Quantifying Human Cadaver Eye Response to Firework Overpressure

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ABSTRACT

Due to their explosive nature, fireworks pose unique injury risks to the user and bystanders. Nearly 10,000 people are treated for firework-related injuries per year. The eye is the most frequently injured body part, and accounts for more than 2000 of these injuries. Although it is suggested the pressure wave caused by explosions (i.e. blast overpressure) can cause serious eye injuries, there is no empirical evidence to support this. The purpose of this research is to assess whether overpressure causes eye injury. This study evaluates the response of six human cadaver eyes to explosive charges at distances of 22 cm, 12 cm, and 7 cm from the cornea. Due to variability in consumer fireworks, 10 g charges of Pyrodex gunpowder were used to simulate fireworks in a controlled, repeatable manner. Five commercial fireworks were tested for comparison. A pressure sensor inserted in the vitreous measured intraocular pressure, and four pressure sensors mounted around the eye measured total and static pressures. Pressure measurements were used to calculate rise time, positive duration, impulse, and wave velocity. Minor grain-sized corneal abrasions were the only injuries observed. The abrasion size and pattern suggested unspent gunpowder was projected onto the eye, which was confirmed with high speed video. Increasing proximity to the eye resulted in more abrasions. Intraocular pressure was used to calculate injury risk, which was less than or equal to 0.01% for hyphema, lens damage, retinal damage, and globe rupture. The low calculated injury risk further supports the lack of major injuries observed. The combined presence of injuries caused by projected material and lack of injuries directly caused by the overpressure indicates that serious eye injuries cannot be caused by overpressure at these energy levels.

INTRODUCTION

Consumer fireworks are commonly used in recreation and celebration. While national laws in the United States restrict the size of consumer fireworks, individual state laws vary with regard to the purchase and use of fireworks (US CPSC, 2011). Firework-related injuries in the United States, especially in the month surrounding the Fourth of July, are prevalent among children and adolescents (Smith, 1996; MMWR, 2000; MMWR, 2004). Based on data collected by the United States Consumer Product Safety Commission between December 31, 1991 and December 31, 2010, nearly 10,000 people are treated in an emergency department for fireworks-related injuries annually, of which over 2000 are specifically related to the eye (US CPSC, 2012). Visual impairment necessitates costly medical treatment and drastically affects quality of life (Kuhn, 2006; Frick, 2007; Vitale, 2011). Additionally, the economic burden for treating adult visual disorders is nearly $50 billion a year (Rein, 2006).

Misuse of igniting and viewing fireworks poses unique injury risks to the user and bystanders. Fireworks produce a sharp increase in air pressure (overpressure) followed by an expulsion of material. Much of the current firework-related literature assesses the injurious effects of materials projected at the eye (Smith, 1996; Witsaman, 2006; Khan, 2011). Previous research calculated 100% injury risk for several eye injuries from blunt projectiles (Duma, 2005; Kennedy, 2006; Kennedy, 2007; Kennedy, 2011). Although some studies state that serious eye injuries can be caused by blast overpressure, there is no empirical evidence to directly support this (Mayorga, 1997; DePalma, 2005; Ritenour, 2008; Wolf, 2009). A critical question is whether overpressure from fireworks can cause ocular injury or if injuries are caused solely by projected material. A previous study correlated intraocular pressure (IOP) to eye injury risk (Duma, 2012). Therefore, the purpose of this research is to measure IOP in human cadaver eyes during explosions similar to consumer fireworks and assess ocular injuries sustained in order to more fully understand the effect of overpressure on the eye.

METHODS

Open-field explosive tests were performed on human cadaver eyes. Due to the variability of consumer fireworks, 10 gram charges of Pyrodex gunpowder were used to simulate consumer fireworks in a controlled, repeatable manner. The center of the charge was placed 22 cm, 12 cm, or 7 cm below the cornea to examine the effect of standoff distance on blast characteristics.

Human Cadaver Eye Tests

Six human cadaver eyes were procured from the North Carolina Eye Bank, hydrated with saline-soaked gauze, and stored at 4°C to preserve globe integrity. A maximum of 55 days spanned death and testing, which was previously shown to not affect the response of the eye (Kennedy, 2004). A miniature pressure sensor (Model 060s, 689 kPa, Precisions Measurement Company, Ann Arbor, MI) and a small tube were inserted through the optic nerve into the vitreous fluid and secured in place. The small tube was attached to a gravity-driven lactated ringer's solution to provide human physiologic IOP (14.95 mmHg) during testing (Bisplinghoff, 2005; Sponsel, 2011, Duma, 2012). Eyes were examined for gross injury between tests to ensure globe integrity was maintained. Additionally, fluorescein dye, which stains abraded cells, was topically applied to quantify potential corneal abrasions. Systematic assessment of the stained eye allowed for determination of which injuries were sustained from each test. Tests were conducted with decreasing distance from the cornea to minimize the confounding effects of multiple exposures on a single tissue sample. Charges were offset 2 cm from the front of the cornea to minimize the amount of material projected toward the eye. Four pressure sensors (Model 113B21, 1378 kPa, PCB Piezotronics, Depew, NY) were mounted around the eye (Figure 1). Pressure sensors were zeroed immediately prior to testing. All pressure data were recorded at 300 kHz. High-speed video was recorded at 20,000 fps.

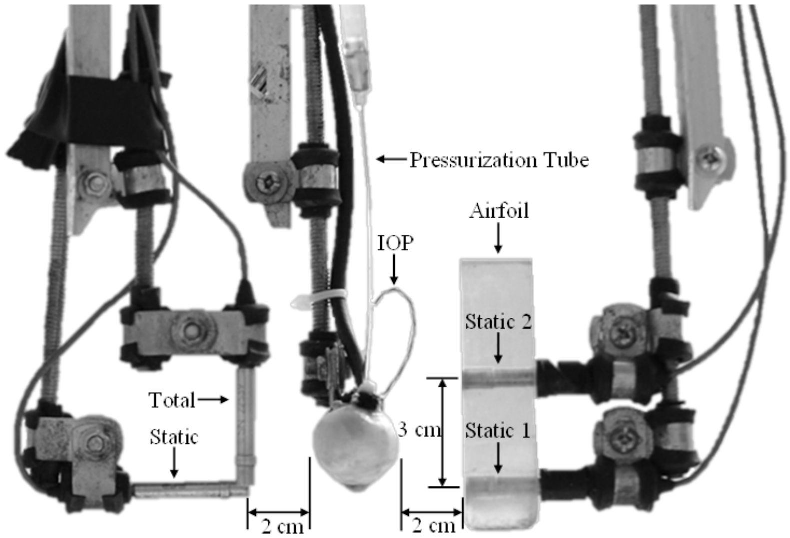

Figure 1. Human cadaver eye test setup.

Pressure Sensor Orientation. The sensing element of "total" pressure sensors was mounted perpendicular to the direction of pressure wave propagation to measure the dynamic and static components of overpressure (Stuhmiller, 1990). The sensing element of "static" pressure sensors was mounted parallel to the direction of pressure wave propagation to measure only the static component of blast overpressure (Stuhmiller, 1990).

Commercial Firework Comparison. Five commercially available fireworks (two bottle rockets and three firecrackers) were tested with the same conditions and test setup as the human cadaver eye tests (but without an eye) for comparison. A correlation between peak total overpressure and peak IOP from the cadaver eye tests was created and used to predict IOP and injury risk for the commercial firework tests. This correlation was used because the eye would experience both the dynamic and static components of blast overpressure in its current orientation perpendicular to the charge.

Intraocular Pressure Analysis. Peak intraocular pressure was used to predict injury risk of physiologic injuries (hyphema, lens damage, retinal damage) from published injury risk curves developed using *in vivo* animal tests (Kennedy, 2011). Injury risk for globe rupture based on human cadaver eye testing was assessed for comparison. Normalized energy was calculated using a published correlation between IOP and normalized energy, assuming the projected area of an unprotected eye was equivalent to a 11.16 mm diameter projectile (Duma, 2012).

Overpressure Analysis. The temporal difference between peak overpressures measured by the two static overpressure sensors mounted 3.0 cm apart in the airfoil-shaped block was used to determine the blast 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 overpressure trace over the positive duration.

RESULTS

A total of 18 charges were exploded at a distance of 22 cm, 12 cm, or 7 cm from six human cadaver eyes (three at each distance). Peak pressure results for these tests are reported in Table 1. Calculated pressure wave characteristics from these tests are reported in Table 2. Eye care professionals generally refer to IOP in millimeters of mercury; therefore, IOP is reported in both units.

Table 1. Peak pressure results for human cadaver eye tests (avg ± stdev)

Standoff Dist.	**Total Pressure**	**Static Pressure**	**IOP**	
cm	kPa	kPa	kPa	mmHg
22	21.1 ± 4.1	16.9 ± 1.8	21.8 ± 6.3	163.6 ± 46.0
12	27.4 ± 3.0	25.2 ± 2.7	26.8 ± 7.3	200.7 ± 54.7
7	51.1 ± 6.9	41.6 ± 7.1	36.5 ± 8.8	273.9 ± 65.8

Table 2. Pressure wave characteristics for human cadaver eye tests (avg ± stdev)

Standoff Dist.	**Wave Velocity**	**Rise Time**	**(+) Duration**	**(+) Impulse**
cm	m/s	ms	ms	kPa*ms
22	379.2 ± 46.0	0.036 ± 0.022	0.285 ± 0.023	2.3 ± 0.3
12	420.3 ± 44.9	0.039 ± 0.020	0.260 ± 0.034	3.0 ± 0.5
7	465.4 ± 68.8	0.051 ± 0.021	0.200 ± 0.038	4.0 ± 0.6

The pressure-time histories of total overpressure, static overpressure, and IOP for a human cadaver eye test with a 7 cm standoff distance are shown in Figure 2. The overpressure trace is comprised of a sharp rise to peak overpressure followed by a positive pressure phase and subsequent negative pressure phase (with respect to atmospheric pressure) that is indicative of a Freidlander waveform (Ritenour, 2008; Mayorga, 1997; Bisplinghoff, 2005).

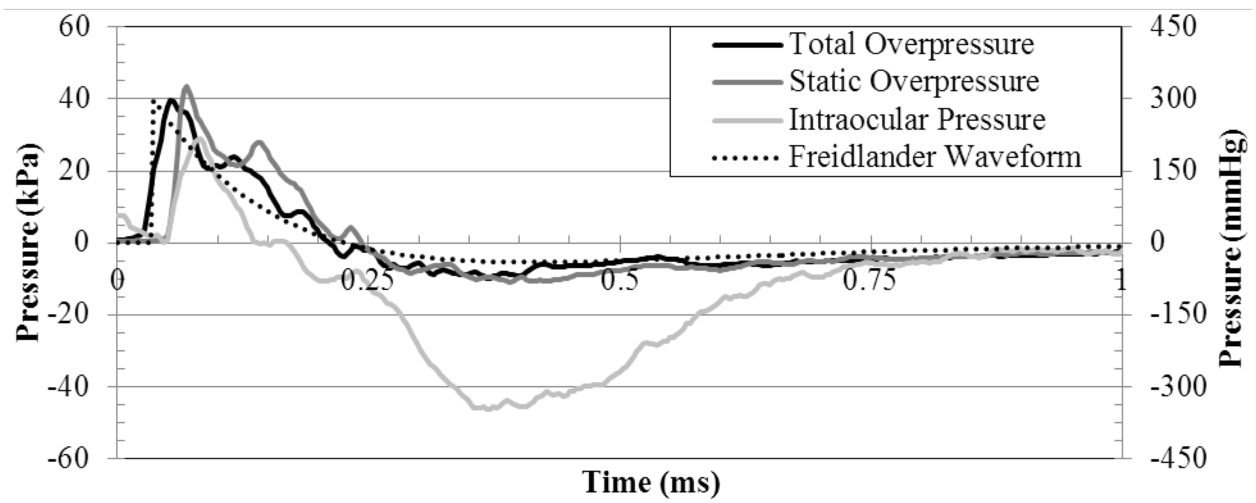

Figure 2. Pressure-time history for a representative human cadaver eye test with a 7 cm standoff distance. The eye does not experience a true a negative IOP, but rather a reduction in pressure relative to atmospheric pressure, as all sensors were zeroed just prior to the event.

Peak IOP was linearly correlated to peak total overpressure and peak static overpressure (Figure 3). These relationships can be used in situations where IOP is not directly measured, such as with the commercial fireworks tested for comparison in this study. Orientation to the blast should be considered when determining which correlation to use.

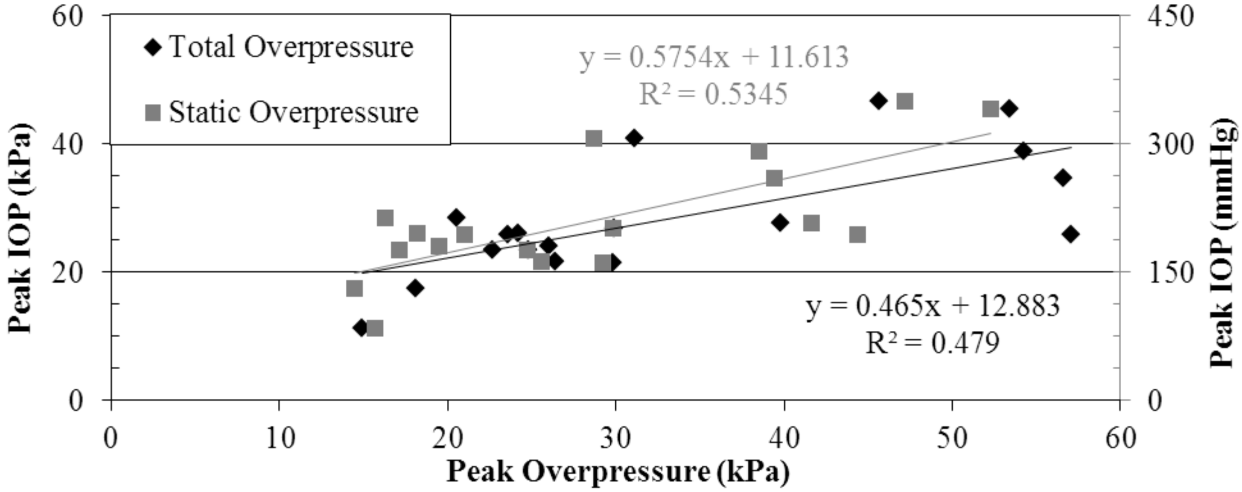

Figure 3. Correlations between peak total overpressure and peak IOP (black) and peak static overpressure and peak IOP (grey).

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 gunpowder being projected onto the eye during the event, which was confirmed with high speed video (Figure 4). More abrasions were observed as standoff distance decreased. Peak IOP predicted extremely low injury risk for all eye injuries assessed (Table 3).

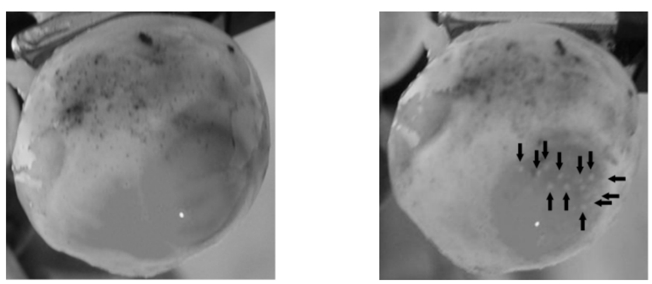

Figure 4. (left) Pre-test photograph for a 7 cm standoff distance test. (right) Post-test photograph with arrows indicating corneal abrasions. Black dots are soot and ash from the previous test. Bright white dot is a camera reflection.

Table 3. Predicted injury risk for various eye injuries for human cadaver eye tests (avg ± stdev)

Standoff Dist. cm	Hyphema %	Lens Damage %	Retinal Damage %	Globe Rupture %
22	0.002 ± 0.001	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
12	0.003 ± 0.002	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
7	0.005 ± 0.002	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000

A total of 18 bottle rockets were exploded at a distance of 22 cm, 12 cm, or 7 cm from where an eye would be located (three at each distance, two bottle rocket brands). Peak pressure results for these tests are reported in Table 4 (note IOP was calculated using the correlation between peak total pressure and IOP derived in Figure 3). Calculated pressure wave characteristics from these tests are reported in Table 5. Peak IOP predicted extremely low injury risk for all eye injuries assessed (Table 6).

Table 4. Peak pressure results for bottle rocket tests (avg ± stdev)

Standoff Dist. cm	**Total Pressure** kPa	**Static Pressure** kPa	**IOP** kPa	mmHg
22	15.4 ± 1.1	12.3 ± 0.9	20.1 ± 0.5	150.7 ± 3.7
12	35.8 ± 1.9	26.0 ± 1.8	29.6 ± 0.9	221.7 ± 6.6
7	74.6 ± 5.6	50.2 ± 4.3	47.6 ± 2.6	356.8 ± 19.4

Table 5. Pressure wave characteristics for bottle rocket tests (avg ± stdev)

Standoff Dist. cm	**Wave Velocity** m/s	**Rise Time** ms	**(+) Duration** ms	**(+) Impulse** kPa*ms
22	357.8 ± 11.8	0.021 ± 0.002	0.114 ± 0.010	0.7 ± 0.1
12	380.3 ± 12.0	0.022 ± 0.002	0.089 ± 0.002	1.2 ± 0.1
7	446.7 ± 26.6	0.022 ± 0.003	0.068 ± 0.022	1.9 ± 0.4

Table 6. Predicted injury risk for various eye injuries for bottle rocket tests (avg ± stdev)

Standoff Dist. cm	**Hyphema** %	**Lens Damage** %	**Retinal Damage** %	**Globe Rupture** %
22	0.002 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
12	0.003 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
7	0.008 ± 0.001	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000

A total of 27 firecrackers were exploded at a distance of 22 cm, 12 cm, or 7 cm from where an eye would be located (three at each distance, three firecracker brands). Peak pressure results for these tests are reported in Table 7 (note IOP was calculated using the correlation between peak total pressure and IOP derived in Figure 3). Calculated pressure wave characteristics from these tests are reported in Table 8. Peak IOP predicted extremely low injury risk for all eye injuries assessed (Table 9).

Table 7. Peak pressure results for firecracker tests (avg ± stdev)

Standoff Dist. cm	**Total Pressure** kPa	**Static Pressure** kPa	**IOP** kPa	mmHg
22	5.4 ± 1.2	4.5 ± 0.8	15.5 ± 0.5	115.9 ± 4.0
12	10.7 ± 4.0	8.5 ± 3.1	17.9 ± 1.9	134.4 ± 13.9
7	19.1 ± 8.0	14.6 ± 4.5	21.8 ± 3.7	163.6 ± 27.9

Table 8. Pressure wave characteristics for firecracker tests (avg ± stdev)

Standoff Dist. cm	**Wave Velocity** m/s	**Rise Time** ms	**(+) Duration** ms	**(+) Impulse** kPa*ms
22	351.5 ± 9.1	0.022 ± 0.005	0.115 ± 0.025	0.2 ± 0.0
12	381.3 ± 13.2	0.031 ± 0.023	0.126 ± 0.065	0.5 ± 0.1
7	412.4 ± 18.9	0.032 ± 0.022	0.108 ± 0.049	0.7 ± 0.1

Table 9. Predicted injury risk for various eye injuries for firecracker tests (avg ± stdev)

Standoff Dist. cm	**Hyphema** %	**Lens Damage** %	**Retinal Damage** %	**Globe Rupture** %
22	0.001 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
12	0.001 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
7	0.002 ± 0.001	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000

DISCUSSION

This study implemented 10 gram charges fabricated to simulate consumer fireworks in a controlled, repeatable manner. Two bottle rockets and three firecrackers were tested for comparison. It was observed for all tests that as standoff distance decreased, rise time increased slightly, peak (total and static) overpressure increased, positive duration decreased, and positive impulse increased. Three pressure wave characteristics of particular interest are peak overpressure, positive duration, and positive impulse. These characteristics should be studied simultaneously; however, the current study focuses on the effect of peak overpressure because a correlation between peak IOP and injury risk was previously derived (Duma, 2012). Increasing either peak overpressure or positive duration may be potentially more injurious; positive impulse, which is affected by both peak overpressure and positive duration, may further be an indicator of injury hazard. Although the bottle rockets produced the highest peak overpressure, the charge had the highest positive impulse due to the longer positive duration of the charge tests. Regardless, the calculated injury risk for all eye injuries assessed was less than or equal to 0.01% for all tests, which indicates that all tests are at the very low end of injury. Table 12 shows relationships between the charge, bottle rocket, and firecracker tests.

Table 10. Summary of blast overpressure wave characteristics.

Rise Time	bottle rocket	<	firecracker	<	charge
Peak Total Pressure	firecracker	<	charge	<	bottle rocket
Peak Static Pressure	firecracker	<	charge	<	bottle rocket
(+) Duration	bottle rocket	<	firecracker	<	charge
(+) Impulse	firecracker	<	bottle rocket	<	charge

Previous studies on the epidemiology of fireworks-related injuries presented at emergency departments note that injuries to the eyeball (21%) and face (20%) occur frequently (Witsaman, 2006). One study reported firecrackers and bottle rockets accounted for 50% of these eye injuries and noted rockets alone comprised 71% of the studied cases where severe eye injuries resulted in vision loss (Smith, 1996). Due to their aerial nature, bottle rockets pose a larger threat of projectile injury than do firecrackers that remain on the ground. Results from the current study support the higher risk of eye injuries caused by bottle rockets. Federal firework regulations 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 (US CPSC, 2001). 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 (Kuhn, 2000; Wilson, 1982). As of June 1, 2011, only four states completely ban fireworks, including those allowed by CPSC regulations: Delaware, Massachusetts, New Jersey, and New York (US CPSC, 2011). 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.

This study quantified the response and injury outcome of human cadaver eyes exposed to firework overpressure. No major eye injuries such as globe rupture were observed; however, minor corneal abrasions were observed. Hyphema, lens damage, retinal damage, and globe rupture were not predicted to have occurred based on the peak IOP recorded. The lack of major injuries from firework overpressure indicates that at these levels, firework overpressure does not cause serious eye injuries.

Limitations. Using human cadaver eyes limited the study to assessing only gross injuries, and not the physiological response of the eye. Therefore, the relationship between IOP and injury risk for physiologic injury is paramount to this study. Human cadaver eyes were exposed to multiple events. This maximized the use of biological tissue and provided a paired data set, thereby eliminating the confounding effects of subject variability. It is possible that successive events can cause microdamage to the tissue which can result in premature failure during a subsequent test that would not have occurred otherwise. As tests were conducted with decreasing standoff distance and because the resulting blast overpressures were of relatively low severity, the potential for adverse effects of multiple exposures was considered negligible. Additionally, the eye is located within the orbit and is surrounded by the soft tissue, musculature, and boney structures of the face. These reflective surfaces create complex pressure waves around the eye during blast overpressure events. Consequently, it is extremely difficult to interpret the isolated response of the eye with these boundary conditions. As there is currently no data regarding the response of the human eye to blast overpressure, the eye was tested in isolation to minimize the confounding effects of multiple reflective pressure waves. This facilitated the direct quantification of the eye response to blast overpressure. Future studies should be performed to understand the effect multiple reflective pressure waves from these structures.

CONCLUSIONS

This study quantified the risk of eye injuries caused by firework overpressure by assessing the human cadaver eye to charges that simulated consumer fireworks. Serious eye injuries such as globe rupture were not predicted by the IOP induced by the overpressure. However, minor corneal abrasions were observed after each test. High speed video analysis confirmed that corneal abrasions were caused by projected unspent gunpowder. The number of corneal abrasions increased with decreased standoff distance. The combined presence of injuries caused by projected material and lack of injuries directly caused by blast overpressure indicates that serious eye injuries from fireworks are caused by projectiles and not blast overpressure. This research lays the foundation for future work in evaluating the response of the eye to blast overpressure and validating anthropomorphic test devices for blast applications.

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