BLUNT TRAUMA OF THE AGING EYE

INJURY MECHANISMS AND INCREASING LENS STIFFNESS

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Objective: To investigate possible injury mechanisms in the eyes of elderly individuals and the effects of lens stiffness on model outputs indicative of injury as a function of age.

Methods: Three separate frontal impact scenarios, a foam particle (30 m/s), steering wheel (15 m/s), and air bag (67 m/s), were simulated with a validated finite-element model to determine the effects of changing lens stiffness on the eye when subjected to blunt trauma. The lens stiffness of the model was increased with increasing age using stiffness values determined from the literature for 3 age groups.

Results: The computational eye model demonstrated increasing peak stress in the posterior portion of the ciliary body and decreasing peak stress in the posterior portion of the zonules with increasing lens stiffness for the 2 most severe impact types, the air bag and steering wheel. Peak deformation of the lens decreased with increasing lens stiffness.

Conclusions: On the basis of the computational modeling analysis, the risk of eye injury increases with age; as a result, the eyes of elderly patients may be more susceptible to ciliary body–related eye injuries in traumatic-impact situations.

Clinical Relevance: These data support the contention that trauma-induced damage to the lens, ciliary body, and zonules may be related to increased stiffness of the lens. The data indicate that all people, especially elderly individuals, should use safety systems while driving an automobile and sit as far from the air bag as is comfortable. Those in sports or work environments requiring protective lenses should wear them. Designers of air bags and automobile companies should continue to work to reduce the potential that the air bag will contact the eye.


As of 2001, more than 25 million people were 70 years or older in the United States, and in 2000 this age group made up 9.1% of the total US population. Elderly people 70 years and older accounted for 10% of all licensed drivers in 2000 as compared with only 8% in 1990, indicating that the number of elderly drivers is on the rise. Numerous discoveries have revealed a relationship between age and certain mechanical characteristics of the eye, particularly those relating to the lens, lens capsule, and cornea. The effects of these age-related changes on the risk of eye injuries are unknown.

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Eye injuries are expensive to treat, affect a large portion of the population, and often result in long-term disability. Medical literature is replete with case studies on air bag–induced eye injuries. For each of these studies, a wide range of ocular injuries was reported, from a minor eyelid or corneal abrasion to a more severe globe rupture or lens dislocation. Duma et al determined the overall risk and severity of eye injuries in automobile crashes and explained the effect of frontal air bags on these patterns. A new 4-level eye injury severity scale was developed that quantifies injuries based on recovery time, need for surgery, and possible loss of sight. Using these levels, it was shown that although occupants in frontal crashes exposed to an air bag deployment (3.1%) sustained an eye injury more often than occupants not exposed to an air bag deployment (2.0%), the air bag provided a beneficial exchange by decreasing the incidence of more severe orbital fractures.

There is a limited amount of experimental data regarding air bag–induced eye injuries in comparison with the number of individual case study publications. Experiments performed by Fukagawa et al

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and Duma and Crandall\textsuperscript{13} illustrated the compounding risk of eye injuries not only from air bag contact but also from particles released from the module during deployment. Of the many existing case studies and limited experimental research involving air bag–induced eye injuries, none have taken into account the effect of occupant age.

Although computational modeling of the human eye has been studied, most models were designed for static solutions and not for traumatic-impact studies.\textsuperscript{14-17} More recently, a finite-element model of the human eye was presented by Kisielewicz et al\textsuperscript{18} and Uchio et al\textsuperscript{19} for use in dynamic events. This model provided useful insights as the first dynamic model, but its nonbiofidelic boundary conditions and lack of thorough validation experimentation made it difficult to use for injury prediction in traumatic-impact scenarios. Stitzel et al\textsuperscript{20} performed a series of eye experiments with foam particles, BBs, and baseballs for validation and development of the Virginia Tech Eye Model (VTEM), a finite-element model used to predict globe rupture due to high-speed blunt impact.

This study investigates the risk of eye injuries in the elderly driving population. Its purpose is to investigate injury mechanisms in the eyes of elderly individuals and the effects of lens stiffness through the use of a finite-element eye model to reveal the effects of aging on the eye when subjected to blunt trauma.

METHODS

The VTEM was used to investigate injury mechanisms in the eyes of elderly individuals in comparison with younger age groups as well as the effects of lens stiffness when subjected to blunt impact (Figure 1). Specifically, a parametric study was performed to determine stress distributions for 3 age groups: 16 to 35 years old, 36 to 65 years old, and 66 years and older. For each age group, the eye was subjected to 3 generalized impact configurations. The detailed eye model includes the corneoscleral shell, consisting of the cornea, sclera, and limbus. The limbus is modeled as a curved region where the cornea and sclera join in the anterior portion of the eye. These ocular and internal ocular structures were represented by a mesh with Lagrange formulations for element properties. The Lagrange structures are located inside a mesh using an Euler representation for fluid flow. This model had a total of 10,020 solid and shell elements. Dynamic modeling was performed using LS-DYNA software (Livermore Software Technology Corporation, Livermore, Calif).

SIMULATION TEST MATRIX

To investigate the range of possible eye injury mechanisms in automobile crashes, a test matrix comprising 9 simulations, 3 separate impact scenarios for each of 3 age groups (lens stiffnesses), was developed. The resulting peak stress and location in the corneoscleral shell, ciliary body, and zonules were analyzed (Table 1). By identifying the peak stress at multiple sites within the eye, injury severity could be assessed for each impact scenario. Lens dislocation was assumed to occur with high stresses in the ciliary body or zonules, and globe rupture was assumed to occur with tearing in the corneoscleral shell, indicated by threshold membrane stress levels.\textsuperscript{20} These impacts simulated a foam particle (30 ms\textsuperscript{-1}), a steering wheel (15 ms\textsuperscript{-1}), and an air bag (67 ms\textsuperscript{-1}). The steering wheel and air bag impact scenarios were indicative of impacts experienced in automobile crashes severe enough to cause globe rupture or other serious eye injuries.

Foam particles were modeled as circular cylinders using 8-node bricks and linear elastic material (Figure 2A). Foam particles were similar to those existing in the dashboard of many automobiles. Foam properties were measured using compression tests on an MTS 810 servohydraulic uniaxial testing machine (Material Testing Systems, Raleigh, NC). The air bag was modeled using 4-node shell elements and the air bag fabric model within LS-DYNA (Figure 2B). This material model is a variation of the orthotropic material model, which does not develop stresses to resist compression or bending, and behaves qualitatively like a fabric. A linear elastic liner was chosen for the air bag fabric. This liner is an additional material that resists bending and compression as it develops resistance to these types of deformation where the fabric does not. It is used because the modeling approximation for fabric can be unstable in its behavior, so the liner increases its stability and makes it behave as expected. The liner is not used to give additional mechanical strength, only stability; thus, its thickness is much lower and is specified as a percentage of the air bag fabric thickness. This was chosen to be 5\% of the thickness of the air bag fabric (eg, fabric with a thickness of 1000 µm would have an added liner of 50-µm thickness). The steering wheel was modeled using the cross-sectional geometry of a common steering wheel (Figure 2C). The steering wheel consisted of a U-shaped aluminum core surrounded by foam. The core was modeled with the density of aluminum and was approximated as a rigid body because of its high elastic modulus in comparison with the eye. A cylindrical specimen of the steering wheel foam was tested in uniaxial compression to obtain an elastic modulus. The foam in the steering wheel was modeled using a linear elastic approximation. All components of the steering wheel were modeled using 8-node brick elements.

Lens stiffness values varied by age group with data obtained from the literature. The lens was modeled as linear elastic, isotropic, and incompressible using force displacement data from human lens nuclei.\textsuperscript{21} Owing to the lack of lens stiffness values suitable for input into the VTEM from previous research, the mean modulus of elasticity for a person 66 years and older was calculated to be 6.89 megapascals (MPa) using the force displacement plots. This elastic modulus was then correlated with the mean value for the equatorial elastic modulus.
for the same age group based on changes in the modulus of equatorial elasticity with age. It was assumed that the modulus of elasticity and the modulus of equatorial elasticity follow the same trend with respect to age. Therefore, equatorial elasticity was used to determine values of the elastic modulus for the other 2 age groups (Table 2, Figure 3). The lens stiffness values corresponded well to the stiffness values of other ocular components modeled in the VTEM, such as the cornea (1.24 MPa), sclera (3.58 MPa), and ciliary body (11.00 MPa). The mean stiffness of the human lens increases by 100% between age groups of 16 to 35 years old and 36 to 65 years old (Table 2). A 233% increase occurs between the means for age groups of 16 to 35 years old and 66 years and older. Therefore, the mean stiffness of a 16- to 35-year-old lens was 30% that of the lens from an elderly (66 years and older) patient.

To examine the variation in response of the lens-zonule-ciliary body complex by age group, differences in stress response during the initial period of loading, which usually corresponded to the first peak in stress encountered in the simulation, were compared. Peak stress in the corneoscleral shell was reported for the location experiencing the maximum stress overall. This was the limbus for the foam particle impacts and the anterior portion of the equator for the air bag and steering wheel impacts. For comparison of stress in the zonules, the peaks were recorded at the posterior interface between the zonules and the lens. Similarly, the peak stresses in the ciliary body were obtained from the posterior insertion point of the zonules to the ciliary body.

A matrix composed of 9 impact simulations, 3 for each age group, was developed to analyze the resulting stresses and their locations in the corneoscleral shell, ciliary body, and zonules. The differences in stress response between each age group were analyzed during the initial loading period, which corresponds to the first peak in stress encountered.

**RESULTS**

The computational eye model demonstrates that increased lens stiffness produces larger stresses on the ciliary body and changes in the response of the lens-zonule-
ciliary body complex (Table 3). Trends in ciliary body peak stress were similar for air bag and steering wheel impacts but not foam impacts. The peak stress encountered generally increased with increasing age and lens stiffness for steering wheel and air bag impacts but decreased for foam impacts (Figure 3). The peak stress in the ciliary body was up to 2.2 times greater for the lenses of elderly individuals than for younger people. There was an increase in the peak stress for the air bag impacts with increasing lens stiffness, but this change was not very sensitive to lens stiffness changes. Zonular peak stresses were generally much more sensitive to changes in lens stiffness. The peak stress in the zonules decreased with increasing age for all 3 impact simulations. Peak deformation of the lens decreased with increasing lens stiffness (Figure 4). Of all of the impact scenarios, the air bag simulations caused the highest stresses in the ciliary body and corneoscleral shell, whereas the steering wheel produced the highest stresses in the zonules.

**COMMENT**

The relationship between age and the mechanics of various ocular components, particularly stiffening of the lens resulting in presbyopia, is supported by previous research. General testing of the mechanical characteristics of the entire lens suggest that aging of the human lens is associated with a progressive loss of mechanical strength.\(^2,^3\) As research data imply, the gradual change in lens stiffness during a lifetime can lead to a lens that is approximately 4 times stiffer than at birth.\(^3\) As stiffness of the lens increases over time, the amount of deformation that the lens can withstand without damage or dislocation decreases.\(^3\) This can result in an increased risk of eye injury with age, not only to the lens itself but also to other internal components of the eye. Moreover, many studies acknowledge the fact that the mechanical integrity of the eye is reduced following any injury or surgery that results in a full-thickness corneal or scleral wound, such as with radial keratotomy, large-incision cataract extraction, and corneal transplant, causing the most weakening.\(^22\) These negative effects are likely to persist years after the procedure. Elderly individuals are more likely to have these procedures and are therefore more likely to sustain eye injuries because of them.

Many of the recent comprehensive studies investigating eye trauma do not specifically address the question of age.\(^31\) However, Moshetova et al,\(^32\) in a study of 426 patients with blunt injuries to the eye, demonstrated that the most frequent complication of this type of injury was hemorrhage to the anterior chamber, or hyphema, in 57.6% of cases. It is well known that damage, including tearing of the ciliary body or iris, which are the more vascularized muscles of the interior of the eye, often results in hyphema. However, without looking at the same data sets for trends based on age, it is impossible to tell if the increased stress in the ciliary body with increasing lens stiffness is an indicator of increased susceptibility of the eye to hyphema with age. Their study does, however, provide an indication of what the eye trauma research community should focus on in the future. It is clear from the finite element model that by changing lens stiffness one alters the response of the eye, increasing stresses in the ciliary body and decreasing stresses in the zonules. Whether this explains a shifting in eye injury patterns (ie, a shift from zonular tears for the younger popula-
tion to ciliary body injury and hyphema for the older population) is a question that needs to be answered by looking at the National Automotive Sampling System data (http://www-nrd.nhtsa.dot.gov/departments/nrd-30/nass/NASS.html) or other injury databases for trends with respect to age. Our study demonstrates that finite element modeling can aid in the understanding of mechanisms that may manifest themselves in the injury distribution seen in the field.

The results demonstrate that zonular stresses are more sensitive to the deformation of the lens, whereas ciliary body stresses are more sensitive to the stiffness of the lens-zonule complex. Since the stiffness of the ciliary body (11.00 MPa) used for the older population (≥66 years, 6.89 MPa) in the current study is close to the stiffness of the lens, the response of the ciliary body could be expected to more closely follow that response. The stiffness of the zonules, 358 MPa, may make the peak stresses developed in them less sensitive to stiffness changes in the lens and more sensitive to changes in the deformation of the lens-zonule-ciliary body complex. There is less deformation of this lens-zonule-ciliary body “diaphragm” for the higher stiffnesses and a decrease in peak stress in the zonules along with this decreasing deformation. However, there is generally an increase in the peak stress in the ciliary body with increasing lens stiffness. Geometry and deformation are probably a large factor in the peak stress analyses. In our study, peak stresses in the ciliary body nearly always occurred in its posterior portion, where the zonules insert. In contrast, peak stresses in the zonules nearly always occurred in their posterior portion, where the lens inserts. This demonstrates that the tensile forces acting on the posterior portion of the “diaphragm” of the eye should be considered potential eye injury mechanisms. Since these stresses are not uniform throughout the ciliary body and zonules, it is clear that geometry plays a strong role in blunt injuries to the eye.

The lack of increased globe stress with increasing lens stiffness points toward other mechanisms dominating the response of the eye to trauma. It is well known that the sclera tends to thin with age, and this is a potential factor as well. However, scleral thinning was not modeled. Since increased lens stiffness did not result in increased stress in the corneoscleral shell, one can eliminate the increase in lens stiffness as a potential implicating factor in the increased incidence of globe rupture found in National Automotive Sampling System studies. This implies other changes, such as scleral thinning and perhaps an increased overall susceptibility of the tissues themselves to rupture. Future work should correlate these changes to the increased risk of globe rupture with increasing age.

The computational eye model demonstrated an increase in peak stress in the posterior portion of the ciliary body along with a decrease in peak stress in the posterior portion of the zonules with increasing lens stiffness for the 2 most severe impact types, the air bag and steering wheel impacts. The peak stress in the ciliary body was up to 2.2 times greater for the lens stiffness value in elderly individuals when compared with that of younger people. Furthermore, when exposed to impact, peak deformation of the lens decreased with increasing lens stiffness, corresponding with aging. According to the computational modeling analysis, the risk of eye injury increases with age; as a result, elderly individuals may be more susceptible to ciliary body–related eye injuries in blunt traumatic-impact events.

On the basis of these results, we have several recommendations to protect the eyes. All drivers, especially elderly ones, are encouraged to wear a seat belt while driving and to sit as far away from the air bag and steering wheel as possible without compromising visibility or driving comfort. Avoiding accidents in the first place is of paramount importance. Second, those using eye-wear should be sure that it is fitted with impact-resistant polycarbonate or Trivex (PPG Industries, Pittsburgh, Pa) lenses. Automobile and safety system designers should continue research on air bag design that minimizes eye contact, and steering wheels should have enough adjustment and shock-absorbing characteristics to make the potential impact to the face less severe. Potential for injury from “missile objects” such as foam due to air bag deployments through the dashboard or steering wheel should be minimized in any automobile design.

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REFERENCES


terations, and increased production of vascular endothelial growth factor (which induces increased vascular permeability).\(^3\)

Although the case reported is the first report, to our knowledge, of the development of reversible macular edema with vision loss in a patient taking rosiglitazone, this is probably not a rare event. A retrospective medical record review of 30 patients given at the annual meeting of the American Academy of Ophthalmology in 2003 by Edwin Ryan, MD, suggested that glitazone use may be linked to the existence of macular edema in patients with diabetes mellitus.\(^4\) Because the administration of thiazolidinediones like rosiglitazone has been associated with the development of edema, the observation of macular edema with vision loss with rosiglitazone administration, reversible when taking a decreased dosage, is not unexpected. Physicians prescribing rosiglitazone (and other thiazolidinediones) should be aware of the possibility of decreased vision associated with the development of macular edema due to the thiazolidinedione. Caution should be exercised when thiazolidinediones are used in those with nephropathy (or congestive heart failure). Options for the management of rosiglitazone (or thiazolidinedione)-induced macular edema with vision loss include dose reduction and discontinuation.

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**Correction**

Error in Table. In the Laboratory Sciences article by Stitzel et al titled “Blunt Trauma of the Aging Eye: Injury Mechanisms and Increasing Lens Stiffness,” published in the June issue of the ARCHIVES (2005;123:789-794), there was an error in Table 3. Line A2 was printed on top of line A1. The table is reproduced correctly as follows. The journal regrets the error.

**Table 3. Stress Data for Impact Simulations**

<table>
<thead>
<tr>
<th>Simulation No.</th>
<th>Object</th>
<th>Age Group, y</th>
<th>Stress, MPa</th>
<th>Corneoscleral Shell</th>
<th>Ciliary Body</th>
<th>Zonules</th>
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<tbody>
<tr>
<td>F1</td>
<td>Foam</td>
<td>16-35</td>
<td>7.82</td>
<td>2.83</td>
<td>16.40</td>
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<tr>
<td>F2</td>
<td>Foam</td>
<td>36-65</td>
<td>7.77</td>
<td>2.75</td>
<td>14.75</td>
<td></td>
</tr>
<tr>
<td>F3</td>
<td>Foam</td>
<td>≥66</td>
<td>7.82</td>
<td>2.58</td>
<td>12.83</td>
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</tr>
<tr>
<td>W1</td>
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<tr>
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</tr>
<tr>
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</tr>
</tbody>
</table>

Abbreviation: MPa, megapascals.

*Arrows indicate increasing stress; up arrows decrease with age, and down arrows increase with age. Double arrows indicate high sensitivity (>1 MPa per age group), whereas single arrows indicate low sensitivity (<1 MPa per age group).*