

EYE INJURY INCIDENCE AND MECHANISMS IN FRONTAL AUTOMOBILE CRASHES

Stefan M. Duma
Mary V. Jernigan
Joel D. Stitzel
Ian P. Herring

Virginia Tech, Impact Biomechanics Laboratory
United States
Paper Number 82

ABSTRACT

The purpose of this study was to determine the incidence of eye injuries resulting from frontal automobile crashes and discuss the relevant injury mechanisms. In order to determine eye injury incidence, cases in NASS were selected from the years 1993 through 1999 that include drivers and front seat occupants only, while excluding ejected occupants and rollovers. In addition, only frontal impacts were considered, which are defined as having a primary direction of force (PDOF) of 11, 12, or 1 o'clock. The analysis included 10,770,828 front seat occupants from 22,236 cases for the years 1993 through 1999. An analysis of the cases indicates that 3.1% of occupants exposed to an airbag deployment sustained an eye injury, compared to 2.0% of those occupants not exposed to an airbag deployment. Moreover, there was a significant increase in the risk of corneal abrasion for occupants exposed to an airbag deployment ($p=0.03$). Although the risk of eye injuries increases with airbag exposure, this study illustrates that airbags reduce the incidence of orbital fractures. To analyze this, A new four level eye injury severity scale was developed that quantifies injuries based on recovery time, need for surgery, and possible loss of sight. A new finite element model of the eye was created using the LS-Dyna dynamic solver and was utilized to examine eye injury mechanisms. The model has the cornea and sclera defined as Lagrangian membrane elements and the liquid aqueous humor and vitreous defined and Eulerian fluids. The model was validated using a range of impacting objects as velocities ranging from 12 m/s to 55 m/s. This model is the first model capable of correctly simulating the large deformation mechanics of blunt ocular trauma. Using the model, it was observed that highly localized strains in the cornea and ciliary body were most closely related to the severe injuries identified in the case studies.

INTRODUCTION

Although airbags have reduced the incidence of fatal and severe injuries in automobile collisions, they have been shown to increase the risk of less severe injuries.[1] These associated minor injuries include upper extremity fractures, skin abrasions, and eye injuries. In particular, the medical literature is replete with case studies on airbag induced eye injuries.[2-63] In addition to airbag induced eye injuries, Müller-Jensen *et al.* found broken windshield glass as a serious eye injury mechanism with 40% of these cases resulting in blindness in at least one eye.[60]

The majority of these case studies focus on only a few occupants, however, four papers, in particular, include numerous cases of airbag induced eye injuries.[45,52,61,62] Duma, *et al.*, present an analysis of 25 airbag induced eye injury cases that found the most serious injuries were a result of the occupant being struck by the airbag during deployment.[61] Ghafouri found bilateral injuries in 27% of 43 airbag induced eye injury cases.[62] Vichnin *et al.* report 14 cases and note that the most severe injuries were to occupants wearing eyeglasses, all of which sustained permanent ocular damage.[52] Stein *et al.* outline a detailed summary of the 97 published case studies that included a wide range of ocular injuries from corneal abrasions to ruptured globes.[45]

There exists a paucity of experimental data on airbag induced eye injuries compared to the number of individual case study publications. Fukagawa *et al.* found that increased inflator aggressivity contributed to increased endothelial cell damage.[13] The most recent airbag related study examined the injury potential of high-speed foam particles released during airbag deployment.[63] This study illustrates the compounding risk of eye injuries from not only airbag contact, but also from particles released from the module during deployment.

Orbital fractures have been reported in the literature occurring in sporting and other accidents, as well as in vehicle crashes.[64-67] Compared with the

number of individual case study publications, there exists a paucity of experimental data on orbital fractures. Several experimental studies have aimed to elucidate injury mechanisms, to estimate fracture tolerance, or to reproduce fractures similar to those observed in real world case studies.[68-74] Although case reports and experimental studies provide insight into the mechanism of injury, the national rate of orbital fracture incidence, type, and severity are unknown for occupants in crashes with and without an airbag deployment.

Although previous studies have provided insight into the interaction between an airbag and the eye or facial bones, the national incidences and relative risks of airbag induced eye injuries and orbital fractures are unknown for occupants in crashes with and without an airbag deployment. The purpose of this paper is to determine the overall risk of eye injuries and orbital fractures in automobile crashes and to discuss the injury mechanisms associated with these injuries.

METHODS

In order to eliminate the inaccuracies associated with small case study projections, a three part study was performed that utilized the NASS database.[75] The two primary advantages of using the NASS are that the database includes an analysis of approximately 5000 cases per year, and the injuries are coded by trained nurses using the Abbreviated Injury Scale (AIS).[76] The AIS scale classifies injuries by body region on a 6-point scale ranging from low severity (AIS1) to fatal (AIS6). The AIS values are assigned for each injury sustained and do not include combined effects from multiple injuries to the same patient. This coding allows for a consistent and accurate distinction and identification of eye injuries. Each crash scene is investigated by a group of trained accident investigators that examine and document vehicle damage, occupant injuries, and crash dynamics. This investigation team also examines the vehicle interior to look for signs such as tissue transfer onto interior components that would indicate mechanisms for each recorded injury. All occupants in the study grant informed consent.

The NASS cases are collected from 24 separate field research teams across the United States (US). Crashes are considered for NASS investigation if they occur on a traffic way, are reported to police, involve a harmful event, and involve at least one towed passenger car, light truck or van. Since it is not practical to investigate every crash in the US every year, each case investigated for the NASS

database is assigned a weighted value, which scales the incidence of the particular crash investigated to a number that represents actual occurrence of similar non-investigated crashes that occur in the US each year. The weighting factor is included in the NASS database for each case. This procedure has been used for national injury projection studies to analyze injury severity and crash characteristics for topics such as lower extremity injury patterns, upper extremity injury patterns, and restraint effectiveness in motor vehicle crashes.[1,61,77-82] The weighted occupant and weighted injury numbers reported represent the weighted numbers based on the actual raw cases. Statistical analyses were performed using the SUDAAN statistical software for weighted survey data (SUDAAN, Research Triangle Park, North Carolina).

Part 1: Eye Injury Incidence

For the eye injury study, cases in NASS were selected from the years 1993 through 1999 that include drivers and front seat occupants only, while excluding ejected occupants and rollovers. In addition, only frontal impacts were considered, which are defined as having a primary direction of force (PDOF) of 11, 12, or 1 o'clock. Eye injuries were defined as damage to the periorbital skin, globe, or orbital bones. Occupants with injuries and total injuries to occupants were analyzed for trends in injury incidence, type and severity. Eye injuries in the NASS database were identified using the current AIS injury codes.[76]

First, crashes with an airbag deployment were considered. For all occupants who were exposed to an airbag deployment, the number of occupants sustaining an eye injury or orbital fracture was compared to the total number who did not sustain an eye injury. Next, an analogous search was performed for crashes in which the airbag did not deploy. Occupants exposed to an airbag deployment were divided into two groups: Group 1 included all occupants who received an airbag induced eye injury or orbital fracture, and Group 2 included all of the remaining occupants. The occupants in Group 2 could have sustained an eye injury or orbital fracture in the crash, but the source would be something other than the airbag. The groups were divided in this way in order to identify occupant characteristics related to incidence of airbag induced injury.

Part 2: Orbital Fracture Incidence

For the orbital fracture portion of the study, cases in NASS were selected from the years 1993 through

2000. Orbital fractures included: blow-in or blow-out fractures, as well as orbital roof or floor fractures. Fractures could be closed, open, displaced, or any combination of these, and were identified in the NASS database using the current AIS injury codes.[42] Unfortunately, the AIS does not allow for further characterization of the orbital fractures; however, the purpose of this paper is to determine whether or not airbags reduce the overall risk of orbital fractures for similar exposure patterns, and in this application, the comparative frequency of orbital fractures is the critical factor. In particular, closed orbital fractures are coded as an AIS 2 level, while open or displaced or comminuted fractures are coded as AIS 3 level. The study of eye injuries and orbital fractures was divided into two parts:

Within the orbital fracture analysis, crashes with an airbag deployment were considered first. For all occupants who were exposed to an airbag deployment, the number of occupants sustaining an eye injury or orbital fracture was compared to the total number who did not sustain an eye injury. Next, an analogous search was performed for crashes in which the airbag did not deploy. Occupants exposed to an airbag deployment were divided into two groups: Group 1 included all occupants who received an airbag induced eye injury or orbital fracture, and Group 2 included all of the remaining occupants. The occupants in Group 2 could have sustained an eye injury or orbital fracture in the crash, but the source would be something other than the airbag. The groups were divided in this way in order to

identify occupant characteristics related to incidence of airbag induced injury.

Part 3: Eye Injury Severity Levels

A new eye injury grouping method was developed to assess the severity of eye injuries based on both the need for ocular surgery and the potential for loss of sight. The AIS system does not address both of these criteria, as it only considers the overall threat to life. Eye injuries were divided into four new injury groups: Level 1 includes minor injuries to the skin, Level 2 injuries are minor injuries to the eye, level 3 includes more serious eye injuries that may require surgery and present a guarded long-term prognosis, and Level 4 injuries are the most serious eye injuries that would result in blindness.

RESULTS

Part 1: Eye Injury Incidence

A total of 10,770,828 weighted occupants from 22,236 cases were included in this study for the seven year period from 1993 to 1999 (Figure 1). Each year, there were more occupants who sustained an eye injury in a non-airbag deployment crash than in a crash with an airbag deployment. As the proportion of airbag-equipped vehicles in the fleet is increasing, the number of occupants who sustain an eye injury in a crash with airbag deployment has also increased.

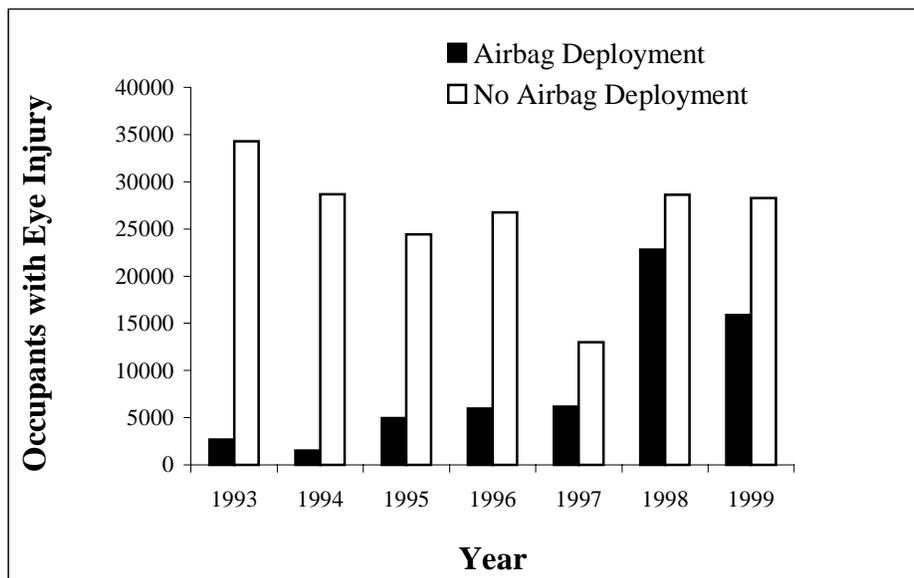


Figure 1. Comparison between number of weighted occupants with eye injuries in crashes with and without an airbag deployment (1993-1999) from 22,236 cases.

For crashes where the occupant was exposed to an airbag deployment, 60,112 weighted occupants (240 cases) sustained an eye injury out of 1,946,924 total weighted occupants (4,789 cases) in similar crashes (3.1%) (Figure 2). In contrast, for crashes without an

airbag deployment, 178,151 weighted occupants (1,225 cases) sustained an eye injury out of 8,823,904 total weighted occupants (17,447 cases) in similar crashes (2.0%). This difference was not statistically significant (p=0.15).

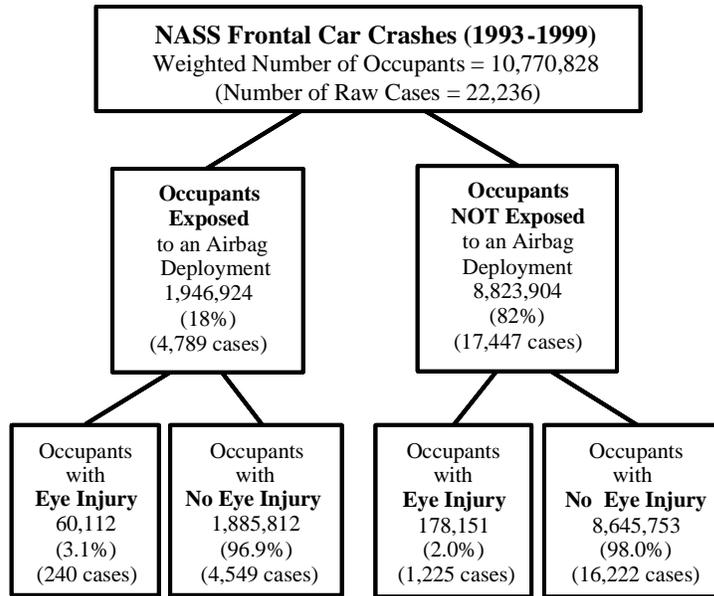


Figure 2. Incidence of eye injury for weighted occupants who were or were not exposed to an airbag deployment (1993-1999).

If the occupants with an eye injury were exposed to an airbag deployment, the airbag was the source of the eye injury for 88% of the injuries. If an airbag did not deploy, the top three sources for eye injury were the windshield (34%), steering wheel (27%), and instrument panel (14%). Regardless of injury source, 76% of the occupants that incurred an eye injury were drivers and 24% were right front seat passengers.

It was found that females represented 65.4% of weighted occupants that sustained an airbag induced eye injury; however, this proportion was not statistically significant (p = 0.19). Also, it was found that 28.7% of weighted occupants who sustained an airbag induced eye injury were wearing glasses, while 25.3% of occupants who did not receive an airbag induced eye injury were wearing glasses. However, this variable was not found to be statistically significant (p=0.81) in predicting risk of airbag induced eye injury. A total of 46.0% of weighted occupants who sustained an airbag induced eye injury were wearing contact lenses, while 10.7% of weighted occupants who did not receive an airbag induced eye injury were wearing contacts. Contact

lens wear was not found to be a statistically significant (p=0.31) variable in predicting risk of airbag induced eye injury. In regard to seatbelt use, it was found that 75.3% of weighted occupants who sustained an airbag induced eye injury were wearing a seatbelt, compared to 85.6% of weighted occupants who did not receive an airbag induced eye injury. This study indicated that the occupants who did not sustain an airbag induced eye injury had a slightly higher rate of seatbelt use; however, the difference was not statistically significant (p=0.45).

Next, the 1,946,924 weighted occupants exposed to an airbag were split into two groups: Group 1 was made up of occupants who sustained an eye injury from the airbag as source, and Group 2 was the remaining set of occupants who were exposed to an airbag deployment, but that did not have an airbag induced eye injury (Table 1). Within a 95% confidence interval, occupant height, age, and crash ΔV were all found to not be significant variables correlating with the risk of incidence of airbag induced eye injury. However, it was found that lighter occupants were more likely to sustain an airbag induced eye injury.

Table 1: Comparison of weighted occupant and crash characteristics for cases with eye injuries by injury source as shown in the Group 1 and Group 2 populations

	Group 1: Airbag Induced Injury		Group 2: No Airbag Induced Injury	
	Mean	Standard Dev.	Mean	Standard Dev.
Occupant Height (in)	67.44	0.49	67.35	0.14
Occupant Weight (lbs)	144.06	5.21	160.56	2.84
Occupant Age (yrs)	36.31	7.07	160.56	2.84
ΔV (mph)	11.73	1.68	13.68	0.29

Part 2: Orbital Fracture Incidence

A total of 12,429,580 weighted occupants from 25,464 cases were included in the orbital fracture study for the eight-year period from 1993 to 2000. A total of 24,605 weighted occupants sustained an orbital fracture. Each year, there were more occupants who sustained an orbital fracture when not exposed to an airbag deployment than there were occupants with orbital fracture when exposed to an airbag deployment (Figure 3). The number of occupants who sustained an orbital fracture in a crash with airbag deployment also increased overall through the years 1993-2000 in accordance with the increased number of airbag equipped vehicles in the driving fleet.

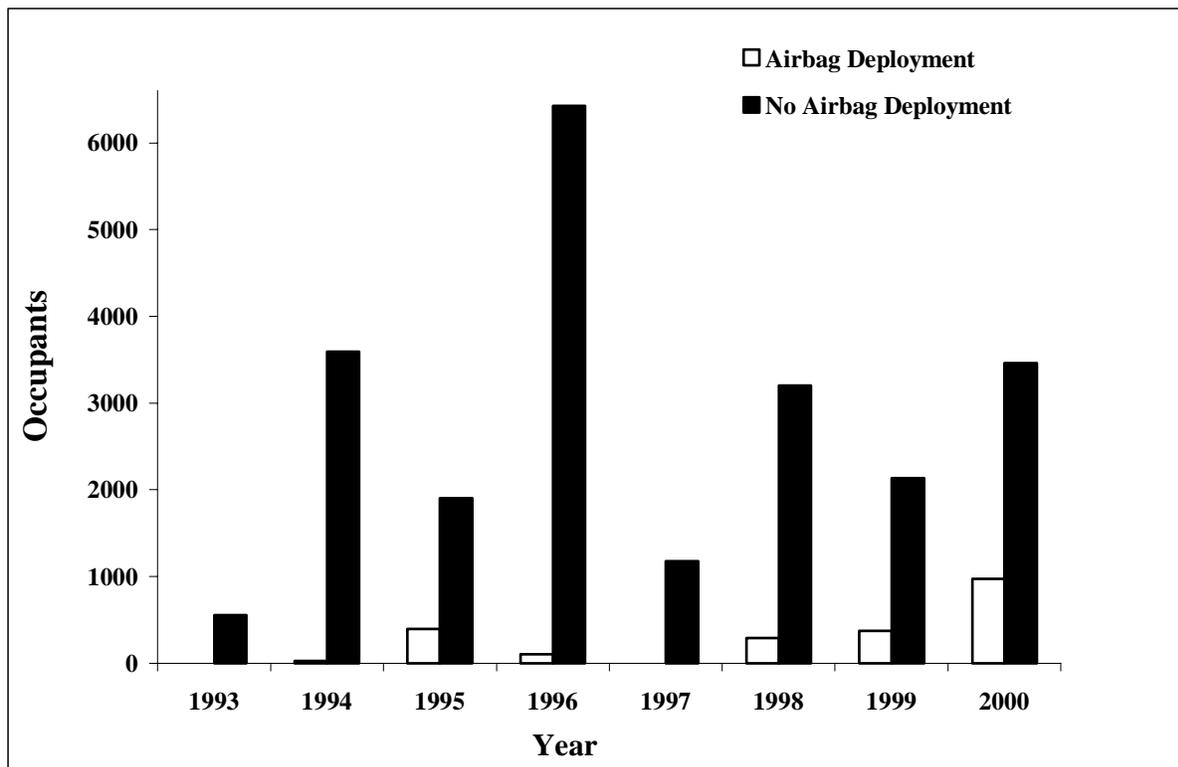


Figure 3. Weighted occupants with orbital fractures in frontal crashes that were or were not exposed to an airbag deployment by crash year from 25,464 cases.

For crashes where the occupant was exposed to an airbag deployment, 2,156 weighted occupants (18 cases) sustained an orbital fracture out of 2,421,893 total weighted occupants (6,094) in similar crashes (0.09%) (Figure 4). In contrast, for crashes without an airbag deployment, 22,449 weighted occupants (216 cases) sustained an orbital fracture out of 10,007,687 total weighted occupants (19,370 cases)

in similar crashes (0.22%). Although occupants who were not exposed to an airbag deployment sustained orbital fractures more than twice as often as occupants who were exposed to an airbag deployment, the chi square test of independence showed that this difference is not statistically significant (p=0.10).

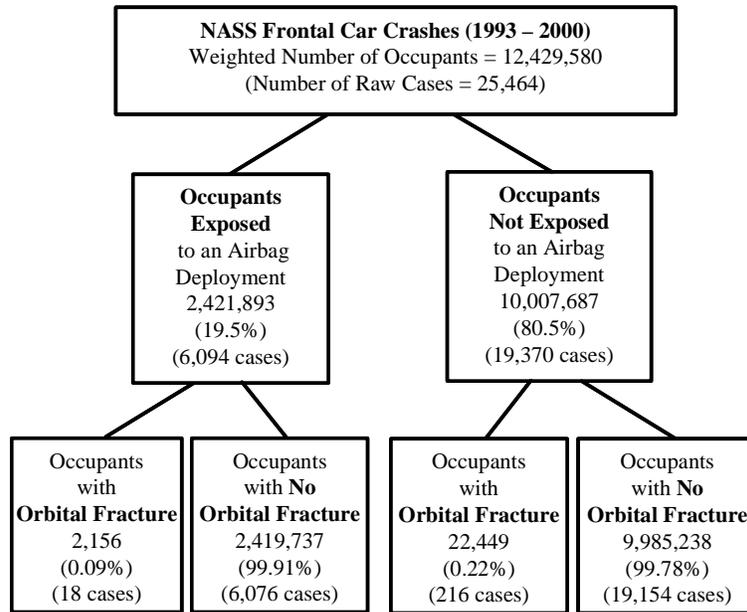


Figure 4. Incidence of orbital fractures for occupants in frontal crashes that were or were not exposed to an airbag deployment for the years 1993 through 2000.

For the total number of orbital fractures that occupants sustained, 26% were to occupants who were exposed to an airbag deployment, while the rest were sustained by occupants who were not exposed to an airbag deployment (74%). For the orbital fractures to occupants who were exposed to an airbag deployment, the majority of the injuries were induced by contact with the vehicle interior (36.6%), followed by the steering wheel (30.7%). Only 11 weighted orbital fractures (1 case) were induced by the airbag as source (0.5%). In contrast, the occupants who were not exposed to an airbag deployment sustained the majority of the weighted orbital fractures from the steering wheel (34.3%), followed by the windshield (32.4%), and the side pillar or other side interior components (15.6%).

For all occupants exposed to an airbag deployment, 84.7% of the weighted occupants with orbital fracture were drivers, while 15.3% were right front seat passengers. When exposed to an airbag deployment,

0.06% of drivers sustained an orbital fracture, compared with 0.24% of passengers. This difference is not statistically significant (p=0.43). In addition, 83.0% of the weighted occupants exposed to an airbag deployment with orbital fracture were male, while 17.0% were female. Of all the males who were exposed to an airbag deployment, 0.15% sustained an orbital fracture, compared with 0.03% of female occupants. Although male occupants sustained an orbital fracture more often than females, occupant sex is not a statistically significant factor in incidence of orbital fracture (p=0.12).

Of all the weighted occupants exposed to an airbag deployment with orbital fractures, 87.5% were wearing a seatbelt, while the rest (12.5%) were not wearing a seatbelt. In addition, it was found that 0.09% of belted occupants sustained an orbital fracture, compared with 0.08% of occupants not wearing a seatbelt. The risk of orbital fracture is not dependent on the rate of seatbelt use (p=0.86).

Within a 95% confidence interval, occupant height, weight, age, and crash ΔV were all found not to be significant variables correlating with the risk of incidence of orbital fracture. The average and standard deviation for the height, weight, age and crash ΔV for the orbital fracture injury group was 60.5 ± 5.6 in, 138.7 ± 20.7 lbs, 25.7 ± 7.6 years, 13.7 ± 1.4 mph compared to $67.1 \pm .3$ in, 160.3 ± 2.3 lbs, 33.7 ± 0.6 years, and 13.7 ± 0.3 mph for the no orbital fracture group.

Part 3: Eye Injury Severity Levels

Although airbag exposure was shown to increase the incidence of eye injuries, more important is the severity of the resulting eye injuries. Sorting the eye injuries into the four newly defined levels, it was shown that eye injuries from crashes without an airbag deployment were distributed as 85.0% Level 1, 4.4% Level 2, 10.1% Level 3, and 0.4% Level 4

(Figure 5). This was a total of 10.5% of the injuries being more serious, representing the categories of Levels 3 and 4 combined. In contrast, the eye injury distribution from crashes with an airbag deployment was 75.3% Level 1, 17.5% Level 2, 7.2% Level 3, and 0.0% Level 4. In these crashes with airbag deployments, only 7.2% of the injuries were more serious Level 3 and 4 injuries. There was a shift in the severity of eye injuries depending on whether or not the occupants were exposed to an airbag deployment, with the lower severity injuries occurring to occupants exposed to an airbag deployment.

When examining the specific injury types, there was a statistically significant ($p=0.03$) increase in risk of corneal abrasions for occupants exposed to an airbag deployment. Of the occupants exposed to an airbag deployment, 0.53% sustained a corneal abrasion, compared with 0.04% of occupants not exposed to an airbag deployment.

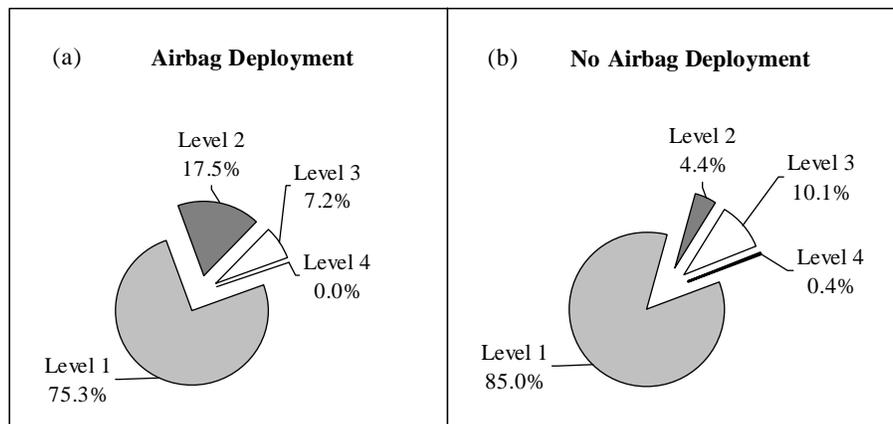


Figure 5: Severity levels of eye injuries sustained in crashes with an airbag deployment (a), and without an airbag deployment (b).

DISCUSSION

Though more occupants were injured when exposed to an airbag deployment, the airbag did provide a beneficial exchange by decreasing the severity of the associated eye injuries. A closer examination factoring in the type of eye injury showed that there was a statistically significant ($p=0.03$) increase in the risk of corneal abrasions for occupants that were exposed to an airbag deployment. Of particular interest to this study is the realization that an increasing proportion of the population will have had corrective vision procedures performed in the years to come. This, combined with the rising proportion

of airbag-equipped vehicles in the fleet, warrants further investigation.

In order to understand the eye injury incidence data, it is useful to discuss the mechanisms of eye injuries. Broadly, there are two mechanisms of eye injuries. The first is penetrating injuries from sharp objects, and the second is blunt trauma. The majority of research focuses on blunt trauma given the fact that design changes can alter the risk of injury in contrast to sharp objects which are going to cause injury as long as they are sharp. In the area of blunt trauma, the best tool for injury prediction is the recently published eye model by Stitzel *et al.* (2002). [83]

This is a model of the human eye and consists of the cornea, sclera, lens, ciliary body, zonules, aqueous humor and vitreous body (Figure 6A). Lagrangian membrane elements are used for the cornea and sclera, Lagrangian bricks for the lens, ciliary, and zonules, and Eulerian brick elements comprise the aqueous and vitreous (Figure 6B). Nonlinear, isotropic material properties of the sclera and cornea were gathered from uniaxial tensile strip tests performed up to rupture. Dynamic modeling was performed using LS-Dyna. Experimental validation tests consisted of 22 tests using three scenarios: impacts from foam particles, BB's, and baseballs onto fresh eyes used within 24 hours postmortem. The energies of the projectiles were chosen so as to provide both globe rupture and no rupture tests. Displacements of the eye were recorded using high speed color video at 7100 frames per second. The matched simulations predicted rupture of the eye when rupture was seen in the BB and baseball tests, and closely predicted displacements of the eye for the foam tests. Globe rupture has previously been shown to occur at peak stresses of 9.4 MPa using the material properties included in the model. Because of dynamic effects and improvements in boundary conditions resulting from a more realistic modeling of the fluid in the anterior and posterior chambers, the stresses can be much higher than those previously predicted, with the globe remaining intact. The model is empirically verified to predict globe rupture for stresses in the corneoscleral shell exceeding 23 MPa, and local dynamic pressures exceeding 2.1 MPa. The model can be used as a predictive aid to reduce the burden of eye injury, and can serve as a validated model to predict globe rupture.

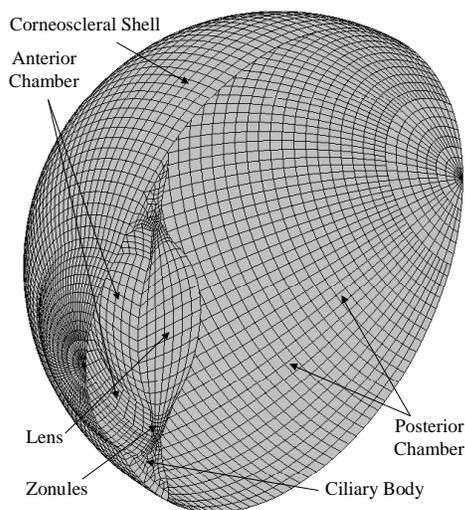


Figure 6A. Lagrangian mesh of eye showing corneoscleral shell, lens, zonules, and ciliary body.

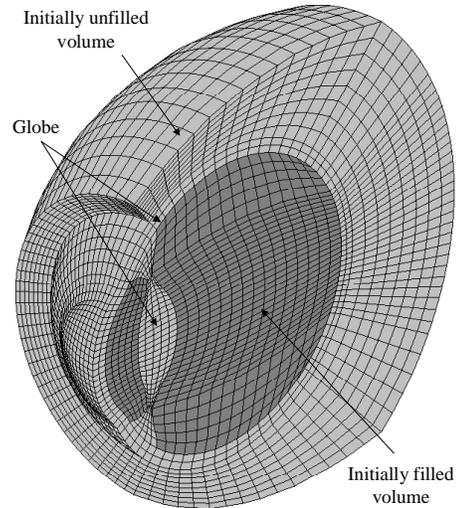


Figure 6B. Eulerian mesh showing initially filled volume (dark gray) and initially unfilled volume (light gray).

While a few studies show that there may be no increased risk of injury associated with eyes that have undergone photorefractive keratectomy (PRK), automated lamellar keratoplasty (ALK), and laser assisted in situ keratomileusis (LASIK), they are in the minority.[84-87] Far more studies indicate that these types of surgical procedures weaken the cornea and make it significantly more susceptible to injury for years after the procedure.[24,32,87-98]

CONCLUSIONS

This paper presents the most comprehensive eye injury study to date as it investigates 10,770,828 weighted occupants from 22,236 cases for the years 1993 through 1999. An analysis of the cases indicates that 3.1% of occupants exposed to an airbag deployment sustained an eye injury, compared to 2.0% of those occupants not exposed to an airbag deployment. Moreover, there was a significant increase in the risk of corneal abrasion for occupants exposed to an airbag deployment ($p=0.03$). The current trend of increasing the number of airbags in the fleet as well as the increasing percentage of the population electing for corrective vision surgery is potentially alarming. This vulnerability allows for the current trend of reduction of more severe injuries due to the airbag exposure to be reversed, a concern that warrants the continued investigation of airbag design, eye correction procedures, and eyewear protection.

In addition, this paper presents an analysis of 24,605 weighted occupants from 25,464 cases that sustained

an orbital fracture between the years 1993 and 2000. It is shown that occupants who were not exposed to an airbag deployment sustained an orbital fracture more than twice as often as occupants not exposed to an airbag deployment. While this difference is not statistically significant ($p=0.10$), the low p -value does indicate that 90% of the variance is explained by airbag exposure. As more airbag cases become available in accordance with the increased implementation of airbags into the automotive fleet, it is likely that this difference will become significant.

Although airbags have been shown to increase the incidence of some minor injuries, it appears that in the case of orbital fractures, the airbag has a protective effect. This can be attributed to the airbag preventing the occupant's face from contacting the steering wheel or the windshield. In addition, of the nearly 2.5 million weighted occupants exposed to an airbag deployment, only 11 orbital fractures (1 case) were a result of contact with the airbag components, and in particular, the airbag cover. In summary, both the incidence and the overall severity of orbital fractures decreased with exposure to airbag deployment as a result of the protective attributes of the airbag design.

REFERENCES

- Deery HA, Morris AP, Fildes BN, Newstead SV. Airbag Technology in Australian Passenger Cars: Preliminary Results from Real World Crash Investigations. *Crash Prev Inj Cont*, Oct, 1999; 1(2):121-8.
- Ball DC, Bouchard CS. Ocular morbidity associated with airbag deployment: a report of seven cases and a review of the literature. *Cornea*, Mar, 2001; 20(2):159-63.
- Bhavsar AR, Chen TC, Goldstein DA. Corneoscleral laceration associated with passenger-side airbag inflation. *Br J Ophthalmol*, June, 1997; 81(6):514-5.
- Biechl-Lautenbach KS, Gloor B, Walz F. Severe perforating eye injury caused by an air bag in a traffic skid accident. *Klin Monatsbl Augenheilkd*, Mar, 1996; 208(3):196-200.
- Braude LS. Passenger side airbag ocular injury while wearing sunglasses. *Br J of Ophthal*, Apr, 1995;79(4):391.
- Cacciatori M, Bell RWD, Habib NE. Blow-out fracture of the orbit associated with inflation of an airbag: a case report. *Br J Oral Maxillofac Surg*, 1997; 35:241-2.
- Campbell JK. Automobile air bag eye injuries. *Nebraska Med J*, Sept, 1993; 306:7.
- Chialant D, Damji KF. Ultrasound biomicroscopy in diagnosis of a cyclodialysis cleft in a patient with corneal edema and hypotony after an air bag injury. *Can J Ophthalmol*, 2000; 35:148-50.
- Dalmotas DJ, German A, Hendrick BE, Hurley RM. Airbag Deployments: The Canadian Experience. *J Trauma*, Apr, 1995; 38(4):476-81.
- Driver PJ, Cashwell R, Yeatts P. Airbag-associated bilateral hyphemas and angle recession. *Am J Ophthalmo*, Aug, 1994; 118(2):250-1.
- Dubois J, Stewart E. Ocular injuries from air bag deployment. *J Ophthalmic Nurs Techn*, July/Aug, 1998; 17(4):147-50.
- Duma, S.M., Kress, T.A., Porta, D.J., Woods, C.D., Snider, J.N., Fuller, P.M., Simmons, R.J., "Air Bag Induced Eye Injuries: A Report of 25 Cases," *The Journal of Trauma*, Vol. 41, No. 1, pp. 114-119, 1996.
- Fukagawa K, Tsubota K, Kimura C, Hata S, Mashita T, Sugimoto T, Oguchi Y, Corneal Endothelial Cell Loss Induced by Air Bags. *Ophthalm*, 1993; 100:1819-23.
- Gault JA, Vichnin MC, Jaeger EA, Jeffers JB. Ocular injuries associated with eyeglass wear and airbag inflation. *J Trauma*, 1995; 38(4):494-7.
- Geggel HS, Griggs PB, Freeman MI. Irreversible Bullous Keratopathy after Air Bag Trauma. *The CLAO J*, 1996; 22(2):148.
- Giguere JF, St-Vil D, Turmel A, Di Lorenzo M, Pothel C, Manseau S, Mercier C. Airbags and children: a spectrum of C-spine injuries. *J Pediatr Surg*, Jun, 1998; 33(6):811-6.
- Goldberg MA, Valluri S, Pepose JS. Air bag related corneal rupture after radial keratotomy. *Am J of Ophthalmol*, Dec, 1995; 120(6):800-2.
- Han DP. Retinal detachment caused by air bag injury. *Arch Ophthal*, Oct, 1993; 111:1317-8.
- Hunt L. Ocular injuries from driver's air bag. *Insight*, Apr, 1995; 20(1):18-9.
- Ingraham HJ, Perry HD, Donnenfeld ED. Airbag keratitis. *N Engl J Med*, May, 1991; 324(22):1599-600.
- Kuhn F, Morris R, Witherspoon CD. Eye injury and the air bag. *Curr Opin Ophthalmol*, June, 1995; 6(3):38-44.
- Larkin GL. Airbag mediated corneal injury. *Am J Emerg Med*, 1991; 9:444-6.
- Lee WB, O'Halloran HS, Pearson PA, Sen HA, Reddy SH. Airbags and bilateral eye injury:

- five case reports and a review of the literature. *J of Emerg Med*, 2001; 20(2):129-34.
24. Lemley HL, Chodosh J, Wolf TC, Bogie CP, Hawkins TC. Partial dislocation of laser in situ keratomileusis flap by air bag injury. *J Refract Surg*, 2000;16:373-4.
 25. Leshner MP, Durrie DS, Stiles MC. Corneal edema, hyphema, and angle recession after air bag inflation. *Arch Ophthalmol*, Oct, 1993; 111:1320-2.
 26. Lueder GT. Air bag-associated ocular trauma in children. *Ophthalmol*, Aug, 2000; 107(8):1472-5.
 27. Manche EE, Goldberg RA, Mondino BJ. Air bag related ocular injuries. *Ophthalmic Surg*, Mar, 1997; 28(3):246-50.
 28. McDermott ML, Shin DH, Hughes BA, Vale S. Anterior segment trauma and air bags [letter]. *Arch Ophthalmol*, 1995, 113(12):1567-8.
 29. Michaeli-Cohen A, Neufeld M, Lazar M, Geyer O, Haddad R, Kashtan H. Bilateral corneal contusion and angle recession caused by an airbag [letter]. *Br J Ophthalmol*. 1996; 80(5):487.
 30. Mishler KE. Hyphema caused by airbag. *Arch Ophthalmol*, Dec, 1991; 109:1635.
 31. Molia LM, Stroh E. Airbag injury during low impact collision. *Br J Ophthalmol*, May, 1996; 80(5):487-8.
 32. Norden RA, Perry HD, Donnenfeld ED, Montoya C. Air bag-induced corneal flap folds after laser in situ keratomileusis [In Process Citation]. *Am J Ophthalmol*, 2000; 130:234-5.
 33. O'Halloran HS, Draud K, Stevens JL. Primary enucleation as a consequence of airbag injury. *J Trauma*, June, 1998; 44(6):1090.
 34. Onwuzuruigbo CJ, Fulda GJ, Larned D, Hailstone D. Traumatic blindness after airbag deployment: bilateral lenticular dislocation. *J Trauma*, 1996; 40(2):314-6.
 35. Rimmer S, Shuler JD. Severe ocular trauma from a driver side air bag. *Arch Ophthalmol*, June, 1991; 109:774.
 36. Rosenblatt M, Freilich B, Kirsch D. Air bag-associated ocular injury. *Arch Ophthalmol*. Oct, 1993; 111(10):1318.
 37. Rosenblatt M, Freilich B, Kirsch D. Air bags: trade-offs. *N Eng J Med*, 1991; 21:1518.
 38. Ruiz-Moreno JM. Air bag-associated retinal tear. *Eur J Ophthalmol*, Jan-Mar, 1998; 8(1):52-3.
 39. Sastry SM, Copeland RA, Mezghebe H, Siram SM. Retinal hemorrhage secondary airbag related ocular trauma. *J Trauma*, 1995; 38(4):582.
 40. Scott IU, Stark WJ. Airbag associated ocular injury. *Arch Ophthalmol*, Oct, 1993; 111:1318.
 41. Shah GK, Penne R, Grand MG. Purtscher's retinopathy secondary to airbag injury. *Retina*, 2001; 21(1):68-9.
 42. Singer HW. Potential air bag-related eye injuries require special ER attention. *J Ophthalmic Nurs Technol*, Jan-Feb, 1998; 17(1):21-2.
 43. Smally AJ, Binzer A, Dolin S, Viano D. Alkaline chemical keratitis: eye injury from airbags. *Ann Emerg Med*, Nov, 1992; 21:1400-2.
 44. Smock WS, Nichols GR. Airbag module cover injuries. *J Trauma*, Apr, 1995; 38(4):489-93.
 45. Stein JD, Jaeger EA, Jeffers JB. Air bags and ocular injuries. *Trans Am Ophthalmol Soc*, 1999; 97:59-82.
 46. Steinmann R. A 40-year-old woman with an air bag-mediated injury. *J Emerg Nurs*, Aug, 1992; 18(4): 308-10.
 47. Stitzel, J., Duma, S., Herring, I., Cormier, J., Hurst, W., "A Nonlinear Finite Element Model of the Eye with Experimental Validation for the Prediction of Globe Rupture," *Stapp Car Crash Journal*, Vol. 46, pp. 81-102, 2002.
 48. Stranc MF. Eye injury resulting from the deployment of an airbag [letter]. *Br J Plastic Surg*, July, 1999; 52(5):418.
 49. Swanson-Biearman B, Mrvos R, Dean BS, Krenzelok EP. Air bags: lifesaving with toxic potential. *Am J Emerg Med*, Jan, 1993; 11(1):38-9.
 50. Totten VY, Fani-Salek MH, Chandramohan K. Hyphema Associated with Air Bag Deployment in a Pediatric Trauma Patient. *Am J Emer Med*, 1998; 16(1):102.
 51. Tsuda Y, Wakiyama H, Amemiya T. Ocular injury caused by an air bag for a driver wearing eyeglasses. *Jpn J Ophthalmol*, May-June, 1999; 43(3):239-40.
 52. Vichnin MC, Jaeger EA, Gault JA, Jeffers JB. Ocular injuries related to air bag inflation. *Ophthalmic Surg*, Dec, 1995; 26(6):542-8.
 53. Walter DP, James MR. An unusual mechanism of airbag injury. *Injury*, 1996; 27(7):523-4.
 54. Walz FH, Mackay M, Gloor B. Airbag deployment and eye perforation by a tobacco pipe. *J Trauma*, Apr, 1995; 38(4):498-501.
 55. Weinman, SA. Automobile Air Bag-Mediated Injury: A Case Presentation. *J Emerg Nurs*, Feb, 1995; 21(1):84-5.
 56. Whitacre MM, Pilchard WA, Kan SM. Air bag injury producing retinal dialysis and detachment. *Arch Ophthalmol*, Oct, 1993; 111:1320.

57. White JE, McClafferty K, Orton RB, Tokareqicz AC, Nowak ES. Ocular alkali burn associated with automobile air-bag activation. *CMAJ*, Oct, 1995; 153(7):933-4.
58. Zabriskie NA, Hwang IP, Ramsey JF, Crandall AS. Anterior lens capsule rupture caused by air bag trauma. *Am J Ophthalmol*, June, 1997; 123(6):832-3.
59. Zacovic JW, McGuirk TD, Knoop KJ. Bilateral Hyphemas as a Result of Air Bag Deployment. *Am J Emer Med*, 1997; 15(3):323.
60. Müller-Jensen K, Hollweck W. Serious eye injuries produced by windshield damage – an actual problem in ophthalmology. *14th Annual Stapp Car Crash Conference, Ann Arbor, Michigan*, Nov 1970.
61. Duma SM, Kress TA, Porta DJ, Woods CD, Snider JN, Fuller PM, Simmons RJ. Air Bag Induced Eye Injuries: A Report of 25 Cases. *J Trauma*, 1996; 41(1):114-9.
62. Ghafouri A, Burgess SK, Hrdlicka ZK, Zagelbaum BM. Air bag related ocular trauma. *Am J Emerg Med*, July, 1997; 15(4):389-92.
63. Duma SM, Crandall JR. Eye injuries from airbags with seamless module covers. *J Trauma*, Apr, 2000; 48(4):786-9.
64. Cacciatori M, Bell RWD, Habib NE. Blow-out fracture of the orbit associated with inflation of an airbag: a case report. *Br J Oral Maxillofac Surg* 1997;35:241-2.
65. Hartzell KN, Botek AA, Goldberg SH. Orbital fractures in women due to sexual assault and domestic violence. *Ophthalmol* 1996;103(6):953-7.
66. Hatton MP, Watkins LM, Rubin PAD. Orbital Fractures in Children. *Ophthal Plast Reconstr Surg* 2001;17(3):174-9.
67. Huber A, Fischer J, Simbrunner J. An unusual case of a blow-out fracture. Entrance of a bone fragment into the frontal lobe after a ski accident. *Neurochirurgia (Stuttg)* 1993;35(4):137-9.
68. Bullock JD, Warwar RE, Ballal DR, Ballal RD. Mechanisms of orbital floor fractures: a clinical, experimental, and theoretical study. *Trans Am Ophthalmol Soc* 1999;97:87-113.
69. Fujino T. Experimental 'blowout' fracture of the orbit. *Plast Reconstr Surg* 1974a;54:81-2.
70. Fujino T, Makino K. Entrapment mechanism and ocular injury in orbital blowout fracture. *Plast Reconstr Surg* 1980;65:571-4.
71. Hudson JW, Russell RM, Gerard DA, Lake HP. Experimentally Induced Facial Third Fractures in Unembalmed Human Cadaver Heads. *J Trauma* 1997;42(2):705-10.
72. Jin HR, Shin SO, Choo MJ, Choi YS. Relationship between the extent of fracture and the degree of enophthalmos in isolated blowout fractures of the medial orbital wall. *J Oral Maxillofac Surg* 2000;58(6):617-21.
73. Warwar RE, Bullock JD, Ballal DR, Ballal RD. Mechanisms of orbital floor fractures: a clinical, experimental, and theoretical study. *Ophthalmic Plast Reconstr Surg* 2000;16(3):188-200.
74. Waterhouse N, Lyne J, Urdang M, Garey L. An investigation into the mechanism of orbital blowout fractures. *Br J Plast Surg* 1999;52(8):607-12.
75. National Highway Traffic Safety Administration (NHTSA), National Automotive Sampling System (NASS), Crashworthiness Data System, 1993-1999, *Department of Transportation (DOT) HS 808985, 8*, Washington D.C., 1999.
76. Association for the Advancement of Automotive Medicine (AAAM), *The Abbreviated Injury Scale (AIS) 1998 Revision*, Des Plaines, IL, 1998.
77. Atkinson T, Atkinson P. Knee injuries in motor vehicle collisions: a study of the National Accident Sampling System database for the years 1979-1995. *Accident Analysis and Prevention*, Nov, 2000; 32(6): 779-86.
78. Farmer CM, Braver ER, Mitter EL. Two-vehicle side impact crashes: The relationship of vehicle and crash characteristics to injury severity. *Acc Anal Prev*, May, 1997; 29(3): 399-406.
79. Miller TR, Pindus NM, Douglass JB. Medically related motor vehicle injury costs by body region and severity. *J Trauma*, Feb, 1993; 34(2):270-5.
80. Reiff DA, McGwin G, Rue LW: Splenic Injury in Side Impact Motor Vehicle Collisions: Effect of Occupant Restraints. *J Trauma* 2001;51(2):340-345.
81. Segui-Gomez M: Driver Air Bag Effectiveness by Severity of the Crash. *Am J Public Health* 2000;90(10):1575-1581.
82. Viano DC, Culver CC, Evans L, Frick M, Scott R. Involvement of older drivers in multivehicle side-impact crashes. *Accid Anal Prev*, Apr, 1990, 22(2):177-88.
83. Stitzel J, Duma S, Cormier J, Herring I: A Nonlinear Finite Element Model of the Eye with Experimental Validation for the Prediction of Globe Rupture, *Stapp Car Crash Journal*, 2002.
84. Campos M, Lee M, and McDonnell PJ. Ocular integrity after refractive surgery: effects of photorefractive keratectomy, phototherapeutic keratectomy, and radial keratotomy. *Ophthalmic Surg*, 1992; 23:598-602.

85. Casebeer JC, Shapiro DR, Phillips S. Severe ocular trauma without corneal rupture after radial keratotomy: case reports. *J Refract Corn Surg*, 1994; 10:31-3.
86. John ME Jr, Schmitt TE. Traumatic hyphema after radial keratotomy. *Ann Ophthalmol*, 1983; 15:930-2.
87. Peacock LW, Slade SG, Martiz J, Chuang A, Yee RW. Ocular integrity after refractive procedures. *Ophthalmol*, 1997; 104:1079-83.
88. Alvi NP, Donohue EK, Curnyn K, Sugar J. Rupture of radial keratotomy sites after presumed blunt trauma. *Ophthal Surg Las*, 1995; 26:574-5.
89. Binder PS, Waring GO, Arrowsmith PN, Wang C. Histopathology of traumatic corneal rupture after radial keratotomy. *Arch Ophthalmol*, 1988; 106:1584-90.
90. Chaudhry NA, Smiddy WE. Displacement of corneal cap during vitrectomy in a post-LASIK eye. *Retina*, 1998; 18:554-5.
91. Glasgow BJ, Brown HH, Aizuss DH, Mondino BJ, Foos RY. Traumatic dehiscence of incisions seven years after radial keratotomy. *Amer J Ophthalmol*, 1988; 106:703-7.
92. Leung AT, Rao SK, Lam DS. Traumatic partial unfolding of laser in situ keratomileusis flap with severe epithelial ingrowth. *J Cataract Refract Surg*, 2000; 26:135-9.
93. Lindquist TD. Complications of corneal refractive surgery. *Int Ophthalmol Clin*, 1992; 32:97-114.
94. McDonnell PJ, Lean JS, Schanzlin DJ. Globe rupture from blunt trauma after hexagonal keratotomy. *Am J Ophthalmol*, 1987; 103:241-2.
95. Pearlstein ES, Agapitos PJ, Cantrill HL, Holland EJ, Williams P, Lindstrom RL. Ruptured globe after radial keratotomy. *Amer J Ophthalmol*, 1988; 106:755-6.
96. Rashid ER, Waring GO. Complications of refractive keratotomy. In: Waring GO, ed. *Refract Keratol Myopia Astigm*. St. Lewis, MO: Mosby; 1992:863-936.
97. Vinger PF, Mieler WF, Oestreicher JH, Easterbrook M. Ruptured globes following radial and hexagonal keratotomy surgery. *Arch Ophthalmol*, 1996; 114:129-34.
98. Zhaboyedov GD, Bondavera GS. Traumatic rupture of the eyeball after radial keratotomy. *Vestnik Oftalmologii*, 1990; 106:64-5.

CONTACT

Stefan M. Duma, Virginia Tech, Impact Biomechanics Laboratory. 114T Randolph Hall, MC 0238. Blacksburg, VA 24061. duma@vt.edu - www.ibl.vt.edu - (540) 231-3945