Blunt Eye Trauma: Empirical Histopathologic Paintball Impact Thresholds in Fresh Mounted Porcine Eyes

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PURPOSE. Ballistic studies were conducted using gelatin-embedded abattoir-fresh porcine eyes suspended within clear acrylic orbits to discern the energy required to produce specific ocular injuries. Paintball impact provides a robust ballistic model for isolating and quantifying the role of direct blunt force in ocular trauma.

METHODS. Fifty-nine porcine orbital preparations received direct blows from 0.68 caliber (16–18 mm diameter/3.8 g) paintballs fired at impact velocities ranging from 26 to 97 meters per second (2–13.5 J). Five additional eyes not subjected to ballistic impact were also evaluated as controls. Impact energies were correlated with histopathologic damage.

RESULTS. Minimum impact energies consistently producing damage in experimental eyes unobserved in control specimens were: 2 joules—posterior lens dislocation, zonulysis, capsular damage in experimental eyes uncommon in control specimens; 3.5 joules—moderate angle recession; 4 joules—anterior lens dislocation; 4.8 joules—peripapillary retinal detachment; 7 joules—severe angle recession, iridodialysis, and cyclodialysis; 7.5 joules—cornal stromal distaction; 9.3 joules—choroidal segmentation; and 10 joules—globe rupture.

CONCLUSIONS. Impact thresholds correlating traumatic ocular pathology with impact energy followed a positive stepwise progression in severity with impact energies between 2 and 10 joules. Moderate angle recession commensurate with typical clinical traumatic glaucoma was not observed among control eyes, but occurred at relatively low impact energy of 3.5 joules among test eyes. Extensive disruption in and around the angle (iridodialysis/cyclodialysis) consistently occurred at energies >7 joules. Globe rupture required a minimum energy of 10 joules. (Invest Ophthalmol Vis Sci. 2011;52:5157–5166) DOI: 10.1167/iovs.11-7172

A research program was undertaken with the objective of developing the necessary tools and skills for modeling a broad, histopathologic range of ocular blunt trauma. Goals included the development of suitable geometric and material models, implementation into suitable physics-based computer codes, and demonstration of their validity to a real-world blunt trauma problem that might produce a broad clinical range of ocular injuries. Such a range of injuries has been observed with paintball impact into the human eye, so this was chosen for the demonstration problem, to see if it might be possible to design a safer paintball (Sponsel WE, et al. IOVS 2007;48:ARVO E-Abstract 5485). Common injuries include corneal abrasion, hyphema, lens dislocation, cataracts, retinal detachment, choroidal rupture, or total globe rupture, commonly leading to complete loss of the eye.1,2 Most injuries require immediate emergency surgery and numerous follow-up procedures, with at least 30% of eyes attaining best-corrected after-surgery acuity < 20/200.3

It appears that the paintball model might be particularly helpful in elucidating the effects of blunt ocular trauma without accompanying orbital fracture (Gray W, et al. IOVS 2007;49:ARVO E-Abstract 2778). Relevant ballistic data could provide helpful insights to those interested in the design of protective eyewear.

Experimental studies performed on human, monkey, and porcine eyes show that after impact, the sclera expands equatorially, producing corneoscleral stress that can cause rupture of the eye. Such studies have involved blunt objects such as BBs, metal cylinders, foam particles, paintballs, golf balls, squash balls, and baseballs (Umlas JW, et al. IOVS 1995;36: ARVO Abstract 2710).4–8 Some were in vitro experiments in which the eyes were removed from the head and placed in a supporting gelatin, while others were conducted in situ in human cadaveric skulls. In 2005, it was shown that the extraocular muscles do not contribute to the risk of globe rupture, validating both of these approaches.9,10 All used high-speed camera recordings, so deformation and displacement of the eye, speed of the projectile, and globe rupture could be captured. In each study, the kinetic energy associated with each of the blunt projectiles was calculated and used to create an injury risk curve. It has been suggested that less energy is required of small blunt objects than large blunt objects to cause an injury, but there is not a uniform predictor of eye injury. Injuries requiring microscopic histologic examination have not been extensively investigated, with globe rupture, corneal abrasion, and general retinal damage having been standard definitions of eye injury.11

Excellent work has been performed to assess the effects of the larger diameter deformable blunt impact produced by airbags (Umlas JW, et al. IOVS 1995;36:ARVO Abstract 2710)4–8,12 and various deformable and nondeformable low velocity, low mass projectiles. It is hoped that knowledge of the dynamics of intraocular injury caused by continuously deformable but orbitally constrained blunt impact as is produced by paintballs might...
provide insights into the ocular trauma arising from the non-shrapnel blast impact components of detonated improvised explosive devices. The application of such knowledge should hopefully also help mitigate various longstanding industrial and sports-related eye safety concerns.

**METHODS**

The methods used in this study were similar to those used in previous ocular impact research programs9,10,20,21 with modifications necessary to accommodate local capabilities and facilities. Impact experiments were conducted using fresh porcine eyes purchased from Animal Technologies (Tyler, TX). All tenets of the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research were adhered to in the acquisition and postmortem use of these eyes from this reputable scientific vendor. To ensure specimens were as fresh as possible, eyes were harvested and shipped (unfrozen) overnight on ice. The specimens were prepared, mounted in appropriate holders at 4°C, and tested within 24 hours. Preparation of the porcine eyes involved carefully removing any remaining eyelid and peribulbar soft tissue to fully expose the ocular globe and optic nerve. A thin hollow needle or catheter (16-gauge) with attached thick-walled tube (Tygon; Saint-Gobain Performance Plastics; Poestenkill, NY) (9.5-mm outer diameter × 3.2-mm inner diameter) completely filled with a 10% saline solution was carefully inserted through the optic nerve into the vitreous (Fig. 1). The needle was secured to the optic nerve by firmly tying dental floss around the outside of the optic nerve sheath. The remaining leads on the dental floss were then secured to the tube to prevent pullout of the needle. The eye, catheter, and tubing were placed in a clear acrylic, pyramid-shaped holder sized internally to closely approximate the dimensions of the human orbit, and the eye was positioned at the center by the tension of two thin threads. The pyramidal acrylic mount was considered to be a critical feature of this model, because...
our computational studies indicated that normal pyramidal orbital constraints were likely to be of considerable importance in the dynamics of blunt ocular injury unaccompanied by zygomatic or orbital floor fracture.\textsuperscript{19,21,22} The importance of this geometry has been recently documented by Weaver et al.\textsuperscript{22} Also, as documented by Kennedy et al.,\textsuperscript{23} the six intraocular muscles do not contribute to the mechanical response of the eye at high loading rates, allowing a uniform periocular medium to be used to mimic the periorbita. Therefore, the holder was filled with a premixed Knox gelatin solution and placed in a refrigerator, allowing the gelatin to harden.

The catheter and tubing allowed for repressurization of the eye immediately before the test.\textsuperscript{9} The saline bag was elevated to achieve the proper hydrostatic pressure in the eye ($P/H_{11011} = 18$ mm Hg). A manual isolation valve was closed to maintain the pressure during the impact.

\begin{table}[h]
\centering
\begin{tabular}{cccccc}
\hline
Test & Date & Paintball Type & Paintball Weight (g) & Static Pressure (mm Hg) & Velocity (ft/s) & Velocity (m/s) & Energy (J) \\
\hline
1 & 08-Dec-06 & TP & 2.64 & 18.6 & 286 & 87.2 & 10.03 \\
2 & 08-Dec-06 & TP & 2.66 & 18.1 & 193 & 58.8 & 4.60 \\
3 & 08-Dec-06 & TP & 2.66 & 69.8 & 94 & 28.6 & 1.09 \\
4 & 08-Dec-06 & TP & 2.66 & 16.5 & 85 & 25.9 & 0.89 \\
5 & 08-Dec-06 & TP & 2.66 & 18.1 & 290 & 88.4 & 10.4 \\
6 & 08-Dec-06 & M & 3.16 & 16.5 & 285 & 86.9 & 11.88 \\
7 & 08-Dec-06 & M & 3.15 & 18.6 & 292 & 89.0 & 12.51 \\
8 & 08-Dec-06 & M & 3.15 & 18.1 & 181 & 55.2 & 4.79 \\
9 & 08-Dec-06 & M & 3.17 & 18.1 & 190 & 57.9 & 5.32 \\
10 & 09-Feb-07 & SR & 2.15 & 18.1 & 101.1 & 30.8 & 1.02 \\
11 & 09-Feb-07 & SR & 2.16 & 16.5 & 204.4 & 62.3 & 4.19 \\
12 & 09-Feb-07 & SR & 2.15 & 16.0 & 305.2 & 93.0 & 9.30 \\
13 & 09-Feb-07 & FM & 3.08 & 16.5 & 111.4 & 34.0 & 1.78 \\
14 & 09-Feb-07 & SR & 2.12 & 16.0 & 305.6 & 93.1 & 9.20 \\
15 & 09-Feb-07 & SR & 2.14 & 17.6 & 300 & 91.4 & 8.95 \\
16 & 13-Feb-07 & SR & 2.14 & 15.5 & 160 & 48.8 & 2.54 \\
17 & 13-Feb-07 & SR & 2.14 & 17.1 & 152 & 46.3 & 2.30 \\
18 & 13-Feb-07 & SR & 2.14 & 16.5 & 232 & 70.7 & 5.35 \\
19 & 13-Feb-07 & SR & 2.14 & 14.5 & 306 & 93.3 & 9.31 \\
20 & 14-Feb-07 & M & 3.1 & 16.5 & 265 & 80.8 & 10.11 \\
21 & 14-Feb-07 & M & 3.11 & 17.6 & 165 & 50.3 & 3.93 \\
22 & 14-Feb-07 & M & 3.1 & 15.5 & 305 & 93.0 & 13.95 \\
23 & 14-Feb-07 & M & 3.1 & 16.5 & 195 & 59.4 & 5.48 \\
24 & 14-Feb-07 & M & 3.1 & 18.1 & 157 & 47.9 & 3.55 \\
25 & 15-Feb-07 & TP & 2.65 & 16.5 & 265 & 80.8 & 8.64 \\
26 & 15-Feb-07 & TP & 2.65 & 16.5 & 173 & 52.7 & 3.68 \\
27 & 15-Feb-07 & TP & 2.65 & 16.5 & 317 & 96.6 & 12.57 \\
28 & 15-Feb-07 & TP & 2.65 & 16.5 & 194 & 59.1 & 4.63 \\
29 & 15-Feb-07 & TP & 2.65 & 68.2 & 168 & 51.2 & 3.47 \\
30 & 15-Feb-07 & TP & 2.65 & 17.1 & 166 & 50.6 & 3.39 \\
31 & 15-Feb-07 & M & 3.1 & 18.1 & 215 & 65.5 & 6.66 \\
32 & 15-Feb-07 & M & 3.08 & 16.5 & 267 & 81.4 & 10.20 \\
33 & 15-Feb-07 & M & 3.08 & 17.6 & 168 & 51.2 & 4.04 \\
34 & 16-Feb-07 & M & 3.11 & 17.1 & 299 & 91.1 & 12.91 \\
35 & 16-Feb-07 & M & 3.07 & 17.1 & 204 & 62.2 & 5.95 \\
36 & 16-Feb-07 & M & 3.07 & 17.1 & 195 & 59.4 & 5.42 \\
37 & 16-Feb-07 & M & 3.09 & 17.6 & 172 & 52.4 & 4.25 \\
38 & 16-Feb-07 & M & 3.09 & 17.1 & 263 & 80.2 & 8.42 \\
39 & 16-Feb-07 & TP & 2.62 & 17.1 & 172 & 52.4 & 3.60 \\
40 & 16-Feb-07 & TP & 2.62 & 17.1 & 322 & 98.1 & 12.76 \\
41 & 16-Feb-07 & TP & 2.65 & 18.1 & 196 & 59.7 & 4.73 \\
42 & 16-Feb-07 & TP & 2.65 & 18.1 & 160 & 48.8 & 3.15 \\
43 & 03-Mar-07 & SR & 2.15 & 15.5 & 307 & 93.6 & 9.41 \\
44 & 03-Mar-07 & SR & 2.15 & 16.0 & 342 & 104.2 & 11.68 \\
45 & 03-Mar-07 & SR & 2.16 & 16.0 & 2.73 & 0.8 & 0.00 \\
46 & 23-Mar-07 & SR & 2.16 & 16.5 & 150 & 45.7 & 2.26 \\
47 & 23-Mar-07 & SR & 2.16 & 16.5 & 155 & 47.2 & 2.41 \\
48 & 23-Mar-07 & M & 3.12 & 17.1 & 299 & 78.9 & 9.72 \\
49 & 23-Mar-07 & M & 3.12 & 16.5 & 271 & 82.6 & 10.64 \\
50 & 23-Mar-07 & M & 3.10 & 16.5 & 218 & 66.4 & 6.84 \\
51 & 23-Mar-07 & M & 3.12 & 16.5 & 117 & 35.7 & 1.98 \\
52 & 23-Mar-07 & M & 3.13 & 16.5 & 120 & 36.6 & 2.09 \\
53 & 23-Mar-07 & TP & 2.65 & 16.5 & 318 & 96.9 & 12.45 \\
54 & 23-Mar-07 & TP & 2.65 & 17.1 & 297 & 90.4 & 10.86 \\
55 & 23-Mar-07 & TP & 2.65 & 17.1 & 243 & 74.1 & 7.27 \\
56 & 23-Mar-07 & TP & 2.65 & 17.1 & 130 & 39.6 & 2.08 \\
57 & 23-Mar-07 & TP & 2.65 & 17.1 & 128 & 39.0 & 2.02 \\
58 & 23-Mar-07 & TP & 2.65 & 17.6 & 250 & 76.2 & 7.69 \\
59 & 23-Mar-07 & TP & 2.66 & 16.5 & 304 & 92.7 & 11.42 \\
\hline
\end{tabular}
\caption{Summary of Impact Experiments}
\end{table}

FM, frozen marballizer; M, marballizer; SR, solid rubber; TP, tactical performance.
A static strain-gauge type pressure transducer mounted in the tubing between the intravenous bag and the isolation valve was used to verify that the proper intraocular pressure has been achieved (Fig. 1).

Ballistic testing was conducted by Southwest Research Institute personnel at ballistic range facilities in San Antonio, TX. Paintballs were launched using a custom paintball gun (Tippmann 98; Tippmann Sports, LLC; Fort Wayne, IN). This paintball gun uses a fixed internal pressure regulator to achieve a nominal launch velocity of 91 meters per second. To achieve a broad range of lower velocities, the paintball gun was modified by (1) connection to an external compressed gas source and regulator (bypassing the internal regulator), and (2) shortening the standard 30.5-cm long barrel to 15.2 cm. Launch velocities were measured using two infrared chronographs (light screens) placed 61 cm apart (Oehler Model 57; Oehler Research; Austin, TX).

All ocular impacts and rupture characteristics were documented using a high-speed video camera (Phantom V-7; Vision Research, Inc., Wayne, NJ). A mirror placed above the specimen and inclined at a 45° angle (Figs. 2, 3) provided two orthogonal views with a single camera. Images were recorded at 30,000 frames per second, resulting in a pixel resolution of 256 x 256. Initially, visual obscuration (from the colored polyethylene glycol solution) after bursting of the paintball limited postimpact observation. However, after experimenting with different
camera viewing angles, clear postimpact images with the bursting paintballs were obtained.

Most commercially available paintballs are approximately 17 mm in diameter (0.68 caliber) and can be characterized as fluid-filled spheres consisting of a rigid to semirigid gelatin shell enclosing a water-soluble paint solution (ASTM F 1799-04). The gelatin shell is typically a Type B gelatin produced from bovine skin, and the fill is a colored polyethylene glycol solution. In this study, three common types of paintballs were evaluated in an attempt to characterize differences in trauma potential. Included were a generic low quality (and less expensive) commercial paintball commonly used by amateurs. The second paintball was a higher quality, so-called match grade paintball. The primary difference was in the dimensional quality control exercised during construction of the gelatin shell. The match-grade paintball displaced a lower diametrical variability, in principal achieving a smaller variance in launch velocity because of the more consistent inner barrel fit. In tests, the match grade paintball also displayed a more consistent burst energy threshold (minimum impact energy required to break the gelatin shell). However, the average energies required for bursting (0.22–0.24 J) were well below the minimum energies required for injury, so quality differences (i.e., differences in paintball type) could not be differentiated. The third ‘paintball’ projectile was a solid soft rubber sphere (same diameter as paintball) typically used by police departments for training.

Simultaneous high-speed video images of the two perpendicular views along the flight path and eyeball were subject to detailed postimpact detailed analysis using software provided by the camera manufacturer (Vision Research, Inc.). The resolution of the camera (Phantom 7.3; Vision Research, Inc.) was 256 × 256 pixels per mm. Gross deformation of the globe, specifically posterior displacement and subsequent rebound, were characterized for each impact event. Individual measurements were made of the changes in axial length (from anterior cornea to external optic nerve root), horizontal width, and vertical height. The postimpact measurements were taken at the point of maximum paintball travel, with change defined as the difference between deformed and undeformed values. The trajectory and the point of impact of the paintball on each ocular/orbital preparation could also be accurately derived from the perpendicular simultaneous images. After ballistic impact conditions were detailed, each eye was placed in buffered 10% formalin solution and transported to the ocular pathology laboratory for macroscopic assessment, embedding, sectioning, platting, and histopathologic evaluation. Control eyes were handled in the same manner as the test eyes but were not submitted to paintball impact.

Posttest analysis of the video images was undertaken to characterize the gross deformation, posterior displacement, and subsequent rebound of each eye specimen. The analysis was conducted using software provided by the camera manufacturer (Vision Systems, Inc.; Sheridan, CO). Individual measurements were made of the change of eye length, transverse width, and vertical height. These measurements were then combined to estimate volumetric change. The postimpact measurements were taken at the point of maximum paintball travel, with change defined as the difference between deformed and undeformed values. Kinetic energy values were derived using the classical mechanics equation for a nonrotating rigid body \( (E_k = \frac{1}{2} mv^2) \), in which mass is measured in kilograms and speed in meters per second, providing energy in joules.

### RESULTS

#### Ballistic Studies

Fifty-nine eyes were evaluated, data for which is shown in Table 1. Uncertainty in globe deformation measurements obtained from the image analysis was initially estimated to be ± 0.6 mm based on the pixel resolution of the approximate 152 × 102 mm viewing area. However, statistical analysis of 100 replicate measurements from objects of known length revealed a more realistic value of ± 0.65 mm (1 SEM). Uncertainty in the velocity was estimated to be ± 0.013 meters per second based on the chronograph position uncertainty, and mass uncertainty was estimated as ± 0.005 g, the smallest division on the balance. The uncertainties of calculated quantities (e.g., energy) were estimated by propagation of the component uncertainties. Intraocular pressures were collated for static preimpact measurements only, because obvious mechanical failures with the nanometric transducer during the rapid pressure rise phase immediately after impact on multiple specimens suggested that other dynamic postimpact intraocular pressure data also might not be reliable.

The general trends in measured quantities were in the expected directions, for example the eye length decreased (because of compression) and the width and height increased (because of lateral expansion) as the impact velocity and energy increased (Fig. 4). Note that length and volume change show negative trends because of the method chosen for plotting, with negative values indicating compression. Overall, the correlations are poor, because the data display considerable scatter and variability. Not all impacts were perfectly centered, and a significant number of paintballs impacted with considerable offset (see Fig. 5). It is important to appreciate that axial distortion of the globe as the paint loculus passes between the eye’s equator and the orbital rim can actually produce elongation in such instances. However, removing this data did not significantly alter the correlations. Our data appear to indicate that there is no significant difference in eye response with respect to paintball type when normalized to impact energy, because every paintball burst on impact, and most pathologic changes appeared to be associated with the continued anteroposterior progression of the liquid paint bolus within the orbital shell. These findings with the porcine eye should be contrasted to a key study using a human eye model in which normalized energy is directly associated with the level of trauma observed.\(^{24}\)

![Blunt Eye Trauma Thresholds](http://tvst.arvojournals.org/article-pdf/52/8/5150/5150_1.pdf)

**FIGURE 5.** Distribution of porcine globe impact sites within the acrylic orbits. Central corneal impact (CC) was attained in 26 instances as shown in the central boxed numeral. Offset corneoscleral impact was observed in the eight radially displaced anterior globe sectors as shown (TC, top center; TR, top right; CR, center right; BR, bottom right; BC, bottom center; BL, bottom left; CL, center left; TL, top left). Posterior displacement (PD, in negative mm) of the central cornea relative to its preimpact position within the orbit is shown for each sector, with the mean and SE of that mean value in parentheses. Rebound displacement (RD, in positive mm) of the central cornea relative to its preimpact position within the orbit is similarly shown for each sector, with the mean and SE of that mean value.
<table>
<thead>
<tr>
<th>Test</th>
<th>Paintball Type</th>
<th>Velocity (ft/s)</th>
<th>Hit Location</th>
<th>Corneal Abrasion</th>
<th>Corneal Stroma Trauma</th>
<th>Angle Recession Minor</th>
<th>Angle Recession Moderate</th>
<th>Angle Recession Severe</th>
<th>Iris Detachment</th>
<th>Iris Segmentation</th>
<th>Ciliary Detachment</th>
<th>Ciliary Segmentation</th>
<th>Globe Rupture</th>
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<tbody>
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<td>1</td>
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<td>286</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BC, bottom center</td>
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<tr>
<td>2</td>
<td>TP</td>
<td>193</td>
<td>CL-Hit</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td></td>
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<td>BL, bottom left</td>
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<td>3</td>
<td>TP</td>
<td>94</td>
<td>TL-Miss</td>
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<td></td>
<td></td>
<td>CR, center right</td>
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<tr>
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<td>x</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>M, marballizer</td>
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<tr>
<td>5</td>
<td>TP</td>
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<td>CC-Hit</td>
<td>x</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SR, solid rubber</td>
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<td>BC-Hit</td>
<td>x</td>
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<td></td>
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<td>TC, top center</td>
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<tr>
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<td>TR, top right</td>
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<tr>
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<td>CL-Hit</td>
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BC, bottom center; BL, bottom left; BR, bottom right; CL, center left; CR, center right; M, marballizer; SR, solid rubber; TC, top center; TL, top left; TP, tactical performance; TR, top right.
As expected, posterior displacement of the eye and the amount of rebound subsequent to impact also increased with impact velocity and energy. The greater scatter in rebound might be explained by the observation that when paintball impact was off the centerline, the paintball tended to get pushed between the orbitally proportioned acrylic holder and eye, thereby squeezing and expanding the eye along the impact direction instead of compressing it, as was the case for centerline impacts. In extreme cases, the eye was ejected back toward the gun. Detailed study of the ocular compressive and rotational effects of these more oblique and tangential hits provided new insights into likely mechanisms for optic nerve avulsion and evulsion (Sponsel WE, et al. IOVS 2008;49:ARVO E-Abstract 5257).

Globe rupture occurred on six experiments with velocities ranging from 81 to 97 meters per second (10–12.4 J), and was observed for all paintball types. This threshold is slightly higher than was observed in previous studies, where consistent globe rupture was achieved at energies in excess of 7.9 J (44% probability of rupture). Rupture appeared to depend on achieving a centerline hit. Slightly off-center hits at equivalent and higher velocities did not result in rupture. In all cases, the rupture occurred near the limbus.

On an area normalized basis (normalized to cross-sectional area of the paintball sphere) globe rupture was observed at values from 44,060 to 54,630 J/m². Previous studies evaluating a wider variety of projectiles have shown better correlations between globe rupture threshold and normalized energy than with impact energy alone. In those studies, globe rupture in a human eye model was observed at normalized energy values from approximately 29,000 to 65,000 J/m². In this study, only paintballs were evaluated, so area normalized values are stated for reference only.

Pathology of the Eye Specimens

Thirty-four eyes—29 representative ballistic specimens and five control eyes—were subjected to detailed pathology. The findings are summarized in Table 2. Figure 6 displays the lowest threshold energies at which each category of injury was observed in the test eyes and not seen in the similarly handled and mounted control specimens not subjected to paintball impact. Over the range of impact velocities tested (26–97 m/s), the severity of injury generally increased with impact velocity and energy. However, in six experiments, high-speed video images revealed that when the paintball trajectory was off-center and nearly grazed the eye, notable effects on the optic nerve were observed. As mentioned above, those findings led to another productive new avenue of enquiry (Sponsel WE, et al. IOVS 2008;48:ARVO E-Abstract 5257).

For the present purpose of associating direct impact energy with corneoscleral and intraocular pathologic outcomes, those six globes were removed from this analysis.

The general categories of trauma observed in the experiments included the following: (1) corneal abrasion; (2) trauma to the corneal stroma; (3) angle recession; (4) detachment and
segmentation of the iris and ciliary body; (5) detachment and segmentation of the retina; (6) lens dislocation; (7) zonule and lens capsule rupture; (8) choroid detachment and segmentation; and (9) globe rupture.

Corneal abrasion was ubiquitously observed on all tests where the paintball made contact with the corneal surface. Abrasion was manifested as complete or partial removal of the corneal epithelium (Fig. 7). In our tests, trauma to the stroma was observed as partial delamination of one or more of the collagen lamellae (Fig. 7).

Iridodialysis is the segmental separation of the peripheral iris stroma or iris root from the angle (Fig. 8). Angle recession is defined as separation of the longitudinal and circular muscle of the ciliary body and subsequent widening of the angular region, often resulting in localized detachment of the ciliary body from the sclera (Fig. 8). It is thought to result from anomalously high static or dynamic pressures in the anterior chamber and aqueous humor. Left untreated, it can result in traumatic glaucoma (elevated intraocular pressure). Although somewhat subjective, angle recession was categorized in this series of tests as either minor, moderate, or severe based on visual characterization of the degree of localized separation. Severe angle recession was often accompanied by partial or complete detachment and segmentation (tearing into numerous segments) of the iris and ciliary body (Fig. 8). In extreme cases where global rupture also occurred in the cornea or near the limbus (corneoscleral junction), segments of the iris and ciliary were often ejected through the rupture opening.

Detachment of the retina from the choroid was observed in almost all specimens examined except for a few of the control specimens. Retinal detachment often occurs after death, even in the absence of trauma, because of the loss of intraocular pressure. Tearing or segmentation of the retina was also ubiquitously observed, but because of its fragile nature may be an artifact of the pathology (i.e., retinal tearing during cutting of the thin sections). Indeed, peripheral retinal detachment was observed as partial delamination of one or more of the collagen lamellae. In our tests, trauma to the stroma was observed as partial delamination of one or more of the collagen lamellae (Fig. 7).

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Lens dislocation manifested in the posttest pathology by the lens being at other than its normal location inside the eye. Posterior dislocations were noted over the full range of impact velocities, but anterior dislocations were only observed at somewhat elevated velocities. In those cases, the lens was thrust forward into the anterior chamber, possibly the result of postimpact rebound energies (Fig. 10). Lens dislocation was accompanied by rupture of the lens capsule, the tough outer membrane that encapsulates the weaker crystalline lens material. In thin section, segments of the ruptured capsule are observed as short curled-up segments in the vitreous or aqueous humor. Rupture of the zonule fibers was evident on low-power assessment wherever the capsule was ruptured in related thin sections.

Detachment of the choroid was observed over the full range of impact conditions, but intrachoroidal segmentation was observed in only two tests at velocities comparable to those required for globe rupture. At low velocities, the choroid typically detached from the sclera at a location immediately posterior to the ciliary body (Fig. 9). At higher velocities, ciliary detachment was occasionally accompanied by a non-uniform choroidal detachment at discrete locations around the internal periphery. Complete detachment of the choroid was not observed.

Globe rupture is characterized by a tear that perforates completely through the corneoscleral shell (Fig. 11). Rupture was observed during six tests at the highest impact velocities and energies. Four rupture occurred at the limbus, one in the sclera just posterior to the limbus, and one in the cornea, possibly the result of an impact penetration. In all cases, rupture was accompanied by ejection of the aqueous humor, lens, and vitreous, and often segments of the retina, iris, and ciliary body.
Correlation of the Trauma Data with Impact Conditions

Corneal abrasion, minor angle recession, and retinal detachment were observed at all impact energies, but also observed to some extent in at least one of the five control specimens. Figure 5 shows the categories of ocular trauma (discussed in the previous section) and the range of impact energies over which they were observed in the experiments. Therefore, the degree to which impact energy might have contributed to the extent of these more minor levels of trauma cannot be assessed with confidence. The plot is a summary of hit data obtained from the 34 pathology specimens, with the data from the six experiments in which the paintball partially or completely missed the eye not included. The minimum energy for each category is taken as a qualitative threshold for that category (Fig. 5). For example, the lowest energies at which globe rupture and choroid segmentation were observed are approximately 10 and 9.3 joules, respectively. For impacts significantly <9.3 joules, neither type of trauma would be expected to occur.

DISCUSSION

Impact of paintballs can result in severe ocular damage, significant loss of vision, and in extreme cases, complete loss of the eye. Common injuries include corneal abrasion, hyphema, angle recession glaucoma, lens dislocation, cataracts, retinal detachment, choroidal rupture, and catastrophic globe rupture (commonly leading to permanent after-surgery vision of <20/200). Most injuries require immediate emergency surgery and numerous follow-up surgeries. Current estimates suggest that at least 30% of the ocular injuries result in permanent after-surgery vision of <20/200.

A number of excellent papers exist that focus heavily on bursting pressures, but that was not the primary focus of our research. A recent article by Kennedy et al. found to be significantly stronger than human eyes in resisting globe rupture, requiring a force approximately twice that for human eyes (porcine 71.1 kJ/m² vs. human 35.5 kJ/m²). We also used a lower yet overlapping range of velocities to stratify the thresholds for specific types of damage.

The threshold values should be treated with some caution for a number of reasons. First, the number of experiments on which they are based is limited. A greater level of confidence will only result after a significantly larger experimental data set is obtained, but the present findings appear to provide a compelling starting point for more refined future correlation studies. Secondly, as stated above, porcine eyes have been shown to be approximately twice as strong as human eyes, so the...
threshold injury data and application to human eyes should be interpreted with that in mind.

Because of the low velocity threshold for bursting of the paintball, the level of trauma was similar for both paintball types at similar impact energies. The current paintball gelatin shell material does not create significantly higher shock pressures on impact than water or the paintball filler (polyethylene glycol) alone. There appears to be no reason to change the paintball shell material. Numerical modeling of the human eye using Eulerian finite-volume code CTH predicts that the same level of trauma as the complete paintball (filler and gelatin shell) suggests that mechanical modification of the shell will not be a productive technique for mitigating paintball impact trauma. Several additional trauma mitigation mechanisms (alternate paintball designs) were considered after studying these findings, but only those that also significantly reduced the projectile mass showed any promise. There seems little likelihood that additional trauma mitigation mechanisms (alternate paintball designs) were considered after studying these findings, but only those that also significantly reduced the projectile mass showed any promise.31 There seems little likelihood that such modifications would be acceptable to current users, given the accompanying degradation in flight characteristics. Projectile designs that rely on crushing do not present any additional trauma mitigation potential over solid or liquid projectiles of equal mass and impact energy. Simply stated, the level of trauma inflicted appears to be driven primarily by the mass and energy of the paintball.11 Ironically, these seemingly immutable physical characteristics of paintballs, which limit their ability to modulate their potential to harm the eye, makes them a potentially ideal tool for further investigations of ocular and other neural injuries induced by blunt trauma.

References