Evaluation of Eye Injury Risk from Consumer Fireworks

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ABSTRACT

Eye injuries affect approximately two million people annually. Various experimental studies have been performed to evaluate potentially injurious conditions from blunt objects using animal and human cadaver eyes. 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 if projectile characteristics are unknown. Additionally, the measurement of IOP and the association of IOP to injury risk in experimental tests has opened up the field to studying eye injury mechanisms from overpressure. The current manuscript presents recent experimental tests that evaluated the response of human cadaver eyes exposed to firework overpressure. Consumer fireworks serve as a model of low level blast, and provides a foundation to studying higher blast overpressures (i.e., that would be observed in military combat). Although some studies state that eye injury can result solely from primary blast (overpressure), there is no empirical evidence in the literature to support this. Future experimental studies should be conducted to assess this statement.

Key Words: Firework, Pressure, 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]. Based on data collected between December 31, 1991 and December 31, 2010, the U.S. Consumer Product Safety Commission (CPSC) estimated 9855 persons are treated in an emergency department for fireworks-related injuries annually, and that 2141 of these injuries are specifically related to the eye [70]. Firework-related injuries in the United States, especially in the month surrounding the Fourth of July, are prevalent among children and adolescents [71-73]. The eye remains the most frequently injured body part in these incidents, accounting for nearly a quarter of all reported firework-related injuries [71]. Bottle rockets and firecrackers comprise nearly 50% of these injuries [71]. Despite national laws that restrict the size of consumer fireworks, individual state laws are inconsistent with regard to the purchase and use of fireworks [74].

Firework explosions produce a sharp increase in ambient pressure (overpressure) and temperature followed by an expulsion of material. Improper preparation and ignition of fireworks displays as well as and inadequate viewing distances pose unique injury risks to the user and bystanders. Much of the current firework-related literature assesses the injurious effects of projected materials to the eye [71,75,76]. The effect of projected material is not inconsequential; previous research calculated 100% injury risk for several eye injuries from blunt projectiles [62,63,68,77]. Although some studies state that ocular injuries such as globe rupture and conjunctival hemorrhage can be caused by blast overpressure, there is no clear evidence that directly supports this [78-80]. The critical question is whether overpressure from fireworks can cause ocular injury or if injuries are caused solely by projected material. 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 [35-69]. Recently, intraocular pressure (IOP) was correlated IOP to eye injury risk [25]. Therefore, the purpose of this research is to measure IOP of enucleated cadaveric eyes during explosions similar to consumer fireworks and assess ocular injuries sustained in order to more fully understand the effect of blast overpressure on the eye

METHODS

Six human eyes were procured from the North Carolina Eye Bank (Winston Salem, NC, USA) and stored in refrigerated saline. The time interval between death and testing did not exceed 55 days, which was previously shown to not affect eye rupture pressures [12]. As tissue was never exposed to a freeze-thaw cycle, globe integrity was preserved. A miniature pressure sensor (Model 060S, 689 kPa, Precision Measurement Company, Ann Arbor, MI, USA) that had a frequency response of 10 kHz and a small tube were inserted through the optic nerve into the vitreous fluid and secured in place. A 25 gauge needle was inserted in the small tube and attached to lactated ringer’s solution to provide normal human physiologic IOP of 1.993 kPa (14.95 mmHg) throughout the test [25,64,81]. Eyes were examined for injury before and after each test to ensure globe integrity was maintained. A fluorescein dye was used to visualize any corneal abrasions. As testing occurred in the open air, eyes were periodically rinsed with saline to maintain tissue hydration.

Firework tests were performed on human cadaver eyes using a custom test setup designed to measure IOP and overpressure. The test setup consisted of a metal frame that suspended the eye approximately 1 m from the ground. A total of four pressure sensors (Model 113B21, 1379 kPa, PCB Piezotronics, Depew, NY, USA) were mounted around the eye (**Figure 1**). These pressure sensors had a resonance frequency response greater than 500 kHz and measured frequency content up to 100 kHz without distortion. They were designated as “total” or “static” sensors based on their orientation [82]. Total (face-on) sensors measured both the dynamic and static components of the overpressure wave, and were mounted such that the sensing element was perpendicular to the direction of wave propagation. Static (side-on) sensors measured the static component of the overpressure wave, and were mounted such that the sensing element was parallel to the direction of wave propagation. The sensor array consisted of a total overpressure sensor (total) and a static overpressure sensor (static left) adjacent to the eye, and two static overpressure sensors (static right 1, static right 2) mounted 3.0 cm apart in a polycarbonate airfoil-shaped block (**Figure 1**).

The temporal difference between peak overpressures measured by the two static overpressure sensors mounted in the airfoil-shaped block was used to determine the overpressure wave velocity. Rise time was calculated as the time interval between initiation of positive overpressure and the time at peak overpressure. Positive duration was calculated as the time interval between initiation of positive overpressure and the time when overpressure returned to zero. Positive impulse was calculated using trapezoidal integration of the total pressure trace over the positive duration.

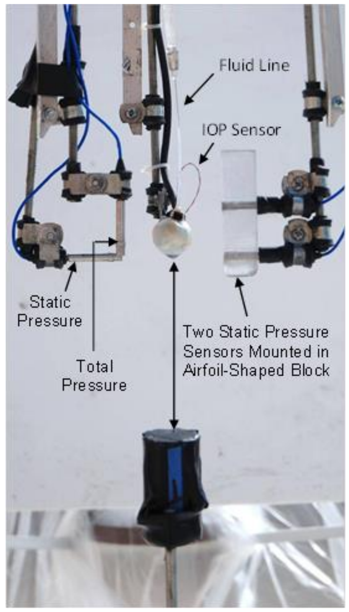

Figure 1. Close-up photograph of experimental test setup with a human cadaver eye.

Due to the large variability of consumer fireworks, this study implemented charges fabricated in house to simulate consumer fireworks in a controlled, repeatable manner. These charges consisted of cardboard tubes filled with 10 grams of Pyrodex® gunpowder that exploded perpendicular to the long axis of the tube. The 10 gram charges were fixed to a metal rod such that the center of the gunpowder was 22 cm, 12 cm, or 7 cm below the cornea. The rod was attached below the center of the gunpowder and did not obstruct the explosion. The long axis of the 10 gram charges was oriented parallel to the anterior-posterior axis of the eye. The three standoff distances were chosen to examine the effect distance has on peak overpressure. The test matrix was designed such that tests were conducted with decreasing distance from the cornea. The charge was offset 2.0 cm from the front of the cornea to minimize the amount of material projected towards the eye. Five commercially available fireworks (two bottle rockets, three firecrackers) were oriented and tested with the same conditions as the 10 gram charges, but without an eye, for comparison. The high incidence of injuries from firecrackers and aerial devices motivated the testing of both firecrackers and bottle rockets in the current study [22,83].

A data acquisition system (TDAS PRO, Diversified Technical Systems, Inc., Seal beach, CA, USA) collected data at 301887.0 Hz. The standard TDAS PRO anti-aliasing filter (4,300 Hz) was bypassed for this test series because the frequency content of the blast overpressure exceeded 4,300 Hz. However, the TDAS PRO sensor input modules (SIMs) have a bandwidth of 0-25 kHz which acts as a low-pass filter with a frequency cutoff of 25 kHz. All pressure data were zeroed immediately prior to the event. A Phantom v9.1 camera (Vision Research, Wayne, NJ, USA) was used to capture high speed video at 20,000 frames per second with a resolution of 256 x 192 pixels.

Injury risk was assessed for each human cadaver eye test using a two-step process. First, normalized energy was determined using the correlation between IOP and normalized energy developed from projectile testing conducted by Duma et al. (2012) [25]. The correlation for the large aluminum rod (11.16 mm diameter) was used to best match the area of an unprotected eye that would be exposed to a firework explosion. Second, injury risk was determined using injury risk curves based on normalized energy as an injury predictor for hyphema, lens damage, retinal damage, and globe rupture. These injury risk functions were developed by Kennedy et al (2011) from analyzing a meta-analysis of over 250 eye impacts reported in the literature [63]. Various methods were tested for injury risk prediction accuracy and the final recommended risk functions employ survival analysis using the maximum likelihood method to estimate parameters.

Injury risk was assessed for each firecracker or bottle rocket test in a similar way, but with an additional step. As IOP was not measured for the firecracker and bottle rocket tests, peak total overpressure was used to determine peak anticipated IOP based on a linear correlation developed by Duma et al. (2012) [25]. The anticipated IOP was then used to determine injury risk.

RESULTS

A total of 18 charges were exploded at distances of 22 cm, 12 cm, or 7 cm from six cadaveric eyes. The resulting overpressure time histories show a steep rise to peak overpressure followed by a positive overpressure phase and subsequent negative overpressure phase that is indicative of a Freidlander wavefom [79,80,82]. Peak IOP ranged between 11.3 - 46.7 kPa. Peak total overpressure and peak static overpressure ranged between 15.0 - 57.0 kPa and 14.5 - 52.3 kPa, respectively. Normalized energy ranged between 2.8 – 112.0 J/m^2. Peak IOP correlated to 0.0% injury risk for lens damage, retinal damage, and globe rupture, for all tests. Maximum injury risk for hyphema was 0.01%, which only occurred in three of the five 7 cm tests. Peak IOP (y, kPa) was linearly correlated to peak total overpressure (x, kPa) for the charges ($y = 0.46x + 12.97$, $R^2 = 0.5$).

A total of 18 commercial bottle rockets and 27 commercial firecrackers were exploded without an eye present. For the bottle rockets, peak total overpressure and peak static overpressure ranged between 14.0 – 82.6 kPa and 11.2 – 55.2 kPa, respectively. Normalized energy ranged between 46.2 – 123.0 J/m^2. Peak IOP correlated to 0.00% injury risk for lens damage, retinal damage, and globe rupture, and maximum injury risk for hyphema was 0.01%, which only occurred at the 7 cm distance for the bottle rocket tests. For the firecrackers, peak total overpressure and peak static overpressure ranged between 3.7 – 29.4 kPa and 3.4 – 19.4 kPa, respectively. Normalized energy ranged between 34.9 – 63.4 J/m^2. Peak IOP correlated to 0.00% injury risk for hyphema, lens damage, retinal damage, and globe rupture for the firecracker tests.

No globe ruptures or corneal lacerations were observed; however, minor corneal abrasions were observed. The abrasion size and pattern suggested injuries were sustained from unspent Pyrodex® being projected onto the eye during the event, which was confirmed with high speed video. As expected, more abrasions were observed as the standoff distance decreased.

DISCUSSION

This is the first study to investigate the effects of overpressure on the human eye. The overpressures recorded in the current study represent low blast energies. For comparison, a 10 gram charge of Pyrodex®, at 22 cm, 12 cm, and 7 cm standoff distances correspond to detonating 0.45 kg TNT at approximately 7.33 m, 4.57 m, and 3.05 m, respectively [82]. These comparisons are based on peak overpressure but not positive duration or positive impulse, which can also affect the standoff distance. Higher severity blast overpressures can be experienced during military combat. Combat-related blast injuries are occurring more frequently with the increased use of explosives and improvised explosive devices (IEDs) in current military conflicts [31]. While the lung was once most susceptible to blast injury, the use of improved protective chest equipment has disproportionally left the face and eyes vulnerable to concomitant blast injuries[35]. Approximately 5% (797) of all reported injuries sustained in the War in Iraq between 2003-2005 were eye injuries [76]. Studies have reported approximately 82% of all severe ocular injuries sustained during military combat are the result of munitions fragmentation [29,30]. Additionally, as many military explosives are buried, the risk of injury from projectiles would be expected to be much greater. It is unclear whether severe ocular injuries such as lens damage, retinal damage or globe rupture can be caused by higher blast overpressures. However, the relationship between peak IOP and peak total overpressure noted in this study indicates that an extremely large peak blast overpressure would be required to induce an IOP large enough to cause globe rupture, given an internal rupture pressure of 970 ± 290 kPa [25,64]. It is expected that more lethal corporal injuries resulting from such a large blast event would likely take precedence over potential ocular injuries. Further studies should be performed to evaluate the response and injuries resulting from higher blast overpressures. It should be noted that such a study would require the use of high energy explosives such as TNT, C4, or Comp-B.

Federal firework regulations currently limit the amount of pyrotechnic material in consumer fireworks to 50 mg for firecrackers and 130 mg for bottle rockets in order to minimize the risk of injury from these devices [84]. Individual state laws may additionally prohibit the distribution, purchase, and use of these devices to further decrease injury risk from misuse. Previous studies noted that states and countries banning the use of fireworks observed lower incidences of eye injuries due to fireworks [22,84]. As of June 1, 2011, only four states completely ban fireworks, including those allowed by CPSC regulations: Delaware, Massachusetts, New Jersey, and New York [74]. Therefore, it is expected that states without fireworks regulations will observe a higher incidence of fireworks-related injuries than states that regulate fireworks. Where fireworks are allowed, it is suggested that persons adhere to rules of their use and be familiar with the risks associated with projected material.

Future Directions in Experimental Blast Testing

Shock tubes and advanced blast simulators are often used to simulate open-field blast overpressures. A typical gas-driven shock tube schematic is shown in **Figure 2**. One advantage of using a shock tube or advanced blast simulator is that they simulate free-field blast overpressures without creating projected material, which is potentially injurious. This allows for the study of an isolated idealized shock wave and its potential injurious effects on the eye. Proper characterization of the shock wave dynamics in a shock tube or advanced blast simulator will yield data that can be used to compare the resulting shock wave data to free-field overpressures from high explosives.

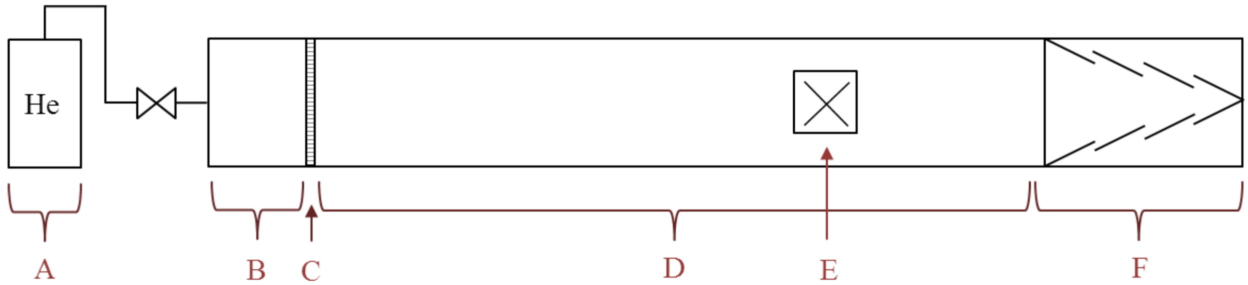

Figure 2. Gas-driven shock tube schematic. A. Compressed Helium Gas; B. Driver Section (high pressure region); C. Diaphragm ; D. Driven Section (low pressure region); E. Test Location; F. End Wave Eliminator

Porcine eye testing in an advanced blast simulator is currently being conducted to better understand the response of the eye to overpressures up to 30 psi. These tests are specifically designed to study the effect of orbit shape, measure peak overpressure and peak IOP, and quantify eye injury risk. Eyes are potted in a 10% gelatin solution to simulate the fat and musculature. Eyes are pressurized to physiologic pressure (14.95 mmHg) throughout the test using a gravity-fed system. A pressure sensor inserted through the optic nerve into the vitreous measures IOP throughout the event. High speed video is used to quantify tissue strain and global motion by tracking movement of a dot pattern printed on the sclera (**Figure 3**). Reflected and static overpressures are measured for each test. Using the pressure-time history, positive duration, positive impulse, and wave velocity are calculated for each test. This test series will yield experimental data that can be used to validate computational and physical models of the eye and will improve the understanding of how the eye responds to overpressure loading.

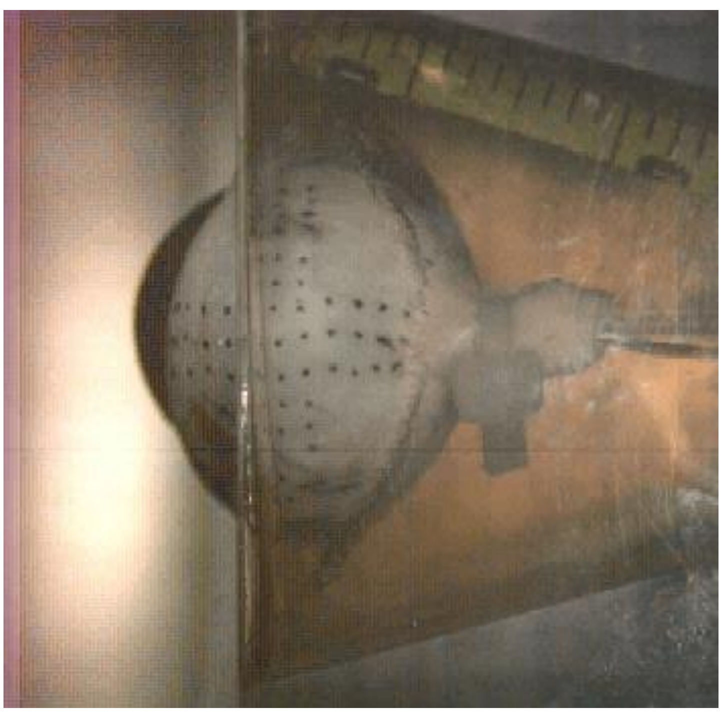

Figure 3. Photograph of porcine eye potted in a synthetic orbit and gelatin, in an advanced blast simulator.

Computational Models of the Eye for Blast Loading

A number of computational models of the eye have been developed [52-54,85,86]. Many of these are well validated for blunt impacts to the eye. However, with the increase in experimental eye testing for blast overpressure conditions, these models can be further validated for high-rate conditions such as blast. Weaver et al. developed and validated a computational model of the human eye using various orbit geometries and various projectile impacts to study the effect of anthropometry on injury risk parameters such as stress, strain, and pressure [52,53,54]. Bhardwai et al. developed a 3D fluid-structure computational model of blast loading on the human eye [85]. This model was used to assess reflected waves on facial features and indicated an increase in loading on and around the eye due to the pressure wave. High-stress and high-strain regions that could indicate injury risk for tissue failure were identified. Esposito et al. developed a finite element model of the human eye and its internal structures to assess primary blast loading on the eye [86]. This model was used to assess pressure wave propagation in the orbit of the eye and concluded that the complex shape of the orbit may generate a standing wave potentially harmful to the eye. Comparisons between isolethality and isopeak conditions indicated peak overpressure may affect eye injury risk more than positive duration. Reverse engineering was employed to determine and validate the parameters used in this model based on available experimental data. Experimental data could supplement this validation.

SUMMARY

This paper summarizes our most recent experimental test series that exposed human cadaver eyes to firework overpressure. This study quantifies the risk of eye injuries caused by firework overpressure. Serious eye injuries such as globe rupture were neither observed nor predicted by the peak IOP caused by the overpressure. However, minor corneal abrasions were observed after each test. High speed video analysis confirmed that the corneal abrasions were caused by projected unspent gunpowder. The extent of corneal abrasion depended on charge standoff distance. The combined presence of injuries caused by projected material and lack of injuries directly caused by overpressure indicates that serious eye injuries from the fireworks studied herein can be caused by projectiles and not overpressure. This research provides a foundation for future work related to eye exposure during higher overpressures. Currently, higher overpressures are being experimentally tested using shock tubes and advanced blast simulators. The response of the eye during these extremely high-rate loading schemes will provide critical insight to eye injuries related to overpressure as well as validation data for computational and physical models of the eye.

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