MOTOR VEHICLE AIRBAGS AND RELATED OCULAR INJURY

by

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Adviser's Signature.................................................................

Date of Submission

June 1995
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I certify that it has not been submitted, in part or whole, for a higher degree in any other university and/or institution.

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ABSTRACT

The aim of this study is to document current literature regarding those ocular injuries sustained due to airbag deployment during a motor vehicle accident. Airbags have been proven to reduce morbidity and mortality but eye health care professionals and the larger community have to be aware of those injuries which may occur during airbag deployment.

A literature review was undertaken and from this review approximately eighteen different eye injuries have been documented. While nearly all of the eye injuries sustained due to airbag deployment had good prognoses some did not. The airbag has undergone changes in order to reduce injury but it will work properly and pose little threat to the occupant of a motor vehicle if it is used in conjunction with the wearing of seat belts for optimal performance, hence the term supplementary restraining system.

Studies undertaken in Australia in 1988 showed that 83% of drivers injured in motor vehicle accidents were wearing seat belts therefore the airbag has more potential in lowering this statistic. So that by the use of seat belts and airbags in conjunction injuries to areas such as the face and head including eyes can be considerably reduced.

It is apparent that injuries sustained to the head and face area are greater in accidents where a vehicle is not equipped with an airbag. Thus with an airbag the severity of such injuries should decrease.

Technology has gone on thus far to redesign the airbag to reduce potential injury to the benefactor (1) and even gone on to create airbags that deploy during side impact to protect occupants from injury (2) and in the not too distant future airbags for rear seat passengers may also become a reality (3).
As the cost of supplying airbags goes down they are thought to be most cost effective in terms of the morbidity and mortality reduction and thus bring overall benefit to the community because of this fact.

Literature has proven with data and fact that airbags do indeed save lives and reduce injury to those occupants in airbag equipped motor vehicles (4).
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INTRODUCTION

Since the late 1980's airbags have proliferated in the motor vehicle commercial market, although they were first introduced as early as 1974 in the USA on a select General Motors model range. Checks on these vehicles years later with airbags have shown that the airbag system was still functional and reports of their airbags being deployed up to 15 years later have been documented.

The availability of airbags in cars meant various side effects, including physical injuries to the face and to other parts of the body. The result has been apparent in medical and professional literature documenting injuries specific to airbag deployment. It is in the interests therefore of both eye health care professionals such as Ophthalmologists, Orthoptists, and the general community to be aware of any factors which may have the potential to cause ocular injury such as the airbag during a motor vehicle accident.

Becoming more aware becomes significant, in the case of the airbag, as most manufacturers now include airbags as standard safety equipment in Australia, thereby leaving the consumer with no choice when buying a car they like, (other than that of choosing to buy an alternative vehicle with no airbag equipped).

This point of having no choice or control over the airbag was part of much debate and controversy in the USA from the mid '70s to mid '80s regarding the fitting of airbags to motor vehicles, hence the lag in introduction of the airbag from 1974 to the late 1980s on a wide scale (5).
The controversy revolved around three main points:-

(1) Cost benefit ratio i.e. that the airbag cost is substantially higher and predicted benefit no greater than the corresponding cost and benefit of the 3 point seat belt (5).

(2) A lack of real-world testing i.e. testing the airbag's performance in those most commonly occurring car accidents (5).

(3) The high failure rate of airbags and their potential injuries to occupants. This is demonstrated by an Experimental Safety Vehicle test in the USA in March 31, 1972 where according to criteria set, dummies in vehicle were 'killed' because of airbag deployment (5).

While ocular injuries are the main concern of this study it is also important to note that other injuries have been documented as a result of airbag deployment. Such injuries may include spinal fractures and broken fingers (6). These and other injuries will be briefly mentioned at a later part of this study. Such injuries may justify further investigations into the potential total injuries one may suffer post airbag deployment. These total injuries should then be compared against those injuries that may have been caused had there been no airbag present which should justify the use of airbags.
METHODOLOGY

The method of investigation in this study was a literature review which included medical/professional and technical/professional literature.

Technical literature provided information on the workings of the airbag system. This information varied only slightly in terms of different components used by various car manufacturers. The results were mostly obtained from various car manufacturers manuals explaining generally how their individual systems worked.

The medical/professional literature was mainly obtained from Ophthalmological journals documenting mostly in terms of case studies the various eye injuries caused by airbags. Data was, however, limited in terms of car manufacturers reluctant to give specific detail on airbag workings (which may have been beyond the scope of this study anyway).

Medical data is also limited by the fact that because airbags are only a recent entity as a product of mass volume, reports are only now (very late 1980's to now) emerging on outer and other types of injuries and is also dependent on the current reporting of these injuries by way of publishing relevant details in professional literature. A literature review was undertaken to compile available data on ocular injuries caused by abusing medical and other professional publications and technical literature was reviewed for understanding on airbag technology.
LITERATURE REVIEW

In this literature review two types of literature were used. These comprised medical and technical literature mainly by way of professional journal publications.

The Technical literature began by explaining the overall workings of the airbag then went on to describe the major components of the airbag system.

The Medical literature documented in case study format those ocular injuries which had been inflicted as a direct result of airbag deployment, after motor vehicle accidents.
AIRBAG TECHNOLOGY

History of Airbags
The first patent for an airbag was awarded in 1953 to John Hetrick, an inventor in Pennsylvania, USA (7). According to Hetrick's testimony to the Government Committee, Hetrick recalls that he and his wife were driving with their daughter between them when Hetrick was forced to brake quickly. The parents reached out their arms to keep the child on the front seat and the concept of a protective 'cushion' was born. This idea was later translated into the popular child (restraint) safety seat (8). The inspiration to design a useful and preventive device came in 1944 when Hetrick saw the sudden inflation of a canvas protective cover surrounding a Navy torpedo undergoing repair (8). When compressed air from that torpedo was accidently released "the canvas bay blew up as quick as the blink of an eye" stated Hetrick (8). With the patent in hand Hetrick's wife wrote to the major U.S. car manufacturers, hoping they would respond by inviting Hetrick to help co-develop an airbag restraint system. They, however, showed no interest, but over the years did some experimenting with the airbag of their own (8). Hetrick's patent expired in 1970. Even though his is the true prototype of the airbag any due wealth has eluded Hetrick. The expiration of his patent left his invention to the public domain and so available to anyone (8). This meant, however, that many car manufacturers went on to experiment and develop their own airbag systems without any input from Hetrick.

General Motors and companies called Allied Chemical Co. and Eaton worked together to develop the airbag. The company offered drivers side airbags in 1974. Later on Ford Motor Company followed suit and eventually led Daimler Benz to offer airbags by the mid 1980's to certain (flagship) models of the Mercedes Benz range. Thereinafter airbags have gained a strong commercial market (7).
How Airbags Work

Some appreciation of airbags can be gained by following the sequence of airbag deployment as shown in Fig1. In a typical frontal accident, one vehicle collides head-on into a second. Sensors in the airbag-equipped vehicle detect the crash in the first 20 milliseconds (21). (1 millisecond is one one thousand of a second).

Deployment is initiated when electric current flows from the vehicle battery through the sensors to a thin wire embedded into a pyrotechnic material called the Squib (3). The squib burns and initiates an igniter mix, typically boron potassium nitrate, a very rapidly burning energetic compound. The igniter ignites the propellant, usually composed of sodium azide and an oxidizer. The propellant burns, producing primarily nitrogen gas, which inflates the airbag (3).

Figure 1

Airbag Deployment Sequence

Source: Breed, 1992

Once the sensor has detected the crash, the airbag is fully deployed in approximately 30 milliseconds, about one fifth the time it takes to blink an eye (or at a speed of 200K/h!) Since the airbag contains large holes or vents, it immediately begins deflating and is substantially deflated within a fraction of a second. The entire process is so fast that even if it were to deploy inadvertently, although it would startle the
driver, it should not significantly interfere with the driver's ability to see the road or to drive the vehicle to a safe stop (3).

An average male driver in a typical vehicle sits with his chest about 30cm from the steering wheel as illustrated in Fig 2. (Unfortunately it appears that airbags are designed taking only characteristics of the average male. Data on female characteristics was not available).

Figure 2. \hspace{1cm} Airbag Design Criteria

Source: Breed, 1992

A requirement for airbag system design is that the occupant cannot move more than 13cm toward the steering wheel before the airbag is fully inflated (10). Since the inflator takes approximately 30 milliseconds to inflate an airbag, a sensor must detect a crash 30 milliseconds before the occupant has moved 13cm. In a typical 48Km/h frontal barrier crash, this is between 15 and 20 milliseconds from the start of the crash (9). If the occupant moves more than 13cm before the bag is fully inflated, he or she runs the risk of being injured by the deploying bag. Actually, since many occupants sit closer than 30cm from the steering wheel, the risk of injury is greater (3). This should
invoke researchers to re-evaluate the design of the airbag in this instance so as to attempt to eliminate this disadvantage to those drivers closer than 30cm from the steering wheel, thereby discussing potential injury from airbag deployment.

Airbags are designed to protect occupants in frontal impacts where the velocity change is between about 20Km/h and 48Km/h. The airbag is actually designed to protect the average male occupant in a 48Km/h frontal barrier accident (3). Many accidents take place at higher velocities, involve smaller and older occupants, and differ substantially from frontal barrier impacts; thus people will continue to be injured (11).
Figure 3 is a basic representation on what occurs during airbag deployment. A vehicle travelling at approximately 18Km/h hits a solid object front on. The airbag is inflated. The driver’s head and chest impacts are absorbed thus awaiting striking the steering wheel. The airbag is then quickly deflated via rear ventilation holes.

Source: Honda Motor Co., 1991
Airbags can cause injury if the occupant is out of position and resting against the airbag when it deploys (3). An example might be an accident involving a small driver who sits very close to the steering wheel and crashes at 48Km/h. In this case, it is quite likely that, even if the driver has the seat belt on, he/she will be resting against the steering wheel at the time the airbag deploys and could sustain more injury due to the airbag deploying than if the airbag had not deployed (3). This is not the fault of the airbag system, but inherent in the 'trade-offs' that lead to the particular airbag design. Airbags today have contributed significantly to saving lives and reducing injury; nevertheless, there is potential for significant improvement (11).

System Description

Basically, an airbag system consists of one to five sensors, one or two airbag modules supporting structures for each module, a knee bolster and a Diagnostic and Energy Reserve Module (DERM) (3). A typical system is shown in Figure 4. The most striking difference between various systems is the number, kind and location of the sensors (10).

Figure 4. Motor Vehicle Airbag System

Source: Breed, 1992
Sensors are the brains of the airbag system. They determine when and if the airbag will be deployed. There are two categories of sensors depending on their function: discriminating, and safing or arming sensors (3).

Discriminating sensors make the determination that the vehicle is in a crash that requires the airbag to be deployed, while safing sensors merely confirm that an accident of any severity is taking place. Safing sensors, however, are less sophisticated than discriminating sensors and are usually mounted in the passenger compartment of the vehicle. Discriminating sensors, on the other hand, are critical to the proper functioning of the airbag system. To understand discriminating crash sensor technology, one must begin with an understanding of where sensors are mounted.

There are two areas in a motor vehicle where a crash can be detected. One area is where the car crashes, the crush zone, and the other is everywhere else in the car that is rigidly attached to the frame or vehicle structure, the non-crush zone. The crush zone is that part of the vehicle that is being substantially deformed by the accident up until the time that the sensor is required to decide whether to deploy the airbag. The crush zone almost always propagates rearward, in the case of a frontal impact, from the point of contact. That is, cars crush progressively. Most cars are designed to crush in this manner. If this were not the case, the repair cost would be larger as more of the vehicle would be damaged in the accident (3).

It takes about 30 milliseconds from the time that the sensor has sensed that a crash requiring an airbag is in progress for the gas generator to inflate the airbag. When an airbag is deployed, it emerges from its housing (in the centre of the steering wheel) with great force and velocity (approx. 200 Km/h) (4) and as mentioned there is a potential for injury to an occupant if he/she is too close to the airbag as it is deploying. Therefore airbag systems are designed so that an occupant seated in the mid-seating position does not interact with the deploying airbag (3) (Fig 2).
In a typical case, for example, the occupant seated about 30cm from the airbag before it deploys and moves no more than 13cm relative to the airbag before it is fully deployed. To assure this, sensors are designed so that, in a crash, they are able to sense the crash and initiate the airbag deployment 30 milliseconds before the occupant has moved 13cm.

The sensor designer studies data from a variety of staged crashes and adjusts the sensor so that it triggers in time on all of the required crashes and does not trigger on the crashes where the airbag is not required. The problem with this approach is that the designed must have data from all of the relevant crash and non-crash events. Most of the crashes staged by car manufacturers, however, are frontal and angle barrier impacts (3), which represents a small percentage of actual accidents (10). There are relatively little crash data available for those crashes that make up the majority of real world accidents (3).

There are two types of sensors used. More than 90% of all crash sensors are electromechanical, with electronic sensors making up the balance. Typically sensors used in the crush zone of the car are electromechanical air clamped ball-in-tube sensors, (See Fig 5).

![Ball in the Sensor Sensor Diagram](https://example.com/sensor_diagram.png)

Source: Honda Motor Co., 1991
These sensors rely on the flow of air between the ball and tube to control the motion of the ball and thus determine the operation of the sensor. These sensors inherently measure velocity change and thus are ideally suited for use in the crush zone. Sensors based on a spring and ball or mass system are also widely used - these are found mostly in the non crush zone, (See Fig 6).

Figure 6. Spring and Weight (mass) Sensor

DURING IMPACT

Source: Honda Motor Co., 1991
These sensors are completely sealed and filled with nitrogen to alleviate any corrosion problems. The sensor itself consists of a weight attached to a spring which moves forward at the point of impact, making a complete circuit.

Problems With Sensors
There have now been a number of complaints from people involved in accidents, that the airbag did not function properly. In some studies a significant number of deployments occurred when there was little damage to the vehicle (8). In other studies a number of owners have complained that the airbag did not deploy when there was significant damage to the vehicle after an accident and the occupant was injured (8). The consumer is unable to gauge whether the airbag should have deployed except by the damage their vehicles are sustaining.

People naturally believe that if the vehicle sustains significant damage, the airbag should deploy and if little damage exists, the airbag should not deploy (8). This doctrine of perceived damage may become eventually the airbag deployment criterion in the future.

Airbag Module
Airbags have initially been used for driver protection, but increasingly, passenger side airbags are being installed. The risk of fatality for rear-seat occupants and is only slightly less than for front-seat occupants (8). However, due to the infrequent use of the rear-seat it is unlikely that airbags will be installed to protect rear-seat occupants in the near future (3).

The driver airbag system consists of an airbag module, steering wheel and steering column that supports the module. The airbag module consists of an airbag, an inflator and a cover. The airbag system designer can select from a variety of inflator characteristics and airbag sizes and shapes. Occupant simulation modelling using
computers is used to match these characteristics to achieve the optimum protection. Since the characteristics of inflators vary with temperature these simulations are conducted at the temperature extremes. For the passenger compartment this range is usually -40°C - 95°C (10).

Most inflators contain sodium azide as the primary gas-producing propellant. Sodium azide burns in the presence of an oxidizer to form nitrogen and sodium oxide. The Sodium oxide is either trapped in the combustion chamber or condensed and filtered out by the cooling and filtering system. Some sodium oxide and other particulates pass through the filter system and into the airbag. For this reason the airbag is coated on the inside with neoprene rubber. Any hot particles are trapped in this rubber coating and prevented from burning a hole in the bag fabric.

The manufacture of sodium azide pellets for use in inflators has been fraught with problems, including a number of plant fires and explosions. Sodium azide is also very toxic to humans. Since sodium azide requires a high pressure to burn properly inflators are designed to withstand very high pressures of over 100 atmospheres. For these reasons, there has been a great deal of research to find a substitute propellant. One such material is nitro cellulose, which when properly formulated, burns rapidly at low pressure and does not have to be filtered.

The nitro-cellulose inflator is considerably smaller and lighter than the sodium azide inflator, and the airbag does not have to be coated with neoprene since the inflator does not produce hot particles. Although this inflator is currently only used for a smaller version of the airbag -Eurobag- or Facebag, tests are underway on other propellants that have similar properties to nitro-cellulose but produce much less carbon dioxide. It is believed inflators of the future may probably be non sodium azide burning and will be much smaller cleaner and less expensive.
The Design

The airbag design involves the selection of the diameter and thickness of the airbag and vent size. The thickness of the bag is determined by tethers or straps that are attached to the front and back panels. The overall bag size and shape is based on the geometry of the vehicle. The larger the passenger compartment and the greater the distance of the occupant from the steering wheel, the larger the airbag.

The size of the vents is also determined by occupant simulation modelling and is based on the crash pulse of the vehicle, and the steering column collapse. It is the flow of gas through the vents that dissipates the energy of the occupant as he/she compresses the airbag. If the vents are too large a large heavy occupant in a severe crush will compress the airbag too soon. If the vents are too small, a small light occupant will rebound off the airbag. The airbag vent size is affected by the collapsing force provided by the steering column. This collapse is a second mechanism for absorbing energy, and the force required to collapse the steering column is also an important design parameter of the airbag system.

Injuries caused by deploying airbags can possible be more severe on the passenger's side. The passenger airbag has a much larger volume and yet must interact with the occupant at about the same time as the driver's side airbag. (See Fig 7) As a result the passenger's side inflator must be more vigorous than the driver's side inflator (3).

When an automobile accident occurs, proper use of a seat belt is the most basic form of passenger protection. But when the accident is a frontal collision, the additional use of the Airbag System can ease the impact of the collision, especially to the passenger's face (9).

The passenger seat differs from the driver's seat in that the passenger's posture is not constant, and the passenger is often a child. Because of such large physical variations,
the passenger-side airbag system had to be analysed from numerous perspectives. In order to cover the variables in size and posture, it was necessary above all to make the airbag as large as possible. As a result, how to store and deploy the airbag became a difficult technical problem but, with advanced technology and exhaustive testing, these problems were overcome. Car manufacturers have been able to develop a system whose main characteristic is its low impact to the passenger when being deployed (9).

Figure 7. Driver's and Passenger's Side Airbag

Source: Honda Motor Co., 1991
On vehicles equipped with passenger side airbag, the operation is almost identical to the driver's side, however, the size of the bag on the passenger's side is twice that of the driver's side (120 litres). The main reason for this is that the size and posture of the passenger can vary greatly. Because of the airbag's large size, it is deployed from the top of the dash, unfurling in an upward motion first before filling outward. See Figure 8.
A driver can frequently anticipate an accident and restrain himself during panic breaking that frequently precedes a crash. The passenger, on the other hand, may not be alert or may be a small child who can be propelled forward prior to the collision.

If the occupant is wearing a seat belt, out-of-position injuries for both driver and passenger substantially become less of an issue, except for smaller drivers who sit close to the steering wheel. Airbag systems are supplemental restraint systems meaning that they are to be used with seat belts (12) (10) (3).

Knee Bolster
Knee bolsters are used more in the USA in conjunction with airbags to absorb the kinetic energy of the lower torso, i.e. the upper legs and knees, which is half of the total energy of the occupant (12). These are needed more so in the USA as seat belt wearing rates are lower than that of Australia, for if an occupant is wearing a seat belt a knee bolster would probably not be necessary (3). They are made of collapsable tubes, perforated steel and foam.

Self Diagnosis of the Airbag
In the USA one of the requirements of the passive restraint Federal Motor Vehicle Safety Standard is that the integrity of the electric circuit associated with the airbag be monitored. This is called DERM - Diagnostic and Energy Reserve Module which at minimum, passes a small current through the airbag system circuit. The total resistance is monitored of the circuit and if this resistance increases above an acceptable level, an indicator light on the instrument panel or steering wheel column is turned on indicating a fault in the system, (See Fig 9).
Designing the System - Occupant Modelling

There are many choices for each of the components that make up the airbag system. The actual system design is usually accomplished using computers and occupant simulation models. These models begin with a mathematical description of the vehicle, including the crash pulse, and the interior vehicle geometry and the durability for which the air system is designed (See fig 10).

Source: Honda Motor Co., 1991
When will an airbag work?

A severe frontal collision with:

- another vehicle
- a stationary object
- slight offset

When will it not work?

When the vehicle:

- is hit from behind
- is hit from the side
- rolls over

When it might not work

An impact caused from:

- dropping into a hole
- a collision with a pole
- colliding with the bed of a truck

Source: Honda Motor Co., 1991
In summary Figure 10 demonstrates when an airbag should deploy. It also demonstrates those situations when the airbag is not designed to deploy. Therefore it can be seen that the airbag is designed only to work in those situations deemed by the designers to warrant deployment, and requires an impact of substantial force before it will deploy.
AIRBAG MEDIATED OCULAR AND OTHER INJURIES

The airbag restraint system has been described as a means of reducing injuries and deaths in frontal accidents (6). This conclusion is based on crash investigations and statistical extrapolation, but few data exist to document specific ocular injury patterns after airbag deployment. Therefore what may emerge from further study is a decrease in motor vehicle accident fatalities, but also a pattern of ocular injuries specific to airbag use. What will follow will be thus far documented injuries to the human eye post airbag deployment. (Please refer to Appendix section for reference to labelled human eye diagrams).

The main structures of the eye will be described briefly so as to familiarize oneself with the structure. Following this description will be different ocular conditions which have manifest themselves in occupants of vehicles in which airbags did deploy during motor vehicle accidents.

The Eyelids

The eyelids subserve a protective function for the eye(13). They protect against environmental trauma, light damage, and the drying effects of constant exposure of the eye. The lid may be divided into four layers. The first or outer layer is the skin or epidermal layer, then the muscular layer, torsal layer, and finally the conjunctival layer which is a continuous layer that covers the inside of the eye lid and the outer surface of the eye(13).

Injuries Documented

1. Ecchymosis of the lids

   This is a pathologic condition resulting in where bleeding into the tissue occurs, resulting in discolouration of the eye under the skin - a bruise(14,15,16).
2. **Oedema of the lids**
   This is the swelling of the tissue in the eyelids due to fluid accumulation (15, 16).

3. **Laceration of the lids**
   Cut or gash in the skin of upper or lower eye lids. (16)

4. **Mechanical Ptosis of the lids**
   This is a functional defect which manifests itself by drooping of the upper eye lid. In this case caused by damage to the muscle of the eyelid (15, 17).

All of the above conditions, according to the documented case studies, resolved with no lingering effect.

**The Conjunctiva**

A thin, transparent mucous membrane lining inner surfaces of the eyelids and covering outer surface of the eyeball, excluding the cornea (23).

**Injuries Documented**

5. **Conjunctival Hyperemia**
   Eye redness caused by congestion of blood vessels in conjunctiva (15).

6. **Subconjunctival Haemorrhage**
   Bleeding from small blood vessels under the conjunctiva; often spontaneous from trauma or even coughing. This creates a harmless but striking bright red appearance over the sclera or white of the eye (14, 16).

The above conditions were noted to have resolved spontaneously.
The Sclera
This is the white of the eye. It is opaque, fibrous and serves as the protective outer layer of the eye. It contains collagen and elastic fibres. It is a very tough layer, hence its protective qualities (23).

Injuries Documented
7. Scleral Laceration
This may present in the form of a tear or gash in the white of the eye.
Prognosis is good, if not too severe a laceration (15)

The Cornea
This is the transparent front segment of the eye that covers the iris, pupil, and anterior chamber, and provides about two thirds of the eye's focusing power. It is made up of 6 separate layers (13).

Injuries Documented
8. Chemical Keratitis
This is by far the most commonly reported of all ocular injuries sustained in airbag equipped motor vehicles post collision. It is inflammation of the cornea characterised by loss of lustre and transparency. It is also characterized by an abnormal accumulation of cells and fluid into the cornea that are not present under normal conditions. This is triggered by the chemical sodium hydroxide and ash by products of airbag deployment. This may lead to corneal burns and further sight effecting complications (18,15,19,45,28) (See Discussion Section).

9. Corneal Abrasions
An injury characterized by a scraped area of corneal surface, accompanied by a loss of superficial tissue (epithelium). (18,15,19,23)
10. **Corneal Oedema**

   This is a hazy, swollen cornea. (18,15,19,23)

   Except for the Chemical Keratitis, abrasions and oedema all healed spontaneously with no after effects on vision.

**The Anterior Chamber**

This is the fluid filled space in the eye between the iris and the innermost surface of the cornea.

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**Injuries Documented**

11. **Angle Recession**

   This is the narrowing of the angle which is the front surface of the iris and back surface of the cornea where fluid filters out of the eye. With this angle being recessed (as the name of the condition implies) chances of the pressure in the eye increasing due to blockage of the filtering could lead to complications such as visual loss (20).

12. **Hyphema**

   This is the abnormal presence of blood in the interior chamber, which usually follows blunt trauma to the eye such as airbag deployment may do (15,18,16,20).

   Angle recession requires constant monitoring of the pressure inside the eye for a specified time to make sure no complications arise in those cases where it has been reported due to airbag injury - no problems have arisen.

   Hyphema may resolve spontaneously otherwise the blood may need to be removed.
The Iris
Pigmented tissue lying behind the cornea that (1) gives colour to the eye (e.g. blue eyes) and (2) controls the amount of light entering the eye by varying size of the black pupil opening (23).

Injuries Documented
13. Traumatic Iritis
This is a pathological condition which is characterized by inflammation of the iris. It can cause pain, tearing, blurred vision, small pupil, and a red congested eye.(24)

The Lens
The natural crystalline lens of the eye: It is transparent and biconvex shaped intraocular tissue that helps bring rays of light to a clear focus on the retina. It performs one-third of focusing power for the eye.

Lens capsule = Elastic bag enveloping the eyes' crystalline lens, helps control shape of lens.

Injuries Documented
14. Lens Subluxation
Partial or complete displacement of crystalline lens from its normal position. A dislocated lens (15).

15. Traumatic Cataract
Opacity or cloudiness of the crystalline lens; may present a clear image from forming on the retina. Lens may require surgical removal if visual loss becomes significant. In this case as the name implies caused by trauma.
16. Vossius Ring
Temporary ring-shaped deposit of pigment from the iris found on the front surface of the lens. This is almost always found after blunt trauma such as airbag deployment (16).

17. Phacodonesis
This pertains to the lens "wobbling" with eye movement (42).

The Vitreous Humor
This is the transparent, colourless jelly-like or gelatinous mass which fills the rear two-thirds of the eye ball between the lens and the retina.

Injuries Documented
18. Vitreous Haemorrhage
This is the abnormal presence of blood in the Vitreous Humor usually the result of trauma (16,21,22). This condition usually resolves in a matter of weeks.

The Retina
Part of the eye (but originally part of the brain) that converts images from the eyes' optical system (cornea and lens) into electrical impulses sent along the optic nerve for transmission to the brain. It forms the thin membranes lining of the rear two-thirds of the eye ball. It consists of 11 main layers.

Injuries Documented
19. Retinal Detachment
Separation of the retina from the underlying epithelial layer. This disrupts visual cell structure and thus usually markedly disturbs vision. Usually requires immediate surgical attention (22).
20. **Retinal Oedema**

This is swelling of the retinal tissue due to fluid accumulation (22, 16, 15).

21. **Retinal Dialysis**

This is a tear usually in the peripheral parts of the retina. Usually caused by blunt trauma (16).

Retinal disturbances are usually serious in that significant disruption to vision may occur that could also be permanent in nature. They usually require immediate specialist attention.

**The Orbit**

Pyramid-shaped (apex towards back of head) cavity in the skull, about 2 inches deep and lined by the orbital bones: (contains the eye ball muscles, blood and nerve supply and fat.

**Injuries Documented**

22. **Orbital Fracture**

It is the bones which line this cavity that have reportedly been broken due to airbag deployment. Usually caused by trauma to eye or orbit (16). (See Appendices C and D).

**Ocular Injury**

Soft tissue injuries may occur to the face and eyelids which are abrasive in nature and may be treated with warm soaks daily and possibly local antibiotic ointment. Satisfactory healing usually occurs with this type of injury (25). Chemical burns may also occur to these areas because inflation of the airbag requires an explosion of a material that produces a residual highly alkaline sodium hydroxide (25). These skin chemical burns may be treated with irrigation with normal saline solution for about
twenty minutes and the application of appropriate ointments such as local antibiotics two to three times daily.

The highly alkaline sodium hydroxide has also shown to have caused the most common of all ocular injuries post airbag deployment that is Chemical Keratitis. This should be recognised and treated promptly. The normal pH of the tears is in the range of 7.3-7.7; therefore, if people give medical attendants a history of being involved in an accident in which an airbag had deployed pH should be checked immediately. If the pH level is over 8 treatment should be started using large amounts of saline to wash out or irrigate the eye. This should be done from between half to one hour. Therefore litmus testing of pH should become a standard procedure when airbags have been thought to have deployed. These patients should also continue medical monitoring of eye condition carefully should treatment need to be changed or altered in any way. Corneal abrasions are thought to be caused by scums in the airbag. Design changes to the airbag should reduce this type of injury and careful medical follow-up is required.

Hyphema, subconjunctival haemorrhage, retinal oedema and haemorrhages may occur with this type of direct trauma to the eye as has been reported. Some of these may be harder to treat with poor prognoses even post treatment. Many facial injuries, cranial injuries and fatalities are prevented by airbag activation in motor vehicles. The above ocular injuries are an unfortunate by-product. However, it is much more certain that these injuries would have been much greater had these occupants hit their heads on the steering wheel rim or dashboard and the possibility of being thrown out of the car, through the windshield.

Drivers and passengers should be advised to always wear their seat belts which further reduces the risk of injury post airbag.
Other Injuries Reported
Injuries other than those to the human eye have also been reported. Such injuries may become common to airbag equipped vehicles. It is for this reason that such injuries are reported for the benefit of appropriate health personnel and the community at large.

* Burns and abrasions, and lacerations to the face, cheek, neck and arms - due to chemical by-products and friction caused during airbag deployment (26).

* Mandibular joint tenderness - that is soreness of the jaw bone where it is attached to the head (4).

This may have been caused by the occupant being out of position and by the airbag deploying forced the head of the driver between the edge of the airbag and the closed window of the car door.

* Spine injuries due to excessive flexing or bending of the spine which may lead to upper spine fractures, (See Fig 11).

In Diagram 1JA an unrestrained driver accelerating toward an inflating airbag causes a flexion mechanism in the upper spine. On the other hand the restrained driver who sits too close to the steering wheel may suffer a
hypertension of the cervical spine as the airbag expands upwards, (See Fig 11B).
Figure 11A  
Flexion of upper spine in unrestrained driver

Source: Blacksin, 1993

Figure 11B  
Hyperextension of spine in restrained driver

Source: Blacksin, 1993
Broken fingers and bleeding noses have also been reported, commonly associated with airbag deployment. The fingers being forced against the vehicle's interior at great speed, in the cases of broken fingers. In the case of bleeding noses, the sheer force at which the airbag deploys hits the nose at great speed causing it to bleed similar to that of being hit by an object in the facial area (27).

It can be illustrated therefore that airbags are indeed the cause of injury but one must consider that injuries sustained may have been far less serious than injuries which may be inflicted where no airbag was present.
DISCUSSION

As more and more cars are equipped with airbags, the number of reports of airbag-related eye injuries is also bound to grow (25). When a new product, originally introduced to increase safety, is itself documented to be the possible cause of trauma, it is then time to re-evaluate and further examine the product's usefulness, as is the case with the airbag.

This study of the international literature found many reporting on airbag-related eye injuries. A basic analysis of the details of ocular trauma, the outcome, and the circumstances of the motor vehicle accident (MVA), as found in such reports is as follows.

The title of the first report says it all as to the cause of injury: "Severe Ocular Trauma From a Driver's Side Airbag". However, if one reads the "Comments" section of this report, doubts arise. The authors admit that "there is a no way of knowing whether the airbag was protective in this case of ocular injmy or if it forced the patient's head laterally against the driver's side window" (16). The patient's visual acuity improved from 75% to 100% without treatment. In a second report "mild bilateral keratitis was seen in a 2 year old child (thrown from the rear seat to beneath the dashboard) (19) visual acuity 1 month after the injmy was 85% in the right eye and 90% in the left. A third report described one patient with corneal abrasions (24). Two weeks after the accident visual acuity was 95%. In a fourth report the author attributed a hyphema to the airbag (17). Visual acuity improved to 90% by the 16th day post injury.

In a fifth case, lid ecchymoses and edema, subconjunctival haemorrhage, corneal abrasion, and the right misaligned eye is turning about 20°-30° from the normal straight position, following a head-on crash (24). all injuries resolved completely. A sixth case report described a case of mild alkaline keratitis in one eye of the driver.
One week after injury visual acuity reached 95%. Details of the injuries were not published.

An eighth report described the most severe injury and the only one with significant and permanent visual damage (15). The patient suffered periorbital fractures, hyphema, lens displacement, vitreous haemorrhage, and retinal tears in one eye. Visual acuity 8 months following the injury was 60% capacity.

We must ask ourselves some questions following these reports: Were all of these injuries actually caused by the airbag and what would have happened to those injured had the car not been equipped with an airbag. Would they have escaped without injury? Or would they have escaped at all? Is it preferable to sustain corneal abrasions from an airbag or to hit the car's hard interior surfaces?

The airbag probably is responsible for certain eye injuries. All cases of proven chemical keratitis can reasonably be attributed to the material used (approximately 70g of sodium azide is ignited, inflating the 60 litre airbag in 10 milliseconds) (18); talc powder may also inflict abrasions. Minor blunt trauma may occur when the eye (moving forward) and the airbag (moving in the opposite direction) contact each other. Eye injuries can also result, if the inflating bag forces the individual's head sideways. However, such reports have to be firmly proven before the motor vehicle airbag is blamed for causing bone fractures.

There are at best two but possible three or even more collisions during a motor vehicle accident. The first collision is between the car and another object; the car abruptly slows down or is instantly brought to a halt. The second collision is between the occupant, who is travelling at the speed the car had been travelling, and the car's interior. Additional impact may result from rebounding. Imagine a collision of 80Km/h with the car's speed immediately falling to 0Km/h, but the driver is still
moving forward at 80Km/h; even if the seat belt is worn, the airbag provides an important cushion to absorb the body's kinetic energy.

The airbag prevents injury and death in motor vehicle accidents; its benefits far outweigh its risks. While it is everyone's responsibility to continue reporting and remaining aware of injuries that in fact have been caused by airbags, it is also so that those in the medical, legal, technical and general community do not derive false or unrealistic impressions of the Airbag System.

It is ironic that back in 1973 Volvo, the Swedish car manufacturer most commonly associated with its safety first attitude, opposed airbags stating that a properly worn seat belt in a well built vehicle will protect an individual in almost every case where survival is viewed as likely in an accident (28). This attitude was consistent with the opposition and controversy which surrounded the airbag from the mid to late seventies especially in the USA (5).

This controversy mainly consisted of concerns that the airbag would cause injury (maybe even death), and was not cost effective as opposed to the cost effective seat belt (5).

The previous section presented has shown that airbags caused injuries to the eyes, face and spine, as they inflated into a spherical ball. It is at this point that two important questions might be raised.

1. Is the spherical ball shape of the airbag engulfing the vehicle occupant's face by following the contours of the bony prominences of the face, thereby increasing contact of the airbag with the face and eyes? See Figure 12

2. Is the way that airbags are folded playing a role in causing injury?
These two questions have been raised and answered by most car manufacturers (8,28).
The question of airbag deployment shape has been answered by manufacturers by putting tethers inside the airbag to pull them down from a ball shape to a flatter doughnut. This found that the risk of eye injury and facial injury would be much reduced (29). (See Fig 13).
The way the airbags are folded also was thought to be potentially injury producing.\(^{(8)}\) How this has been alleviated is by using a system called an 'E' Fold which allows the airbag to inflate and move in a straight ahead direction toward the body rather than the alternative method of unfolding and wiping across the head and body.\(^{(8)}\)
Airbag Size and Shape

Airbags now come in many sizes. The smaller facebags or Eurobag of 30-45 litres was developed in Europe on the assumption that most front seat occupants would be wearing their seat belts at the time of an accident, therefore a larger airbag was not needed (30). These airbags do very little indeed for those occupants not wearing seat belts. They provide protection for the neck and face of a belted occupant in a frontal crash. They cost less, are more simple and do not take up the space of the larger alternative airbags. The bigger bags up to 70 litres (but usually 60 litres), however, when inflated were developed mainly for the US market where less people wear seat belts, therefore have a greater chance because of their large size to 'catch' an unbelted occupant in the event of a collision (30). The larger or 70 litre airbags offer protection for the head, face, chest and in some instances the stomach. They are also better at protecting occupants in angled crashes. They are thought to be the better choice of the two (8).

Sensors

The sensors signal the airbag to inflate. (3) Most sensors are electromechanical in nature such as the ball in tube mentioned previously. In Australia this kind is used but some systems used by other manufacturers use an electronic sensor system only. These are more expensive but are quickly becoming the sensor of choice because they can convey to the airbag system more about a crash that is going to happen. The worst part of the crash occurs at 50 to 100 milliseconds after the first touch of a collision. But by then it is thought that it is too late for the airbag to be inflated. The sensor must signal the need to fire the airbag within 15 milliseconds of first contact.

These electronic sensors use sophisticated circuitry and electrics to analyse what occurs in the first split second, and attempt to decide what type of collision will occur. It is then the system will know whether it needs to deploy the airbag or not.
Inflators

Nearly all inflators are based on the ignition of sodium azide, which in turn burns to produce the nitrogen needed to inflate the airbag (3). The speed of the inflation is reliant on the amount and formula used of the azide. As mentioned the airbag advances towards the occupant at approximately 200 Km/h, whatever the severity of the collision. Many manufacturers have likened this to a pillow-like effect in the face; experts disagree (8). It is the speed of the inflation that is thought to cause some of those injuries mentioned.

A dilemma for manufacturers here is to trade off the need for a fast, hard inflation, against the risk of injury to the out-of-position occupant in a small accident. The gas that is produced is quickly vented from an inflated airbag and these escaping gases have been the cause of burns. These vents have now been moved to the rear of the deploying airbag where the chance of burns is much less. A man in New Jersey, United States of America (USA) has taken a motor company to court for burns sustained post airbag deployment (31). At time of writing no outcome had yet been resolved by the US court.

The Airbag in Australia

In 1988, the Federal Office of Road Safety commissioned the Monash University Accident Research Centre to undertake a study of occupant protection in modern passenger cars (33). The projects report was based on 227 cars involved in crashes in which at least one occupant was killed or admitted to hospital. Researchers in this study found that, while the seat belt continued to be the main occupant protective measure in frontal crashes, many restrained drivers received serious head, face, chest and abdominal injuries through impacts, mainly with the steering wheel or belt contact, even when there was no major structural deformation to the occupied area and impact speeds were not excessive. Injuries were also sustained to upper and lower limbs.
The same study also found that, while some 94% of front seat occupants were reported to be wearing seat belts on the road, among those admitted to hospital or killed, only 83% were judged to have been wearing seat belts.

In Australia with a seat belt wearing rate of 94% amongst front seat occupants, the majority of drivers injured (83%) were wearing a seat belt, hence, there is considerable potential for a driver airbag to reduce head, face, chest and abdominal injury as well as provide passive safety to those drivers not restrained by a seat belt during a collision (in which the airbag would deploy).

It is also noted that the Insurance Institute for Highway Safety in the USA has reported that amongst belted drivers airbags would further reduce driver fatalities by 28%. (32) This further justifies airbag use in terms of mortality reduction.

In another study by the Highway Loss Data Institute in the USA found that drivers of airbag-equipped cars were 25% less likely to have suffered moderate and severe injury and 24% less likely to have been admitted to hospital than drivers who only had seat belt equipped cars (32).
Table 1 shows that for those drivers wearing a seat belt in an airbag equipped vehicle the risk of fatal injury is reduced by some 15% compared to only having a seat belt on without an airbag. (See Table 1)

<table>
<thead>
<tr>
<th>Risk of Fatal Injury*</th>
</tr>
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<tr>
<td><strong>Frontal crash 80km/hr barrier impact speed</strong></td>
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</table>

Source: Henderson, 1995
CONCLUSION

There is overwhelming evidence that airbags save lives and reduce morbidity (34). The speed of the vehicles at the time of the crash was 48 to 72 Km/h in cases which reported and provided data, and one cannot avoid the following question: Would not the injuries have been more severe if the cars had not been equipped with airbags? An analysis of data revealed that motor vehicle-related eye injuries are indeed sight threatening (18). Of 150 eyes sustaining motor vehicle-related serious injuries in the US Eye Injury Registry database, whose information was collected largely before the widespread use of airbags, 12% had to be surgically removed or enucleated. 41% of eyes with adequate ophthalmological follow-up remained legally blind (25).

This is not suggesting that the reports on airbag-related eye injuries are not true nor is it also suggesting that when a product has been proven time and time again to prevent injuries and trauma caused by it should not be reported. Such reports may be very useful in enhancing product design as seen in the development of the tethered airbag, and even reports advocating the use of protective eyewear while driving a car without an airbag.

Also recommendations have been made to improve occupant protection during a collision. These included energy absorbing steering wheels, improved seat belts, knee bolsters, improved padding in instrument panels, and continuous improvement in airbag design so as to minimize injury.

From information presented in car crashes in which airbags have deployed, the lifesaving benefits of the airbag as a supplemental restraint system have been praised. Injuries caused by deploying airbags are rare, despite this study. It should be noted that this supplemental restraint system lessens injury severity and cannot eliminate all motor vehicle crash induced injuries.
It is unanimous that airbags are valuable, important and are a necessary part of any vehicle's safety features, especially for those in the community seeking motor vehicles in which maximum possible safety is offered.
REFERENCES


(2) Our family should meet your family, brochure. 1994 Volvo, Australia.


APPENDICES
Appendix A

Section of Human Eye

Appendix B

Cutaway Section of the Eye

Source: The Ophthalmic Assistant, 1990
Surface Anatomy of Right Orbital Margin

Supraorbital notch

Eyebrow crossing

Supraorbital margin

Trochlea for superior oblique tendon

Superciliary ridge

Maxillary process of frontal

Frontal process of maxilla

Lacrimal crest of frontal process of maxilla

Medial palpebral ligament

Maxilla

Supraorbital notch

Lateral suture

Frontozygomatic suture

Zygomatic process of frontal

Strong lateral margin of orbit

Zygomatic

Infraorbital margin

Zygomatico-maxillary suture

Source: Clinical Anatomy of the Eye, 1990

Appendix D
The Right Orbit - Anterior View

Supraorbital notch

Optic canal

Orbital plate of frontal

Trochlear fossa

Orbital plate of maxilla

Greater wing of sphenoid

Lesser wing of sphenoid

Zygomatic

Zygomatico-facial foramen

Anterior ethmoidal foramen

Zygomatic foramen

Lacrimal groove

Inferior orbital fissure

Source: Clinical Anatomy of the Eye, 1990