# Literature Review of Eye Injuries and Eye Injury Risk from Blunt Objects

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**ABSTRACT**

Eye injuries affect approximately two million people annually. Various studies that have evaluated the injury tolerance of animal and human eyes from blunt impacts are summarized herein. These studies date from the late 60s to present and illustrate various methods for testing animal and human cadaver eyes exposed to various blunt projectiles including metal rods, BBs, baseballs, and foam pieces. Experimental data from these studies have been used to develop injury risk curves to predict eye injuries based on projectile parameters such as kinetic energy and normalized energy. Recently, intraocular pressure (IOP) has been correlated to injury risk which allows eye injuries to be predicted when projectile characteristics are unknown. These experimental data have also been used to validate numerous computational and physical models of the eye used to assess injury risk from blunt loading. One such physical model is the the Facial and Ocular CountermeasUre Safety (FOCUS) headform, which is an advanced anthropomorphic device designed specifically to study facial and ocular injury. The FOCUS headform eyes have a biofidelic response to blunt impact and eye load cell data can be used to assess injury risk for eye injuries.

Key Words: Projectile, Impact, Eye, Injury, Risk

## INTRODUCTION

Annually, approximately two million people in the United States suffer from eye injuries that require treatment [1]. The most common sources of eye injuries include automobile accidents [2-13], sports-related impacts [14-17], consumer products [18-27], and military combat [28-31]. These events result in nearly 500,000 cases of lost eyesight in the United States each year [32]. These injuries affect quality of life and are expensive to treat, given an estimated annual cost of $51.4 billion associated with adult vision problems in the United States [33,34]. Previous research has documented various etiologies of eye injuries, studied parameters that affect eye injury risk, and developed computational and physical models of the eye that can assess eye injury risk during various loading schemes [35-43]. This paper summarizes a number of the studies that are related to blunt eye impacts.

## EXPERIMENTAL EYE IMPACT TESTS

Previous research has investigated ocular injuries from projectile impacts for a variety of blunt objects with known projectile characteristics to determine the eye injury tolerance. These studies comprise much of the historical experimental eye tests that are currently used to assess and predict eye injuries from blunt impacts. Data from these experiments have been used as motivation for further experimental studies and the development and validation of a number of computational models of the eye for various loading schemes [51-60].

The main eye injuries assessed in much of the literature are: corneal abrasion, hyphema, lens damage, retinal damage, and globe rupture. These injuries are listed with increasing severity. Corneal abrasion is the loss of the epithelial layer of cells on the cornea. As epithelial cells can regrow, corneal abrasions generally resolve on their own. Hyphema, or bleeding in the anterior chamber, is a relatively minor injury that rarely requires medical treatment. Lens damage, including lens dislocation and cataract (clouding of the lens), can often be repaired by surgically replacing the lens. Retinal damage, which is most commonly observed during a retinal detachment, requires prompt surgical intervention to restore eyesight. Globe rupture occurs when the sclera and/or cornea tears, exposing the inside of the eye. Surgery is necessary to either fix or enucleate the damaged eye. While hyphema, corneal abrasion, and globe rupture can often be easily identified upon visual inspection of the eye, lens and retinal damage are generally diagnosed by an optometrist or ophthalmologist.

As many eye injuries are physiologic in nature, and because it is unethical to test human volunteers in potentially injurious conditions, live or anesthetized animals have been used to model human eye injury. Human cadaver eyes and postmortem animal eyes can, however, be used to assess gross injury such as corneal abrasion and globe rupture. Therefore, this section is split into two subsections to cover historical animal and human cadaver eye tests. Table 1 at the end of this section summarizes results from all animal and human cadaver eye studies mention herein.

*Animal Eye Experiments*

Weidenthal et al. (1964) conducted blunt impact tests on 28 anesthetized *macaca mulatta* (rhesus) monkeys using a brass rod projected at the eye at various energy levels. Hyphema, contusion deformity, and globe rupture were reported [44]. Ten of the 28 eyes had hyphema, five of the 28 eyes had contusion deformity, and five of the 28 eyes had globe rupture. The eyes that sustained a globe rupture may have rendered assessment of other intraocular injuries difficult, if not impossible.

Weidenthal et al. (1966) conducted blunt impact tests on 235 porcine eyes using a BB projected at the eye mounted in various materials [45]. Some of the porcine eyes were tested *in situ* before enucleation for comparison with enucleated eyes mounted in a 10% gelation solution or in a stone mold. Additionally, eyes were mounted in plasticene and 20% gelatin solution. Most of the data are insufficient to account for specific test conditions and injury pathologies. However, it was concluded that eyes mounted in a 10% gelatin solution best matched the response of eyes tested before enucleation.

Delori et al. (1969) conducted blunt impact tests on 75 enucleated porcine eyes using a BB projected at the eye mounted in a 10% gelatin solution [46]. Unfortunately, the data presented are insufficient to account for the specific injury pathologies and frequency at which these injuries occurred. However, this study presented the time-history of anterior pole, posterior pole, and corneal deformation due to impact by analyzing high-speed video of each test.

McKnight et al. (1988) conducted blunt impact tests on 20 anesthetized cats that had previously undergone radial keratotomy (RK) in one eye (three cats had bilateral RK) using a BB projected at the eye [19]. Twenty-three eyes were impacted with BBs at various velocities. The remaining 17 eyes were tested as controls. While all eyes suffered a hyphema, only four of the operated eyes ruptured; none of the unoperated eyes ruptured.

Green et al. (1990) conducted blunt impact tests on 11 anesthetized *macaca fascicularis* monkeys to observe fracture of the orbital floor [47]. This was done by dropping a brass cylinder down a tube to directly impact the globe. These tests resulted in 16 eyes with blow-out fracture, and six eyes with no blow-out fracture. Globe rupture was observed in five of the 16 eyes with blow-out fracture.

Duma et al. (2000) conducted blunt impact tests on 13 porcine eyes using foam objects projected at the eye *in situ* [7]. This study presented injury results for corneal abrasion by quantifying the area of the cornea damaged due to impact. Eight of the 13 eyes resulted in corneal abrasions affecting between 10% and 75% of the cornea.

Scott et al. (2000) conducted blunt impact tests on 21 enucleated porcine eyes using three steel rods projected at eyes mounted in a 10% gelatin solution [48]. These tests presented injury results for corneal abrasion, hyphema, lens damage, retinal damage, and globe rupture. Injuries were categorized as: Level 0 (no injury), Level 1 (injury to the iris or ciliary body, disruption of anterior chamber angle, lens injury without dislocation), Level 2 (lens dislocation or retinal damage), Level 3 (lens dislocation and retinal damage, possibly with iris or ciliary body injury), or Level 4 (globe rupture). Five tests resulted in Level 0 injury; two tests resulted in Level 1 injury; six tests resulted in Level 2 injury, six tests resulted in Level 3 injury, and no tests resulted in Level 4 injury. Two tests had no injury level listed. An interesting observation of this study was that injury outcome suggested lens damage occurred concurrently with retinal injury 100% of the time, but that the reciprocal was not true; i.e, retinal injury did not always occur concurrently with lens damage.

Kennedy et al. (2006) conducted blunt impact tests on 65 enucleated porcine eyes using various objects (airsoft pellets, BBs, paintballs, foam particles, plastic rods, aluminum rods) projected at eyes mounted in a 10% gelatin solution [17]. These tests presented injury results for globe rupture. Twenty-three of the 65 tests resulted in globe rupture.

Duma et al. (2012) conducted a series of 36 blunt impact tests on 12 enucleated porcine eyes using metal rods and BBs [25]. These tests presented injury results for globe rupture. Four of the 36 tests resulted in globe rupture.

*Human Cadaver Eye Experiments*

Delori et al. (1969) conducted blunt impact tests on two enucleated human cadaver eyes using a BB projected at eyes mounted in a 10% gelatin solution [46]. Unfortunately, the data presented are insufficient to account for the specific injury pathologies and frequency at which these injuries occurred, with the exception of a single test on a human cadaver eye which resulted in globe rupture.

Vinger et al. (1999) conducted blunt impact tests on two enucleated human cadaver eyes using baseballs projected at eyes mounted in 10% gelatin solution [15]. One eye was impacted by a CD-25 baseball at 75 mph and did not rupture. The other eye was impacted by a CD-250 baseball at 55 mph and did rupture.

Stitzel et al. (2002) conducted blunt impact tests on 22 enucleated human cadaver eyes using foam projectiles, BBs, and baseballs projected at eyes mounted in a 10% gelatin solution [49]. These tests presented injury results for globe rupture. Specifically, four of the eight BB tests and four of the five baseball tests resulted in globe rupture. None of the foam particles resulted in globe rupture. Additionally, a computational model of the eye to predict globe rupture was developed and validated using this experimental data. Using this computational model, globe rupture was predicted to occur when principal stress exceeded 23 MPa in the corneoscleral shell.

Kennedy et al. (2006) conducted blunt impact tests on 61 enucleated human cadaver eyes using various objects (airsoft pellets, BBs, paintballs, foam particles, plastic rods, aluminum rods) projected at eyes mounted in a 10% gelatin solution [17]. These tests presented injury results for globe rupture. Twenty-two of the 61 tests resulted in globe rupture.

Table 1. Summary of animal and human cadaver experimental eye tests.

| Study | Eye Model | Test Conditions | Outcomes |
|---|---|---|---|
| Weidenthal 1964 | 20 anesthetized monkey eyes | Brass rod projectile (1.26 J – 2.96 J) | 10/28 eyes resulted in hyphema<br>5/28 eyes resulted in globe rupture |
| Weidenthal 1966 | 235 (*in situ* and enucleated) pig eyes | Air rifle BB projectile (0.78 J) | Insufficient data to account for specific test conditions and injury pathology<br>10% gelatin solution best matched response of *in situ* eyes |
| Delori 1969 | 75 enucleated pig eyes | Air rifle BB projectile (0.68 J) | Insufficient data to account for specific test conditions and injury pathology<br>High-speed video of each test used to track anterior pole, posterior pole, and corneal deformation |
| McKnight 1988 | 20 anesthetized cat eyes (radial keratotomy performed in one or both eyes) | BB gun (0.34 J – 0.99 J) | 4/23 operated eyes ruptured<br>0/17 unoperated eyes ruptured |
| Green 1990 | 11 anesthetized monkey eyes | Brass rod drop test (0.89 J – 3.56 J) | 5/16 eyes resulted in globe rupture |
| Vinger 1999 | 2 enucleated human cadaver eyes | Baseball projectile (46.4 J & 82.2 J) | 1/2 eyes resulted in globe rupture |
| Duma 2000 | 13 (*in situ*) pig eyes | Foam particle projectile (0.034 J – 1.446 J) | 8/13 eyes resulted in corneal abrasion covering 10%-75% of the cornea |
| Scott 2000 | 21 enucleated pig eyes | Steel rod projectile (0.36 J – 1.89 J) | 5/21 eyes had no injury<br>2/21 eyes had injury to iris/ciliary body, anterior chamber angle disruption, or lens damage without dislocation<br>6/21 eyes had lens dislocation or retinal damage<br>6/21 eyes had lens dislocation and retinal damage<br>2 eyes had no specific injuries listed |
| Stitzel 2002 | 22 enucleated human cadaver eyes | BB, foam particle, and baseball projectile (0.004 J – 134.5 J) | 8/22 eyes resulted in globe rupture |
| Kennedy 2006 | 65 enucleated pig eyes<br>61 enucleated human cadaver eyes | Airsoft pellet, paintball, delrin impactor, plastic rod, foam particle, aluminum rod, BB projectile (0.01 J – 20.75 J) | 23/65 pig eye tests and 22/61 human eye tests resulted in globe rupture |
| Duma 2012 | 12 enucleated pig eyes | Aluminum rod, BB projectile (0.047 J – 2.257 J) | 4/36 eyes resulted in globe rupture |

## EYE INJURY RISK FUNCTIONS

Injury risk functions are useful tools that relate measurable parameters to injury outcomes [53-61]. The development of accurate injury risk functions relies heavily on compiling experimental injury data and measured test parameters. Fortunately, many of the experimental eye impact studies described in the previous section reported a portion or all of the data that could be reassessed in more detail and utilized for this purpose. Several experimental studies, in addition to providing injury results and measured parameters, also presented injury risk models for eye injuries. Each of these studies investigated the development of injury risk models based on various parameters and their relationship to injury outcome.

Duma et al. (2000) determined kinetic energy was the most significant parameter related to injury among univariate models (mass, velocity, energy) using linear logistic regression of data from experimental impact tests with foam particles [7]. This study presented an injury risk function that used kinetic energy to predict the probability of corneal abrasion.

Similarly, Scott et al. (2000) correlated kinetic energy to resulting injury. Using a chi-square analysis, this study showed a strong association between kinetic energy and lens dislocation, and a strong association between kinetic energy and retinal damage [48]. This study also correlated projectile momentum to resulting injury; however, a chi-squared analysis indicated no association between projectile momentum and injury.

Duma et al. (2005) presented a meta-analysis of eight previous experimental eye impact studies. Projectile mass and velocity were shown to be poor predictors of injury. This study presented injury risk curves that used either normalized energy or kinetic energy to predict the probability of corneal abrasion, lens dislocation, retinal damage, and globe rupture [62]. It was determined that normalized energy was a better predictor than kinetic energy because it accounts for the size of the projectile. Additionally, confidence intervals and 50% risk of injury values were determined for corneal abrasion, hyphema, lens dislocation, retinal damage, and globe rupture, for both kinetic and normalized energy.

Kennedy et al. (2006) presented binary logistic regression injury risk functions that used either kinetic energy or normalized energy to predict the risk of globe rupture for porcine eyes and human cadaver eyes [17]. This study corroborated the findings of Duma et al. (2005) that normalized energy is a better predictor than kinetic energy.

Kennedy et al. (2011) presented a comprehensive meta-analysis of over 250 eye impacts reported in the literature [63]. This study presented injury risk functions for hyphema, lens damage, retinal damage, and globe rupture. However, in contrast to earlier efforts to develop eye injury functions with logistical regression, the final risk functions presented in this study were determined using a more robust survival analysis. The final recommended risk functions employ 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 were presented for hyphema, lens damage, retinal damage, as well as globe rupture. Figure 1 shows the injury risk curves based on normalized energy as an injury predictor.

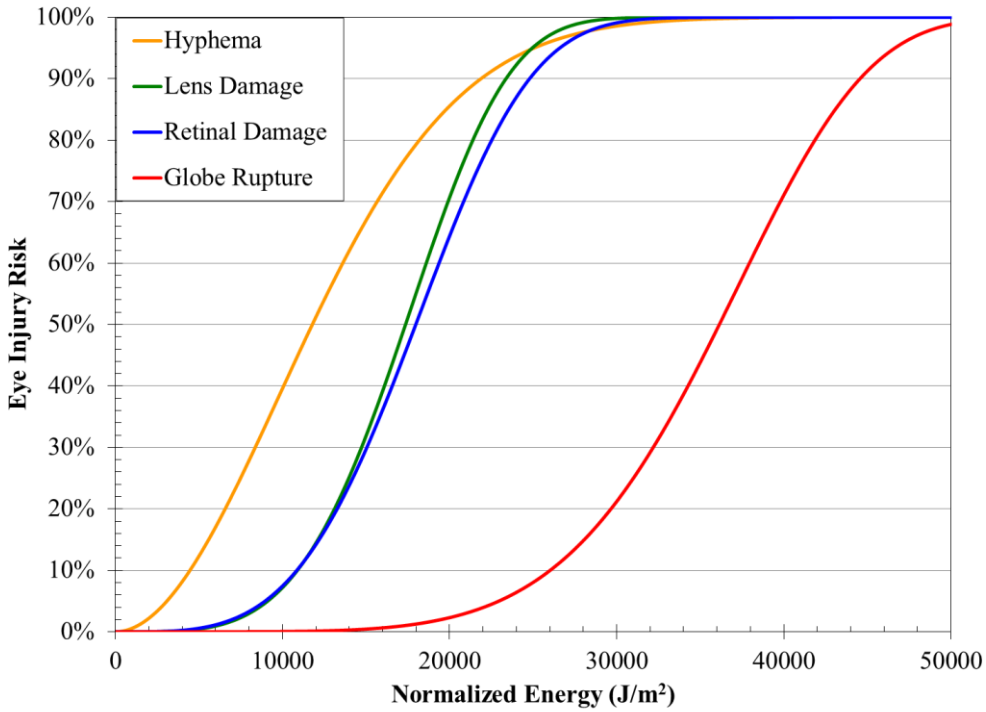


Figure 1. Final injury risk curves for hyphema, lens damage, retinal damage, and globe rupture using normalized energy as the injury predictor. Image modified from [63].

When projectile characteristics are unknown or there is no known projectile impact (i.e., water streams, pressure wave loading), it becomes necessary to use a parameter other than energy for injury risk assessment. Intraocular pressure can be used in these cases. One study determined a static loading threshold for human eye rupture to be 0.36 ± 0.2 MPa [12]. Additionally, two studies determined a dynamic loading threshold for human globe rupture to be 0.91 ± 0.29 MPa [12] and 0.97 ± 0.29 MPa [64]. Interal pressurization was used as a method to both statically and dynamically load the eye. A small pressure sensor was inserted into the eye to measure IOP for these tests. Similarly, experimental tests were conducted to determine the failure threshold of the eye due to an increase in IOP and to determine the material properties of the eye under high-rate loading [65]. This study calculated an average maximum true stress of 18.89 ± 4.81 MPa for both equatorial and meridional directions of the eye, an average maximum true strain along the equator of 0.041 ± 0.014, and an average maximum true strain along the meridian of 0.058 ± 0.018. Intraocular pressure measurements were used to calculate stress. High speed video analysis of markers printed on the sclera were used to calculate strain. Data from these studies have been primarily used for validation of computational models of the eye where IOP and peak stresses are the main criteria used to infer injury [36,49,51-54]. Overall, these experimental studies illustrate that measuring IOP during experimental tests provides another parameter for injury risk analysis.

Duma et al. (2012) investigated both the correlation between IOP and kinetic energy, and the correlation between IOP and normalized energy [25]. Intraocular pressure was measured throughout each test and normalized energy was calculated for each projectile. Overall, kinetic energy showed better correlation to IOP than normalized energy for all points. However, when separated by projectile type, there was a higher correlation between IOP and normalized energy than between IOP and kinetic energy for both cylinders. Three separate correlation curves were presented for IOP and normalized energy, one for each projectile (**Figure 2**). Normalized energy was previously determined to have a stronger correlation with injury than kinetic energy. The correlation between IOP and normalized energy presented in this study can be used with previously developed injury risk curves based on normalized energy to determine injury risk for eye injuries in cases where projectile characteristics are unknown or incalculable [26,27].

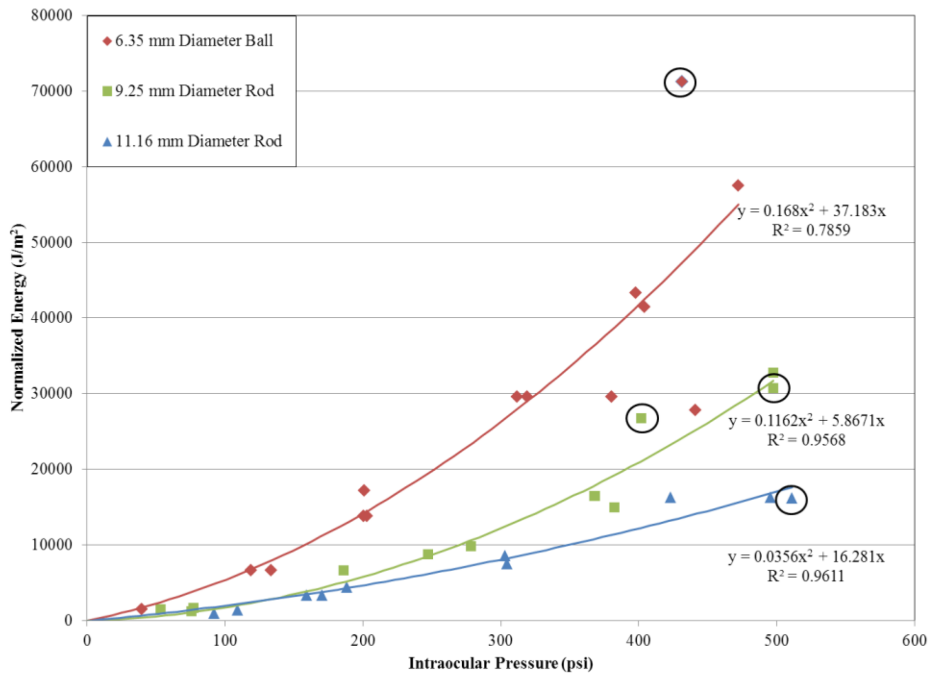


Figure 2. Correlation between intraocular pressure (IOP) and normalized energy for three blunt projectiles. Image modified from [25].

Duma et al. (2012) conducted a series of 38 tests on 8 porcine eyes using two water streams and various stream velocities to investigate the safety of water streams (i.e., water toys and water park streams) [66]. As water streams flow continually they do not have a tangible mass associated with them; therefore, kinetic and normalized energy cannot be directly quantified for these cases. This study implemented the correlations from Duma et al. (2012) to predict eye injury risk from water streams based on IOP [25]. Globe rupture was neither predicted nor observed in this study. Risk for hyphema was predicted to be as high has 20.7%; however, because cadaver tissue cannot be properly perfused, hyphema could not be directly assessed. Risk for lens dislocation and retinal damage was less than or equal to 1.3% for all tests.

## DEVELOPMENT AND VALIDATION OF THE FOCUS HEADFORM

The Facial and Ocular CountermeasUre Safety (FOCUS) headform is an advanced anthropometric test device specifically designed to quantify and assess injury risk due to facial and ocular loading (Figure 3). The FOCUS headform has eight segmented facial bones (frontal (x2), zygoma (x2), maxilla (x2), mandible, nasal) and two eyes that are instrumented with load cells. The FOCUS headform was developed and validated for facial impact with blunt objects [11,35,37-40,42,43,47,67,68].

Figure 3. The FOCUS headform (left) is an advanced anthropomorphic test device that has eight facial bone segments (middle) and two eyes (right) instrumented with load cells.

The eyes of the FOCUS headform were initially developed and validated in a three-part study by Kennedy et al. (2007) [68]. This study characterized the force-deflection response of the eye due to blunt loading. Human cadaver eyes were tested *in situ* and in various orbit designs. Biofidelity of the FOCUS headform eye was assessed by matching the response of the FOCUS headform eye to the response of the human cadaver eye (**Figure 4**). Muscles were either left intact or transected for the *in situ* eyes. It was determined that the effect of extraocular muscles was negligible when considering the response of the eye [69].

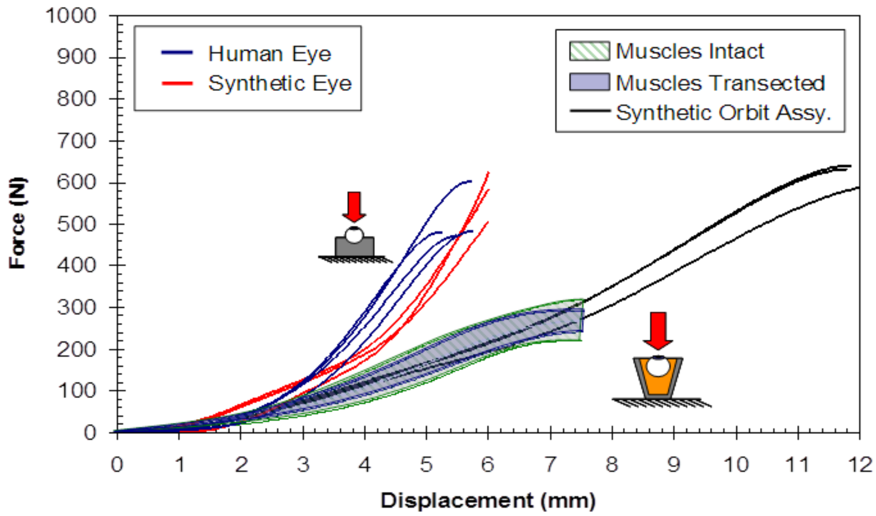


Figure 4. Force-displacement curves for human cadaver and FOCUS headform synthetic eyes. Matched response confirms biofidelity of the FOCUS headform synthetic eye. Image modified from [68].

Nearly 400 impact tests were conducted using the FOCUS headform to correlate the FOCUS headform eye response to various eye impact scenarios [63]. Six spherical projectiles varying in size from 3.2 mm to 17.5 mm in diameter were tested and reported by Kennedy et al. (2007) (**Figure 5**). Using the peak load reported by the FOCUS headform eye load cell for each impact, injury risk functions for hyphema, lens damage, retinal damage, and globe rupture were presented for each projectile. It was determined the FOCUS headform eye load cell response was proportional and highly correlated to the kinetic energy of the projectile. However, to most accurately predict eye injury risk, projectile size (or contact area with the eye) must be known. If the projectile size is unknown, a conservative estimate of projectile size should be used to evaluate injury risk (i.e. assume smallest projectile). It should be noted this could lead to an overestimation of eye injury risk. Despite this, the FOCUS headform injury criteria can be used to evaluate eye injuries for various sized objects, which further enhances the capability of the headform.

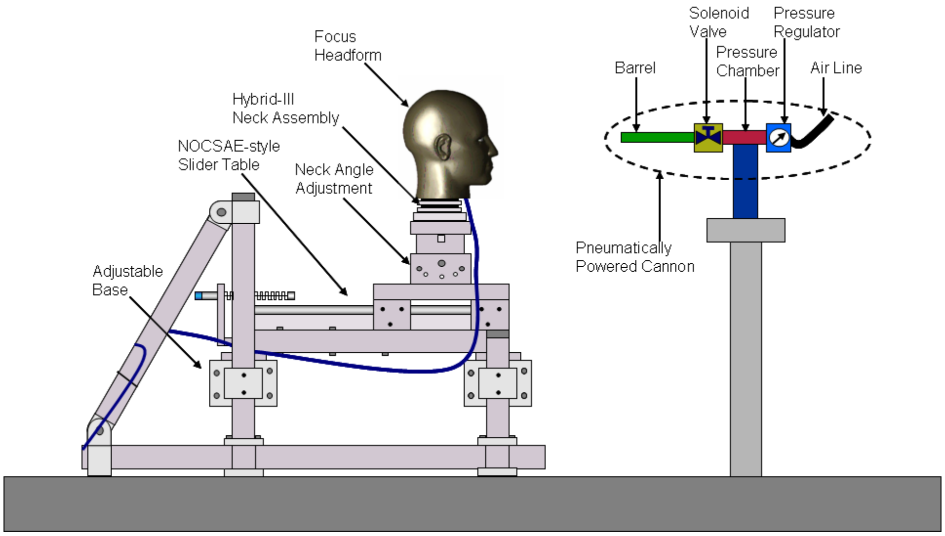


Figure 5. Projectile impact test setup for FOCUS headform blunt eye impacts conducted on a NOCSAE slider table. Image modified from [68].

## SUMMARY

This paper summarizes the history of eye injuries and injury risk from blunt objects. Data generated by numerous experimental eye impact studies have been used to develop and validate injury risk curves as well as computational and physical models of the eye. These tests were conducted on human cadaver eyes and *in vivo* animal eyes. Boundary conditions around the eye (orbit shape, musculature/fat simulation) were shown to affect the biofidelity and the response of the eye.

Injury risk curves for various eye injuries were developed using *in vivo*, *in situ*, and *in vitoo* experimental data. Kinetic energy, normalized energy, and IOP were all correlated to injury risk. The final recommendation for assessing eye injury risk for hyphema, lens damage, retinal damage, and globe rupture is to use survival analysis with maximum likelihood to estimate parameters [63]. When kinetic energy or normalized energy cannot be determined, can be used to predict injury. This may be increasingly useful for assessing eye injuries when projectile characteristics are incalculable, such as from blast overpressure.

The FOCUS headform is an advanced anthropomorphic test device designed specifically for facial and ocular injury assessment. The FOCUS headform eye load was determined to be proportional to the kinetic energy of a projectile. While the FOCUS headform eyes were determined to be biofidelic, future work with the FOCUS headform should include modifying the eye to be area-sensitive so that kinetic as well as normalized energy of a projectile can be determined.

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