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Driver and Front Seat Passenger Fatalities Associated with Air Bag Deployment. Part 2: A Review of Injury Patterns and Investigative Issues*

ABSTRACT: Assessment of the role of air bag deployment in injury causation in a crash of any severity requires analysis of occupant, vehicle, and impact data. The potential injurious role of an air bag is independent of crash severity and is more obvious in minor collisions, particularly those involving "out-of-position" occupants. Factors such as occupant height and other constitutional and medical factors, intoxication, age, type, and proper use of other restraint systems, pre-impact braking and multiple impacts can contribute to an occupant being "out-of-position." Two injury mechanisms are described in out-of-position occupants: "punch-out" when the individual covers the air bag module before deployment and "membrane-force" when the occupant contacts a partly deployed air bag. Each mechanism is associated with injury patterns. In adults, "punch-out" can cause thoraco-abdominal trauma and "membrane-force" loading can lead to craniocervical injury. This can also occur in short-statured occupants including children subjected to both types of loading. In more severe collisions, other factors, e.g., intrusion, steering column and seatbelt loading and other occupant compartment contacts, can contribute to trauma.

KEY WORDS: forensic science, motor vehicles, air bags, wounds, and injuries

Real-world data can explain not only the isolated unexpected or unusual trauma from air bag deployment in collisions of any severity as described in the preceding paper but also other factors contributing to injury causation particularly in higher speed crashes (1,2). An increased medical awareness of trauma patterns occurring in air bag-protected occupants involved in crashes of varying severity will not only assist in the clinical assessment of these injured individuals but also help resolve medicolegal issues regarding whether air bag deployment contributed to these injuries (3).

Methods

The methods used in the Air Cushion Restraint Study (ACRS) by Transport Canada were described previously (1). The study of the Canadian case series of fatalities associated with "first-generation" air bag deployment proceeded to a comprehensive review of the medical and engineering literature to define investigative issues that could arise regarding the relationship of air bag deployment and injury causation particularly as it relates to the North American automobile fleet (1). Cases from the ACRS were considered from the perspective of these investigative issues. This paper addressed the following:

1. The circumstances in which a motor vehicle occupant is "out-of-position" relative to a deploying air bag in a collision of any severity.
2. The consequent injuries associated with air bag deployment and whether patterns exist that could link the observed trauma to air bag deployment.
3. The factors in higher severity collisions other than air bag deployment, which must be considered in the cause of trauma.

Observations and Discussion

"Out-of-Position" Front Seat Occupant—Predisposing Factors

Various factors can contribute to a driver and right front passenger being "out-of-position" or in "near-position" relative to a deploying air bag. (See Table 1)

The risk of air bag deployment trauma is apparently increased in women (55,56). Dalmotas et al. found that about half of male and 3/4 of female drivers sustained an injury (25,57). Three of the five low severity frontal collisions in our Canadian study were women who were less than or equal to 5 ft. 4 in. in height (1). Despite National Highway Traffic Safety Administration (NHTSA) data indicating that 22 (19 drivers, 3 passengers) of 62 confirmed air bag deployment adult fatalities (56 drivers; 6 passengers) from 1990–1999 were women who were 5 ft. 2 in. (155 cm) or less, proximity to the air bag module, not height or gender, is the critical factor (5,9,10,12–19, 21–23,28,58).

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TABLE 1—*"Out-of-position" front seat occupant—predisposing factors.*

- Large Physique—Obesity (3)
- Short Stature—adjustment of car seat forward to reach floor pedals
  - Skeletal conditions (e.g., scoliosis, achondroplasia) (4,5)
  - Driver ≤ 5 ft. 4 in. (160 cm) (1,3,6,7–22) (see Observations and Discussion)
- Other Position Changes
  - Occupant of any age improperly seated, reaching, leaning forward (1,4,10,19,23–35)
  - Driver slumped over steering wheel due to drowsiness, medical condition (Case 1), intoxication (1,6,7,9,12,13,20–22,24,25,36–39) (see Observations and Discussion)
  - Forward movement of occupant of any age due to:
    - Pre-impact Braking
    - Preceding Minor (< air bag deployment threshold) Impact(s) and exacerbated if Manual Restraint System (see Observations and Discussion)
    - Not Used (1,2,4,5,8,10–12,15–17,20–22,24,26–28,30,31,33,34,37,39–53)
    - Slack (heavy clothing contributory); Slow lock-up (1,4,10,21,23)
    - Relaxation of Inertia-activated Belt after minor impact followed by air bag deployment in major impact (10,28)
    - Improperly Worn; Lap Belt only (1,25–28,34,44–46,54)
- Child-safety seat in right front seat (see Observations and Discussion)

An estimated 5% of the adult-air bag-caused fatalities in the United States have involved slumping forward despite restraint use (28). In the case of the pulmonary artery tear described in the Canadian study, the minor vehicular damage, the shallow angle of departure from the road, the lack of any evident evasive braking or steering maneuvers before impact and the presence of a significant level of alcohol in the deceased's blood suggested that the restrained driver could have passed out and was slumped over the steering wheel when the crash occurred (1,7,25,57). Similarly, in the case of a 37-year-old male driver described in the Canadian data, alcohol intoxication was considered a factor leading him to be slumped over the steering wheel (1).

Case 1 (6)

A 74-year-old unrestrained male driver (168 cm or 5 ft. 7 in.; 70 kg or 154 lb) was in a 1991 Ford Mustang that struck the side of a bus. There was significant underride with maximum intrusion at the windshield (estimated speed was 50 km/h or 31 mph based on witnesses who were following). Vehicle damage at bumper level was minor and a relatively soft crash pulse of long duration was suspected. Before the impact, these witnesses observed the driver slumped over the steering wheel. Autopsy showed coronary artery thrombus. Bilateral rib fractures were noted. Lacerations of the left scalp and forehead were observed and blood spatter was evident on the air bag. An autopsy documented intracerebral hemorrhages. Although these injuries were initially assumed to be from the deployed air bag, head contact with the windshield header (a portion of the eyebrow was seen on sunvisor) was observed. These injuries were consistent with the deceased's upper body going over the air bag (untethered type).

In the United States, up to about 70% of drivers and adult passengers wear seatbelts, whereas in Canada, the frequency is about 90% (5,6,25,26,36,56,57,59–61). Although air bag systems were introduced as a passive restraint to address occupant non-compliance in the use of harness restraints in the United States, usage of a lap-shoulder belt is essential for reducing the risk of air bag deployment injury by preventing the individual from moving forward before actual air bag deployment. A manual restraint also holds the occupant in position in front of the air bag (9,16,24). Otherwise, an unbelted or improperly belted occupant can sustain a head injury from various internal contacts (e.g., windshield header, windshield, sunvisor when going over the air bag; A-pillar in offset or side impact) if the air bag is missed as described in Case 1 (2,9,13,16,48,62). Because air bag systems cannot control occupant movements (e.g., ejection) in various crash types, harness restraint usage remains essential for adequate protection (2,40,41,59). There is no evidence that drivers in air bag-equipped vehicles reduce seatbelt use or become more careless because they believe that the air bag alone offers sufficient protection (43,60). Drivers and right front passengers who stop wearing lap/shoulder belts because they have an air bag can increase their fatality risk about 40% (34). NHTSA statistics show low seatbelt usage among those fatally injured by air bags (19,28). Forty of 62 adult fatalities (36/56 drivers; 4/6 passengers) were not belted (19). About 5% (3 drivers) were not properly belted (19).

Children (i.e., ≤12 years of age) are at increased risk for air bag deployment injury even in low speed collisions. (8,10,12,17,25,26,28–30,40,45,50,55). As of November 1999, according to NHTSA data, 86 had died from air bag deployment (19). Of the 63 not in safety seats, 59 were unrestrained or improperly restrained and, notably, pre-impact braking had occurred in 52 cases. This scenario was described in a Canadian case study of a 4-year-old boy who suffered a fatal neck injury (1). Recent U.S. statistics show that although 93% of infants are restrained in some manner, restraint usage drops to 65% for pre-teens, mirroring adult usage (45).

NHTSA has documented 23 children who were in child safety seats (rear-facing = 18; forward-facing = 5) when they died from air bag deployment (19). Because the back of a rear-facing child safety seat (RFCSS) is close to the dashboard, the force of the activated air bag is transmitted to the infant's head and the child is propelled against the vehicle seat (6,8,10,26,34,43–45,50,53,61). Similarly, the effectiveness of restraint systems in reducing injuries in adult front seat occupants can be decreased by loading from the rear (e.g., by an unrestrained rear passenger) (13,22,28). Forward-facing seats also position a child closer to the instrument panel (34,42,44,53,61). In some instances, the appropriate restraint for age and weight (a safety seat instead of a lap-shoulder belt) is not used or not used properly (19,28,45). American and Canadian guidelines recommend that children be secured by an appropriate restraint in the rear seat and that a RFCSS not be used in the right front seat if an air bag is present (4,10,12,19,28,34,43–45,54,56,61,63).

Out-of-Position Front Seat Occupant—Injury Mechanisms and Patterns

The Canadian series described infrequent (e.g., pulmonary artery laceration) and unusual (e.g., pulmonary "blast" hemorrhage) air bag deployment injuries and their mechanisms (1). Use of anthropometric dummies and surrogates has elucidated injury mechanisms, which explain fatal and severe injuries in the out-of-position occupant from air bag deployment in low-velocity collisions (20,24,39). If the path of deployment is blocked by the occupant, then increased pressure builds in the cushion during its inflation and high forces are exerted on the driver or passenger (24,39). As shown in dummy testing, the highest loads are generated when a body region is very close to (≤13 mm or 1/2 in.) or against the air bag module at the time inflation is initiated (15,20,24). The initial "punch-out" phase, which lasts less than 10 ms, causes thoracic and abdominal injuries when an occupant covers the air bag module (e.g., unbelted occupant, driver slumped over steering wheel as noted in our pulmonary artery tear case, pre-impact braking as noted in our previously described aortic laceration case) restricting the air bag from escaping during its initial pressurization (1,3,7,10,11,20,24,39). Additional load on the air bag module caused by significant forward momentum of the occupant could further increase the break-out pressure and loading severity (7). In testing situations, the head and neck will not fully restrict bag break-out but in real-world crashes, the force of the air bag including the module cover can result in injury to these sites in short-statured occupants including children (1,10,11,15,19,20,23, 24, 28,29,34,35,47,57,61). The "membrane-force" phase occurs after the air bag has partly deployed (7,20,24,39). The individual in the path of the inflating bag restricts its expansion and is subject to loading by the consequent increased bag pressure (20,24). The force generated can be as high as in the "punch-out" phase but a larger loading area of the torso is involved (20,24). Energy-absorbing steering wheels can reduce loading (11,39). "Membrane-force" loading can lead not only to thoraco-abdominal injuries but also head (e.g., basal skull fracture as observed in a 37-year-old male driver in the Canadian data) and neck trauma (e.g., cervical spine fracture-dislocation as noted in a case of C_1-C_2 dislocation occurring in a side collision in the Canadian series) in occupants by means of an "uppercut" or chin hyperextension (1,6,10,16,20,21, 23, 24,27,28,35,46,49,54,55,64–68). Alternatively, neck flexion after the air bag has struck the chest could lead to injury in an unrestrained occupant (29,65). Neck hyperextension can be exacerbated in a restrained child by submarining under the shoulder strap (49). The craniovertebral junction is vulnerable to trauma in children because of the large head and weak cervical musculature, relatively lax supporting ligaments and a minimally stable joint space created by relatively flat condyles and the shallow articular surface of C_1 in this age group (35,49,54).

The aged are less tolerant of trauma and elderly drivers are vulnerable to the force of the deployed air bag particularly if they are close to the steering wheel (8–10,13,18,22, 24,25,28,48,50,69). In the NHTSA data, 31 of the 62 adult fatalities were more than 60 years of age (24 $\geq$65 years) (19). In another series, 35% of the adult fatalities from air bag deployment were 65 years or older (28). One of our 5 frontal collision fatalities was over 65 years of age (1).

The force of a deployed air bag can propel occupants against internal vehicle structures (e.g., windshield header, roof, rear-view mirror) and individuals (e.g., a child into a right front passenger) causing additional trauma (3,19,26–29,32,35,46,47,53). Reconstruction of the collision in the previously described pediatric fatality in the Canadian case series showed that the child's upper torso was projected rearward and down by the deploying air bag, causing his head to strike and break a floor-mounted automatic transmission shift lever. An occipital scalp contusion was seen at autopsy (1,26,27).

Real-world collision experience has confirmed research observations of life-threatening and fatal air bag deployment injury patterns in out-of-position occupants including children (Table 2) (15,19,39,48,52,70). Isolated injuries of the craniocervical and thoraco-abdominal areas in adults can imply "membrane-force" and "punch-out" mechanisms respectively. Craniocervical trauma in the short-statured including children can be caused by both mechanisms.

Higher Severity Collisions—Other Factors Contributing to Injury

The risk of a serious injury from a deployed air bag is independent of crash severity and many injuries have been described in low to moderate severity collisions (1,3,7,13,16,21–23,26,27,32,39, 42,46–48,53–55,71,74). Others have been described in high severity crashes ($>$40 km/hr or 25 mph) (13,14,17,22,29,48,49,61,65, 68,72–75,77) (Table 2). Isolated injuries (e.g., flail chest, atrial rupture, pulmonary hemorrhage), particularly if infrequent or unusual in motor vehicle collisions, observed in high severity colllisions in the Canadian series raised the possibility of air bag deployment as a causative factor; however, in higher severity impacts, factors other than air bag deployment must be considered in injury causation. These factors can be useful in identifying an occupant who could be at high risk for serious injury (1,52).

In high severity crashes, the energy of the air bag deployment and the impact must be considered in the cause of injuries (20,24,42). High crash forces exceeding the limits of human tolerance coupled with occupant factors (e.g., large build, "out-of-position") can exceed the energy management capabilities of the air bag ("bottoming out") (3,11,31,40,41,43,63). Significant intrusion was noted in most cases of high severity collisions in the Canadian series (1). A driver either "out-of-position," inadequately restrained (Case 7 of Canadian series) or unbelted (Case 8 in Canadian series), even in a less severe crash, can load the steering wheel through the inflated air bag bending its rim or compressing its column (manifest as shear capsule separation) (1,3,13,19,21,38, 39,63,75,77).

Case 2

A belted 38-year-old male driver of a 1998 Pontiac Sunfire sustained major chest and abdominal injuries (cardiac, superior vena cava and hepatic lacerations) following a severe frontal impact with extensive underride ($\Delta V = 48$ km/h or 30 mph). His untethered air bag deployed in an initial minor impact (sideswipe of another car) and was not available for the major impact (collision with pickup truck). The load-limiting device on the seatbelt retractor, designed to work in conjunction with the air bag, could have exacerbated the force to the driverís chest during contact with the steering assembly by increasing forward excursion during the major impact.

An initial collision can trigger air bag inflation and when another impact follows, the cushion has partly or completely deflated leading to steering column loading or impact with other internal vehicle structures (3,29). This was seen in separate cases of flail chest and ruptured atrium in the Canadian series (1). Damage to the steering assembly can be an indicator of occult intrathoracic and intra-abdominal trauma in an individual who initially does not look seriously injured because of relative mitigation of external and other internal injuries (head, thoracic wall) by the inflated air bag (1,3,9,13,32,48,52,63,75). Alternatively, multiple injuries sustained in a severe crash can mask an occult air bag caused injury (73). Significant occupant compartment intrusion with associated high decelerative forces in a severe crash can overcome the protection offered by any air bag-manual restraint system and can be a risk factor linked with internal trauma (2,3,6,9,13,48,52,59,62). The likelihood of intrusion is greater in non–barrier-type crashes because the vehicle crush is more localized (11). Intrusion can displace the steering column affecting the path of the deploying air bag, although this may not reduce its effectiveness (11). Although manual and air bag restraint systems lessen the chance of serious head, chest and abdominal trauma, they do not protect against fractures of the lower extremities resulting from either intrusion at the instrument panel and toe pan areas or "submarining" under the air bag (2,3,6,11,13,38,48,56,62,63,78–80).

Air bags enhance the effectiveness of seatbelts by allowing greater load distribution in frontal crashes (11,16,39,41,58). During crash tests, seatbelt loading peaks at approximately 50 ms of the

TABLE 2—*Fatal and non-fatal serious injuries in drivers and front passengers associated with air bag deployment—Literature review.*

Craniocerebral Trauma

- Skull Fracture(s), nos* (c)† (19,28,53)
  - Base (nos, "ring," "hinge") ± Calvarium (c) (1,19,36,46,64)
    - Associated vascular tear (cavernous sinus, carotid artery) (17,19)
  - Depressed, nos (co)‡ (19)
  - Occiput (c) (19)
  - Calvarium only (co) (61)
- Subdural/subarachnoid/intraventricular hemorrhage (c) (3,13,15,16,19,28, 42,49,64)
- "Brain injury," "head injuries," nos (c) (19,53)
  - Maceration (co) (19)
  - Cerebral edema (c) (15,28,19,61)
  - "Closed head injury" (c) (1,19,56,61)
  - "Diffuse axonal injury" (c) (23,28,42)
  - Cerebral contusion (c) (19,28,47)
  - Cerebral hemorrhage, nos (c) (19,46,61)

Brain Stem—Cervical Spine Trauma

- "Decapitation" or "neck transection" (co) (19)
- Cervical spine injury or "neck fracture," nos (c) (19,64)
  - Atlanto-occipital or atlanto-axial dislocation (c) (1,16,19,23,25–29,38, 46,49,54,64)
  - Other fractures–dislocations (C_2 to C_7) (c) (1,13,19,28,29,36,46,65,68)
- Brainstem "injuries," nos (64)
  - Ponto-medullary tear or transection (c) (16,23,49)
  - Medullary hemorrhage/tear/transection (19)
  - Laceration or transection, nos (c) (19,36,64)
  - Brainstem or pons contusion/hemorrhage (c) (13,19,28)
- Cervical spinal cord "injuries," nos (c) (19,28)
  - Compression, laceration or transection (c) (19,25–28,46,54,64)
  - Contusion (co) (46)

Other Neck Injuries

- Transection or crushing of trachea-larynx (c) (19)
- "Blunt trauma to neck with asphyxia" or neck swelling leading to airway closure (19,25,36,57)
- "Neck injury," nos (co) (19)

Thoracic Injuries

- "Massive intrathoracic hemorrhage" (19)
- Heart injury, nos (19)
  - Laceration of heart or myocardium, nos (19,22,28,64)
  - Laceration of atria/ventricles (1,13,19,22,38,64,71,72)
  - Laceration of valve(s), nos (19, 64)
    - Tricuspid (19)
    - Aortic (14,73)
  - Contusions (13,19,22,38)
  - "Blunt force trauma to the chest resulting in sudden heart stoppage" (19)
- Lacerations of great vessels
  - Aorta, nos (1,19,56,64)
    - Thoracic, nos (19,38)
    - Ascending thoracic (19,74,75)
    - Arch (19,22)
    - Descending thoracic–isthmus (16,72)
    - Abdominal (19,21)
    - Aortic dissection (19)
  - Vena cava
    - Superior (19,22)
    - Inferior (c) (46)
  - Brachocephalic artery (Intima) (72)
  - Pulmonary vein (19)
  - Pulmonary artery (1,7,25,57)
- Azygos vein laceration (76)
- Lung injuries
  - Contusions (c) (13,19,28,38,46,64)
  - Hemorrhage = "Blast injury" (1)
  - Lacerations (19,38)
  - (Hemo) Pneumothorax (13,16,19,28,46,77)
- Multiple rib fractures–"crushing chest injury," "flail chest" (1,13§,19‖, 22,36)
- Thoracic spine fractures–spinal cord laceration (c) (19,46,64,65)

Abdominal and Retroperitoneal Injuries

- Lacerations of spleen, liver, bowel, mesentery (3,13,16,19,21,22,36,38, 48,64)
- Avulsion of kidney (co) (32)

* nos–Not otherwise specified.
† (c)–Injury described in children also.
‡ co–Injury described in children only.
§ Rib fractures contributing to respiratory failure in a 79-year-old man with lung cancer; belted driver, $_{\Delta}v = 35$ km/h (22 mph).
‖ 74-year-old female, 220 lb (100 kg), 65 in. (163 cm).

crash phase, which is close to the time required for air bag inflation (11,37). If activation of the air bag is delayed, a restrained occupant can experience seatbelt loading and an unbelted individual who moves forward can sustain unnecessary injury from the inflated air bag (22,23,28,37,48). Delayed deployment of an air bag could be a risk factor for heart injuries (22). Delayed deployment can occur if the air bag activation system senses a low deceleration pulse from either localized vehicle deformation or a relatively longer crushing time during the collision (e.g., impacts with narrow fixed objects and the more yielding rear or sides of vehicles, bumper over-ride and under-ride impacts (our Case 1), angled/offset-frontal crashes, the last comprising a significant number of real world collisions) (3,9,11,22,23, 37,43,48,55,63). Seatbelt loading can lead to internal injuries in high severity crashes and the elderly are particularly vulnerable even in potentially survivable impacts (3,9,78,81,82). Seatbelt pretensioners, which have a force-limiter feature lessen the chance of belt-induced chest and abdominal injury but can be ineffective when an air bag deploys early in multiple impacts (our Case 2) (10).

Conclusion

As more air bag-equipped vehicles enter the North American fleet, air bag deployment will figure more prominently in crashes. Meaningful analysis of how a restraint system such as an air bag can cause injury during a motor vehicle collision depends on an in-depth assessment of occupant, vehicle, and impact factors. Being "out-of-position" is the major risk factor for air bag deployment injury in a crash of any severity. Trauma patterns can be correlated with injury mechanisms arising from air bag deployment. The role of the air bag is more evident in minor, survivable collisions than in more severe crashes in which multiple factors come into play (55). These must be considered in any assessment of an injury, observed or described, before it can be attributed to air bag deployment. When many injuries are observed in high speed crashes, the role of air bag deployment could be incidental, the major factor, or one of several factors in injury causation. Air bag deployment will still be a consideration in trauma assessment even with the increased use of manual restraints and the introduction of "depowered air bags" (4,7).

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