Determination of Significant Parameters for Eye Injury Risk from Projectiles

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Background: Eye injuries affect a large proportion of the population and are expensive to treat. This article presents a parametric analysis of experimental data to determine the most significant factors for predicting ocular injuries or tissue lesions.

Methods: Using logistic regression, statistical values were generated to determine significant projectile characteristics for predicting ocular injury in published studies. Projectiles included BBs, metal rods, and foam particles with velocities ranging from 2 m/s to 122 m/s.

Results: A normalized energy (energy per projected area) value was found as the best predictor for ocular injury. Using this predictor, a 50% injury risk of corneal abrasion, lens dislocation, hyphema, retinal damage, and globe rupture was found to be 1,503 kg/s^2, 19,194 kg/s^2, 20,188 kg/s^2, 30,351 kg/s^2, and 23,771 kg/s^2, respectively.

Conclusion: Normalized energy was the most significant predictor of injury type and tissue lesion. This finding is of great value for history-taking management triaging and as a design aid to minimize the risk of ocular injury for consumer products.

Key Words: Eye injuries, Risk predictors, Projectile, Energy, Normalized energy.

J Trauma. 2005;59:960–964.

With over 2.4 million eye injuries resulting in personal misery and the loss of billions of dollars in direct and indirect costs, the societal cost of eye trauma is enormous.[1–3] Some of the most severe eye injuries are caused by high-speed projectiles from fireworks, sports equipment, firearms and BB guns, or contact with various parts of the car's interior in automobile crashes.[4–8] Sporting equipment most often involved in eye injuries includes baseballs, squash balls, and hockey sticks. Fingers and elbows of the players are also common sources.[6,9,10]

Being able to predict eye injury occurrence on the basis of missile characteristics would help both prevention and treatment. Although numerous studies have examined the eye's response to projectile loading, we are unaware of any attempt to combine all previously published experimental data to identify a single predictor for the most common eye injuries resulting from projectile impact.[4,10–19]

The purpose of this study, based on a meta-analysis of data from previous experiments, is to determine which projectile characteristics are the most significant predictors of eye injury and to generate injury risk curves for significant predictors. These curves allow for the calculation of the probability of eye injury on the basis of the energy and geometry of various projectiles.

MATERIALS AND METHODS

A literature review was conducted on ocular contusion experiments. Data from all relevant publications were sorted according to projectile characteristics such as type, mass, and diameter, as well as tissue lesion. Because eyes that have undergone radial keratotomy are known to sustain open globe injury at lower energy levels than eyes without radial keratotomy, only unoperated eyes were included in this study.[14,16,20]

All types of tissue lesions potentially resulting from projectile impact were included in the data set, and the occurrence or lack of each abnormality was noted. Five eye injury groups were established: corneal abrasion, hyphema, lens dislocation, retinal damage, and globe rupture. For simplification, certain abnormalities with common anatomic and/or physiologic characteristics were combined into a single group. For instance, hyphema included hemorrhage whether originating from iris, ciliary body, or angle trauma, and retinal trauma, whether tear or detachment, was termed as retinal damage.

Eye specimens included human, porcine, monkey, and cat. Some studies used anesthetized living animal models. Because no studies have concluded that in vivo eyes suffer injury at different energy levels than fresh in vitro eyes, in vivo, in situ, and in vitro studies were analyzed together. Projectiles used to impact the eye included BBs, foam, metal rods, baseballs, and squash balls. Impact velocities ranged from 2 m/s to 122 m/s.

Submitted for publication May 7, 2004.
Accepted for publication April 21, 2005.
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DOI: 10.1097/01.ta.0000174830.55282.32

PETITIONERS' EXHIBIT 1041
Prime Time Toys et al. v. Spin Master, Inc.
IPR2023-01348

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Table 1 Summary of Previous Ocular Experiments

Injury Studied	Projectile	No. of Cases	Studies
Corneal abrasion	Foam, metal rod	24	Duma (2000), Scott (2000)
Hyphema	Foam, metal rod, BB	39	Weidenthal (1964), McKnight (1988), Scott (2000)
Lens dislocation	Foam, metal rod, BB	44	Weidenthal (1964), Duma (2000),Scott (2000)
Retinal damage	Foam, metal rod, BB	26	Duma (2000), Scott (2000)
Globe rupture	Foam, metal rod, BB, baseball, squash ball, golf ball	71	Weidenthal (1964), Delori (1969), Green (1990), Umlas (1995), Duma (2000), Scott (2000), Stitzel (2002)

A logistic regression analysis was performed on the experimental data to determine significant predictors for eye injury on the basis of p values and Goodman-Kruskal gamma values (a correlation coefficient with values near 0.0 indicating no association between two subjects and values of 1.0 representing high association between predictor and injury).

Predictors used in the statistical analysis included diameter, mass, velocity, and energy. A normalized energy value of energy per projected area of the projectile (Equation 1) was also analyzed to determine whether normalized energy was a more significant injury predictor than kinetic energy alone. The projected area is the contact surface area for a flat impacting object or the cross-sectional area of a sphere.

$$\text{Equation 1: Normalized Energy}\left(\frac{\text{kg}}{\text{s}^2}\right) = \frac{\text{Kinetic Energy}}{\text{Projected Area}}$$

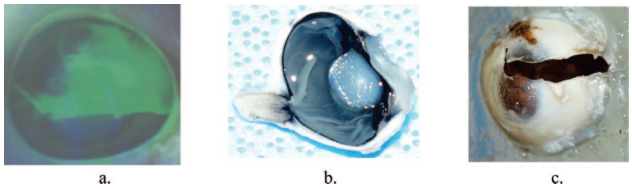

Fig. 1. *(A) Corneal abrasion occurs when epithelial cells are removed from the cornea. (B) A retinal detachment is characterized by a separation of the retina's sensory and pigment layers. (C) Globe rupture with an inside-out mechanism.*[21]

RESULTS

A total of eight studies involving projectile impact experiments on eyes were identified in the literature. These eight studies contained 104 individual tests, with some noting a variety of observed injuries (Table 1). Eye injuries noted for some experiments included corneal abrasion, retinal detachment, and globe rupture (Fig. 1).

The statistical analysis revealed that normalized energy was the most effective injury predictor, yielding the most statistically significant p values and Goodman-Kruskal gamma values (Tables 2 and 3). Both mass and velocity were considered poor predictors, with relatively higher p values and lower Goodman-Kruskal gamma values in comparison with other measures.

A general form of the injury risk function (Equation 2) can be used with specific injury parameters to predict the probability of injury given a projectile's normalized energy or kinetic energy (Table 4). The variable x refers to a predictor and its corresponding value used for a specific study. The variables a and b are constants specific to a particular predictor and eye injury.

Among all of the predictors tested, normalized energy yielded the best injury risk curve with the lowest p values and highest Goodman-Kruskal gamma values, where all injuries showed normalized energy to be a significant predictor ($p <$

Table 2 Summary of p Values for Various Eye Injuries and Predictors

	Normalized Energy (kg/s^2)	Diameter (m)	Kinetic Energy (J)	Mass (g)	Velocity (m/s)
Corneal abrasion	0.001	0.964	0.001	0.001	0.520
Hyphema	0.001	0.001	0.244	0.005	0.001
Lens dislocation	0.001	0.001	0.678	0.001	0.200
Retinal damage	0.001	0.001	0.001	0.141	0.540
Globe rupture	0.001	0.003	0.019	0.499	0.003

Table 3 Summary of Goodman-Kruskal Gamma Values for Various Eye Injuries and Predictors

	Normalized energy (kg/s^2)	Diameter (m)	Kinetic energy (J)	Mass (g)	Velocity (m/s)
Corneal abrasion	0.97	0.01	0.97	0.71	0.31
Hyphema	0.94	1.00	0.20	0.82	0.82
Lens dislocation	0.98	1.00	0.26	0.12	0.38
Retinal damage	1.00	1.00	0.92	0.01	0.27
Globe rupture	0.80	0.24	0.51	0.26	0.45

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Table 4 Injury Risk Curve Coefficients for Significant Predictors and Injury Groups

	Predictor (x)	a	b
Corneal abrasion	Normalized energy (kg/s^2)	5.03	0.0034
	Kinetic energy (J)	5.07	27.5371
Hyphema	Normalized energy (kg/s^2)	10.60	0.0005
Lens dislocation	Normalized energy (kg/s^2)	7.38	0.0004
Retinal damage	Normalized energy (kg/s^2)	71.47	0.0023
	Kinetic energy (J)	5.50	5.0481
Globe rupture	Normalized energy (kg/s^2)	4.65	0.0002
	Kinetic energy (J)	3.04	0.7688

$$\text{Equation 2: Probability of Injury (\%)} = \frac{1}{1 + e^{a-bx}}$$

0.05 for all cases). The formulation of normalized energy to predict corneal abrasion, lens dislocation, hyphema, retinal damage, and globe rupture are presented in Figure 2. Using normalized energy, a 50% injury risk of corneal abrasion, lens dislocation, hyphema, retinal damage, and globe rupture were found to be 1,503 kg/s^2, 19,194 kg/s^2, 20,188 kg/s^2, 30,351 kg/s^2, and 23,771 kg/s^2, respectively.

Occasionally, it is more useful and statistically significant to exclude projectile area when evaluating injury risk functions. Kinetic energy alone was not as significant a predictor for ocular injury as normalized energy, yielding less significant p values and lower Goodman-Kruskal gamma values. Kinetic energy was found to be a significant predictor for corneal abrasion, retinal damage, and globe rupture ($p < 0.05$ for all cases); therefore, injury risk curves for these injuries were also generated (Fig. 3). A 50% risk of corneal abrasion occurred at 0.184 J, as opposed to 1.090 J for retinal damage and 3.949 J for globe rupture.

For all significant predictors of eye injury, a logit analysis was performed to calculate the confidence intervals at 50% risk (Table 5). In the case of normalized energy for

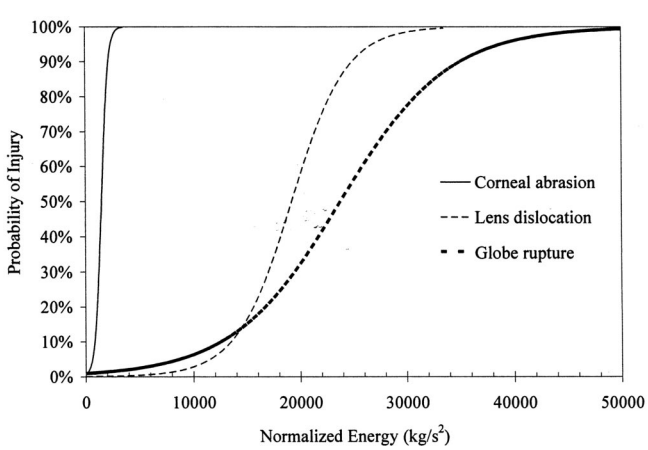

Fig. 2. *Injury risk curves for corneal abrasion, lens dislocation, and globe rupture as a function of normalized energy ($p < 0.05$ for all cases).*

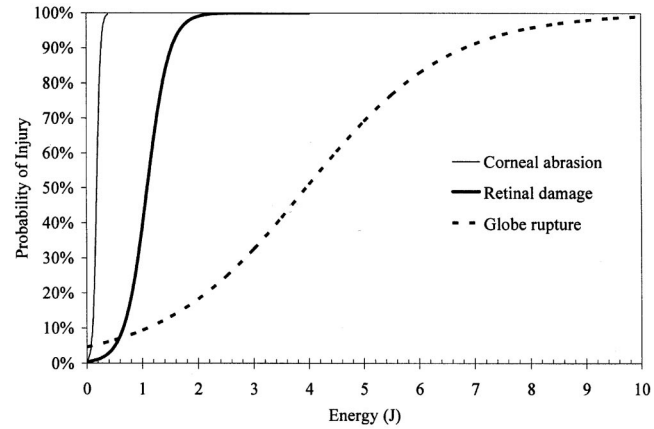

Fig. 3. *Injury risk curves for corneal abrasion, retinal damage, and globe rupture as a function of kinetic energy ($p < 0.05$ for all cases).*

predicting hyphema or retinal damage, an insufficient number of data exist from which to develop confidence intervals, which is discussed in more detail later in this article.

DISCUSSION

This study is the first to derive injury risk functions on the basis of a pooling and reevaluation of data from previously published eye impact experiments. Such data pooling yields a larger database able to cover a broader range of projectile characteristics and observed injuries.

Previous experiments attempted to determine thresholds at which specific tissue abnormalities in the eye occur. Several studies used projectile characteristics such as velocity and energy to predict the occurrence of various eye injuries. Duma et al. studied corneal abrasion in porcine eyes loaded with foam particles ejected from seamless module covers in automobile airbags.[17] It was determined from the study that the combination of mass and velocity as kinetic energy served as the most significant predictor of corneal abrasion. In the study from Scott et al., the internal structures of enucleated porcine eyes were studied after being impacted by projectiles of various velocities and mass.[18] In conjunction with the Duma study, Scott found that injury occurrence was directly associated with the kinetic energy of the projectile, whereas momentum was shown to be a poor predictor. These findings were confirmed in the current study.

Previous experimental studies have determined various factors for predicting eye injuries, including tissue level failure stresses.[17–19] Although tissue level failure stress provides a clear understanding of the injury mechanism, it is not always feasible to investigate risk in this manner. The clinician or design engineer often needs a fast way to quantify risk for a given projectile. The current study provides these quick reference guides.

Previous studies have established energy as an effective injury predictor for the internal structures of the eye and for corneal abrasion.[17,18] The drawback of kinetic energy as an injury predictor is that this does not factor in the projected

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Table 5 Confidence Intervals for 50% Risk of Injury

	Predictor	50% Risk	Lower Bound	Upper Bound
Corneal abrasion	Normalized energy (kg/s^2)	1,503	775	2,214
	Kinetic energy (J)	0.184	0.096	0.266
Hyphema	Normalized energy (kg/s^2)	20,188	—*	—**
Lens dislocation	Normalized energy (kg/s^2)	19,194	1,367	24,242
Retinal damage	Normalized energy (kg/s^2)	30,531	—*	—*
	Kinetic energy (J)	1.090	0.810	1.514
Globe rupture	Normalized energy (kg/s^2)	23,771	20,194	30,714
	Kinetic energy (J)	3.949	2.865	10.545

*Insufficient data for estimating upper and lower confidence limits.

area of the projectile. This meta-analysis established normalized energy as the best external predictor for the probability of eye injury caused by impact from blunt objects. The analysis presented in this study would not be effective if the objects were sharp and threaten penetration or perforation.[21] A normalized energy value (energy per projected area) provides estimation of the applied energy.

Discussion regarding the normalized energy levels at which various types of injuries occur is also warranted. It may seem counterintuitive that a 50% risk of retinal damage occurs at a higher normalized energy level, 30,351 kg/s^2, than that for globe rupture, at 23,771 kg/s^2. This is attributable in part to the limited number of experimental studies available in the literature and the regions of the eye to which the impact occurs. Many of the studies reviewed in this article focused on blunt impacts to the cornea, which may have led to a high occurrence of globe rupture without consequentially causing retinal damage. In addition, not all injury types were noted in all of the studies, possibly excluding some potential tests that actually did incur retinal damage. Finally, some of the eye injury groups evaluated in this study had a limited amount of injurious tests compared with noninjurious tests, in particular regarding retinal damage. Most of the experimental data on retinal damage involved energy levels at which the injury did not occur. Therefore, the injury-risk curve displays a much sharper threshold between injury and noninjury than the other injury types.

Even though normalized energy was found to be a significant predictor of both hyphema and retinal damage, an insufficient amount of data were available to generate confidence intervals for these risk functions. Therefore, a future area of research would be to conduct more impact tests for the purposes of generating more injury data. These data would likely lead toward the estimation of the confidence intervals and further validation of the predictions from the injury risk functions.

In summary, the findings from this study provide several benefits for health care providers and patients and for the consumer and industry. The results can be used as an aid to conduct innovative research in impact biomechanics for, among others, the automotive, aviation, and recreational industries. Anthropomorphic test devices are currently in use to test human responses to various impacts such as automobile or aviation collisions. For the anthropomorphic test devices to simulate human responses accurately, they must be validated with existing data from impact experiments. Currently, these "crash dummies" lack a synthetic eye that can be used to predict ocular injury in a collision. The injury risk curves generated from this study can be used as a design aid to validate the biofidelity of a synthetic eye. In addition, significant predictors may serve as guidelines for determining the necessary instrumentation and values that the synthetic eye must be able to measure to accurately identify injuries to the eye. The significance of designing a synthetic eye with high biofidelity is extremely important; otherwise, the synthetic eye will incorrectly predict the occurrence of eye injuries. All these data help preventing injuries by means of reduced risk, but they also help the ophthalmologist in understanding eye injury occurrence and severity.

The study also has limitations. These originate in certain assumptions that needed to be made to achieve a sufficiently large data set from previously published studies. It was assumed that there was no species variation between human and animal eyes; it was also assumed that there was no difference between testing in vivo versus in vitro. These assumptions were made on the basis of a lack of experimental data showing that these assumptions cannot be made. With more experimental data, it may be possible to elucidate the effects of these assumptions and validate the injury-risk curves for use in predicting injury.

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