Numerical Modeling of Paintball Impact Ocular Trauma: Identification of Progressive Injury Mechanisms

Walt Gray, William E. Sponsel, Frank W. Scribbick, Amber R. Stern, Carl E. Weiss, Sylvia L. Groth, and James D. Walker

**PURPOSE.** To create a computer-based numerical simulation model for comparison with empiric paintball–ocular ballistic study findings, allowing identification of the dynamic physical mechanisms (stress, strain, pressure) responsible for intraocular traumatic injury accompanying blunt ocular impact. Virtual experiments with numerical models could exploit mathematical “instrumentation” to facilitate internal observation impossible with physical experiments alone.

**METHODS.** Models of human eye structures and orbit were implemented into the finite-volume Eulerian numerical hydro-code CTH. Numerical simulation results were compared with dynamic imaging and postimpact histopathology obtained during previous ballistic impact experiments on fresh porcine eyes impacted with paintballs. Forty numerical simulations and 59 impact experiments were conducted as part of the study.

**RESULTS.** Time-lapse correlations showed the CTH models to be dynamically commensurate with orbital penetration and globe deformation measured from ballistic high-speed videos. CTH also predicted the types and levels of damage observed in detailed postimpact pathologic assessments of porcine specimens. High strain in the ciliary body and zonule corresponded with angle recession and lens displacement pathologically. Globe rupture was attained at the highest paintball impact velocities in both the porcine ballistic studies and CTH models, consistent with predicted dynamic intraocular pressures. The simulations also revealed that phenomena such as macular Berlin’s edema, midperipheral retinoschisis, and choroidal and retinal detachment might be explained by focal dynamic pressure-wave reflection from the interior surface of the globe.

**CONCLUSIONS.** Significant insight was gained regarding the physical mechanisms responsible for injury. CTH predictions corresponded closely with previous ballistic experimental results, adding intraocular detail otherwise unattainable. (Invest Ophthalmol Vis Sci. 2011;52:7506–7513) DOI:10.1167/iovs.11-7942

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, lens dislocation, cataract, retinal detachment, choroidal rupture, and catastrophic globe rupture (commonly leading to complete loss of the eye). Most injuries require immediate emergency surgery and numerous follow-up surgeries. Current estimates suggest that at least 30% of the injuries result in permanent after-surgery vision of <20/200.

Although wearing of effective eye protection (such as currently required at commercial paintball gaming facilities) has been shown to mitigate or entirely eliminate many of the injuries, children quite often fail to use proper safety equipment, especially during unsupervised activities where most injuries occur. For this reason it has been suggested that the most practical solution is the development of a safer paintball, one that greatly reduces the risk and severity of injury during direct impact with the eye. However, before this can be accomplished, a fundamental understanding of the relationship between paintball characteristics (materials and impact parameters) and trauma must be developed.

In this pursuit, numerical models of the eye and bony orbit were developed and implemented in computer-based numerical code CTH, and a series of calculations performed for comparison with the experimental data generated during an earlier phase of the study. CTH was chosen as the numerical model because of its proven ability to handle shock-wave generation and propagation. However, contrary to our initial perceptions, the simulation results suggest that impact-generated shocks do not contribute significantly to ocular trauma. The experimental data were generated by impacting a number of commercially available paintballs into porcine (pig) eye specimens mounted in an acrylic pyramid-shaped holder filled with gelatin (Knox; Fig. 1). When the same experimental setup and parameters were modeled in CTH, the results were well correlated with experimental observations. This provided a measure of confidence in the ability of CTH to model this type of problem. Importantly, it allowed for identification of dynamic physical mechanisms (stress, strain, pressure, etc.) responsible for intraocular injury not obtainable from experiments alone. The CTH model was then used to evaluate proposed safer paintball designs, which was the primary objective of this study.

**METHODS**

**Experimentation**

Fifty-nine ocular impact experiments were conducted in an earlier phase of the study to provide empiric data useful for comparison with and validation of the numerical models. Only a brief summary of the experiments and techniques is provided here; for more details the reader is referred to Sponsel et al. Impact experiments were conducted by launching three different types of projectiles at mounted porcine eye specimens, solid rubber balls (training rounds), high-
quality match-grade paintballs (Marballizer), and lower-quality recreational-grade paintballs (Tactical Performance). Each specimen was mounted in gelatin (Knox)-filled acrylic pyramid-shaped holders that simulated the bony orbit (acrylic) and extraocular muscles (gelatin). Previous researchers have demonstrated that the extraocular muscles do not significantly influence the dynamic response of the eye during an impact event; thus, gelatin is commonly used in place of the muscles.\(^5\)\(^,\)\(^9\) All impacts were documented using a high-speed video camera (Phantom v7; Vision Research Inc., Wayne, NJ), with a mirror placed above the specimen and inclined at a 45° angle to obtain two orthogonal views with one camera. Posttest analysis of the high-speed video images (~30,000 frames/s) characterized the gross deformation, posterior displacement, and subsequent rebound of each eye specimen. Individual measurements were made of the change in eye length (from cornea to optic nerve root), width, and height (two directions perpendicular to projectile impact trajectory). Glaze rupture, which occurred on six experiments with velocities ranging from 80 to 97 m/s (10–12.4 J), was observed for all projectile types. Rupture appeared to depend on achieving a centerline hit (i.e., slightly off-center hits at equivalent and higher velocities did not result in rupture). In all cases the rupture occurred near the limbus, that is, the junction between the cornea and sclera.\(^4\)

Numerical Modeling

A three-dimensional (3D) model of the paintball, eye, and the gelatin-filled acrylic holder was implemented into CTH.\(^10\) CTH is a 3D Eulerian finite-volume hydrocode developed by Sandia National Laboratory for the simulation of high-deformation and high-strain-rate events such as impact and penetration. For a number of years, CTH has been the simulation of high-deformation and high-strain–rate events such as impact and penetration. For a number of years, CTH has been a key accomplishment of this program. The first step in the numerical modeling effort was development of a dimensionally correct eye model and implementing it into CTH. Dimensional and geometric details of the eye and orbit were taken predominantly from a single reference.\(^11\) The structures important to modeling dynamic response and trauma were identified as the cornea, aqueous humor, iris, zonule, lens, vitreous, sclera, choroid, retina, optic nerve, and dura. Although high-fidelity modeling of these structures is important for determining strain and strain accommodation between layers (for comparison with the fine details of trauma), it soon became apparent that mesh size limitations (due to the thinness of these tissues) did not readily adapt to the capabilities of CTH, especially for full 3D descriptions. Fortunately, previous researchers demonstrated that adequate modeling of gross ocular deformation could be accomplished by combining the cornea, sclera, retina, and choroid into a single corneoscleral shell.\(^12\)\(^,\)\(^15\)

Ocular tissue and fluid properties were extracted from the available literature (Table 1).\(^12\)\(^–\)\(^22\) Mechanical property data for the retina and zonule were limited, so in the numerical modeling some assumptions had to be made. For example, the retina was assumed to be similar to the optic nerve and the zonule similar to the ciliary body. In the simple model the retina, choroid, and sclera were modeled as a single membrane using the scleral properties. CTH modeling assumed a Mie–Grüneisen\(^23\) formulation for all equations of state, and a modified Johnson–Cook\(^24\) rate-dependent plasticity model to describe the stress-strain relationships for all materials. The heat capacity, Grüneisen, and Hugoniot parameters of all tissues were taken to be those of water. This assumption was considered reasonable because human tissue is thought to contain considerable water either in solution or (high-strain–rate response) in the same code. In contrast to many other material response codes, CTH is particularly well suited to handle and predict catastrophic material failure, such as sclera rupture. Adapting and demonstrating the usefulness of CTH for ocular trauma modeling was a key accomplishment of this program.

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### Table 1. Summary of Material Properties Used in the Numerical Simulations

<table>
<thead>
<tr>
<th>Factor</th>
<th>Density (kg/m³)</th>
<th>Young’s Modulus (Pa)</th>
<th>Poisson’s Ratio</th>
<th>Sound Speed (m/s)</th>
<th>Yield Stress (Pa)</th>
<th>Failure Stress (Pa)</th>
<th>Heat Capacity [J/(kg-K)]</th>
<th>Grüneisen Parameter</th>
<th>Up-Us Slope</th>
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<tbody>
<tr>
<td>Optic nerve</td>
<td>1400</td>
<td>6.56E+06</td>
<td>0.49</td>
<td>1540</td>
<td>1.50E+03</td>
<td>9.49E+06</td>
<td>3664</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Dura</td>
<td>1400</td>
<td>3.58E+08</td>
<td>0.47</td>
<td>1540</td>
<td>9.40E+06</td>
<td>9.49E+06</td>
<td>3664</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Lens</td>
<td>1079</td>
<td>6.89E+06</td>
<td>0.49</td>
<td>1540</td>
<td>9.40E+06</td>
<td>1.75E+07</td>
<td>3664</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Iris</td>
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<td>1.24E+08</td>
<td>0.42</td>
<td>1540</td>
<td>9.40E+06</td>
<td>9.45E+06</td>
<td>3664</td>
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<td>2</td>
</tr>
<tr>
<td>Ciliary body</td>
<td>1400</td>
<td>3.58E+08</td>
<td>0.47</td>
<td>1540</td>
<td>9.40E+06</td>
<td>9.49E+07</td>
<td>3664</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Zonule</td>
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<td>3.58E+08</td>
<td>0.47</td>
<td>1540</td>
<td>9.40E+06</td>
<td>1.05E+07</td>
<td>3664</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Corneosclera</td>
<td>1400</td>
<td>3.58E+08</td>
<td>0.47</td>
<td>1540</td>
<td>9.40E+06</td>
<td>9.49E+07</td>
<td>3664</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Aqueous humor</td>
<td>1003</td>
<td>—</td>
<td>—</td>
<td>1503</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Vitreous</td>
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<td>—</td>
<td>—</td>
<td>1528</td>
<td>—</td>
<td>—</td>
<td>3664</td>
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<td>2</td>
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<tr>
<td>Orbital bone</td>
<td>1610</td>
<td>9.81E+10</td>
<td>0.35</td>
<td>2503</td>
<td>1.57E+08</td>
<td>1.57E+08</td>
<td>1256</td>
<td>0.1</td>
<td>2</td>
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</table>
suspension. The Johnson–Cook plasticity model is intended for materials subjected to large strains at high strain rates undergoing thermal softening during deformation. The von Mises flow stress is expressed as

$$\sigma = [A + B\varepsilon^n][1 + C\ln \dot{\varepsilon}^*][1 - T^*]^m$$

where $\varepsilon$ is the equivalent plastic strain, $\varepsilon^*$ is the dimensionless plastic strain rate ($\dot{\varepsilon}/\dot{\varepsilon}_0$), and $T^*$ is the homologous temperature. To implement the model in CTH the user must provide estimates of the five material constants: $A$, the yield stress; $B$ and $n$, the effects of strain hardening; $C$, the effects of strain rate; and $m$, the effects of thermal softening. At the low strain rates encountered in the paintball impact experiments, the effects of strain rate, strain hardening, and thermal softening are deemed to be of minor importance. Thus implementation of the Johnson–Cook model required only estimates of the yield stress and Poisson’s ratio, with all other parameters set to 0 or 1, as appropriate. The melting temperature was set to an artificially high value to ensure that melting and thermal softening did not occur in the simulations.

It should be noted that measured human tissue mechanical properties vary considerably depending on such factors as age, sex, and the measurement method. Therefore, the values used in the numerical simulations represent an average of values gathered from the literature.

One of the disadvantages of CTH’s Eulerian formulation is the fineness of the computational mesh required to resolve the behavior of materials undergoing large deformations and strain. Typically 5 computational cells across the thickness of a component are used. However, due to computer memory constraints, the minimum cell size was set to 0.02 mm, resulting in 4 cells across the corneoscleral shell thickness and 2 cells across the paintball shell thickness. Thus, the behavior of the paintball shell was only partially resolved. However, at the velocities considered in the simulations, the shell readily ruptured and did not contribute significantly to the eye deformation or trauma, the principal contribution coming from the paintball’s mass and momentum. Nonetheless, the overall size of the CTH model was on the order of 10 million cells, requiring significant parallel computer capacity and run times on the order of 3 to 4 weeks (in real time), depending on the paintball impact velocity. A potential remedy for this problem is the use of a Lagrangian finite element model with shell elements to represent tissue layers. Use of such a model can potentially reduce run times to a few days. Motivated by this prospect, a preliminary eye model (containing only 320,000 elements) was input to LS-DYNA, another commonly used finite element code. However, the large deformations and catastrophic material failures (characteristic of the paintball impact problem) created problems for LS-DYNA that we were unable to overcome within the available budget and time. Thus use of the LS-DYNA finite element model was abandoned and all results reported herein were obtained using the Eulerian CTH model.

To take advantage of symmetry and reduce the size of the computational mesh, the CTH model assumed that the eye specimen was a right pyramid square in cross-section. This allowed for division of the problem space into four symmetrically equivalent quadrants. Thus, only one quarter of the actual problem domain was solved; solutions in the other quadrants were obtained by reflection. The adaptive mesh refinement feature in CTH was also used, allowing the computational mesh to be automatically adjusted to larger and smaller cell sizes, depending on the velocities of material in each cell.

RESULTS

Pathology

In all, 34 test specimens and 5 control specimens were subjected to detailed postimpact pathology. Over the range of impact velocities tested (25.9 to 96.6 m/s) the severity of injury generally increased with impact velocity and energy. The general categories of trauma observed in the experiments included; (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. Figure 2 shows the categories of ocular trauma and the impact energy at which each was first observed in the experiments. This minimum energy level is taken as a qualitative threshold for that category. For example, the lowest energies at which globe rupture and choroid segmentation were observed were approximately 10 and 9.3 J, respectively. Thus for impacts significantly < 9.3 J, neither type of trauma would be expected to occur.

Corneal abrasion was ubiquitously observed in all tests where the paintball made contact with the corneal surface. Abrasion was manifested as complete or partial removal of the corneal epithelium, the thin skin-like outermost layer of the cornea. Severe angle recession was often accompanied by partial or complete detachment and segmentation (tearing into numerous segments) of the iris and ciliary body. In extreme cases where globe rupture also occurred in the cornea or near the limbus (corneal–scleral juncure), segments of the iris and ciliary body were often ejected through the rupture opening.
Detachment of the retina from the choroid was observed in almost all test specimens. Tearing or segmentation of the retina was also ubiquitously observed, but due to its fragile nature may have been an artifact of the pathology (i.e., retinal tearing during cutting of the thin sections). Detachment of the retina from the optic nerve was not observed in control specimens, but was observed in tests at more severe impact conditions than those where only retinal detachment and segmentation occurred (5 vs. 2 J; see Fig. 2).

Lens dislocation was observed over the full range of impact velocities, most often posteriorly (into the vitreous), but at the higher velocities the lens occasionally rebounded and came to rest in the anterior chamber. Dislocation was often accompanied by rupture of the lens capsule and zonule fibers. Detachment of the choroid was also observed over the full range of impact conditions, but choroid segmentation was observed in only two tests at velocities comparable to those required for globe rupture. At low velocities, the choroid detached from 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.

Comparison of Model Predictions with Experiments

The 3D models successfully predicted the rupture characteristics of the paintball and overall deformation of the cornea and corneoscleral shell (Figs. 3, 4). Empirically observed ocular distortions, rotations, and intraorbital displacements observed in the porcine ballistic specimens were also faithfully reproduced in the CTH models of comparable impact velocity and impact offset. Among these was the gradual fusiform axial elongation and transverse globe narrowing that can occur with off-center hits as the paint loculus passes along the orbital margin, compressing the globe’s equator. CTH was also predictive of the intraorbital displacement of the globe, which also varied with impact velocity and offset. Consistent with ballistic experimental observations, CTH predicted that globe rupture occurs in the limbus (corneal–scleral junction) at velocities in excess of 82 m/s. At velocities >30.5 m/s, high strains were predicted in the cornea, limbus, angle (the region between the aqueous humor and ciliary body), ciliary bodies, and zonule (Fig. 5). Rupture of the zonule and associated lens dislocation...
were also predicted for velocities in excess of 30.5 m/s. This is generally consistent with the trauma observed in pathology, except that mild angle recession and lens dislocation was occasionally observed at velocities < 30.5 m/s.

CTH predicted that strain decreases systematically away from the angle, reaching nearly zero at the posterior pole of the sclera (Fig. 5). This prediction is difficult to reconcile with the pathology because (1) the individual layered components (sclera, choroid, retina) were not modeled in CTH, (2) the trauma observed in the components could have resulted from other factors not related to strain, and (3) some of the trauma could have been an artifact of the pathology process. However, evidence from the video images suggests that large compressive and lateral deformations were typically limited to areas forward of the ora serrata, consistent with the predicted strain distributions. The pyramidal shape used to simulate the orbit provided space (width and height) around the eye that was somewhat larger than that encountered in the average human. Although this obviously contributes to the lateral expansion and high strains in the globe, whether the trauma produced is more or less than that which may be encountered in real events is uncertain. Weaver et al.26 demonstrated that a decrease in this space often contributes increased stress and trauma due to globe contact with the interior surfaces of the orbit. Different orbit geometries were not evaluated in this study, so the effect of variable orbit geometry cannot be further assessed.

An unexpected result from the numerical modeling effort was the identification of three previously unexplained trauma mechanisms: lens displacement, optic nerve avulsion, and pressure-induced retinal detachment. The numerical simulations clearly reveal that high pressure in the anterior chamber during impact compression results in rearward lens displacement and zonule rupture; contact between the cornea and lens is not required (Gray W, et al. IOVS 2008;49:ARVO E-Abstract 2778; Fig. 6). The simulations also showed that forceful intrusion of a blunt object adjacent to the globe equator often produces high-velocity rotational strain of sufficient magnitude to sever the optic nerve; forward displacement of the globe is not required (Sponsel WE, et al. IOVS 2008;49:ARVO E-Abstract 5257; Fig. 7). A more detailed report of these findings is forthcoming.

As predicted by CTH, initial high-pressure shock waves produce little damage to the ocular structures and tissues due...
to the relatively short durations of the shocks (10–20 $\mu$s), but longer duration and lower amplitude pressure waves can result in severe deformation, stretching, and strain damage. Importantly, late-term dynamic pressure-wave reflections off interior surfaces of the globe can result in separation of layered tissues such as the choroid and retina (Fig. 8). Contra-coup type injuries, especially retinal and choroidal detachment opposite from the impact point, have sometimes been difficult to explain. The numerical modeling results clearly show that pressure reflections off the posterior segment result in a localized negative pressure region of sufficient magnitude to cause detachment of the retina from the choroid (Fig. 8).

**Limitations of the Model**

The CTH model developed for this study presented limitations as to high-fidelity representations of human eyes. Due to the fine grid resolution required to fully capture the mechanical response of components, the sclera, choroid, retina, and cornea were combined into a single corneoscleral shell. Although this proved adequate to model the gross deformation of the globe, the fine details of strain partitioning between layers as well as layer detachment and segmentation could not be captured. Because the majority of corneoscleral thickness is represented by the sclera, combining all layers into a single tissue with the properties of the sclera should not cause any signifi-
cant discrepancies when evaluating overall globe deformation and rupture. This has been previously verified by a number of researchers.\textsuperscript{12,13}

All material properties used in this study were obtained from the literature, and not independently verified. As indicated in the literature sources, properties were assumed to apply to all orientations (i.e., possible anisotropies were not modeled). Grytz et al.\textsuperscript{27} modeled the anisotropic response of collagen fibrils in the sclera during intraocular-related pressure deformations. Their modeling showed that increased intraocular pressure causes reorientation of the fibrils in a radial direction, resulting in decreased radial expansion. Assessment of the effect of this phenomenon on the responses observed herein was difficult to quantify. Clearly, the pressure rise and deformation rates experienced in dynamic impact-type events are several orders of magnitude greater than those experienced in hydrostatic-like intraocular events. Based on the authors’ experience with high-velocity impact events, we speculate that the anisotropic nature of the sclera response (radial versus axial) will not be significant during highly dynamic impacts. Obviously, modeling of such fine microstructural details is not possible in CTH. However, anisotropic effects could be handled in CTH if the directional variations of material properties were characterized. A lack of well-characterized materials and failure criteria are fundamental limitations of many numerical models and constitute the subject of ongoing research.

The pyramidal acrylic holder was used in the study for convenience and to provide some level of realism by including the orbital structure in our experiments and calculations. For computational convenience its geometry was somewhat simplified, eliminating some geometric asymmetries of the actual human orbit. In addition, it was somewhat larger that a nominal human orbit, thus allowing additional space around the eye for radial expansion during the impact event. What effect this had on the degree of trauma observed was not possible to assess because we did not include orbital geometry variation in our study. However, the observations and conclusions are not invalidated because the same responses would still be observed for other orbit sizes, only to differing degrees. For example, on impact the eye would still expand radially; strains would still be concentrated near the ora serrata, zonule rupture, angle recession; and lens displacement would still occur. The modeling results do provide an explanation for optic nerve avulsion, that is, rapid rotation of the globe due to off-center contact and friction-coupled loading by the paintball. In our model there was sufficient space for the paintball to penetrate beyond the globe equator, so the effect is perhaps more dramatic that might be encountered in a human with a smaller orbit. How much penetration is required and how the geometry of the orbit affects this are uncertain, given that these phenomena were only preliminarily explored herein. However, the conclusion is still valid: off-center impacts have the potential to create optic nerve avulsion.

**DISCUSSION**

In 1996, Uchio et al.\textsuperscript{13} began working with a simulation model of an eyeball based on finite element analysis on a supercomputer, prompting studies on the likely effects of traumatic impacts on eyes that have undergone various ocular surgical procedures.\textsuperscript{26–30} Stitzel et al.\textsuperscript{12} developed a nonlinear finite element model of the eye with experimental validation of the prediction of globe rupture in 2002 and continuous investigations of the mechanisms of ocular injury using empiric and finite element simulation have followed from that group.\textsuperscript{31–35} including studies of paintball bursting pressure.\textsuperscript{32} Their modeling focused on catastrophic ocular failure and predicted human eye rupture at 73 m/s. Our study extended the previous work by focusing on external ocular distortions and accompanying internal injuries at lower impact energies, thereby gaining an understanding of various other clinically important sources of visual loss. It is also important to note the results of the 2006 study by Kennedy et al.\textsuperscript{33} demonstrating that human eyes rupture at lower impact energy than porcine eyes. The CTH model in this study was based on human globe and orbit specifications, and the ballistic studies were conducted on porcine eyes inserted into acrylic holders simulating a human sized- and oriented orbit.\textsuperscript{35} This CTH model predicts orbit-constrained globe rupture at an energy level approximately 70% that observed with our porcine eye ballistic experimentation. The external ocular deformations and intraorbital globe displacements observed empirically and predicted by CTH were very similar through the compressive and early rebound stages in all eyes at a subrupture impact level. It thus seems reasonable to conjecture that the internal ocular structural changes demonstrated by the CTH model might be very similar to those occurring in the ballistic specimens at energies lower than the rupture threshold (10 J). Several recent studies have used finite element analysis to explore the mechanisms of specific forms of ocular injury, including optic nerve trauma,\textsuperscript{36} and various forms of retinal injury.\textsuperscript{37–39}

The present study also used numerical modeling to evaluate several alternate paintball designs, but only those that significantly reduced the projectile mass showed promise. The level of trauma appears to be driven primarily by the mass and energy of the paintball. Due to the low-velocity threshold for paintball bursting, the level of trauma was similar for all paintball types (at the higher velocities and energies typical of paintball impact conditions). The current outer shell material (gelatin) does not create significantly higher shock pressures (on impact) than those of water or the paintball filler (polyethylene glycol) alone. Thus, there appears to be no reason to change the paintball shell material. CTH predicted that impact with an equivalent sphere of polyethylene glycol alone would create the same level of ocular trauma as that of the complete paintball (filler and gelatin shell). Contrary to the initial objective of the research project, mechanical modification of the paintball’s outer shell (to create an earlier burst) does not appear to be a productive strategy for mitigating impact trauma.

**CONCLUSION**

CTH has not been used extensively for the solution of bioengineering problems, but the results of this study clearly demonstrate its utility, especially for highly dynamic events such as paintball impact. CTH predictions were in good agreement with the porcine eye gross deformation measured from the high-speed video images. The model predicts that globe rupture occurs only at the highest impact velocities (~83–92 m/s), again in general agreement with the experiments. For the range of velocities evaluated (~26–97 m/s), no differences in ocular trauma were observed for the different paintball types tested. The shell material readily ruptured on impact, suggesting that mechanical alteration of the shell to achieve early rupture would not be an effective strategy for the design of a safer paintball.

The numerical modeling effort was especially fruitful in illuminating predominant ocular trauma mechanisms during blunt force impact. In particular, contra-coup type injuries were easily explained as the result of pressure reflections. The numerical simulations clearly reveal that high hydrostatic pressure in the anterior chamber during impact compression results in posterior lens displacement and zonular rupture. The
simulations also suggest that forceful intrusion of a blunt object off-center and adjacent to the globe equator can produce high-velocity rotational strain of sufficient magnitude to sever the optic nerve.

References


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