High-Rate Internal Pressurization of Human Eyes to Predict Globe Rupture

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Objective: To determine the dynamic rupture pressure of the human eye by using an in vitro high-rate pressurization system to investigate blunt-impact eye injuries.

Methods: Internal pressure was dynamically induced in the eye by means of a drop-tower pressurization system. The internal eye pressure was measured with a small pressure sensor inserted into the eye through the optic nerve. A total of 20 human eye tests were performed to determine rupture pressure and characterize rupture patterns.

Results: The high-rate pressurization resulted in a mean (SD) rupture pressure of 0.97 (0.29) MPa (7275.60 ± 2175.18 mm Hg). A total of 16 eyes ruptured in the equatorial direction, whereas 4 ruptured in the meridional direction. There was no significant difference in the rupture pressure between the equatorial and meridional directions (P = .16).

Conclusion: As the loading rate increases, the rupture pressure of the human eye increases.

Clinical Relevance: Eye injuries are expensive to treat, given that the estimated annual cost associated with adult vision problems in the United States is $51.4 billion. Determining globe rupture properties will establish injury criteria for the human eye to prevent these common yet devastating injuries.


More than 1.9 million people experience eye injuries in the United States each year.1 Automobile accidents,2-7 sports-related impacts,8,9 consumer products, and military combat10 are some of the causes of the severe eye injuries that occur.11 These injuries are expensive to treat, given that the estimated annual cost associated with adult vision problems in the United States is $51.4 billion.12,13 Of the total number of eye injuries in the country, more than 600,000 sports injuries occur each year and 40,000 of them require emergency care.14 A 2002 study found that more than 9000 globe ruptures occur in the United States each year.15 A blunt impact, like that of a baseball, will cause the eye to compress, with an increase in internal pressure that can result in globe rupture (Figure 1). The rupture starts away from the impact location, demonstrating that the cause is the increase in internal pressure. Determining globe rupture properties will provide the needed information for establishing injury criteria for the human eye to help prevent these common yet devastating injuries.

Information about safe intraocular pressures is of particular use to the clinical ophthalmologist.16 In published research, the rupture pressure of eyes has been examined to determine the effect of ocular surgery,5,16-20 and, to our knowledge, only 1 study has been published on the rupture pressure of healthy human eyes.21 Burnstein et al17 studied the strength of postmortem human and porcine eyes after photorefractive keratectomy by increasing intraocular pressure gradually with nitrogen gas until globe rupture occurred. The eye was attached to the nitrogen gas system by a 25-gauge butterfly needle that was inserted into the anterior chamber at the limbus. Pressure was increased by 0.03 MPa (225.02 mm Hg) at 5-second intervals. Burnstein et al found the mean (SD) rupture pressure of human eyes subjected to photorefractive keratectomy to be 0.46 (0.12) MPa (3450.28 ± 900.07 mm Hg), whereas porcine eyes subjected to photorefractive keratectomy were observed to rupture at 0.53 (0.10) MPa (3975.33 ± 750.06 mm Hg). In 2 eyes undergoing phototherapeutic keratectomy, Burnstein et al found rupture pressures of 0.55 and 0.68 MPa (4125.34 and 5100.42 mm Hg, respectively). Voorhies21 performed both static and dynamic tests on healthy postmortem human and porcine eyes by similar methods. The static rupture pressure for hu-
man eyes was found to be 0.36 (0.20) MPa (2700.22 [1500.12] mm Hg), whereas the dynamic rupture pressure was 0.91 (0.29) MPa (6825.56 [2175.18] mm Hg).

The previous studies tested rupture pressure in human and porcine eyes; however, these studies were limited in that no high-rate dynamic tests were performed that would realistically simulate a dynamic ocular injury, such as sports-related injuries, automobile injuries, military combat, or injuries caused by consumer products. Moreover, the majority of these studies were focused on testing specimens that had been subjected to corrective eye surgery before testing and had segmented eye tissue. Therefore, the purpose of this study was to analyze the high-rate rupture pressure of healthy human eyes by means of an internal pressurization system.

METHODS

High-rate pressurization was accomplished with a custom pressure system that was built to examine rupture properties of the human eye (Figure 2). The test setup consisted of a drop tower that was used to create a hydraulic system to pressurize the human eye in a dynamic event. To initiate the event, a weight was dropped onto a piston that was inserted into the hydraulic cylinder. Preparation of the system included adding water through the cylinder to act as the medium for pressurization and to produce an approximate initial intraocular pressure of 0.002 MPa (15.00 mm Hg) before rupture. Connecting the eye to the system was a 16-gauge intravenous needle inserted into the optic nerve (Figure 2). To secure the optic nerve to the needle, a medical suture was used while a cylindrical placement guide held the eye in place below the needle. To ensure that the optic nerve was sealed, it was covered with a flexible coupling and then secured with a plastic fastener.

The high-rate dynamic event occurred when the weight was suspended above the piston at a height of 17.78 cm and then released. The impact of the weight onto the piston caused the water to be displaced throughout the system, which created a high-rate increase in intraocular pressure resulting in the rupture of the eye. To capture this event, high-speed video and data acquisition were used. A video camera (Ultima APX-RS; Photon Inc, San Diego, California) captured video at 10 000 frames per second with a resolution of 512 x 512 pixels, while the data acquisition system collected data at 30 000 Hz. The pressure transducer data and the high-speed video were correlated to determine the pressure at the time of rupture.

To acquire the internal pressure of the human eye, an in situ pressure sensor was used. A small pressure sensor (model 060; Precision Measurement Co, Ann Arbor, Michigan) was inserted into the eye through the optic nerve. The pressure transducer was rated for a range of 0 to 3.45 MPa (0-25877.13 mm Hg) and a frequency response of 10 000 Hz, which are ideal for this application.

Twenty human eyes were procured from the Roanoke Eye Bank (Roanoke, Virginia) and the North Carolina Eye Bank (Winston-Salem). The eyes had not undergone corneal transplantation or other operations before testing. The eyes were never frozen and were kept in isotonic sodium chloride solution in glass jars and refrigerated until testing. A previous study showed a lack of correlation between age and rupture pressure, as well as time from harvest to test and rupture pressure ($R^2=0.06$), so these factors were not taken into consideration. Statistical analyses were performed by $t$ test, with $\alpha=0.05$ used to determine statistical significance. All test procedures were reviewed and approved by the Virginia Tech Institutional Review Board.

RESULTS

The high-rate pressurization of 20 human eyes resulted in a mean (SD) rupture pressure of 0.97 (0.29) MPa (7275.60 [2175.18] mm Hg) (Table). The failure pressure ranged from 0.57 to 1.59 MPa (4275.35-11 925.98 mm Hg) (Figure 3). The dynamic loading rate was 36.50 (15.35) MPa/s (273 772.5 [115 134.3] mm Hg/s) for the 20 human eye tests. High-speed video for each test showed

Figure 1. Baseball impact with a human eye within a gelatin orbit resulting in globe rupture. A, Before impact. B, Rupture occurring on impact (arrow). C, Ruptured globe.

Figure 2. Schematic diagram of the pressure system used to examine high-rate rupture pressures of human eyes. DAS indicates data acquisition system.
the location of each rupture. Of the 20 eyes tested, 18 ruptured at the equator, while the remaining 2 ruptured through the cornea. The eyes were then examined to determine the direction of the rupture. Four ruptured in the meridional direction while 16 ruptured in the equatorial direction. A 2-tailed unpaired, unequal variance *t* test showed that the difference in the rupture pressure between the equatorial mean of 0.93 (0.30) MPa (6975.57 [2250.19] mm Hg) and the meridional mean of 1.13 (0.21) MPa (8475.70 [1575.13] mm Hg) was not significant (*P* = .16).

**COMMENT**

Previous studies have performed quasi-static and dynamic tests to determine the rupture pressure of human eyes.17,18,21,23 Both Campos et al18 and Pinheiro et al22 tested the effects of refractive surgery. Campos et al18 used porcine eyes and were unable to report rupture pressure results because of the capability of the manometer used. The test series completed by Pinheiro et al22 used an artificial anterior chamber to investigate the integrity of the cornea, thereby determining rupture pressure for the cornea rather than the sclera. Although these studies are useful for their specific purposes, the current study is intended as a more general approach that can be used for scleral injuries that occur from increasing internal pressure, such as a blunt impact.

The human eye is both anisotropic and viscoelastic.17,21,23 Previous dynamic tests performed by Voorhies21 were executed by means of a loading rate of approximately 2.77 MPa/s (20 776.71 mm Hg/s)21; however, for the current test series, a higher loading rate was desired to more accurately predict a dynamic ocular injury observed from impact with blunt objects. The high-rate rupture pressure device achieved an average loading rate of 36.5 MPa/s (273 772.5 mm Hg/s), which is an order of magnitude greater than those in the previous dynamic tests.21 The time to rupture was also measured and resulted in a mean of 28.27 (6.26) milliseconds, compared with 0.46 (0.23) seconds in previous dynamic tests performed by Voorhies.

In the study by Voorhies, a pressure transducer was placed at a location before the needle interface between the eye and the system and was assumed to reflect the internal pressure of the human eye.21 In comparing the current results with the previous rupture pressure data, it is important that, because of pressure loss across the needle during the event, the upstream pressure used for the previous testing is higher than that actually experienced by the eye (Figure 4). A measurement error is introduced when the upstream pressure is used instead of the direct internal pressure.

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<th>Test No.</th>
<th>Rupture Pressure, MPa</th>
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Mean (SD) 0.97 (0.29) 28.3 (6.2) 36.5 (15.3)

Conversion factor: To convert the rupture pressure from megapascals to millimeters of mercury, multiply by 7500.617.

**Figure 3.** Rupture pressure with respect to time for 20 human eyes. To convert the rupture pressure from megapascals to millimeters of mercury, multiply by 7500.617.
The location of the pressure sensor inside the eye was also a concern because of the change in pressure gradient as the water was injected into the eye. A test was performed with 2 sensors within 1 eye to compare the results of 2 identical pressure sensors in different locations during the event. Regardless of the location of the pressure sensors, the pressure output was the same.

All eyes were stored in isotonic sodium chloride solution and were refrigerated before testing. Sclera is largely acellular, and its strength comes from collagen fibers similar to those found in ligaments. Because the tissue was never exposed to a freeze-thaw cycle and was stored in refrigerated isotonic sodium chloride solution, the globe’s integrity was preserved before the testing.

The principal rupture location for the 20 tests was the equator. Other research has also shown the equator as the prime location for a rupture occurring from a blunt impact, such as a baseball. Because failures occur primarily at the equator of the eye, this study, along with previous studies, suggests that the equator is the weakest portion of the eye.

Accurate response characteristics of the eye must be known for a model to behave realistically and to predict when failure of local tissues will occur. Although the rupture location was primarily the equator, the ruptures occurred in 2 different directions: along the equator and along the meridian. However, the difference in the rupture pressure between the equatorial and meridional directions was not significant.

These data are essential for the continuing improvement in prediction of eye injury. This research will provide the necessary information to advance current mathematical and computer models of eye injury risk assessment and potentially reduce the incidence of eye injuries from blunt impacts.

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REFERENCES