2): 377-82.
- Thomas R, McManus JG, Johnson A, Mayer P, Wade C, Holcomb JB (2009) Ocular injury reduction from ocular protection use in current combat operations. Journal of Trauma 66(4): S99-S103.

- Vinger PF, Sparks JJ, Mussack KR, Dondero J, Jeffers JB (1997) A program to prevent eye injuries in paintball. *Sports Vision*. 3:33-40.
- Vinger PF, Duma SM, Crandall J (1999) Baseball hardness as a risk factor in eye injuries. *Archives of Ophthalmology* 117:354-358.
- Weidenthal DT (1964) Experimental ocular contusion. *Archives of Ophthalmology* 71: 111-115.
- Weidenthal DT, Schepens CL (1966) Peripheral fundus changes associated with ocular contusion. *American Journal of Ophthalmology* 62: 465-477.

X. APPENDIX A: TABULATION OF HUMAN RISK FUNCTION CORRIDORS

Each table shown provides a compilation of nominal values and upper and lower estimates for the amount of normalized energy required to pose a specified risk of injury. Estimates shown are from the survival analysis risk function, based on a weibull distribution, with parameter estimates determined using a maximum likelihood approach.

Table 10: Tabulation of estimates for nominal levels of normalized energy for a given estimate of risk for hyphema. Additionally, the 5% to 95% upper and lower confidence limits are shown.

Injury Risk Estimate	Normalized Energy Estimated From Risk Function (kJ/m²)	Normalized Energy Lower Confidence Limit (kJ/m²)	Normalized Energy Upper Confidence Limit (kJ/m²)
1%	1.33	0.47	3.75
2%	1.90	0.78	4.64
3%	2.35	1.05	5.27
4%	2.74	1.30	5.76
5%	3.08	1.53	6.18
6%	3.39	1.76	6.55
7%	3.68	1.97	6.89
8%	3.96	2.18	7.19
9%	4.21	2.38	7.47
10%	4.46	2.57	7.74
20%	6.57	4.39	9.82
30%	8.37	6.10	11.47
40%	10.07	7.80	13.00
50%	11.78	9.51	14.59
60%	13.61	11.28	16.41
70%	15.66	13.11	18.70
80%	18.19	15.08	21.94
90%	21.88	17.49	27.37
91%	22.39	17.79	28.18
92%	22.95	18.11	29.07
93%	23.56	18.46	30.08
94%	24.26	18.85	31.23
95%	25.06	19.28	32.57
96%	26.00	19.78	34.18
97%	27.17	20.38	36.24
98%	28.75	21.16	39.06
99%	31.27	22.36	43.74

Table 11: Tabulation of estimates for nominal levels of normalized energy for a given estimate of risk for lens damage. Additionally, the 5% to 95% upper and lower confidence limits are shown.

Injury Risk Estimate	Normalized Energy Estimated From Risk Function (kJ/m²)	Normalized Energy Lower Confidence Limit (kJ/m²)	Normalized Energy Upper Confidence Limit (kJ/m²)
1%	6.09	3.79	9.78
2%	7.23	4.83	10.84
3%	8.01	5.56	11.53
4%	8.61	6.15	12.05
5%	9.11	6.66	12.47
6%	9.54	7.10	12.83
7%	9.93	7.50	13.15
8%	10.28	7.86	13.43
9%	10.59	8.20	13.69
10%	10.89	8.51	13.93
20%	13.11	10.94	15.72
30%	14.73	12.70	17.08
40%	16.10	14.15	18.31
50%	17.36	15.40	19.57
60%	18.60	16.53	20.94
70%	19.91	17.60	22.52
80%	21.39	18.68	24.49
90%	23.37	19.98	27.35
91%	23.63	20.14	27.74
92%	23.92	20.31	28.16
93%	24.22	20.49	28.63
94%	24.56	20.69	29.16
95%	24.95	20.92	29.76
96%	25.40	21.17	30.46
97%	25.94	21.48	31.33
98%	26.65	21.87	32.48
99%	27.75	22.46	34.29

Table 12: Tabulation of estimates for nominal levels of normalized energy for a given estimate of risk for retinal damage. Additionally, the 5% to 95% upper and lower confidence limits are shown.

Injury Risk Estimate	Normalized Energy Estimated From Risk Function (kJ/m²)	Normalized Energy Lower Confidence Limit (kJ/m²)	Normalized Energy Upper Confidence Limit (kJ/m²)
1%	5.79	3.39	9.88
2%	6.98	4.44	10.96
3%	7.79	5.20	11.66
4%	8.42	5.82	12.19
5%	8.95	6.35	12.62
6%	9.41	6.82	12.99
7%	9.82	7.25	13.32
8%	10.20	7.64	13.62
9%	10.54	8.00	13.89
10%	10.86	8.33	14.14
20%	13.27	10.95	16.08
30%	15.05	12.84	17.64
40%	16.56	14.34	19.14
50%	17.97	15.59	20.73
60%	19.37	16.68	22.49
70%	20.84	17.70	24.53
80%	22.52	18.74	27.06
90%	24.79	20.00	30.72
91%	25.08	20.15	31.22
92%	25.41	20.32	31.77
93%	25.76	20.50	32.37
94%	26.15	20.69	33.04
95%	26.59	20.91	33.82
96%	27.11	21.17	34.72
97%	27.74	21.47	35.84
98%	28.56	21.85	37.33
99%	29.84	22.43	39.68

Table 13: Tabulation of estimates for nominal levels of normalized energy for a given estimate of risk for globe rupture. Additionally, the 5% to 95% upper and lower confidence limits are shown.

Injury Risk Estimate	Normalized Energy Estimated From Risk Function (kJ/m²)	Normalized Energy Lower Confidence Limit (kJ/m²)	Normalized Energy Upper Confidence Limit (kJ/m²)
1%	17.27	11.30	26.39
2%	19.50	13.61	27.95
3%	20.95	15.18	28.92
4%	22.05	16.40	29.64
5%	22.95	17.42	30.22
6%	23.71	18.30	30.71
7%	24.38	19.09	31.14
8%	24.98	19.79	31.52
9%	25.52	20.43	31.87
10%	26.02	21.03	32.18
20%	29.65	25.43	34.58
30%	32.18	28.44	36.41
40%	34.26	30.76	38.16
50%	36.14	32.64	40.02
60%	37.94	34.20	42.09
70%	39.79	35.58	44.50
80%	41.86	36.91	47.48
90%	44.56	38.40	51.71
91%	44.91	38.58	52.28
92%	45.28	38.77	52.89
93%	45.69	38.97	53.57
94%	46.14	39.19	54.33
95%	46.65	39.44	55.19
96%	47.24	39.71	56.20
97%	47.95	40.04	57.43
98%	48.88	40.46	59.05
99%	50.29	41.07	61.57

XI. APPENDIX B: FOCUS INJURY RISK FUNCTIONS BY PROJECTILE SIZE

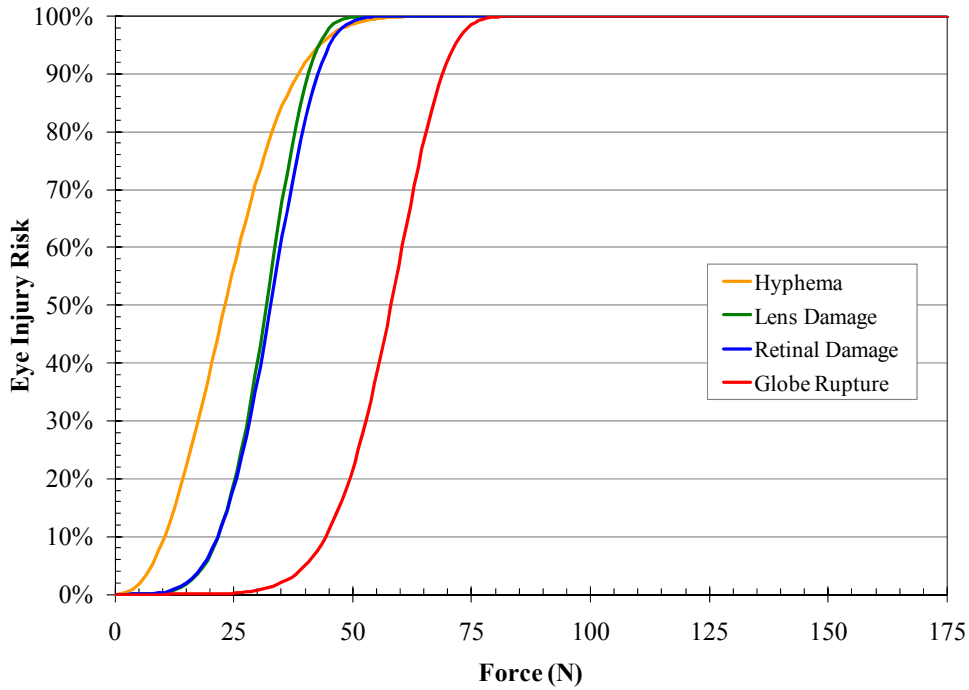


Figure 18: Eye injury risk curves for FOCUS headform subjected to an impact using a 3.2 mm projectile. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

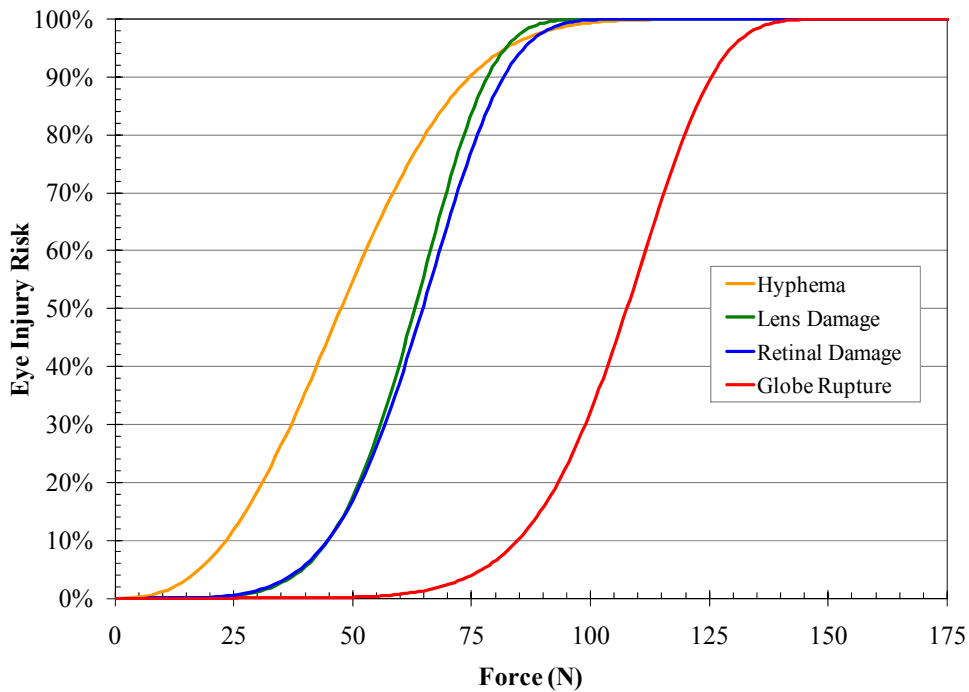


Figure 19: Eye injury risk curves for FOCUS headform subjected to an impact using a 4.5 mm projectile. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

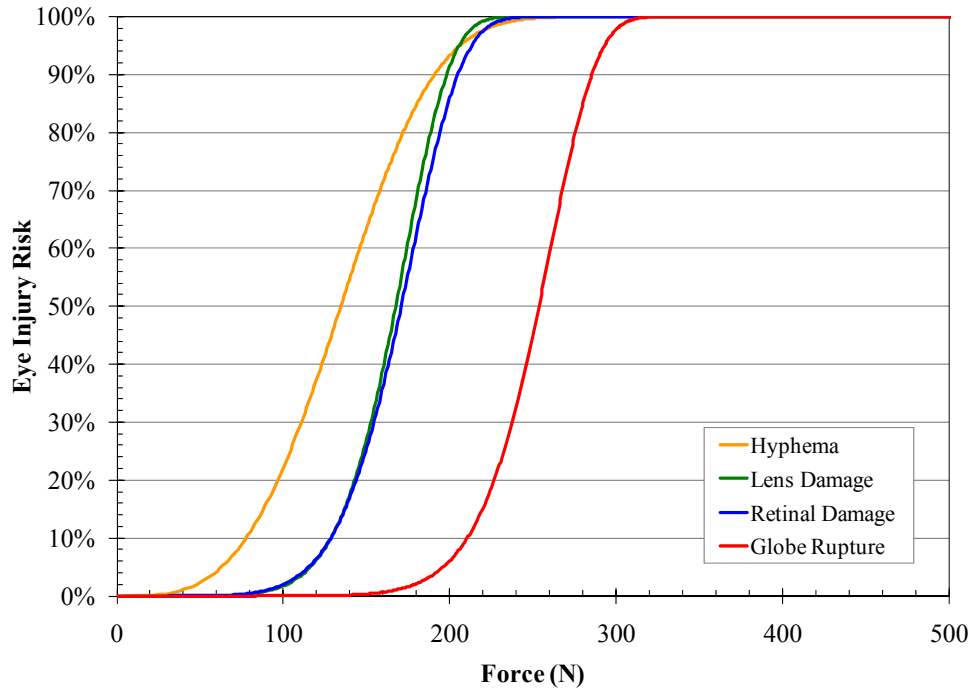


Figure 20: Eye injury risk curves for FOCUS headform subjected to an impact using a 6.4 mm projectile. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

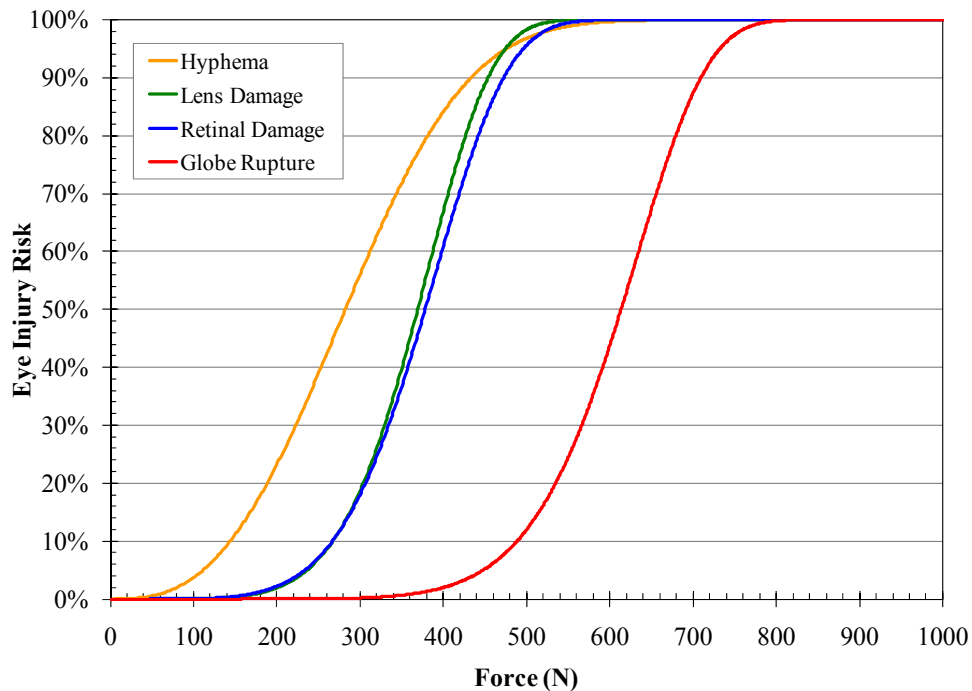


Figure 21: Eye injury risk curves for FOCUS headform subjected to an impact using a 9.5 mm projectile. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

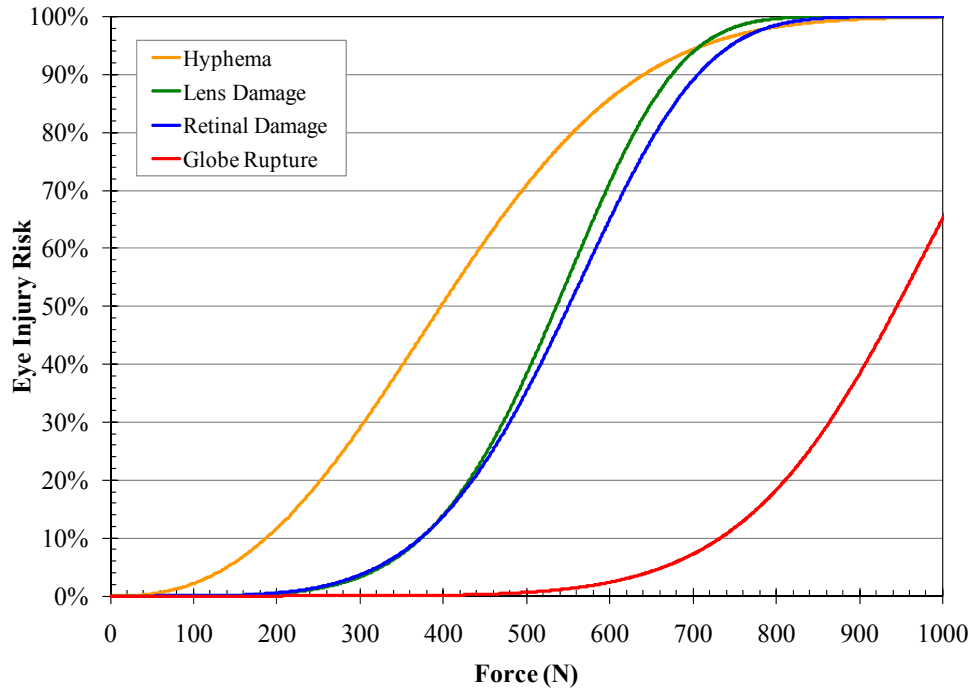


Figure 22: Eye injury risk curves for FOCUS headform subjected to an impact using a 12.7 mm projectile. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

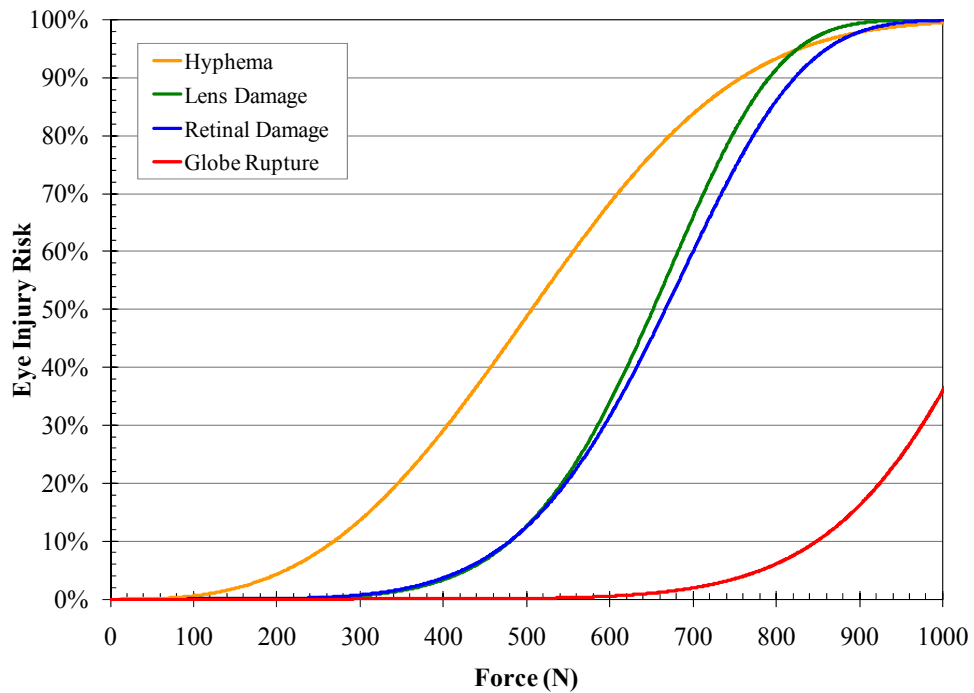


Figure 23: Eye injury risk curves for FOCUS headform subjected to an impact using a 15.9 mm projectile. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

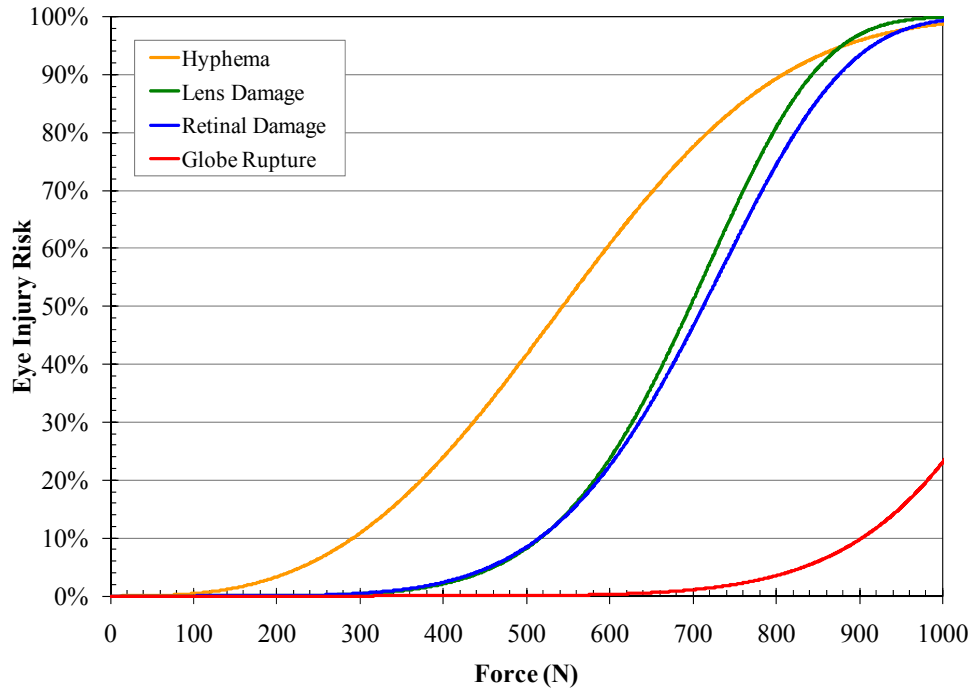


Figure 24: Eye injury risk curves for FOCUS headform subjected to an impact using a 17.5 mm projectile. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

XII. APPENDIX C: FOCUS INJURY RISK FUNCTIONS BY INJURY TYPE

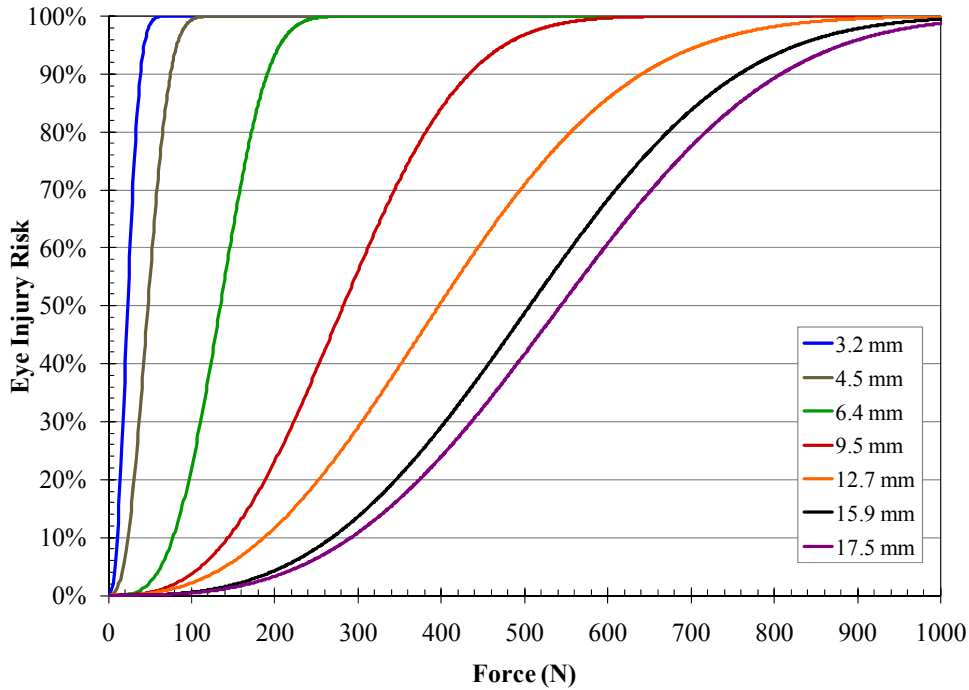


Figure 25: Eye injury risk curves for hyphema when using the FOCUS headform to assess impact severity. Risk curves are shown for projectiles ranging in size from 3.2 mm to 17.5 mm in diameter. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

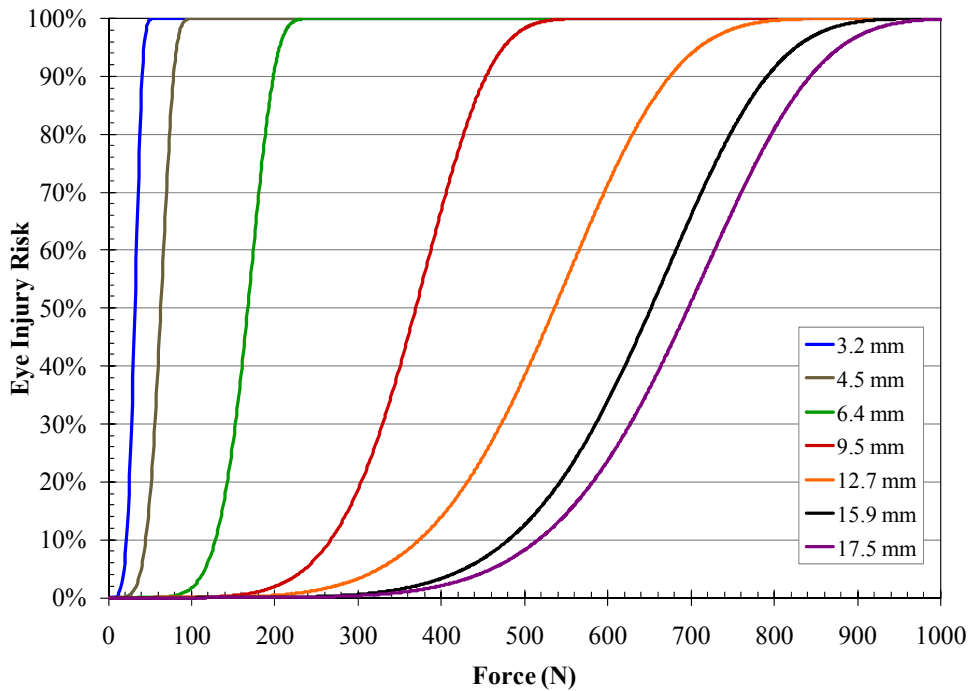


Figure 26: Eye injury risk curves for lens damage when using the FOCUS headform to assess impact severity. Risk curves are shown for projectiles ranging in size from 3.2 mm to 17.5 mm in diameter. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

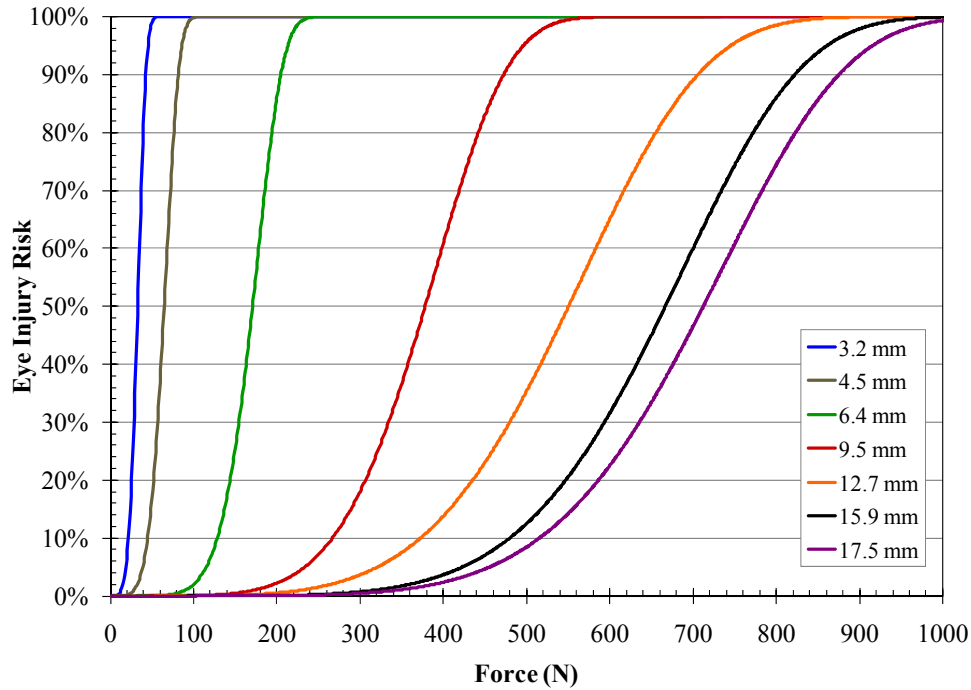


Figure 27: Eye injury risk curves for retinal damage when using the FOCUS headform to assess impact severity. Risk curves are shown for projectiles ranging in size from 3.2 mm to 17.5 mm in diameter. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

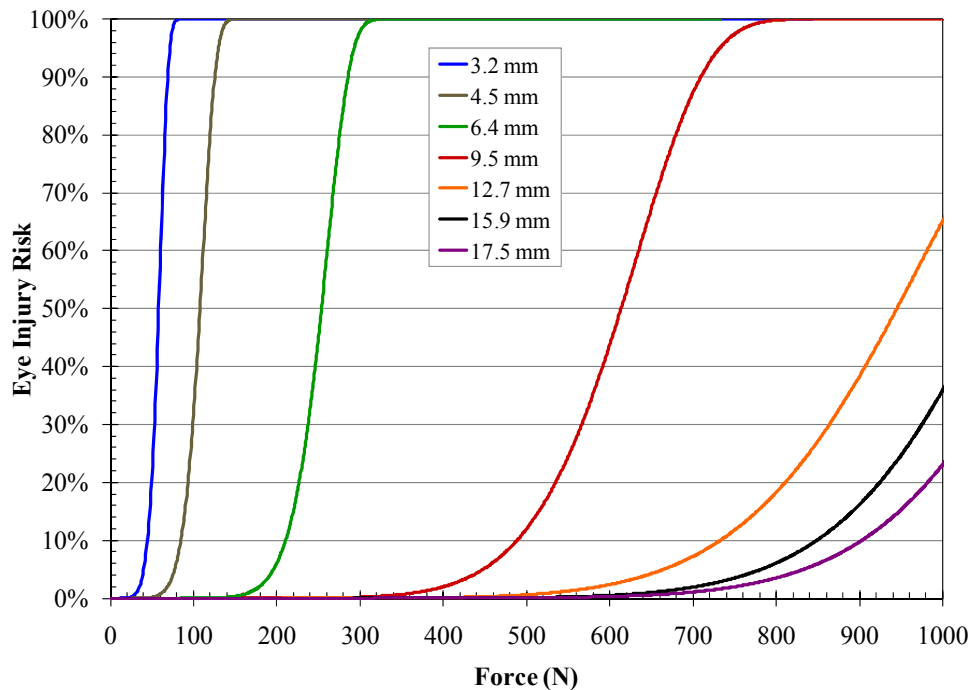


Figure 28: Eye injury risk curves for globe rupture when using the FOCUS headform to assess impact severity. Risk curves are shown for projectiles ranging in size from 3.2 mm to 17.5 mm in diameter. Note that the maximum force limit for the FOCUS eye load cell is 1000 N.

XIII. APPENDIX D: EYE INJURY DATABASE

Table 14: Eye injury database for initial logistic regression analysis.

Test Number	Author (Year)	Species	Diameter (mm)	Mass (g)	Velocity (m/s)	Normalized Energy (kJ/m ³)	CA	HY	LD	RD	GR
1	Delori (1969)	Human	4.5	0.4	71.9	56.9	*	*	*	*	1
2	Duma (2000)	Pig	12.5	0.3	4.8	0.0	*	*	*	*	0
3	Duma (2000)	Pig	12.5	0.3	5.6	0.0	*	*	*	*	0
4	Duma (2000)	Pig	12.5	0.3	7.0	0.1	*	*	*	*	0
5	Duma (2000)	Pig	12.5	0.2	39.3	1.0	0	*	0	0	0
6	Duma (2000)	Pig	12.5	0.2	41.6	1.1	0	*	0	0	0
7	Duma (2000)	Pig	12.5	0.2	46.0	1.3	1	*	0	0	0
8	Duma (2000)	Pig	12.5	0.2	57.7	2.2	1	*	0	0	0
9	Duma (2000)	Pig	12.5	0.2	87.6	5.2	1	*	0	0	0
10	Duma (2000)	Pig	12.5	0.2	25.5	0.4	0	*	0	0	0
11	Duma (2000)	Pig	12.5	0.2	18.3	0.3	0	*	0	0	0
12	Duma (2000)	Pig	12.5	0.2	57.7	2.9	1	*	0	0	0
13	Duma (2000)	Pig	12.5	0.5	31.7	2.2	1	*	0	0	0
14	Duma (2000)	Pig	12.5	0.6	26.8	1.7	1	*	0	0	0
15	Duma (2000)	Pig	12.5	0.6	29.9	2.0	0	*	0	0	0
16	Duma (2000)	Pig	12.5	0.6	29.9	2.1	1	*	0	0	0
17	Duma (2000)	Pig	12.5	0.6	72.4	11.8	1	*	0	0	0
18	Green (1990)	Monkey	12.5	303.0	3.7	17.0	*	*	*	*	1
19	Green (1990)	Monkey	12.5	303.0	3.7	17.0	*	*	*	*	0
20	Green (1990)	Monkey	12.5	303.0	4.0	19.4	*	*	*	*	0
21	Green (1990)	Monkey	12.5	303.0	4.0	19.4	*	*	*	*	0
22	Green (1990)	Monkey	12.5	303.0	4.1	20.8	*	*	*	*	1
23	Green (1990)	Monkey	12.5	303.0	4.1	20.8	*	*	*	*	0
24	Green (1990)	Monkey	12.5	303.0	4.2	21.3	*	*	*	*	0
25	Green (1990)	Monkey	12.5	303.0	4.2	21.3	*	*	*	*	0
26	Green (1990)	Monkey	12.5	303.0	4.2	21.8	*	*	*	*	1
27	Green (1990)	Monkey	12.5	303.0	4.2	21.8	*	*	*	*	1
28	Green (1990)	Monkey	12.5	303.0	4.3	22.8	*	*	*	*	0
29	Green (1990)	Monkey	12.5	303.0	4.3	22.8	*	*	*	*	0
30	Green (1990)	Monkey	12.5	303.0	4.4	24.2	*	*	*	*	0
31	Green (1990)	Monkey	12.5	303.0	4.4	24.2	*	*	*	*	1
32	Green (1990)	Monkey	12.5	303.0	4.6	26.6	*	*	*	*	0
33	Green (1990)	Monkey	12.5	303.0	4.6	26.6	*	*	*	*	0
34	McKnight (1988)	Cat	4.5	0.4	45.3	22.5	*	1	*	*	*
35	McKnight (1988)	Cat	4.5	0.4	45.3	22.5	*	1	*	*	*
36	McKnight (1988)	Cat	4.5	0.4	57.9	36.9	*	1	*	*	*
37	McKnight (1988)	Cat	4.5	0.4	57.9	36.9	*	1	*	*	*
38	McKnight (1988)	Cat	4.5	0.4	57.9	36.9	*	1	*	*	*
39	McKnight (1988)	Cat	4.5	0.4	57.9	36.9	*	1	*	*	*
40	McKnight (1988)	Cat	4.5	0.4	57.9	36.9	*	1	*	*	*
41	McKnight (1988)	Cat	4.5	0.4	57.9	36.9	*	1	*	*	*
42	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	*	1	*	*	*
43	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	*	1	*	*	*
44	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	*	1	*	*	*
45	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	*	1	*	*	*
46	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	*	1	*	*	*
47	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	*	1	*	*	*
48	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	*	1	*	*	*
49	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	*	1	*	*	*
50	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	*	1	*	*	*
51	Scott (2000)	Pig	6.4	2.6	23.8	23.3	1	0	0	0	0
52	Scott (2000)	Pig	6.4	2.6	23.8	23.3	*	1	1	*	0
53	Scott (2000)	Pig	6.4	2.6	27.1	30.1	*	1	1	*	0
54	Scott (2000)	Pig	6.4	2.6	30.5	38.2	*	*	1	*	0
55	Scott (2000)	Pig	6.4	2.6	36.0	53.2	*	*	1	1	0
56	Scott (2000)	Pig	6.4	2.6	38.1	59.6	*	*	1	1	0
57	Scott (2000)	Pig	6.4	2.6	32.3	42.8	*	*	1	1	0
58	Scott (2000)	Pig	6.4	2.6	33.2	45.2	*	1	1	1	0
59	Scott (2000)	Pig	6.4	3.5	19.2	20.4	*	1	*	*	0
60	Scott (2000)	Pig	6.4	3.5	18.9	19.7	*	*	0	*	0

Table 14 (continued): Eye injury database for initial logistic regression analysis.

Test Number	Author (Year)	Species	Diameter (mm)	Mass (g)	Velocity (m/s)	Normalized Energy (kJ/m ²)	CA	HY	LD	RD	GR
61	Scott (2000)	Pig	6.4	3.5	18.6	19.1	*	*	1	*	0
62	Scott (2000)	Pig	6.4	3.5	20.7	23.7	*	1	1	*	0
63	Scott (2000)	Pig	6.4	3.5	26.2	37.9	*	*	1	1	0
64	Scott (2000)	Pig	6.4	3.5	20.7	23.7	*	*	1	*	0
65	Scott (2000)	Pig	6.4	3.5	33.0	60.2	*	*	1	1	0
66	Scott (2000)	Pig	9.5	45.5	4.0	5.1	1	0	0	0	0
67	Scott (2000)	Pig	9.5	45.5	4.3	5.9	1	0	0	0	0
68	Scott (2000)	Pig	9.5	45.5	5.2	8.6	1	0	0	0	0
69	Scott (2000)	Pig	6.4	45.5	5.2	19.4	1	0	0	0	0
70	Stitzel (2002)	Human	6.4	0.1	4.3	0.0	0	*	*	*	0
71	Stitzel (2002)	Human	6.4	0.1	5.4	0.0	0	*	*	*	0
72	Stitzel (2002)	Human	6.4	0.1	6.0	0.0	0	*	*	*	0
73	Stitzel (2002)	Human	6.4	0.1	10.6	0.1	*	*	*	*	0
74	Stitzel (2002)	Human	6.4	0.1	14.2	0.2	*	*	*	*	0
75	Stitzel (2002)	Human	6.4	0.1	14.3	0.2	*	*	*	*	0
76	Stitzel (2002)	Human	6.4	0.1	18.9	0.4	*	*	*	*	0
77	Stitzel (2002)	Human	6.4	0.1	23.0	0.6	*	*	*	*	0
78	Stitzel (2002)	Human	6.4	0.1	26.7	0.9	*	*	*	*	0
79	Stitzel (2002)	Human	6.4	0.1	26.8	0.9	*	*	*	*	0
80	Stitzel (2002)	Human	6.4	0.1	28.6	1.0	*	*	*	*	0
81	Stitzel (2002)	Human	6.4	0.1	31.0	1.2	*	*	*	*	0
82	Stitzel (2002)	Human	76.1	146.5	30.1	14.6	*	*	*	*	0*
83	Stitzel (2002)	Human	76.1	146.5	34.4	19.1	*	*	*	*	1*
84	Stitzel (2002)	Human	76.1	146.5	35.5	20.3	*	*	*	*	1*
85	Stitzel (2002)	Human	76.1	146.5	41.2	27.3	*	*	*	*	1*
86	Stitzel (2002)	Human	76.1	146.5	42.8	29.5	*	*	*	*	1*
87	Stitzel (2002)	Human	4.5	0.4	53.0	33.1	*	*	*	*	0
88	Stitzel (2002)	Human	4.5	0.4	53.8	34.1	*	*	*	*	0
89	Stitzel (2002)	Human	4.5	0.4	55.8	36.7	*	*	*	*	0
90	Stitzel (2002)	Human	4.5	0.4	59.7	42.0	*	*	*	*	0
91	Stitzel (2002)	Human	4.5	0.4	85.2	85.6	*	*	*	*	1
92	Stitzel (2002)	Human	4.5	0.4	90.4	96.3	*	*	*	*	1
93	Stitzel (2002)	Human	4.5	0.4	91.7	99.1	*	*	*	*	1
94	Stitzel (2002)	Human	4.5	0.4	122.4	176.6	*	*	*	*	1
95	Umlas (1995)	Pig	41.0	24.7	45.7	19.6	*	*	*	*	1*
96	Weidenthal (1966)	Pig	14.0	272.0	2.4	5.3	*	*	*	0	*
97	Weidenthal (1964)	Monkey	15.9	283.0	3.0	6.4	*	0	0	*	0
98	Weidenthal (1964)	Monkey	15.9	283.0	3.0	6.4	*	0	0	*	0
99	Weidenthal (1964)	Monkey	15.9	283.0	3.0	6.4	*	0	0	*	0
100	Weidenthal (1964)	Monkey	15.9	283.0	3.1	7.0	*	0	0	*	0
101	Weidenthal (1964)	Monkey	15.9	283.0	3.1	7.0	*	0	0	*	0
102	Weidenthal (1964)	Monkey	15.9	283.0	3.1	7.0	*	0	0	*	0
103	Weidenthal (1964)	Monkey	15.9	283.0	3.1	7.0	*	1	0	*	0
104	Weidenthal (1964)	Monkey	15.9	283.0	3.1	7.0	*	1	0	*	0
105	Weidenthal (1964)	Monkey	15.9	283.0	3.9	10.8	*	0	0	*	0
106	Weidenthal (1964)	Monkey	15.9	283.0	3.9	10.8	*	0	0	*	0
107	Weidenthal (1964)	Monkey	15.9	283.0	3.9	10.8	*	0	0	*	0
108	Weidenthal (1964)	Monkey	15.9	283.0	3.9	10.8	*	1	0	*	0
109	Weidenthal (1964)	Monkey	15.9	283.0	3.9	10.8	*	1	0	*	0
110	Weidenthal (1964)	Monkey	15.9	283.0	3.9	10.8	*	1	0	*	0
111	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	*	1	0	*	1
112	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	*	1	0	*	0
113	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	*	1	0	*	0
114	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	*	1	0	*	0
115	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	*	1	0	*	0
116	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	*	0	0	*	0
117	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	*	0	0	*	0
118	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	*	0	0	*	0
119	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	*	0	0	*	0
120	Weidenthal (1964)	Monkey	15.9	283.0	4.6	14.9	*	1	0	*	1

Table 14 (continued): Eye injury database for initial logistic regression analysis.

Test Number	Author (Year)	Species	Diameter (mm)	Mass (g)	Velocity (m/s)	Normalized Energy (kJ/m ²)	CA	HY	LD	RD	GR
121	Weidenthal (1964)	Monkey	15.9	283.0	4.6	14.9	*	1	0	*	1
122	Weidenthal (1964)	Monkey	15.9	283.0	4.6	14.9	*	1	0	*	1
123	Weidenthal (1964)	Monkey	15.9	283.0	4.6	14.9	*	1	0	*	1
124	Weidenthal (1964)	Monkey	15.9	283.0	4.6	14.9	*	0	0	*	0
125	Weidenthal (1966)	Pig	4.5	0.3	66.4	47.8	*	*	1	1	*
126	Kennedy (2006)	Human	6.0	0.1	88.3	16.0	*	*	*	*	0
127	Kennedy (2006)	Human	6.0	0.1	91.6	17.5	*	*	*	*	0
128	Kennedy (2006)	Human	6.0	0.1	92.1	17.4	*	*	*	*	0
129	Kennedy (2006)	Human	6.0	0.1	117.8	28.4	*	*	*	*	0
130	Kennedy (2006)	Human	17.3	3.2	71.7	35.1	*	*	*	*	1
131	Kennedy (2006)	Human	17.3	3.2	71.3	34.6	*	*	*	*	1
132	Kennedy (2006)	Human	6.0	0.2	73.0	19.7	*	*	*	*	0
133	Kennedy (2006)	Human	6.0	0.2	76.3	20.3	*	*	*	*	0
134	Kennedy (2006)	Human	6.0	0.2	78.3	22.0	*	*	*	*	0
135	Kennedy (2006)	Human	6.0	0.2	85.3	26.3	*	*	*	*	0
136	Kennedy (2006)	Human	17.3	3.1	65.5	28.6	*	*	*	*	1
137	Kennedy (2006)	Human	17.3	3.2	71.1	34.5	*	*	*	*	0
138	Kennedy (2006)	Human	17.3	3.2	97.9	65.0	*	*	*	*	1
139	Kennedy (2006)	Human	6.0	0.1	93.6	17.8	*	*	*	*	0
140	Kennedy (2006)	Human	6.0	0.1	109.7	24.9	*	*	*	*	0
141	Kennedy (2006)	Human	17.3	3.2	68.0	31.4	*	*	*	*	0
142	Kennedy (2006)	Human	17.3	3.2	73.3	36.6	*	*	*	*	1
143	Kennedy (2006)	Human	6.0	0.2	75.0	20.6	*	*	*	*	0
144	Kennedy (2006)	Human	6.0	0.2	87.3	27.8	*	*	*	*	0
145	Kennedy (2006)	Human	17.3	3.2	71.1	34.6	*	*	*	*	1
146	Kennedy (2006)	Human	17.3	3.2	70.8	34.0	*	*	*	*	0
147	Kennedy (2006)	Human	17.3	3.2	107.2	78.1	*	*	*	*	1
148	Kennedy (2006)	Human	17.3	3.2	75.3	38.7	*	*	*	*	1
149	Kennedy (2006)	Human	17.3	3.2	72.0	35.5	*	*	*	*	1
150	Kennedy (2006)	Human	17.3	3.2	108.0	79.5	*	*	*	*	1
151	Kennedy (2006)	Human	17.3	3.2	112.5	86.5	*	*	*	*	1
152	Kennedy (2006)	Human	30.0	9.5	8.9	0.5	*	*	*	*	0*
153	Kennedy (2006)	Human	6.0	0.2	81.2	24.0	*	*	*	*	0
154	Kennedy (2006)	Human	17.3	3.2	109.4	81.5	*	*	*	*	1
155	Kennedy (2006)	Human	19.9	112.6	8.7	13.8	*	*	*	*	0
156	Kennedy (2006)	Human	19.9	112.6	8.6	13.4	*	*	*	*	0
157	Kennedy (2006)	Human	19.9	112.6	8.5	13.2	*	*	*	*	0
158	Kennedy (2006)	Human	7.6	0.3	23.5	2.1	*	*	*	*	0
159	Kennedy (2006)	Human	7.6	0.3	24.0	2.2	*	*	*	*	0
160	Kennedy (2006)	Human	9.8	0.7	20.2	1.9	*	*	*	*	0
161	Kennedy (2006)	Human	9.8	0.7	19.3	1.7	*	*	*	*	0
162	Kennedy (2006)	Human	7.6	0.3	23.8	2.1	*	*	*	*	0
163	Kennedy (2006)	Human	7.6	0.3	24.5	2.3	*	*	*	*	0
164	Kennedy (2006)	Human	9.8	0.7	19.2	1.7	*	*	*	*	0
165	Kennedy (2006)	Human	9.8	0.7	17.8	1.5	*	*	*	*	0
166	Kennedy (2006)	Human	4.5	0.0	45.7	2.6	*	*	*	*	0
167	Kennedy (2006)	Human	4.5	0.0	38.1	1.8	*	*	*	*	0
168	Kennedy (2006)	Human	4.5	0.0	44.7	2.5	*	*	*	*	0
169	Kennedy (2006)	Human	4.5	0.0	41.2	2.1	*	*	*	*	0
170	Kennedy (2006)	Human	4.5	0.0	47.2	2.7	*	*	*	*	0
171	Kennedy (2006)	Human	4.5	0.0	43.7	2.3	*	*	*	*	0
172	Kennedy (2006)	Human	4.4	0.3	11.0	1.4	*	*	*	*	0
173	Kennedy (2006)	Human	4.4	0.3	11.5	1.5	*	*	*	*	0
174	Kennedy (2006)	Human	4.4	0.3	11.4	1.5	*	*	*	*	0
175	Kennedy (2006)	Human	4.4	0.3	11.2	1.4	*	*	*	*	0
176	Kennedy (2006)	Human	4.4	0.3	10.2	1.2	*	*	*	*	0
177	Kennedy (2006)	Human	9.2	3.6	44.1	51.8	*	*	*	*	1
178	Kennedy (2006)	Human	9.2	3.6	50.4	67.6	*	*	*	*	1
179	Kennedy (2006)	Human	9.2	3.6	56.0	83.6	*	*	*	*	1
180	Kennedy (2006)	Human	9.2	3.6	59.2	93.3	*	*	*	*	1

Table 14 (continued): Eye injury database for initial logistic regression analysis.

Test Number	Author (Year)	Species	Diameter (mm)	Mass (g)	Velocity (m/s)	Normalized Energy (kJ/m ²)	CA	HY	LD	RD	GR
181	Kennedy (2006)	Human	9.2	3.6	43.6	50.5	*	*	*	*	1
182	Kennedy (2006)	Human	9.2	3.6	42.1	47.2	*	*	*	*	1
183	Kennedy (2006)	Human	11.2	5.2	43.7	50.6	*	*	*	*	1
184	Kennedy (2006)	Human	11.2	5.2	44.1	51.6	*	*	*	*	1
185	Kennedy (2006)	Human	11.2	5.2	53.2	75.1	*	*	*	*	1
186	Kennedy (2006)	Human	11.2	5.2	44.7	53.0	*	*	*	*	1
187	Kennedy (2006)	Pig	6.0	0.1	97.8	19.7	*	*	*	*	0
188	Kennedy (2006)	Pig	6.0	0.1	101.8	21.4	*	*	*	*	0
189	Kennedy (2006)	Pig	6.0	0.1	94.7	18.1	*	*	*	*	0
190	Kennedy (2006)	Pig	6.0	0.1	115.6	27.3	*	*	*	*	0
191	Kennedy (2006)	Pig	17.3	3.2	71.7	35.1	*	*	*	*	0
192	Kennedy (2006)	Pig	17.3	3.2	99.0	66.1	*	*	*	*	0
193	Kennedy (2006)	Pig	17.3	3.2	106.1	76.8	*	*	*	*	1
194	Kennedy (2006)	Pig	17.3	3.2	108.9	80.0	*	*	*	*	1
195	Kennedy (2006)	Pig	6.0	0.2	74.7	20.1	*	*	*	*	0
196	Kennedy (2006)	Pig	6.0	0.2	77.1	21.4	*	*	*	*	0
197	Kennedy (2006)	Pig	6.0	0.2	72.5	18.9	*	*	*	*	0
198	Kennedy (2006)	Pig	6.0	0.2	87.4	27.6	*	*	*	*	0
199	Kennedy (2006)	Pig	17.3	3.2	67.1	30.7	*	*	*	*	0
200	Kennedy (2006)	Pig	17.3	3.2	100.2	68.1	*	*	*	*	1
201	Kennedy (2006)	Pig	17.3	3.2	101.9	70.6	*	*	*	*	0
202	Kennedy (2006)	Pig	17.3	3.2	103.3	72.5	*	*	*	*	1
203	Kennedy (2006)	Pig	17.3	3.2	111.0	83.9	*	*	*	*	1
204	Kennedy (2006)	Pig	6.0	0.1	92.5	17.5	*	*	*	*	0
205	Kennedy (2006)	Pig	6.0	0.1	115.6	27.3	*	*	*	*	0
206	Kennedy (2006)	Pig	17.3	3.2	68.0	31.4	*	*	*	*	0
207	Kennedy (2006)	Pig	17.3	3.1	95.6	59.5	*	*	*	*	0
208	Kennedy (2006)	Pig	17.3	3.2	109.5	81.5	*	*	*	*	1
209	Kennedy (2006)	Pig	17.3	3.2	108.9	79.7	*	*	*	*	1
210	Kennedy (2006)	Pig	6.0	0.2	67.2	16.5	*	*	*	*	0
211	Kennedy (2006)	Pig	6.0	0.2	84.0	25.1	*	*	*	*	0
212	Kennedy (2006)	Pig	17.3	3.1	66.8	29.8	*	*	*	*	0
213	Kennedy (2006)	Pig	17.3	3.2	100.6	69.1	*	*	*	*	0
214	Kennedy (2006)	Pig	17.3	3.2	114.1	88.3	*	*	*	*	1
215	Kennedy (2006)	Pig	17.3	3.2	106.4	76.4	*	*	*	*	1
216	Kennedy (2006)	Pig	17.3	3.2	109.7	81.9	*	*	*	*	1
217	Kennedy (2006)	Pig	17.3	3.2	106.4	77.3	*	*	*	*	1
218	Kennedy (2006)	Pig	17.3	3.2	101.8	70.2	*	*	*	*	1
219	Kennedy (2006)	Pig	6.0	0.2	83.3	24.9	*	*	*	*	0
220	Kennedy (2006)	Pig	17.3	3.2	100.7	69.4	*	*	*	*	1
221	Kennedy (2006)	Pig	19.9	112.6	8.7	13.6	*	*	*	*	0
222	Kennedy (2006)	Pig	19.9	112.6	8.8	14.1	*	*	*	*	0
223	Kennedy (2006)	Pig	19.9	112.6	8.4	12.9	*	*	*	*	0
224	Kennedy (2006)	Pig	19.9	112.6	8.8	14.2	*	*	*	*	0
225	Kennedy (2006)	Pig	7.6	0.3	5.7	0.1	*	*	*	*	0
226	Kennedy (2006)	Pig	7.6	0.3	15.5	0.9	*	*	*	*	0
227	Kennedy (2006)	Pig	7.6	0.3	10.8	0.4	*	*	*	*	0
228	Kennedy (2006)	Pig	4.5	0.0	25.9	0.8	*	*	*	*	0
229	Kennedy (2006)	Pig	4.5	0.0	22.0	0.6	*	*	*	*	0
230	Kennedy (2006)	Pig	4.5	0.0	29.3	1.1	*	*	*	*	0
231	Kennedy (2006)	Pig	7.6	0.3	13.4	0.7	*	*	*	*	0
232	Kennedy (2006)	Pig	7.6	0.3	19.6	1.5	*	*	*	*	0
233	Kennedy (2006)	Pig	4.5	0.0	16.5	0.3	*	*	*	*	0
234	Kennedy (2006)	Pig	4.5	0.0	32.8	1.3	*	*	*	*	0
235	Kennedy (2006)	Pig	11.2	5.2	33.8	30.2	*	*	*	*	0
236	Kennedy (2006)	Pig	11.2	5.2	37.8	37.8	*	*	*	*	0
237	Kennedy (2006)	Pig	9.2	3.6	28.1	21.1	*	*	*	*	0
238	Kennedy (2006)	Pig	9.2	3.6	34.9	32.4	*	*	*	*	0
239	Kennedy (2006)	Pig	4.4	0.3	96.0	105.2	*	*	*	*	0
240	Kennedy (2006)	Pig	4.4	0.3	165.6	309.8	*	*	*	*	1

Table 14 (continued): Eye injury database for initial logistic regression analysis.

Test Number	Author (Year)	Species	Diameter (mm)	Mass (g)	Velocity (m/s)	Normalized Energy (kJ/m ²)	CA	HY	LD	RD	GR
241	Kennedy (2006)	Pig	4.4	0.3	142.1	226.0	*	*	*	*	1
242	Kennedy (2006)	Pig	4.5	0.0	149.6	26.0	*	*	*	*	0
243	Kennedy (2006)	Pig	4.4	0.3	140.0	222.2	*	*	*	*	1
244	Kennedy (2006)	Pig	4.4	0.3	140.0	223.0	*	*	*	*	1
245	Kennedy (2006)	Pig	4.4	0.3	99.7	113.2	*	*	*	*	1
246	Kennedy (2006)	Pig	4.4	0.3	98.1	109.4	*	*	*	*	1
247	Kennedy (2006)	Pig	4.4	0.3	95.9	102.9	*	*	*	*	1
248	Kennedy (2006)	Pig	4.4	0.3	99.3	112.8	*	*	*	*	1
249	Kennedy (2006)	Pig	4.4	0.3	98.2	109.7	*	*	*	*	1
250	Kennedy (2006)	Pig	4.4	0.3	97.6	108.9	*	*	*	*	0
251	Kennedy (2006)	Pig	4.4	0.3	131.7	197.4	*	*	*	*	1

* Excluded on basis of size > 25 mm.

XIV. APPENDIX E: EYE INJURY DATABASE WITH INJURY DATA POOLED

Table 15: Eye injury database (with data pooling) used for survival analysis and final risk functions.

Test Number	Author (Year)	Species	Diameter (mm)	Mass (g)	Velocity (m/s)	Normalized Energy (kJ/m ²)	HY	LD	RD	GR
1	Delori (1969)	Human	4.5	0.4	71.9	56.9	1	1	1	1
2	Duma (2000)	Pig	12.5	0.3	4.8	0.0	*	*	*	*
3	Duma (2000)	Pig	12.5	0.3	5.6	0.0	*	*	*	*
4	Duma (2000)	Pig	12.5	0.3	7.0	0.1	*	*	*	*
5	Duma (2000)	Pig	12.5	0.2	39.3	1.0	0	0	0	*
6	Duma (2000)	Pig	12.5	0.2	41.6	1.1	0	0	0	*
7	Duma (2000)	Pig	12.5	0.2	46.0	1.3	*	0	0	*
8	Duma (2000)	Pig	12.5	0.2	57.7	2.2	*	0	0	*
9	Duma (2000)	Pig	12.5	0.2	87.6	5.2	*	0	0	*
10	Duma (2000)	Pig	12.5	0.2	25.5	0.4	0	0	0	*
11	Duma (2000)	Pig	12.5	0.2	18.3	0.3	0	0	0	*
12	Duma (2000)	Pig	12.5	0.2	57.7	2.9	*	0	0	*
13	Duma (2000)	Pig	12.5	0.5	31.7	2.2	*	0	0	*
14	Duma (2000)	Pig	12.5	0.6	26.8	1.7	*	0	0	*
15	Duma (2000)	Pig	12.5	0.6	29.9	2.0	0	0	0	*
16	Duma (2000)	Pig	12.5	0.6	29.9	2.1	*	0	0	*
17	Duma (2000)	Pig	12.5	0.6	72.4	11.8	*	0	0	*
18	Green (1990)	Monkey	12.5	303.0	3.7	17.0	1	1	1	*
19	Green (1990)	Monkey	12.5	303.0	3.7	17.0	*	*	*	*
20	Green (1990)	Monkey	12.5	303.0	4.0	19.4	*	*	*	*
21	Green (1990)	Monkey	12.5	303.0	4.0	19.4	*	*	*	*
22	Green (1990)	Monkey	12.5	303.0	4.1	20.8	1	1	1	*
23	Green (1990)	Monkey	12.5	303.0	4.1	20.8	*	*	*	*
24	Green (1990)	Monkey	12.5	303.0	4.2	21.3	*	*	*	*
25	Green (1990)	Monkey	12.5	303.0	4.2	21.3	*	*	*	*
26	Green (1990)	Monkey	12.5	303.0	4.2	21.8	1	1	1	*
27	Green (1990)	Monkey	12.5	303.0	4.2	21.8	1	1	1	*
28	Green (1990)	Monkey	12.5	303.0	4.3	22.8	*	*	*	*
29	Green (1990)	Monkey	12.5	303.0	4.3	22.8	*	*	*	*
30	Green (1990)	Monkey	12.5	303.0	4.4	24.2	*	*	*	*
31	Green (1990)	Monkey	12.5	303.0	4.4	24.2	1	1	1	*
32	Green (1990)	Monkey	12.5	303.0	4.6	26.6	*	*	*	*
33	Green (1990)	Monkey	12.5	303.0	4.6	26.6	*	*	*	*
34	McKnight (1988)	Cat	4.5	0.4	45.3	22.5	1	*	*	*
35	McKnight (1988)	Cat	4.5	0.4	45.3	22.5	1	*	*	*
36	McKnight (1988)	Cat	4.5	0.4	57.9	36.9	1	*	*	*
37	McKnight (1988)	Cat	4.5	0.4	57.9	36.9	1	*	*	*
38	McKnight (1988)	Cat	4.5	0.4	57.9	36.9	1	*	*	*
39	McKnight (1988)	Cat	4.5	0.4	57.9	36.9	1	*	*	*
40	McKnight (1988)	Cat	4.5	0.4	57.9	36.9	1	*	*	*
41	McKnight (1988)	Cat	4.5	0.4	57.9	36.9	1	*	*	*
42	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	1	*	*	*
43	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	1	*	*	*
44	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	1	*	*	*
45	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	1	*	*	*
46	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	1	*	*	*
47	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	1	*	*	*
48	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	1	*	*	*
49	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	1	*	*	*
50	McKnight (1988)	Cat	4.5	0.4	75.0	61.9	1	*	*	*
51	Scott (2000)	Pig	6.4	2.6	23.8	23.3	0	0	0	*
52	Scott (2000)	Pig	6.4	2.6	23.8	23.3	1	1	*	*
53	Scott (2000)	Pig	6.4	2.6	27.1	30.1	1	1	*	*
54	Scott (2000)	Pig	6.4	2.6	30.5	38.2	1	1	*	*
55	Scott (2000)	Pig	6.4	2.6	36.0	53.2	1	1	1	*
56	Scott (2000)	Pig	6.4	2.6	38.1	59.6	1	1	1	*
57	Scott (2000)	Pig	6.4	2.6	32.3	42.8	1	1	1	*
58	Scott (2000)	Pig	6.4	2.6	33.2	45.2	1	1	1	*
59	Scott (2000)	Pig	6.4	3.5	19.2	20.4	1	*	*	*
60	Scott (2000)	Pig	6.4	3.5	18.9	19.7	*	0	0	*

Table 15 (continued): Eye injury database (with data pooling) used for survival analysis and final risk functions.

Test Number	Author (Year)	Species	Diameter (mm)	Mass (g)	Velocity (m/s)	Normalized Energy (kJ/m ²)	HY	LD	RD	GR
61	Scott (2000)	Pig	6.4	3.5	18.6	19.1	1	1	*	*
62	Scott (2000)	Pig	6.4	3.5	20.7	23.7	1	1	*	*
63	Scott (2000)	Pig	6.4	3.5	26.2	37.9	1	1	1	*
64	Scott (2000)	Pig	6.4	3.5	20.7	23.7	1	1	*	*
65	Scott (2000)	Pig	6.4	3.5	33.0	60.2	1	1	1	*
66	Scott (2000)	Pig	9.5	45.5	4.0	5.1	0	0	0	*
67	Scott (2000)	Pig	9.5	45.5	4.3	5.9	0	0	0	*
68	Scott (2000)	Pig	9.5	45.5	5.2	8.6	0	0	0	*
69	Scott (2000)	Pig	6.4	45.5	5.2	19.4	0	0	0	*
70	Stitzel (2002)	Human	6.4	0.1	4.3	0.0	0	0	0	0
71	Stitzel (2002)	Human	6.4	0.1	5.4	0.0	0	0	0	0
72	Stitzel (2002)	Human	6.4	0.1	6.0	0.0	0	0	0	0
73	Stitzel (2002)	Human	6.4	0.1	10.6	0.1	*	*	*	0
74	Stitzel (2002)	Human	6.4	0.1	14.2	0.2	*	*	*	0
75	Stitzel (2002)	Human	6.4	0.1	14.3	0.2	*	*	*	0
76	Stitzel (2002)	Human	6.4	0.1	18.9	0.4	*	*	*	0
77	Stitzel (2002)	Human	6.4	0.1	23.0	0.6	*	*	*	0
78	Stitzel (2002)	Human	6.4	0.1	26.7	0.9	*	*	*	0
79	Stitzel (2002)	Human	6.4	0.1	26.8	0.9	*	*	*	0
80	Stitzel (2002)	Human	6.4	0.1	28.6	1.0	*	*	*	0
81	Stitzel (2002)	Human	6.4	0.1	31.0	1.2	*	*	*	0
82	Stitzel (2002)	Human	76.1	146.5	30.1	14.6	*	*	*	*
83	Stitzel (2002)	Human	76.1	146.5	34.4	19.1	*	*	*	*
84	Stitzel (2002)	Human	76.1	146.5	35.5	20.3	*	*	*	*
85	Stitzel (2002)	Human	76.1	146.5	41.2	27.3	*	*	*	*
86	Stitzel (2002)	Human	76.1	146.5	42.8	29.5	*	*	*	*
87	Stitzel (2002)	Human	4.5	0.4	53.0	33.1	*	*	*	0
88	Stitzel (2002)	Human	4.5	0.4	53.8	34.1	*	*	*	0
89	Stitzel (2002)	Human	4.5	0.4	55.8	36.7	*	*	*	0
90	Stitzel (2002)	Human	4.5	0.4	59.7	42.0	*	*	*	0
91	Stitzel (2002)	Human	4.5	0.4	85.2	85.6	1	1	1	1
92	Stitzel (2002)	Human	4.5	0.4	90.4	96.3	1	1	1	1
93	Stitzel (2002)	Human	4.5	0.4	91.7	99.1	1	1	1	1
94	Stitzel (2002)	Human	4.5	0.4	122.4	176.6	1	1	1	1
95	Umlas (1995)	Pig	41.0	24.7	45.7	19.6	*	*	*	*
96	Weidenthal (1966)	Pig	14.0	272.0	2.4	5.3	*	*	0	*
97	Weidenthal (1964)	Monkey	15.9	283.0	3.0	6.4	0	0	0	*
98	Weidenthal (1964)	Monkey	15.9	283.0	3.0	6.4	0	0	0	*
99	Weidenthal (1964)	Monkey	15.9	283.0	3.0	6.4	0	0	0	*
100	Weidenthal (1964)	Monkey	15.9	283.0	3.1	7.0	0	0	0	*
101	Weidenthal (1964)	Monkey	15.9	283.0	3.1	7.0	0	0	0	*
102	Weidenthal (1964)	Monkey	15.9	283.0	3.1	7.0	0	0	0	*
103	Weidenthal (1964)	Monkey	15.9	283.0	3.1	7.0	1	0	0	*
104	Weidenthal (1964)	Monkey	15.9	283.0	3.1	7.0	1	0	0	*
105	Weidenthal (1964)	Monkey	15.9	283.0	3.9	10.8	0	0	0	*
106	Weidenthal (1964)	Monkey	15.9	283.0	3.9	10.8	0	0	0	*
107	Weidenthal (1964)	Monkey	15.9	283.0	3.9	10.8	0	0	0	*
108	Weidenthal (1964)	Monkey	15.9	283.0	3.9	10.8	1	0	0	*
109	Weidenthal (1964)	Monkey	15.9	283.0	3.9	10.8	1	0	0	*
110	Weidenthal (1964)	Monkey	15.9	283.0	3.9	10.8	1	0	0	*
111	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	1	1	1	*
112	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	1	0	0	*
113	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	1	0	0	*
114	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	1	0	0	*
115	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	1	0	0	*
116	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	0	0	0	*
117	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	0	0	0	*
118	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	0	0	0	*
119	Weidenthal (1964)	Monkey	15.9	283.0	4.3	13.2	0	0	0	*
120	Weidenthal (1964)	Monkey	15.9	283.0	4.6	14.9	1	1	1	*

Table 15 (continued): Eye injury database (with data pooling) used for survival analysis and final risk functions.

Test Number	Author (Year)	Species	Diameter (mm)	Mass (g)	Velocity (m/s)	Normalized Energy (kJ/m ²)	HY	LD	RD	GR
121	Weidenthal (1964)	Monkey	15.9	283.0	4.6	14.9	1	1	1	*
122	Weidenthal (1964)	Monkey	15.9	283.0	4.6	14.9	1	1	1	*
123	Weidenthal (1964)	Monkey	15.9	283.0	4.6	14.9	1	1	1	*
124	Weidenthal (1964)	Monkey	15.9	283.0	4.6	14.9	0	0	0	*
125	Weidenthal (1966)	Pig	4.5	0.3	66.4	47.8	1	1	1	*
126	Kennedy (2006)	Human	6.0	0.1	88.3	16.0	*	*	*	0
127	Kennedy (2006)	Human	6.0	0.1	91.6	17.5	*	*	*	0
128	Kennedy (2006)	Human	6.0	0.1	92.1	17.4	*	*	*	0
129	Kennedy (2006)	Human	6.0	0.1	117.8	28.4	*	*	*	0
130	Kennedy (2006)	Human	17.3	3.2	71.7	35.1	1	1	1	1
131	Kennedy (2006)	Human	17.3	3.2	71.3	34.6	1	1	1	1
132	Kennedy (2006)	Human	6.0	0.2	73.0	19.7	*	*	*	0
133	Kennedy (2006)	Human	6.0	0.2	76.3	20.3	*	*	*	0
134	Kennedy (2006)	Human	6.0	0.2	78.3	22.0	*	*	*	0
135	Kennedy (2006)	Human	6.0	0.2	85.3	26.3	*	*	*	0
136	Kennedy (2006)	Human	17.3	3.1	65.5	28.6	1	1	1	1
137	Kennedy (2006)	Human	17.3	3.2	71.1	34.5	*	*	*	0
138	Kennedy (2006)	Human	17.3	3.2	97.9	65.0	1	1	1	1
139	Kennedy (2006)	Human	6.0	0.1	93.6	17.8	*	*	*	0
140	Kennedy (2006)	Human	6.0	0.1	109.7	24.9	*	*	*	0
141	Kennedy (2006)	Human	17.3	3.2	68.0	31.4	*	*	*	0
142	Kennedy (2006)	Human	17.3	3.2	73.3	36.6	1	1	1	1
143	Kennedy (2006)	Human	6.0	0.2	75.0	20.6	*	*	*	0
144	Kennedy (2006)	Human	6.0	0.2	87.3	27.8	*	*	*	0
145	Kennedy (2006)	Human	17.3	3.2	71.1	34.6	1	1	1	1
146	Kennedy (2006)	Human	17.3	3.2	70.8	34.0	*	*	*	0
147	Kennedy (2006)	Human	17.3	3.2	107.2	78.1	1	1	1	1
148	Kennedy (2006)	Human	17.3	3.2	75.3	38.7	1	1	1	1
149	Kennedy (2006)	Human	17.3	3.2	72.0	35.5	1	1	1	1
150	Kennedy (2006)	Human	17.3	3.2	108.0	79.5	1	1	1	1
151	Kennedy (2006)	Human	17.3	3.2	112.5	86.5	1	1	1	1
152	Kennedy (2006)	Human	30.0	9.5	8.9	0.5	*	*	*	*
153	Kennedy (2006)	Human	6.0	0.2	81.2	24.0	*	*	*	0
154	Kennedy (2006)	Human	17.3	3.2	109.4	81.5	1	1	1	1
155	Kennedy (2006)	Human	19.9	112.6	8.7	13.8	*	*	*	0
156	Kennedy (2006)	Human	19.9	112.6	8.6	13.4	*	*	*	0
157	Kennedy (2006)	Human	19.9	112.6	8.5	13.2	*	*	*	0
158	Kennedy (2006)	Human	7.6	0.3	23.5	2.1	*	*	*	0
159	Kennedy (2006)	Human	7.6	0.3	24.0	2.2	*	*	*	0
160	Kennedy (2006)	Human	9.8	0.7	20.2	1.9	*	*	*	0
161	Kennedy (2006)	Human	9.8	0.7	19.3	1.7	*	*	*	0
162	Kennedy (2006)	Human	7.6	0.3	23.8	2.1	*	*	*	0
163	Kennedy (2006)	Human	7.6	0.3	24.5	2.3	*	*	*	0
164	Kennedy (2006)	Human	9.8	0.7	19.2	1.7	*	*	*	0
165	Kennedy (2006)	Human	9.8	0.7	17.8	1.5	*	*	*	0
166	Kennedy (2006)	Human	4.5	0.0	45.7	2.6	*	*	*	0
167	Kennedy (2006)	Human	4.5	0.0	38.1	1.8	*	*	*	0
168	Kennedy (2006)	Human	4.5	0.0	44.7	2.5	*	*	*	0
169	Kennedy (2006)	Human	4.5	0.0	41.2	2.1	*	*	*	0
170	Kennedy (2006)	Human	4.5	0.0	47.2	2.7	*	*	*	0
171	Kennedy (2006)	Human	4.5	0.0	43.7	2.3	*	*	*	0
172	Kennedy (2006)	Human	4.4	0.3	11.0	1.4	*	*	*	0
173	Kennedy (2006)	Human	4.4	0.3	11.5	1.5	*	*	*	0
174	Kennedy (2006)	Human	4.4	0.3	11.4	1.5	*	*	*	0
175	Kennedy (2006)	Human	4.4	0.3	11.2	1.4	*	*	*	0
176	Kennedy (2006)	Human	4.4	0.3	10.2	1.2	*	*	*	0
177	Kennedy (2006)	Human	9.2	3.6	44.1	51.8	1	1	1	1
178	Kennedy (2006)	Human	9.2	3.6	50.4	67.6	1	1	1	1
179	Kennedy (2006)	Human	9.2	3.6	56.0	83.6	1	1	1	1
180	Kennedy (2006)	Human	9.2	3.6	59.2	93.3	1	1	1	1

Table 15 (continued): Eye injury database (with data pooling) used for survival analysis and final risk functions.

Test Number	Author (Year)	Species	Diameter (mm)	Mass (g)	Velocity (m/s)	Normalized Energy (kJ/m ²)	HY	LD	RD	GR
181	Kennedy (2006)	Human	9.2	3.6	43.6	50.5	1	1	1	1
182	Kennedy (2006)	Human	9.2	3.6	42.1	47.2	1	1	1	1
183	Kennedy (2006)	Human	11.2	5.2	43.7	50.6	1	1	1	1
184	Kennedy (2006)	Human	11.2	5.2	44.1	51.6	1	1	1	1
185	Kennedy (2006)	Human	11.2	5.2	53.2	75.1	1	1	1	1
186	Kennedy (2006)	Human	11.2	5.2	44.7	53.0	1	1	1	1
187	Kennedy (2006)	Pig	6.0	0.1	97.8	19.7	*	*	*	*
188	Kennedy (2006)	Pig	6.0	0.1	101.8	21.4	*	*	*	*
189	Kennedy (2006)	Pig	6.0	0.1	94.7	18.1	*	*	*	*
190	Kennedy (2006)	Pig	6.0	0.1	115.6	27.3	*	*	*	*
191	Kennedy (2006)	Pig	17.3	3.2	71.7	35.1	*	*	*	*
192	Kennedy (2006)	Pig	17.3	3.2	99.0	66.1	*	*	*	*
193	Kennedy (2006)	Pig	17.3	3.2	106.1	76.8	*	*	*	*
194	Kennedy (2006)	Pig	17.3	3.2	108.9	80.0	*	*	*	*
195	Kennedy (2006)	Pig	6.0	0.2	74.7	20.1	*	*	*	*
196	Kennedy (2006)	Pig	6.0	0.2	77.1	21.4	*	*	*	*
197	Kennedy (2006)	Pig	6.0	0.2	72.5	18.9	*	*	*	*
198	Kennedy (2006)	Pig	6.0	0.2	87.4	27.6	*	*	*	*
199	Kennedy (2006)	Pig	17.3	3.2	67.1	30.7	*	*	*	*
200	Kennedy (2006)	Pig	17.3	3.2	100.2	68.1	*	*	*	*
201	Kennedy (2006)	Pig	17.3	3.2	101.9	70.6	*	*	*	*
202	Kennedy (2006)	Pig	17.3	3.2	103.3	72.5	*	*	*	*
203	Kennedy (2006)	Pig	17.3	3.2	111.0	83.9	*	*	*	*
204	Kennedy (2006)	Pig	6.0	0.1	92.5	17.5	*	*	*	*
205	Kennedy (2006)	Pig	6.0	0.1	115.6	27.3	*	*	*	*
206	Kennedy (2006)	Pig	17.3	3.2	68.0	31.4	*	*	*	*
207	Kennedy (2006)	Pig	17.3	3.1	95.6	59.5	*	*	*	*
208	Kennedy (2006)	Pig	17.3	3.2	109.5	81.5	*	*	*	*
209	Kennedy (2006)	Pig	17.3	3.2	108.9	79.7	*	*	*	*
210	Kennedy (2006)	Pig	6.0	0.2	67.2	16.5	*	*	*	*
211	Kennedy (2006)	Pig	6.0	0.2	84.0	25.1	*	*	*	*
212	Kennedy (2006)	Pig	17.3	3.1	66.8	29.8	*	*	*	*
213	Kennedy (2006)	Pig	17.3	3.2	100.6	69.1	*	*	*	*
214	Kennedy (2006)	Pig	17.3	3.2	114.1	88.3	*	*	*	*
215	Kennedy (2006)	Pig	17.3	3.2	106.4	76.4	*	*	*	*
216	Kennedy (2006)	Pig	17.3	3.2	109.7	81.9	*	*	*	*
217	Kennedy (2006)	Pig	17.3	3.2	106.4	77.3	*	*	*	*
218	Kennedy (2006)	Pig	17.3	3.2	101.8	70.2	*	*	*	*
219	Kennedy (2006)	Pig	6.0	0.2	83.3	24.9	*	*	*	*
220	Kennedy (2006)	Pig	17.3	3.2	100.7	69.4	*	*	*	*
221	Kennedy (2006)	Pig	19.9	112.6	8.7	13.6	*	*	*	*
222	Kennedy (2006)	Pig	19.9	112.6	8.8	14.1	*	*	*	*
223	Kennedy (2006)	Pig	19.9	112.6	8.4	12.9	*	*	*	*
224	Kennedy (2006)	Pig	19.9	112.6	8.8	14.2	*	*	*	*
225	Kennedy (2006)	Pig	7.6	0.3	5.7	0.1	*	*	*	*
226	Kennedy (2006)	Pig	7.6	0.3	15.5	0.9	*	*	*	*
227	Kennedy (2006)	Pig	7.6	0.3	10.8	0.4	*	*	*	*
228	Kennedy (2006)	Pig	4.5	0.0	25.9	0.8	*	*	*	*
229	Kennedy (2006)	Pig	4.5	0.0	22.0	0.6	*	*	*	*
230	Kennedy (2006)	Pig	4.5	0.0	29.3	1.1	*	*	*	*
231	Kennedy (2006)	Pig	7.6	0.3	13.4	0.7	*	*	*	*
232	Kennedy (2006)	Pig	7.6	0.3	19.6	1.5	*	*	*	*
233	Kennedy (2006)	Pig	4.5	0.0	16.5	0.3	*	*	*	*
234	Kennedy (2006)	Pig	4.5	0.0	32.8	1.3	*	*	*	*
235	Kennedy (2006)	Pig	11.2	5.2	33.8	30.2	*	*	*	*
236	Kennedy (2006)	Pig	11.2	5.2	37.8	37.8	*	*	*	*
237	Kennedy (2006)	Pig	9.2	3.6	28.1	21.1	*	*	*	*
238	Kennedy (2006)	Pig	9.2	3.6	34.9	32.4	*	*	*	*
239	Kennedy (2006)	Pig	4.4	0.3	96.0	105.2	*	*	*	*
240	Kennedy (2006)	Pig	4.4	0.3	165.6	309.8	*	*	*	*

Table 15 (continued): Eye injury database (with data pooling) used for survival analysis and final risk functions.

Test Number	Author (Year)	Species	Diameter (mm)	Mass (g)	Velocity (m/s)	Normalized Energy (kJ/m ²)	HY	LD	RD	GR
241	Kennedy (2006)	Pig	4.4	0.3	142.1	226.0	*	*	*	*
242	Kennedy (2006)	Pig	4.5	0.0	149.6	26.0	*	*	*	*
243	Kennedy (2006)	Pig	4.4	0.3	140.0	222.2	*	*	*	*
244	Kennedy (2006)	Pig	4.4	0.3	140.0	223.0	*	*	*	*
245	Kennedy (2006)	Pig	4.4	0.3	99.7	113.2	*	*	*	*
246	Kennedy (2006)	Pig	4.4	0.3	98.1	109.4	*	*	*	*
247	Kennedy (2006)	Pig	4.4	0.3	95.9	102.9	*	*	*	*
248	Kennedy (2006)	Pig	4.4	0.3	99.3	112.8	*	*	*	*
249	Kennedy (2006)	Pig	4.4	0.3	98.2	109.7	*	*	*	*
250	Kennedy (2006)	Pig	4.4	0.3	97.6	108.9	*	*	*	*
251	Kennedy (2006)	Pig	4.4	0.3	131.7	197.4	*	*	*	*

XV. APPENDIX F: FOCUS EYE IMPACT TEST RESULTS

Table 16: Impact test results from FOCUS headform using 3.2 mm projectile.

Test Number	Aspect Tested	Eye Used	Projectile Diameter (mm)	Normalized Energy (kJ/m ²)	Peak Impact Force (N)
1	Left	A	3.2	22.24	35.20
2	Left	A	3.2	25.32	38.97
3	Left	A	3.2	31.01	52.92
4	Left	A	3.2	39.60	63.77
5	Left	A	3.2	44.13	61.06
6	Left	A	3.2	46.61	72.30
7	Left	A	3.2	67.44	52.31
8	Left	A	3.2	66.47	97.56
9	Left	A	3.2	68.61	98.67
10	Left	A	3.2	81.74	108.36
11	Left	A	3.2	81.98	108.16
12	Left	A	3.2	82.17	115.69
13	Left	A	3.2	82.25	113.72
14	Left	A	3.2	87.73	108.16
15	Left	A	3.2	90.37	118.29
16	Left	A	3.2	89.28	109.04
17	Left	A	3.2	90.43	114.16
18	Left	A	3.2	91.27	120.34
19	Left	A	3.2	92.43	122.42
20	Left	A	3.2	91.44	125.60
21	Left	C	3.2	93.74	107.84
22	Left	C	3.2	90.54	114.44
23	Left	C	3.2	92.52	119.72
24	Left	C	3.2	94.86	124.36
25	Left	C	3.2	95.63	119.61
26	Left	E	3.2	12.00	5.02
27	Left	E	3.2	25.21	7.46
28	Left	E	3.2	24.35	9.19
29	Left	E	3.2	21.20	8.24
30	Left	E	3.2	33.45	7.47
31	Left	E	3.2	36.85	17.20
32	Left	E	3.2	43.69	30.97
33	Left	E	3.2	43.32	39.03
34	Left	E	3.2	43.13	36.82
35	Left	E	3.2	48.32	56.45
36	Left	E	3.2	52.19	58.59
37	Left	E	3.2	55.67	87.81
38	Left	E	3.2	56.80	63.19
39	Left	K	3.2	61.04	43.90
40	Left	K	3.2	62.45	37.01
41	Left	K	3.2	67.33	36.98
42	Left	K	3.2	68.07	33.73
43	Left	K	3.2	70.67	34.82
44	Left	K	3.2	69.01	50.43
45	Left	K	3.2	72.39	60.16
46	Left	K	3.2	74.00	63.52
47	Left	K	3.2	78.27	57.46
48	Left	K	3.2	78.07	50.78
49	Left	K	3.2	80.28	66.21
50	Left	K	3.2	81.44	66.77
51	Right	B	3.2	45.65	72.09
52	Right	B	3.2	45.48	81.76
53	Right	B	3.2	46.75	76.91
54	Right	B	3.2	71.17	111.42
55	Right	B	3.2	72.43	119.59
56	Right	D	3.2	73.59	135.71
57	Right	D	3.2	84.46	138.15
58	Right	D	3.2	88.21	156.43
59	Right	D	3.2	87.41	104.47

Table 17: Impact test results from FOCUS headform using 6.4 mm projectile.

Test Number	Aspect Tested	Eye Used	Projectile Diameter (mm)	Normalized Energy (kJ/m ²)	Peak Impact Force (N)
60	Left	C	6.4	15.51	135.92
61	Left	C	6.4	21.59	169.65
62	Left	C	6.4	28.69	206.95
63	Left	C	6.4	43.45	291.97
64	Left	C	6.4	50.40	283.52
65	Left	C	6.4	56.73	305.93
66	Left	C	6.4	95.01	408.41
67	Left	C	6.4	103.29	463.44
68	Left	C	6.4	109.09	416.89
69	Left	C	6.4	135.55	483.08
70	Left	C	6.4	131.58	410.95
71	Left	C	6.4	142.69	428.44
72	Left	C	6.4	141.28	410.12
73	Left	C	6.4	145.05	453.65
74	Left	C	6.4	150.83	409.95
75	Left	E	6.4	147.11	533.22
76	Left	E	6.4	150.86	629.55
77	Left	E	6.4	156.51	625.63
78	Left	E	6.4	157.53	702.48
79	Left	E	6.4	160.05	559.60
80	Left	E	6.4	160.82	570.30
81	Left	E	6.4	157.10	598.61
82	Left	E	6.4	153.92	575.34
83	Left	E	6.4	165.93	554.41
84	Left	E	6.4	161.90	629.74
85	Left	I	6.4	10.56	140.95
86	Left	I	6.4	23.52	226.86
87	Left	I	6.4	22.43	197.15
88	Left	I	6.4	22.07	160.73
89	Left	I	6.4	34.00	245.74
90	Left	I	6.4	40.14	252.54
91	Left	I	6.4	49.77	281.85
92	Left	I	6.4	49.67	313.79
93	Left	G	6.4	43.49	264.36
94	Left	G	6.4	61.65	306.13
95	Left	G	6.4	64.10	435.86
96	Left	G	6.4	71.75	454.33
97	Left	G	6.4	75.94	385.05
98	Left	G	6.4	81.67	444.97
99	Left	G	6.4	89.15	469.99
100	Left	G	6.4	95.02	451.61
101	Left	G	6.4	103.58	466.21
102	Left	G	6.4	103.00	429.16
103	Left	A	6.4	101.69	516.53
104	Left	A	6.4	113.57	554.01
105	Left	A	6.4	116.46	578.16
106	Left	A	6.4	124.39	596.36
107	Left	A	6.4	131.85	497.68
108	Left	A	6.4	130.61	559.31
109	Left	A	6.4	131.98	562.17
110	Right	D	6.4	48.79	311.00
111	Right	F	6.4	49.61	311.76
112	Right	F	6.4	50.81	379.58
113	Right	F	6.4	102.04	548.13
114	Right	F	6.4	104.32	443.50
115	Right	F	6.4	103.62	479.73
116	Right	H	6.4	67.00	363.51
117	Right	H	6.4	145.87	643.59
118	Right	H	6.4	144.60	638.06

Table 18: Impact test results from FOCUS headform using 9.5 mm projectile.

Test Number	Aspect Tested	Eye Used	Projectile Diameter (mm)	Normalized Energy (kJ/m ²)	Peak Impact Force (N)
119	Left	E	9.5	0.93	37.51
120	Left	E	9.5	3.73	123.76
121	Left	E	9.5	5.77	165.28
122	Left	E	9.5	13.76	257.79
123	Left	E	9.5	14.79	300.28
124	Left	E	9.5	19.56	488.88
125	Left	E	9.5	28.66	548.94
126	Left	E	9.5	31.35	619.25
127	Left	E	9.5	36.01	697.17
128	Left	E	9.5	46.05	734.35
129	Left	G	9.5	50.28	564.26
130	Left	G	9.5	54.61	687.84
131	Left	G	9.5	0.00	754.10
132	Left	A	9.5	0.51	32.23
133	Left	A	9.5	4.79	189.29
134	Left	A	9.5	4.62	188.53
135	Left	C	9.5	3.23	123.05
136	Left	C	9.5	9.49	181.65
137	Left	C	9.5	12.54	250.54
138	Left	C	9.5	17.04	310.32
139	Left	C	9.5	17.03	318.30
140	Left	C	9.5	16.85	306.45
141	Left	C	9.5	23.05	351.66
142	Left	C	9.5	25.99	437.35
143	Left	C	9.5	32.13	560.89
144	Left	C	9.5	33.08	575.59
145	Left	I	9.5	31.40	405.67
146	Left	I	9.5	39.67	734.55
147	Left	I	9.5	43.44	736.81
148	Left	I	9.5	49.45	774.23
149	Right	H	9.5	4.27	170.07
150	Right	H	9.5	4.07	141.23
151	Right	J	9.5	4.35	136.77
152	Right	J	9.5	17.62	426.58
153	Right	J	9.5	18.13	519.99
154	Right	J	9.5	17.82	533.48
155	Right	J	9.5	33.92	747.78
156	Right	L	9.5	32.90	566.14
157	Right	L	9.5	35.52	775.29

Table 19: Impact test results from FOCUS headform using 12.7 mm projectile.

Test Number	Aspect Tested	Eye Used	Projectile Diameter (mm)	Normalized Energy (kJ/m ²)	Peak Impact Force (N)
158	Left	G	12.7	0.16	5.04
159	Left	G	12.7	1.63	116.78
160	Left	G	12.7	2.42	113.11
161	Left	G	12.7	1.78	74.85
162	Left	G	12.7	4.59	215.31
163	Left	G	12.7	4.02	187.90
164	Left	G	12.7	4.80	206.33
165	Left	G	12.7	7.81	272.35
166	Left	G	12.7	9.90	253.23
167	Left	G	12.7	11.99	345.66
168	Left	I	12.7	12.09	387.30
169	Left	I	12.7	15.65	433.72
170	Left	I	12.7	15.19	452.97
171	Left	I	12.7	15.66	433.00
172	Left	I	12.7	17.85	494.27
173	Left	I	12.7	23.54	560.34
174	Left	I	12.7	24.20	516.39
175	Left	I	12.7	30.07	882.14
176	Left	E	12.7	1.32	107.80
177	Left	E	12.7	1.74	137.93
178	Left	E	12.7	1.33	109.21
179	Left	E	12.7	6.88	271.80
180	Left	E	12.7	10.88	393.09
181	Left	C	12.7	15.54	530.84
182	Left	C	12.7	15.33	476.89
183	Left	C	12.7	15.06	451.32
184	Left	C	12.7	20.95	538.66
185	Left	C	12.7	24.10	722.96
186	Left	C	12.7	26.78	715.96
187	Left	C	12.7	30.47	666.75
188	Left	C	12.7	30.78	820.98
189	Left	C	12.7	30.39	551.15
190	Right	L	12.7	3.41	191.53
191	Right	L	12.7	2.55	149.02
192	Right	L	12.7	2.23	136.56
193	Right	B	12.7	15.82	559.77
194	Right	B	12.7	15.65	610.32
195	Right	B	12.7	15.32	631.46
196	Right	B	12.7	24.95	794.32
197	Right	B	12.7	25.01	817.35
198	Right	D	12.7	24.26	803.06

Table 20: Impact test results from FOCUS headform using 15.9 mm projectile.

Test Number	Aspect Tested	Eye Used	Projectile Diameter (mm)	Normalized Energy (kJ/m ²)	Peak Impact Force (N)
199	Left	I	15.9	0.49	45.78
200	Left	I	15.9	0.47	68.88
201	Left	I	15.9	3.45	235.72
202	Left	I	15.9	3.42	183.82
203	Left	I	15.9	9.56	445.44
204	Left	I	15.9	9.55	383.57
205	Left	I	15.9	18.61	646.92
206	Left	K	15.9	19.03	675.74
207	Left	K	15.9	0.37	49.05
208	Left	K	15.9	0.54	63.23
209	Left	K	15.9	1.08	134.52
210	Left	K	15.9	1.55	122.06
211	Left	K	15.9	2.20	182.66
212	Left	K	15.9	2.89	213.87
213	Left	K	15.9	4.09	263.23
214	Left	K	15.9	5.23	298.89
215	Left	K	15.9	6.52	351.37
216	Left	K	15.9	7.88	369.88
217	Left	K	15.9	8.78	394.69
218	Left	K	15.9	10.76	438.29
219	Left	K	15.9	12.44	465.59
220	Left	K	15.9	14.35	557.67
221	Left	K	15.9	15.84	571.96
222	Left	K	15.9	17.82	665.15
223	Left	K	15.9	20.21	696.90
224	Left	K	15.9	21.12	917.00
225	Left	K	15.9	0.28	46.86
226	Left	K	15.9	0.61	84.92
227	Left	A	15.9	0.97	115.88
228	Left	A	15.9	1.66	143.21
229	Left	A	15.9	2.04	166.50
230	Left	A	15.9	2.91	208.71
231	Left	A	15.9	4.05	255.52
232	Left	A	15.9	5.04	290.35
233	Left	A	15.9	6.34	325.73
234	Left	A	15.9	7.96	389.14
235	Left	A	15.9	9.10	416.16
236	Left	A	15.9	10.04	537.43
237	Left	G	15.9	11.96	504.04
238	Left	G	15.9	13.60	524.27
239	Left	G	15.9	15.38	577.55
240	Left	G	15.9	16.10	623.20
241	Left	G	15.9	18.18	661.61
242	Left	G	15.9	20.58	747.55
243	Left	G	15.9	18.88	806.44
244	Left	G	15.9	9.68	526.04
245	Left	G	15.9	3.63	236.06
246	Left	G	15.9	0.42	39.53
247	Right	D	15.9	0.41	76.89
248	Right	D	15.9	0.43	65.81
249	Right	D	15.9	0.42	57.12
250	Right	D	15.9	3.51	174.42
251	Right	F	15.9	3.43	219.42
252	Right	F	15.9	3.39	221.50
253	Right	F	15.9	10.48	488.34
254	Right	F	15.9	10.18	507.29
255	Right	F	15.9	10.43	480.37

Table 21: Impact test results from FOCUS headform using 17.5 mm projectile.

Test Number	Aspect Tested	Eye Used	Projectile Diameter (mm)	Normalized Energy (kJ/m ²)	Peak Impact Force (N)
256	Left	A	17.5	0.57	77.25
257	Left	A	17.5	0.57	117.68
258	Left	A	17.5	1.49	130.34
259	Left	A	17.5	2.12	186.68
260	Left	A	17.5	2.82	208.58
261	Left	A	17.5	5.85	345.49
262	Left	A	17.5	7.45	393.10
263	Left	A	17.5	8.64	452.76
264	Left	A	17.5	12.93	576.55
265	Left	A	17.5	14.38	571.27
266	Left	A	17.5	16.02	632.92
267	Left	A	17.5	18.38	705.71
268	Left	A	17.5	19.18	755.31
269	Left	A	17.5	20.24	758.13
270	Left	I	17.5	0.55	69.19
271	Left	I	17.5	1.11	121.13
272	Left	I	17.5	2.21	161.58
273	Left	I	17.5	1.87	142.39
274	Left	I	17.5	2.09	183.12
275	Left	I	17.5	5.37	330.51
276	Left	I	17.5	4.80	310.73
277	Left	I	17.5	7.75	414.65
278	Left	I	17.5	7.88	411.48
279	Left	I	17.5	9.94	424.78
280	Left	I	17.5	10.53	500.52
281	Left	I	17.5	11.32	511.42
282	Left	I	17.5	14.93	616.37
283	Left	I	17.5	15.07	627.76
284	Left	K	17.5	14.75	603.97
285	Left	K	17.5	17.75	695.66
286	Left	K	17.5	19.81	766.34
287	Left	K	17.5	22.86	846.34
288	Right	H	17.5	2.19	161.80
289	Right	H	17.5	2.19	169.80
290	Right	H	17.5	2.11	185.37
291	Right	H	17.5	7.39	395.77
292	Right	H	17.5	7.62	427.99
293	Right	J	17.5	7.41	496.14
294	Right	J	17.5	14.17	717.24
295	Right	J	17.5	14.39	691.14
296	Right	J	17.5	14.53	726.98

U.S. Army Aeromedical Research Laboratory Fort Rucker, Alabama

All of USAARL's science and technical
information documents are available for
download from the
Defense Technical Information Center.

<https://discover.dtic.mil/results/?q=USAARL>



**Army Futures Command
U.S. Army Medical Research and Development Command**