Hunterian Lecture

Maxillofacial and ocular injuries in motor vehicle crashes

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Background: Injuries from motor vehicle crashes constitute a leading cause of death in the young and a high degree of morbidity and mortality in all age groups. Facial trauma has been consistently shown to be the single most common injury to the occupants of vehicles involved in crashes. This has been confirmed by more recent studies which have demonstrated a continuing high incidence of facial fractures amongst belted drivers. Airbags have been advocated as a supplemental restraint system. However, their deployment can cause injury particularly if the driver is of short stature, unrestrained or out of position within the vehicle.

Methods: The Crash Injury Research Engineering Network (CIREN) project aims to correlate the injuries received by occupants in vehicle crashes with the biomechanics of vehicle deformation. All cases of facial injury which presented to the University of Michigan Medical Center, USA in 1999 were retrospectively evaluated with reference to the methods of occupant restraint and to the correlation between the injuries sustained and vehicle deformation.

Results and Conclusions: The case analysis confirmed the value of airbags to the safety of vehicle occupants but reinforced the conclusion that they must still be considered supplemental restraint systems. New generation airbags will minimise the risk of injury even to small stature or out of position occupants as they will prevent deployment in situations where they may have an adverse effect.

Key words: Maxillofacial injuries – Ocular injuries – Motor vehicle crashes – Airbags – CIREN

Injuries from motor vehicle crashes constitute a leading cause of death in the young and a high degree of morbidity and mortality in all age groups.¹ The injuries are due to the significant amounts of kinetic energy released when the steady state of a vehicle occupant is changed by sudden acceleration or deceleration. These changes in velocity with respect to time are measured in 'g-forces', representing multiples of the weight of an object in the earth's gravitational field. Both speed and stopping distances have significant influences on these forces.

During a vehicle crash, four collisions may occur:¹ (i) the actual vehicle collision with another object; (ii) the impact of

the occupants with the vehicle interior; (iii) the collision between organs and hard surfaces; and (iv) collisions between loose 'objects' (including unrestrained passengers) and the occupants.

Seat belt use, airbag deployment and vehicle design features (interior padding and collapsible zones) all increase the stopping distance for occupants in crashes.

Facial trauma has been consistently shown to be the single most common injury to the occupants of motor vehicles involved in accidents.²

This paper demonstrates why airbags are necessary to protect the facial structures in vehicle crashes. A short case

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series also illustrates the risk posed to the facial skeleton and ocular structures from airbag deployment in unrestrained, out of position or short stature occupants.

Are airbags necessary for facial protection?

Between 1974 and 1976, Grattan and Hobbs undertook a landmark study to investigate the injuries sustained by casualties admitted to the Royal Berkshire Hospital as a result of vehicle collision.³ More than 50% of the casualties suffered maxillofacial trauma with a marked overall reduction in facial injuries in belted occupants compared with unbelted casualties. These findings are consistent with the observation that restrained occupants undergo deceleration both uniformly and over a greater distance than those not wearing seatbelts – the ‘ridedown’ effect.¹

However, these authors also demonstrated that drivers wearing seat belts were shown to experience significantly more severe (AIS 3)⁴ steering wheel related facial injury than unbelted comparisons.³ The most likely explanation for this is that in an attempt to reduce seat belt inflicted injury, belts incorporate an ability to stretch and yield under load.³ This allows sufficient forward movement for belted occupants to contact the steering wheel violently. Furthermore, the seat belt modifies the forward trajectory of the head and upper torso making contact between the steering wheel and the face more likely.⁵⁻⁷

Since 1984 in the UK, there has been a dramatic decrease in motor vehicle occupant’s maxillofacial injuries.^{8,9} This has been primarily due to the introduction of compulsory seat belt laws along with innovative improvements in vehicle design such as collapsible energy absorbing steering wheels.⁸ However, figures from the Department of Transport in 1985 and 1988⁹ and many international studies have demonstrated a continuing high incidence of facial fractures amongst belted drivers.¹⁰⁻¹⁴ These studies have clearly identified that the steering wheel assembly accounts for more than half of all facial injuries in restrained drivers.

It has been postulated that the hard, narrow edge of the wheel localises forces on impact with the driver’s face.¹⁵ As such, both field observations and research studies have demonstrated less facial trauma with energy absorbing steering wheels due to their increased dissipation of force, compared with standard structures.¹⁴

Notwithstanding these developments, as recently as 1994, a study of 461 consecutive admissions following vehicle trauma at the Frankford Trauma Centre, Philadelphia, USA, found that the incidence of facial features was the same in both belted and unbelted vehicle occupants.² This study suggested that further protection for the face, to reduce the injurious kinetic energy exchange, is necessary even for the belted driver. As such, the importance of airbags as a supplemental restraint

system can be clearly seen. These devices inflate from the centre of the steering wheel when crash sensors detect the rapid deceleration associated with frontal impact. This ignites an electrical charge on a pyrotechnic device (sodium azide) producing gases (96% nitrogen, 3% carbon dioxide and particulates 1%) within a folded bag. The deployed device prevents violent impact of the face with the steering assembly providing supplemental protection when used with the appropriate lap-shoulder belt.¹⁶

Figures released by the National Highway Traffic Safety Administration (NHTSA) in the USA credit airbags in reducing fatalities in frontal crashes by 30% saving the lives of 4758 drivers and passengers since their introduction in 1986. As described, the deployed bags protect the facial structures. In addition, the incidence of potentially serious cranial, cervical and thoracic injuries is markedly reduced.

Who is at risk of airbag-mediated oculofacial injury?

A pattern of mostly minor, ocular and facial injuries secondary to airbag deployment in correctly restrained occupants has emerged.¹⁶ In addition, there is an accumulating level of evidence that on rare occasions, there is the potential for more serious injuries to be caused by the airbags. This has also been recognised by the automotive industry whose development of airbags has principally taken place within the laboratory.¹⁷ Even within the constraints imposed by this artificial setting, it was recognised at an early stage, that there was the potential for life-threatening injuries to be caused by the airbag. Occupants at risk are those of small stature who sit close to the steering wheel (even if correctly restrained) and particularly those occupants who are inappropriately restrained or not restrained at all.¹⁸

The mechanism of obstructed airbag deployment¹⁸

The airbag deploys within 50 ms and at 160–320 km/h. This can be potentially injurious, particularly if the bag’s normal path is obstructed. Obstruction most often occurs if the driver is unrestrained and, consequently, ‘out of position’.

Automotive engineers have demonstrated mechanisms of injury from airbag deployment loads within the laboratory. Crash performance cannot necessarily be extrapolated from laboratory data. However, these studies have suggested possible aetiologies for airbag related injury in ‘real-life’ crashes.

In a normal deployment, pressure is built up by the airbag gases which overcome the resistance of the inner and outer containers. This allows the bag to break out of the module as the cover tears. Gas then continues to fill

the bag outside the module. Negligible vertical force occurs because the driver only impacts with the deployed, fully inflated bag. As such, the restraining force is evenly distributed over the body.

The initial 'punch-out' phase is of short duration (10 ms) and produces a 'spike' of high force. Following this, the occupant's interaction with the inflating module is characterised by a plateau secondary phase with the inflating bag acting like a membrane. This results in a force of similar magnitude to that during 'punch out', albeit to a much larger surface.

In an obstructed deployment, the gases must build up sufficient pressure to overcome the resistance of the occupant part against the bag in addition to that of the containers. Laboratory tests have demonstrated the concentrated force may be as high as 20 kN well above the established human tolerance in such a mode of loading (Fig. 1).

The 'punch out spike' induces injury to the body part in direct contact with the module. This contrasts with the obstructed plateau phase which can induce injury to body regions away from the module.¹⁹

In recent years, there have been numerous case reports detailing injuries resulting in cardiac tamponade, traumatic avulsions of digits and fractures involving the upper extremities.²⁰⁻²³ Analysis of these cases, in addition to the automotive injury research already described, provides a plausible explanation for airbag-related facial injuries. However, these injuries must be placed in context as serious facial trauma secondary to airbag deployment only occurs in specific, rare circumstances.

How airbags can cause facial injury

Occupants who are short of stature sit, out of necessity, with the seat in the full-forward position, close to the steering wheel. Even if fully restrained they are at risk of 'late deployments' which are defined as the airbag's 'punch-out' phase not occurring until the occupants are so far forward they are near the airbag cover.¹⁸

Alternatively, if short-stature occupants are unrestrained, the initial crash impact, combined with their position close to the wheel, can result in them being thrown forward. As a consequence, the driver's face may be lying adjacent to the steering wheel, when the airbag fabric deploys at 160–320 km/h. Similarly, if the subject's thorax is within the airbag 'deployment zone', there is a change in the pattern of 'punch out'. This can result in not only excessive forces being applied to the thorax but also a greater upward extension of the bag resulting in cervical and facial injury.¹⁷ Finally, the plateau phase of deployment can in these circumstances result in injuries to the facial structures remote to the initial site of bag

Figure 1 Normal and obstructed deployment of an airbag.¹⁸

contact.¹⁷ This is of particular relevance in US where the increased volume of the airbag attempts to compensate for the low prevalence of seatbelt use compared with the UK (68% in all states overall, 90% in the UK).⁸

Case reports from Italy, the UK and North America have described isolated zygomatic complex,²⁴ orbital 'blow-out',²⁵ and temporomandibular joint fractures^{26,27} as a result of airbag deployment in short stature subjects.

Can airbags cause ocular injuries?

There is also increasing concern that airbags can, on occasions, result in ocular injuries.²⁸⁻³¹ Vitreous haemorrhage, retinal detachments and related ocular ruptures constitute the most serious injuries described.^{25,28} In Stein's series, patients involved in accidents with an estimated speed more than 30 mph sustained a greater percentage of vitreous or retinal haemorrhages. Those at slower speeds were more prone to ocular rupture, retinal tears or detachments.

In the subset, with collision speeds of 30 mph or under, driver position with respect to the steering wheel appeared to be the most significant factor. It was postulated that in slower speed crashes early braking occurs throwing the driver forward towards the steering wheel. The earlier in the inflation sequence contact occurs, then the greater is the impact force. Unbelted, out of position occupants move forward faster increasing the risk of striking an expanding bag.²⁹

The impact of the occupant with the airbag results in a shockwave passing through the globe and in rapid 'AP' compression and equatorial expansion of the eye. This may result in rupture of the globe (Fig. 2). The shockwave

Figure 2 Blunt trauma causing airbag-induced ocular injuries.²⁸

reflects off the rear of the orbit producing a rarefaction wave. This can cause separation of the retina from the choroids thereby prejudicing its metabolic homeostasis. Irreparable visual loss due to cell death can result.²⁸

Contusions to the face, eyelid or eyeball result from airbag impact and may be complicated by the development of hyphaemas or other ocular compartment haemorrhage.³²⁻³⁶ Some 20% of hyphaemas will reform after the initial injury and delayed onset glaucoma has been reported from scarring of the anterior chamber drainage system.²⁸

Similarly, high velocity impact with the nylon airbag fabric may result in a corneal abrasion. Larkin³⁷ first reported this in 1991, attributing the abrasion to a seam in the bag. Other reports implicate the weave and density of the nylon bag fabric in causing abrasive, 'scraping'-type injuries.

Crash Injury Research Engineering Network (CIREN)³⁸

CIREN is a collaboration between seven level one trauma centres in North America. Its aims are to correlate the injuries received by vehicle occupants in crashes with the biomechanics of vehicle deformation.

The University of Michigan Medical Center, Ann Arbor, USA, is a level one trauma centre involved in the CIREN project. As part of an on-going research project, I retrospectively evaluated 20 cases presenting between 1997 and 1998 involving patients with facial injuries.

All of these cases met the agreed inclusion criteria for investigation by CIREN and informed consent had been obtained from the patients as per the protocol approved by the University of Michigan Institutional Review Board.

Comprehensive clinical records for each index case were reviewed. These had been prepared by CIREN

Figure 3 Case 52-019-98 – Penetrating eye injury from windscreen wiper stalk

investigators and included scene, vehicle and patient photographic documentation as well as a complete account of each patient's pre- and in-hospital care. Six of these patients sustained serious ocular injuries. The analysis of these cases is now presented with particular reference to the methods of restraint used by the occupants involved and to the correlation between the injuries sustained and vehicle deformation.

Case analyses

Case 52-019-98

Restrained driver – lap shoulder belt. The index vehicle collided with a tree which resulted in the detachment of the steering wheel column. The drive was impaled on the windscreen wiper stalk causing a penetrating eye injury.

Case 52-004-97

Restrained driver – lap shoulder belt. A collision with an HGV trailer pushed the index vehicle backwards. The driver was partially ejected. A compound zygomatic complex fracture and penetrating eye injury occurred from the vehicle 'A' pillar and door.

Case 52-024-97

Not fully restrained – shoulder belt only. The driver was thrown forward while turning the wheel and suffered a compound left ulna bone fracture. A fragment from this acted like a missile, traversing the right maxillary sinus and penetrating the right globe.

Figure 4. Case 52-031-98 – Left retrobulbar haematoma

Case 52-007-98

Not fully restrained – airbag only. An out of position, short stature patient, slid off the deployed airbag and collided with the 'A' pillar. A closed, comminuted left zygomatic complex fracture and penetrating eye injury was the result.

Case 52-031-98

Fully restrained – lap shoulder belt and positive airbag deployment. The index vehicle under-ran an HGV trailer with massive intrusion of the 'A' pillar and windshield header. Frontal bone and left zygomatic complex fractures occurred with the complication of a retrobulbar haematoma.

Case 52-011-98

Fully restrained – lap shoulder belt and positive airbag deployment. There were contusions on the dorsum of the patient's right hand. The force of the airbag deployment, impacted her hand towards her face with a consequent penetrating ocular injury and a closed fracture of the right zygomatic complex.

Discussion of case analyses

These cases demonstrate the reality of vehicle crashes being unpredictable and 'innovative'. Both the penetrating eye injury resulting from the compound ulna bone fragment (Case 52-024-97) and the penetration of the ocular tissues by the windscreen wiper stalk (Case 52-019-98) are rare events. However, as the driver in Case 52-019-98 was restrained, an airbag may well have prevented this injury. Similarly, airbag

Figure 5 Case 52-007-98 – Fractured left zygomatic complex and penetration eye injury

Figure 6 Case 52-024-97 – Ulna bone fragment in right globe

deployment in the vehicle collision with the HGV trailer (Case 52-004-97) would have limited the injuries received.

Case 52-031-98 implicates massive intrusion of the vehicle 'A' pillar and windshield header as the source of the patient's maxillofacial and ocular injuries. An airbag

did deploy in this collision. This questions the bag's complete effectiveness in an impact where gross displacement of the vehicle structures occurs. Further research is evaluating this.

Case 52-007-98 involved a relatively low speed collision. The unrestrained, short stature female driver suffered a left zygomatic complex fracture, complicated by a penetrating eye injury. As she was 'out of position' within the vehicle, she slid over the deployed airbag, contacting the 'A' pillar.

Finally, the significance of short stature female drivers sitting close to the steering wheel is confirmed by the analysis of the sixth case (52-011-98). The airbag deployment resulted in the dorsum of her hand being deflected a high speed towards the right zygomatic complex and eye, forcing the stem of her glasses into the eye, exacerbating her ocular injuries.

Conclusions

This paper demonstrates the value of airbags to the safety of vehicle occupants. However, airbags must be considered as supplemental restraint systems and seatbelts remain the primary safety feature of modern vehicles.

On rare occasions, short stature occupants, even if properly restrained by a seatbelt, are at risk of facial injuries from airbag development.¹⁷ Similarly, in unrestrained, 'out of position' occupants, airbags may cause serious injury.^{17,39}

A spectrum of ocular injuries from abrasions and contusions to retinal detachment have also been reported.^{28,29} Again, the incidence of these injuries is rare and it must be emphasised that in the pre-airbag era serious ocular injury was common.^{40,41}

As such, the efficacy of airbags is clear and must be placed in the context of the 3000 lives per year NHTSA estimates will be saved when all passenger vehicles on the road are equipped with this supplemental safety feature.¹⁷

Furthermore, the new generation 'smart' airbags will minimise the risk of injury, even to small stature occupants as they prevent deployment in situations where they may have an adverse effect.¹⁷

Notwithstanding this, emergency physicians must be aware of the potential for airbag deployment to result in serious oculo-facial injuries occasionally.^{42,43}

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