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RESEARCH LETTER

Mechanisms of Eye Injuries From Fireworks

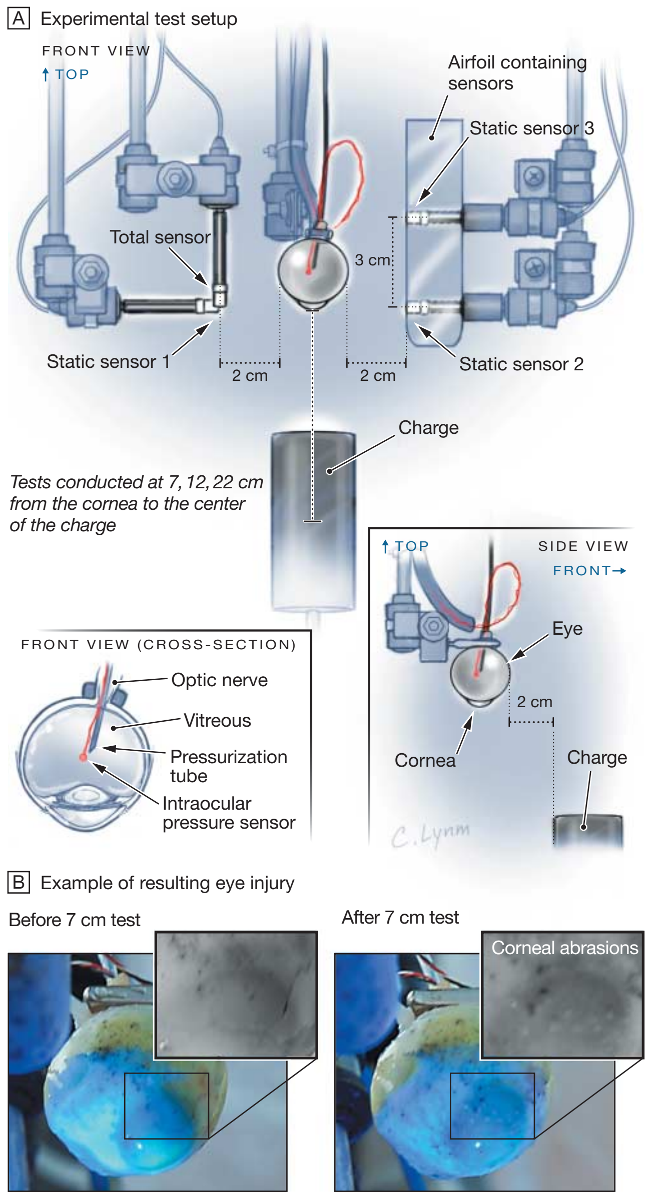
To the Editor: Injuries from fireworks are prevalent among youth.[1] The eye is the most frequently injured body part and accounts for more than 2000 injuries annually.[2,3] Although it is suggested that the pressure wave caused by explosions (ie, blast overpressure) can cause eye injury (scleral bleeding and globe rupture), there is no clear evidence to support this. This study assessed whether blast overpressure or projected material from fireworks causes eye injuries.

Methods. Due to the variability of consumer fireworks, 10 g charges of Pyrodex gunpowder were used to simulate fireworks in a controlled, repeatable manner. Human cadaver eyes were procured from the North Carolina Eye Bank and hydrated with saline-soaked gauze. A maximum of 55 days (mean [SD], 53.3 [1.4] days) spanned death and testing, which was previously shown to not affect the response of the eye.[4] Eyes were pressurized to physiological human intraocular pressure (14.95 mm Hg) before testing. A total of 18 open field blast tests were conducted at distances of 22 cm, 12 cm, and 7 cm from the cornea. Tests were conducted with increasing proximity to the cornea (farthest first) to minimize potential injury. A pressure sensor inserted into the vitreous measured intraocular pressure, and 4 pressure sensors mounted around the eye quantified total pressure, static pressure, and wave velocity (TABLE). Three commercial firecrackers (Bunker Buster, Dixie Dynamite, and Little Dynamite) were tested without an eye (3 tests at each distance; 27 total) to compare total pressure, static pressure, and wave velocity with the charges (FIGURE, part A).

Eyes were visually examined for injury (corneal abrasion, scleral damage, and globe rupture) and photographs were taken before and after each test. Fluorescein dye was used to visualize corneal abrasions. Systematic assessment of the photographs allowed determination of which injuries were sustained from each test (Figure, part B). High-speed video was used for confirmation of injuries.

Intraocular pressures were used to calculate the risk of physiological injuries (hyphema, lens damage, and retinal

Figure. Test Setup and Resulting Eye Injury



A, A miniature pressure sensor (Model 060S, 689 kPa, Precision Measurement Company) and a small tube were inserted through the optic nerve into the vitreous of the eye and secured in place. A bag of lactated Ringer solution attached to the tube provided an initial physiological human intraocular pressure of 1.99 kPa (14.95 mm Hg).[5] Four pressure sensors (Model 113B21, 1379 kPa, PCB Piezotronics) were mounted around the eye. The total sensor, oriented perpendicular to the blast wave front, measured both dynamic and static pressure; the other 3 sensors, oriented parallel to the blast wave front, measured static pressure. All pressure data were collected at 301887.0 Hz (TDAS PRO, Diversified Technical Systems Inc) and zeroed immediately prior to the event. The charge was offset from the cornea to minimize the amount of material projected directly toward the eye. A Phantom v9.1 camera (Vision Research; resolution 256×192 pixels) recorded high-speed video at 20 000 frames per second to allow frame-by-frame analysis of each test event. B, Yellow fluorescein stain with blue light illumination of eye. In the posttest photograph (right), corneal abrasions are visible in the inset (image converted to grayscale). Black dots are soot and ash from the previous test.

Table. Charge and Commercial Firecracker Pressures[a]

Standoff Distance, cm	Pressure, kPa: Total[b]	Pressure, kPa: Static[c]	Intraocular Pressure[d]: kPa	Intraocular Pressure[d]: mm Hg	Wave Velocity, ms[e]	Impulse, Pas[f]
Charge						
22	21.1 (4.1)	16.9 (1.8)	21.8 (6.3)	163.6 (47.2)	379.2 (46.0)	2.3 (0.3)
12	27.4 (3.0)	25.2 (2.7)	26.8 (7.3)	200.7 (54.7)	420.3 (44.9)	3.0 (0.5)
7	51.1 (6.9)	41.6 (7.1)	36.5 (8.8)	273.9 (65.8)	465.4 (68.8)	4.0 (0.6)
Firecracker						
22	5.4 (1.2)	4.5 (0.8)	15.4 (0.5)[g]	115.2 (4.0)[g]	351.5 (9.1)	0.2 (0)
12	10.7 (4.0)	8.5 (3.1)	17.8 (1.8)[g]	133.6 (13.8)[g]	381.3 (13.2)	0.5 (0.1)
7	19.1 (8.0)	14.6 (4.5)	21.7 (3.7)[g]	162.5 (27.7)[g]	412.4 (18.9)	0.7 (0.1)

[a] Data are expressed as mean (SD).
[b] Sum of dynamic and static pressures and reported relative to standard atmospheric pressure (101.4 kPa).
[c] Indicates static pressure sensor 1 and reported relative to standard atmospheric pressure (101.4 kPa).
[d] Reported relative to normal human physiological intraocular pressure of 1.99 kPa and 14.95 mm Hg.
[e] Calculated using temporal difference between peak overpressures measured by static pressure sensors 2 and 3.
[f] Calculated using trapezoidal integration of the total pressure trace over the positive duration (area under the curve).
[g] Calculated using correlation between total pressure and intraocular pressure developed from the charges.

damage) from published injury risk curves developed using in vivo animal tests, which are commonly used in injury biomechanics.[6] Injury risk for globe rupture based on human cadaver eye testing was assessed for comparison. Normalized energy was calculated using a published correlation between intraocular pressure and normalized energy, assuming the projected area of an unprotected eye was equivalent to a 11.16-mm diameter rod.[5]

Results. Minor grain-sized corneal abrasions were the only injuries observed (Figure, part B). The abrasion size and pattern suggested unspent explosive material was projected onto the eye, which was confirmed with high-speed video. Increasing proximity to the eye resulted in more abrasions.

Intraocular pressure increased with increased proximity to the charge (Table). Intraocular pressure y was linearly correlated with total overpressure x [$y(\text{kPa}) = 0.46x(\text{kPa}) + 12.97$; $R^2 = 0.5$]. Injury risk was less than or equal to 0.01% for hyphema, lens damage, retinal damage, and globe rupture.

Comment. The firework blast overpressures measured in this study did not cause serious eye injuries. The only observed injuries were minor corneal abrasions caused by projected material. Calculated injury risk was less than or equal to 0.01% for physiological eye injuries. This study provides information about injury mechanisms of fireworks that could aid in public policy decisions regarding firework laws and in the design of protective equipment. Additionally, this study offers validation data for computational models of the eye.

This study has some limitations that should be addressed in future studies. The eye was isolated from the head to minimize the confounding effects of reflective pressure waves that could affect intraocular pressure. The use of cadaver tissue did not allow for direct assessment of physiological injuries. The distances from the cornea were chosen to eliminate thermal burn as a potential injury mechanism. Eyes were exposed to multiple events to maximize the use of biological tissue and to provide a paired data set to eliminate the confounding effects of subject variability. However, the potential for adverse effects from multiple exposures was considered negligible because the measured blast overpressures were relatively low and no severe injuries were observed.

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Acquisition of data: Alphonse, Kemper, Strom III, Beeman.
Analysis and interpretation of data: Alphonse, Kemper, Duma.
Drafting of the manuscript: Alphonse, Kemper, Strom III, Beeman.
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