J Forensic Sci, Sept. 2002, Vol. 47, No. 5
Paper ID JFS2001364_475
Available online at: www.astm.org

Michael J. Shkrum,[1] M.D.; Kevin J. McClafferty,[2] B.E.Sc.; Edwin S. Nowak,[2] Ph.D.; and Alan German,[3] Ph.D.

Driver and Front Seat Passenger Fatalities Associated with Air Bag Deployment. Part 1: A Canadian Study*

ABSTRACT: Real world motor vehicle collision research of injuries due to deployment of "first-generation" air bags has been conducted by Transport Canada since 1993. Fifty-three fatal crashes (36 frontal impacts; 17 side collisions) involving 48 drivers and 10 right front passengers were reviewed. In the Canadian data, air bag deployment in five of nine low severity frontal crashes (delta-V (ΔV) $<$ 25 km/h or 15 mph) was linked to five deaths, four of whom were autopsied (four adults with craniocervical (basal skull and C_2 fracture with brainstem avulsion; "closed head injury"—no autopsy) or chest trauma (aortic or pulmonary artery tears); one child with atlanto-occipital dislocation). An occupant who is close ("out-of-position") to the air bag at the time of deployment is at risk for injury. In 27 high severity frontal impacts, unusual (e.g., pulmonary "blast" hemorrhage in one autopsied case) or isolated potentially survivable injuries (e.g., clinically documented ruptured right atrium; probable flail chest observed during the autopsy on a decomposed body) localized to the head, neck or chest in three possibly out-of-position drivers pointed to the deployed air bag as a source of injury. In one of 17 side collisions an out-of-position driver sustained a radiographically confirmed C_1-C_2 dislocation in a minimally intruded vehicle.

KEYWORDS: forensic science, motor vehicles, air bags, wounds and injuries

The beneficial and detrimental effects of any motor vehicle restraint system can be best assessed by analysis of real-world collisions (1–8). In contrast to simulated surrogate testing, studies of occupant injuries in such crashes reflect the actual severity of occupant exposure to collision forces (7). Deaths and serious injuries, which have resulted from air bag deployment, particularly during low speed impacts, have caused considerable public controversy.

Methods

Transport Canada initiated the Air Cushion Restraint Study (ACRS) in 1993 to address safety issues surrounding air bag technology (9–13). Initially, any collision, which resulted in deployment of an air bag, was studied but this was later changed to cases in which the occupant associated with the deployment sustained a "major" injury (i.e., at the least was transported to hospital) (9,11,13). Additional cases of air bag deployment in low severity crashes leading to injuries were reviewed under the Special Collision Investigation Programme (9–11).

[1] Staff Pathologist, Department of Pathology, London Health Sciences Centre and Professor, Faculty of Medicine, University of Western Ontario, London, Ontario, Canada.

[2] Research Engineer and Director, respectively, Multi-Disciplinary Accident Research Team, Faculty of Engineering Science, University of Western Ontario, London, Ontario, Canada.

[3] Chief, Collision Investigation, Road Safety and Motor Vehicle Regulation Directorate, Transport Canada, Ottawa, Ontario, Canada.

* Presented as "Canadian Case Studies of Driver and Passenger Fatalities Associated with Airbag Deployment" at the 51st Annual Meeting of the American Academy of Forensic Sciences, Orlando, Florida, February 1999.

Received 19 Oct. 2001; and in revised form 11 March 2002; accepted 23 March 2002; published 14 Aug. 2002.

The collision investigations were done by eight university-based accident research teams working across Canada. The research teams were established by the Road Safety and Motor Vehicle Regulation Directorate of Transport Canada, to study motor vehicle collisions and have been operational for over 25 years. The teams are comprised of full-time engineers and collision investigators with consultants hailing from a diverse group of professions including medicine, engineering, psychology, and law enforcement. The University of Western Ontario Accident Research Team is the only team with a forensic pathologist as a senior medical consultant.

The collision investigation process involved detailed inspections of vehicles and components, scene inspections, interviewing of witnesses and reviewing of medical information (e.g., clinical observations, postmortem reports). The documented information was used by team and Transport Canada personnel to assess collision severity and crashworthiness of the air bag-equipped vehicle, reconstruct vehicle dynamics and occupant kinematics and identify possible injury mechanisms (10,12,13). Information was condensed from detailed collision reports into case summaries.

The delta-V (ΔV) is the change in velocity that occurs during an impact. The delta-V is a good predictor of crash severity and is used in this paper to gauge the severity of the collisions. Delta-V was typically computed by damage analysis methods using the inertial properties of the colliding vehicles, measurements of vehicle deformation, the principal direction of the impact force and pre-determined vehicle stiffness values. In some cases, a damage analysis approach was not suitable and other methods were used for delta-V calculation. When possible, the delta-V was verified using vehicle pre-impact and post-impact trajectory information (10,14–18).

The collisions reviewed in this paper are not a representative Canadian sample of fatal collisions in which there has been deployment of a front air cushion restraint. While many of the fatal cases were randomly sampled from defined geographic areas within Canada, included in the sample are all known deaths in Canada up to 1997 in which the air bag was believed to be a major factor in the fatality.

Results

Over 800 crashes have been investigated. A subset of driver and right front passenger fatalities associated with air bag deployment was studied. A total of 53 fatal crashes was reviewed involving 48 driver fatalities (41 belted) and 10 right front passengers (7 belted). Frontal collisions occurred in 36 impacts; 17 were side impacts.

Low Severity Frontal Collisions (Estimated Speed or $\Delta V < 25$ km/h or 15 mph) = Nine Impacts (Nine Deaths)

Air bag deployment in five impacts was directly related to five fatalities comprising four adult drivers and one child right front passenger (Table 1).

In four other low severity impacts, air bag deployment was merely coincidental to the cause of death. Two drivers drowned. A 36-year-old male restrained driver was in a minivan, which hit several small trees ($\Delta V = 20$ km/h or 12.5 mph) before vaulting into a river. A car, driven by a 42-year-old restrained male, went down an embankment into a swamp where the front undercarriage impacted the ground. The vehicle then rolled coming to rest on its roof in the water. Another driver sustained a basal skull fracture due to roof intrusion after his car hit a moose. An unbelted 74-year-old likely had a cardiac arrest prior to impact causing him to floor the accelerator pedal and veer off the road striking several objects. Autopsy revealed an aortic dissection with extension around the coronary vessels.

Higher Severity Frontal Collisions = 27 Impacts (28 Deaths = 26 Drivers; Two Passengers)

In 16 of the collisions, the impact was offset or angled and involved extensive damage to the left front end. Raking damage along the left side and significant intrusion were often observed. Seven cases were full-frontal impacts while four cases involved extensive underride. Twelve trucks, six fixed objects, six passenger vehicles, two pickup trucks and one bus were struck. Evidence of steering wheel loading by the driver was apparent in 18 cases.

Not all of the higher severity frontal impacts were unsurvivable.

Case 6

A 65-year-old male driver (180 cm or 6 ft; approximately 90 kg or 200 lb) sustained multiple rib fractures i.e., a presumed flail chest. His vehicle (1996 Cadillac Deville) left a highway and traveled across a cornfield. His untethered air bag deployed during ground impacts prior to a more severe impact with a tree ($\Delta V = 34$ km/h or 21 mph). He was found beside his car, two weeks after the collision. Decomposition hindered a conclusive determination of cause of death at autopsy.

Case 7

A 44-year-old restrained male (164 cm or 5 ft 6 in.; 75 kg or 165 lb) was the driver of a 1995 Honda Odyssey minivan which was in a narrow offset (intrusion on driver's side) frontal impact ($\Delta V = 47$ km/h or 29 mph) with a pickup truck. Pre-impact braking was not evident.

The driver was dead at the scene. There was no evidence of seatbelt loading implying a slack seatbelt. The driver's seat was rearward of the middle position but could have been moved when the driver was extricated. Blood smears were seen on the deployed tethered air bag. The steering wheel rim had been loaded on the left lower side and there was spoke deformation (Fig. 2). There was partial shear capsule separation in the steering column.

Among the injuries seen at autopsy, there were contusions of the upper chest and neck, which could have been caused by contact with the air bag, seatbelt, or steering wheel. The cause of death was extensive bilateral pulmonary hemorrhage from blunt chest trauma.

Case 8

An unrestrained 17-year-old female driver of a 1997 Toyota 4-Runner SUV suffered a ruptured right atrium after a severe full-frontal impact ($\Delta V = 50$ km/h or 31 mph) with a concrete bridge

FIG. 1 *(Case 1)—58-year-old restrained female driver sustained a pulmonary artery laceration from air bag deployment after her vehicle struck a utility pole sustaining minor damage ($\Delta V = 20$ km/h or 13 mph).*

FIG. 2 *(Case 7)—44-year-old restrained male driver, in a high severity collision ($\Delta V = 47$ km/h or 29 mph), had extensive pulmonary hemorrhage. Evidence of steering wheel deformation and loading was observed.*

TABLE 1—*Air bag deployment fatalities in low severity frontal collisions—Canadian case studies.*

Case	Occupant	Vehicle	Struck Object	ΔV	Out-of-Position	Air Bag	Fatal Injury	Skin Trauma	Other
1 (9,11,19)	58 yr female driver restrained 160 cm (5′4″); 64 kg (140 lb)	'94 Plymouth Sundance	Utility pole (Fig. 1)	20 km/h (13 mph)	Seat forward. Possibly slumped.	T* Clothing Transfer	Autopsy—Tear of left main pulmonary artery	Chest	No rib fractures BAC^{+} = 17 mmol/L (80 mg%)
2 (13)	79 yr female driver restrained 155 cm (5′2″) 77 kg (169 lb)	'92 Ford Tempo GL	Embankment Pre-impact braking	14 km/h (9 mph)	Seat forward	T	Autopsy—Delayed aortic rupture	Chest	Multiple rib and sternal fractures C_1 fracture
3 (13)	44 yr female driver restrained 157 cm (5′3″) 53 kg (117 lb)	'96 Lexus ES 300	Garage wall	17 km/h (11 mph)	Seat forward	T Cosmetic Transfer	No autopsy "Closed Head Injury"	Unknown	
4 (10)	37 yr male driver unrestrained 170 cm (5′8″) 90 kg (198 lb)	'93 Ford Probe GT	Steel sign post Sideswipe of light standard (intrusion at left B-pillar)	"Minimal" 39 km/h	Possibly slumped	T?	Autopsy—Basal fracture, basilar artery tear, brainstem avulsion	Chest Temple	Odontoid (C_2) fracture Lacerations of lung, liver, spleen. Flail chest. BAC = 53 mmol/L (250 mg%)
5 (11,20–22)	4 yr male right front passenger restrained—torso part of belt behind back 107 cm (3′7″); 18 kg (40 lb)	'95 Hyundai Accent	Rear of car Pre-impact braking	19 km/h (12 mph)	Seat in mid-position Leaning forward	T Clothing Transfer	Autopsy—Atlanto-occipital dislocation with spinal cord transection	Face, neck	Scalp (occiput) contusion

* T—tethered; T?—unknown whether tethered.
⁺ BAC—blood alcohol concentration.

abutment. The vehicle was involved in several minor impacts and consequently the driver could have been out-of-position at the time of the major collision when her tethered air bag deployed. Steering column compression due to occupant loading was seen. No autopsy was done. The injury was observed during internal cardiac massage in the hospital emergency department. Initial impact of the driver's chest with the deployed air bag likely caused the ruptured atrium. Because of the severity of the collision, the chest eventually contacted and compressed the steering column through the inflated air bag.

Side Collisions = 17 Impacts (21 Deaths = 14 drivers; 7 Passengers)

There was severe occupant compartment intrusion in 16 of the 17 side impacts; however, one case showed minimal occupant compartment intrusion.

Case 9

A 20-year-old restrained woman was driving a 1996 Ford Ranger XL pickup truck. Its right front side was struck by the left front of an oncoming multi-purpose vehicle. The driver's tethered air bag deployed. The restrained 21-year-old male passenger had minor cutaneous contusions. The driver was pronounced dead at the scene. No autopsy was performed. Her estimated weight was 52 kg (114 lb.) and her length was 160 cm (5 ft 4 in.). External examination revealed a hypermobile neck and a forehead laceration. A radiograph showed C_1-C_2 dislocation (Fig. 3).

The driver's seat was fully forward to allow her to reach the foot pedals, a position confirmed by family members (Fig. 4). The passenger also noted that the driver could have leaned forward to see the road. Red smears consistent with lipstick were seen on the air bag. One of these was at a fold, which indicated that the driver made contact with the bag when it was partly folded early in the deployment phase. The overall ΔV was determined to be 44 km/h (27.5 mph) with a longitudinal ΔV component of 11 km/h (7 mph). The steering system was undamaged.

FIG. 3 *(Case 9)—20-year-old restrained female driver in vehicle struck on passenger side. Radiograph showing C_1-C_2 dislocation (arrow).*

FIG. 4 *(Case 9)—Driver's seat adjusted fully forward.*

Discussion

An air bag is activated in a vehicle when there is significant deceleration along its longitudinal axis (9,23–26). Most deployments occur in full or offset-frontal vehicle-to-vehicle collisions (5,9–11,26,27). In North America, the threshold range for deployment of a "first-generation" air bag in a frontal crash is 7 to 16 mph (about 11 to 25 km/h) when the impact force is directed $\pm 30°$ (i.e., 10 to 2 o'clock positions) relative to a perpendicular to the vehicle's hood (2,23,24,26–35). A side impact with a sufficient longitudinal component can trigger an air bag and this has been observed in up to 10% to 20% of various case series (our Case 9) (9–11,27,36,37). About 1% to 2% of air bags deploy when there is an impact to the top or undercarriage of the vehicle (our case 6) (9–11,38). Inappropriate deployment from impacts other than frontal can lead to unnecessary injury (25).

Canadian studies have shown that 3/4 of air bag deployments have happened at low velocity i.e., $\Delta V \leq 25$ km/h or 15 mph (9–11,13). At least 1/2 of air bag deployments result in injuries to drivers and passengers (5,9–11,38,39). Minor cutaneous and soft tissue injuries, particularly abrasions, comprise 90% to 95% of the observed trauma and most commonly involve the face and upper extremities (4–6,9–11,38–41). Patterned and non-patterned cutaneous and soft tissue injuries of the head, neck, chest, and abdomen as well as blood, tissue, cosmetic or clothing transfers can help confirm occupant contact with an air bag (e.g., cases 1,2,4,5,7,9) (4,6,13,19–24,38,40,42–52). Although air bag and manual restraint systems combined have been effective in reducing serious head injuries including facial fractures and chest trauma by lessening interior contacts in moderate to severe crashes, these benefits have been partly offset by the increased frequency, relative to belted-only occupants in equivalent crash situations, of the aforementioned superficial injuries as well as upper extremity fractures occurring in low (< 25 km/h or 15 mph, i.e., at the lower limit of air bag deployment threshold) and moderate (25–39 km/h or 15–25 mph) severity impacts (5,9–13,23,27,28,31,34,40,41,53). Nevertheless air bags, alone or supplementing a manual restraint, have reduced driver and right front passenger fatalities particularly in frontal crashes (10,24,26,31,32,34,40,45,51,53–58). Some studies have shown or estimated an overall reduction in belted and unbelted adult occupant fatalities in the order of 10% to 20% (2,12,20,24,26,31,33–35,53–58). In the United States, as of November 1999, an estimated 4094 drivers and 768 right-front passengers had been saved mainly in moderate and severe crashes (59). Between 1990 and 1997, about 150 lives have been estimated to be saved in Canada (28). Unfortunately, certain individuals have been severely or fatally injured from air bag deployment occurring in low speed impacts during which these occupants would have been adequately protected by a manual restraint system (e.g., Cases 1–3) (11,13,23).

A motor vehicle occupant who is close to an air bag at the time of its deployment is at risk for serious injury because of the "aggressive" nature of the air bag system (7–13,19,23,24,26–31, 37,39,41,44,47,49,60–63). "First generation" is used to describe all pre-1998 air bag systems and 1998 air bag systems not yet redesigned (12). The aggressivity of these systems reflects their inflation characteristics, which must prevent an occupant from being pitched far forward by expanding fully within 50 ms after sensing a sufficiently severe crash and which, in the United States, are governed by the unbelted test requirement of a federal regulation which specifies the use of a 50th percentile male hybrid III dummy (equivalent to 5 ft 9 in. or 173 cm; 167 lb or 76 kg) in a 48km/h (30 mph) rigid frontal barrier crash (4,9–13,19,20,23,25,29,30, 36,47,51,59,63,64). The velocity of a deployed "first-generation" air bag can range from 145 km/h to 328 km/h (90 mph to 211 mph) (4,23,28–30,32,36,43–45,47,50,51,60,65–70). Because of the integrated nature of the North American automotive industry, similar air bag systems are used in Canada and, although meeting Canadian performance standards, the protection requirements of certain occupants can be compromised in low severity collisions (9–13,19,20,23,30,62,71). Based on simulated crashes, the recommended distance between a driver's chest and the center of the steering wheel is at least 25 cm (10 in.) which allows for 12.5 cm (5 in.) of forward excursion and "give" in the harness restraint, if worn, before occupant contact with the air bag occurs (13,25,26,28,29,31,45,71,72). Head excursion forward can occur despite the use of a restraint (4,5). Tethered driver air bag maximum excursion distances are from 30 to 37.5 cm (12 to 15 in.); untethered air bags range from 42.5 to 50 cm (17 to 20 in.) (29). The forces exerted by the air bag are greatest in the first 8 to 12.5 cm (3 to 5 in.) of inflation (28,29). The expanded volume of a driver's air bag is 60 L; a passenger's air bag is 120–150 L (U.S. models) (8,30).

The pyrotechnic nature of the deployed air bag is associated with unique and unusual injury mechanisms (e.g., "bag slap" leading to facial trauma, upper extremity fractures from arm flailing or air bag module impact during a turning maneuver, thermal burns of the face and arms from the air bag vents) (1,9–13,23,27,30,39,40,43, 48,65,67).

Traumatic rupture of the pulmonary artery, described in Case 1, is uncommon. Although it has been observed in motor-vehicle-collision-related trauma, most cases are associated with other mediastinal or pulmonary hilar injuries (e.g., bronchial laceration) rather than being isolated (73,74). Although the main pulmonary arteries can be torn anywhere along their course, the observation in Case 1 that the left main branch was lacerated raises the possibility that this site was predisposed because of its proximity to the scarred remnant of the ductus arteriosus, a potential area of weakness in the aorta when it is stressed (19,73,74). A chest wall contusion was observed in Case 1 consistent with air bag contact but no rib fractures were seen in the 58-year-old victim, a finding more likely in a younger more elastic rib cage (19,35,69,74). The relatively thin pulmonary artery could have been torn by hydrostatic forces and barotrauma has been proposed in the causation of cardiac perforation (e.g., atrial rupture, our case 8), heart valve injury and lung trauma arising from air bag deployment (19,35,42,69). Morgenstern et al. described a case of a 36-year-old unbelted female driver who developed bilateral pneumothoraces attributed to the expulsion of high-pressure gases into her lungs from a ruptured deployed air bag (35).

The "viscous tolerance criterion" seeks to explain the rate-sensitivity-predisposition of soft tissue to injury as a product of compression and deformation velocity (1,64,75,76). At low impact velocity (< 5 m/s or 11 mph), which could be experienced by the chest of a belted occupant in a frontal crash, the degree of compression determines the risk of injuries (e.g., rib fractures) (1,64,75,76). Soft tissue tolerance to compression decreases as the velocity of deformation increases, i.e., the "viscous response" (1,75,76). In higher speed impacts, the peak viscous response, i.e., the risk of soft tissue injury can occur before there is maximum compression (1,7,75,76). Such a situation arises when the air bag begins to break through the module cover before maximum chest compression has occurred ("punch-out" phase) (7,61). When the impact velocity to the body (e.g., chest) exceeds 30 m/s (> 67 mph), rib fractures can be absent yet lung trauma including variably severe pulmonary hemorrhage can result (35,64,75–77). Internal injuries without concomitant rib fractures are typical of impulsive or "concussive" loading with low compression (35,64,77). A blast generates stress waves and results in significant pressure differentials at the micro vascular level of an air-blood interface (e.g., alveoli) leading to extravasation of blood (75–77). Lung injury as well as lacerations of the aorta and aortic valve in the absence of chest wall trauma has been described in explosions (78). Such injuries have also been described in association with air bag deployments (our Case 7) (20,66,79–81). Since the forces exerted on an out-of-position occupant directly over the inflating first generation air bag happen at high velocity, then the observed injury patterns can be explained by a viscous mechanism (75).

The interdependence between impact velocity and compression not only influences the physical integrity of internal anatomic structures but also affects their physiologic response to trauma. Fatal blast-induced pulmonary hemorrhage, which can be diffuse or focal, could signify heart rhythm disturbance (78). Because blast trauma is rapid and the survival interval short, pathologic changes may not be evident in the heart (78). The velocity of impact on the mid-chest is a major factor in the evolution of ventricular fibrillation and animal studies have shown that hearts subjected to direct blunt trauma can develop transient and even fatal arrhythmia (1,64,75,81,82). Commotio cordis has been proposed as an injury mechanism for motor vehicle occupants situated too close to a deployed air bag (44,60). NHTSA data cites several cases attributable to this mechanism. For example, a 40-year-old male driver (170 cm or 5 ft 8 in.; 91 kg or 201 lb) was in a collision ($\Delta V = 30$ km/h or 19 mph) during which the deployed air bag caused a sternal fracture and "sudden heart stoppage" (59).

Conclusion

The Canadian case series documented fatalities attributable to first generation air bag deployment occurring in low velocity frontal collisions. All of these deaths involved an occupant who was apparently close to or "out-of-position" relative to a deploying air bag. Three were women drivers who were no more than 5 ft 4 in. tall and had their seats positioned forward. An intoxicated male driver could have been slumped over a steering wheel. A young right front passenger was improperly restrained and leaning forward at the time of air bag deployment. In crashes of any severity, unusual or uncommon trauma localized to the head, neck or chest and substantiated by an accurate postmortem examination raises the possibility of unique injury mechanisms associated with air bag deployment (3,21). This was apparent in three high severity frontal collisions. The fatal injuries (pulmonary "blast" hemorrhage, flail chest, ruptured right atrium) occurred in drivers who could have been out-of-position. Air bag deployment injury can occur in impacts other than frontal crashes. An out-of-position driver suffered a C_1-C_2 dislocation in a side collision.

Acknowledgments

The authors thank Mrs. Paula Miller and Mrs. Lisa Noseworthy for transcription of this manuscript and the Visual Services Department, London Health Sciences Centre for preparation of the figures.

References

1. Viano DC. Cause and control of automotive trauma. Bull NY Acad Med 1988;64:376–421.
2. Viano DC. Restraint effectiveness, availability and use in fatal crashes: implications to injury control. J Trauma 1995;38:538–46.
3. Huelke DF, Moore JL. Field investigations of the performance of air bag deployments in frontal collisions. Accid Anal Prev 1993;25:717–30.
4. Hollands CM, Winston FK, Stafford PW, Shochat SJ. Severe head injury caused by airbag deployment. J Trauma 1996;41:920–22.
5. Morris AP, Thomas P, Brett M, Bruno-Foret J, Thomas C, Otte D, et al. A review of driver airbag deployments in Europe and Japan to date. Paper No. 96-S1-O-03. Proceedings of the 15th International Technical Conference on the Enhanced Safety of Vehicles 1996; May 13–16; Melbourne (Australia). Washington, DC: National Highway Traffic Safety Administration, 1996.
6. Maxeiner H, Hahn M. Airbag-induced lethal cervical trauma. J Trauma 1997;42:1148–51.
7. Horsch J, Lau I, Andrzejak D, Viano D, Melvin J, Pearson J, et al. Assessment of air bag deployment loads. Warrendale, PA: Society of Automotive Engineers, Inc.; 1990 SAE Report No.: 902324.
8. Augenstein JS, Digges KH, Lombardo LV, Perdeck EB, Stratton JE, Malliaris AC, et al. Occult abdominal injuries to airbag–protected crash victims: a challenge to trauma systems. J Trauma 1995;38:502–8.
9. Dalmotas DJ, Hurley J, German A, Digges K. Air bag deployment crashes in Canada. Paper No. 96-S1-O-05. Proceedings of the 15th International Technical Conference on the Enhanced Safety of Vehicles; May 13–16,1996; Melbourne (Australia). Washington, DC: National Highway Traffic Safety Administration, 1996.
10. Dalmotas DJ, German A, Hendrick BE, Hurley RM. Airbag deployments: the Canadian experience. J Trauma 1995;38:476–81.
11. Dalmotas DJ, Hurley RM, German A. Supplemental restraint systems: friend or foe to belted occupants? Proceedings of the 40th AAAM Conference1996; Oct. 7–9; Vancouver (Canada). DesPlaines, IL: Association for the Advancement of Automotive Medicine, 1996.
12. Dalmotas DJ. Assessments of air bag performance based on the 5th percentile female hybrid III crash test dummy. Paper No. 98-S5-O-07. Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles 1998; May 31–June 4; Windsor (Canada). Washington, DC: National Highway Traffic Safety Administration, 1998.
13. German A, Dalmotas DJ, Hurley RM. Air bag collision performance in a restrained occupant population. Paper No. 98-S5-O-04. Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles 1998; May 31–June 4; Windsor (Canada). Washington, DC: National Highway Traffic Safety Administration, 1998.
14. Marquardt JF. Collision severity - measured by delta v. Proceedings of the 21st AAAM Conference 1977; Sept. 15–17; Vancouver (Canada). Des Plaines, IL: Association for the Advancement of Automotive Medicine, 1977.
15. Hight PV, Lent-Koop DB, Hight RA. Barrier equivalent velocity, delta v and CRASH3 stiffness in automobile collisions. Warrendale, PA: Society of Automotive Engineers, Inc.; 1985 SAE Report No.: 850437.
16. Campbell KL. Energy basis for collision severity. Warrendale, PA: Society of Automotive Engineers, Inc.; 1974 SAE Report No.: 740565.
17. CRASH3 User's Guide and Technical Manual. Washington, DC: 1982 National Highway Traffic Safety Administration Publication No.: DOT-HS-805732.
18. Tumbas NS. Measurement protocol for quantifying vehicle damage from an energy basis point of view. Warrendale, PA: Society of Automotive Engineers Inc.; 1988 SAE Report No.: 880072.
19. McClafferty KJ, Shkrum MJ, Chan J, German A. A multi-disciplinary study of a Canadian airbag fatality. Proceedings of the Canadian Multidisciplinary Road Safety Conference X 1997; June 9–11; Toronto. Toronto (Canada): Vehicle Safety Research Centre, Ryerson Polytechnic University, 1997.
20. McCaffrey M, German A, Lalonde F, Letts M. Air bags and children: a potentially lethal combination. J Pediatr Orthop 1999;19:60–4.
21. German A, Dalmotas D, Comeau J, Monk B, Contant P, Gou M, et al. In-depth investigation and reconstruction of an air bag induced child fatality. Paper No. 98-S5-W-19. Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles 1998; May 31–June 4; Windsor (Canada). Washington, DC: National Highway Traffic Safety Administration, 1998.
22. Giguère JF, St-Vil D, Turmel A, DiLorenzo M, Pothel C, Manseau S, et al. Air bags and children: a spectrum of c-spine injuries. J Pediatr Surg 1998;33:811–6.
23. German A, Dalmotas DJ, McClafferty KJ, Nowak ES. Real-world collision experience for airbag technology. Proceedings of the Canadian Society for Mechanical Engineering Conference 1996; May 7–9; Hamilton (Canada).
24. Marsh IV JC. Supplemental air bag restraint systems: consumer education and experience. Warrendale, PA: Society of Automotive Engineers, Inc.; 1993 SAE Report No.: 930646.
25. Breed D, Sanders WT, Castelli V. A complete frontal crash sensor system–1. Warrendale, PA: Society of Automotive Engineers, Inc.; 1993 SAE Report No.: 930650.
26. Braver ER, Ferguson SA, Greene MA, Lund AK. Reductions in deaths in frontal crashes among right front passengers in vehicles equipped with passenger air bags. JAMA 1997; 278:1437–9.
27. Werner JV, Sorenson WW. Survey of airbag involved accidents. An analysis of collision characteristics, system effectiveness and injuries. Warrendale, PA: Society of Automotive Engineers, Inc.; 1994 SAE Report No.: 940802.
28. Air bag deactivation. Road Safety and Motor Vehicle Regulation Directorate, Transport Canada, Mar 1998.
29. Bloch B. The coming revolution in airbag technology. Paper No.98-S5-W-30. Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles 1998; May 31–June 4; Windsor (Canada). Washington, DC: National Highway Traffic Safety Administration, 1998.
30. Struble DE. Airbag technology: what it is and how it came to be. Warrendale, PA: Society of Automotive Engineers, Inc.; 1998 SAE Report No.: 980648.
31. Frame P, MacPherson R. Air bags-legions of fable-consumer perceptions and concerns. Warrendale, PA: Society of Automotive Engineers, Inc.; 1998 SAE Report No.: 980905.
32. National Highway Traffic Safety Administration: Air bag alert. Ann Emerg Med 1996;28:241–2.
33. Graham JD, Goldie SJ, Segui-Gomez M, Thompson KM, Nelson T, Glass R, et al. Reducing risks to children in vehicles with passenger airbags. Pediatrics 1998; 102:130. URL:http://www.pediatrics.org/cgi/content/full/102/1/e3.
34. Evans L. Restraint effectiveness, occupant ejection from cars, and fatality reductions. Accid Anal Prev 1990;22:167–75.
35. Morgenstern K, Talucci R, Kaufman, MS, Samuels LE. Bilateral pneumothorax following air bag deployment. Chest 1998;114:624–6.
36. Chan H, Hackney JR, Morgan RM, Partyka S, Samaha R, Guiseppe J. Frontal air bag deployment in side crashes. Warrendale, PA: Society of Automotive Engineers, Inc.; 1998 SAE Report No.: 980910.

37. Augenstein JS, Perdeck EB, Murtha M, Stratton J, Quigley C, Zych G, et al. Injuries sustained by drivers in air bag crashes. Paper No. 96-S10-O-01. Proceedings of the 15th International Technical Conference on the Enhanced Safety of Vehicles 1996; May 13–16; Melbourne (Australia). Washington, DC: National Highway Traffic Safety Administration, 1996.
38. Huelke DF, Reed RT. Front seat passengers and airbag deployments. Paper No. 96-S1-O-2. Proceedings of the 15th International Technical Conference on the Enhanced Safety of Vehicles 1996; May 13–16; Melbourne (Australia). Washington, DC: National Highway Traffic Safety Administration, 1996.
39. Air bag injuries are mostly minor but a handful are serious, even fatal. Insurance Institute for Highway Safety Status Report 1995 Mar;30 (3):2,4.
40. Antosia RE, Partridge RA, Virk AS. Air bag safety. Ann Emerg Med 1995;25:794–8.
41. Augenstein JS, Perdeck E, Williamson J, Stratton J, Horton T, Digges K, et al. Injury patterns in air bag equipped vehicles. Paper No. 98-S1-O-06. Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles 1998; May 31–June 4; Windsor (Canada). Washington, DC: National Highway Traffic Safety Administration, 1998.
42. Hanna KM, Weiman DS, Pate JW, Wolf BA, Fabian TC. Aortic valve injury secondary to blunt trauma from an air bag. Tenn Med 1997;90:195–6.
43. Smock WS, Nichols II GR. Airbag module cover injuries. J Trauma 1995;38:489–93.
44. Brown DK, Roe EJ, Henry TE. A fatality associated with the deployment of an automobile airbag. J Trauma 1995;39:1204–6.
45. Perez J, Palmatier T. Air bag-related fatality in a short, forward-positioned driver. Ann Emerg Med 1996;28:722–4.
46. Chidester AB, Rutland KW. Air bag crash investigations. Paper No. 98-S6-O-02. Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles 1998; May 31–June 4; Windsor (Canada). Washington, DC: National Highway Traffic Safety Administration, 1998.
47. Jumbelic MI. Fatal injuries in a minor traffic accident. J Forensic Sci 1995;40:492–4.
48. Huelke DF. An overview of air bag deployments and related injuries. Case studies and a review of the literature. Warrendale, PA: Society of Automotive Engineers, Inc.; 1995 SAE Report No.: 950866.
49. Huelke DF, Reed RT. Cranial-vertebral fractures and dislocations associated with steering wheel airbag deployment. Paper No. 96-S1-O-1. Proceedings of the 15th International Technical Conference on the Enhanced Safety of Vehicles 1996; May 13–16; Melbourne (Australia). Washington, DC: National Highway Traffic Safety Administration, 1996.
50. DeGuzman BJ, Morgan AS, Pharr WF. Aortic transection following airbag deployment. N Engl J Med 1997;337:573–4.
51. Morrison AL, Chute D, Radentz S, Golle M, Troncoso J, Smialek J. Air bag-associated injury to a child in the front passenger seat. Am J Forensic Med Pathol 1998;19:218–22.
52. Cooper JT, Balding LE, Jordan FB. Airbag mediated death of a two-year-old child wearing a shoulder/lap belt. J Forensic Sci 1998;43:1077–81.
53. Malliaris AC, DeBlois JH, Digges KH. Air bag field performance and injury patterns. Warrendale, PA: Society of Automotive Engineers, Inc.; 1996 SAE Report No.: 960659.
54. Kahane CJ. Fatality reduction by air bags. Analyses of accident data through early 1996. Washington, DC: 1996 National Highway Traffic Safety Administration Publication No.: DOT HS 808470.
55. Zador PL, Ciccone MA. Automobile driver fatalities in frontal impacts: air bags compared with manual belts. Am J Public Health 1993;83:661–6.
56. Lund AK, Ferguson SA. Driver fatalities in 1985–1993 cars with airbags. J Trauma 1995;38:469–75.
57. Airbags on the passenger side save lives. Insurance Institute for Highway Safety Status Report 1996 Dec;31(10):6.
58. Air bags save lives. Nearly 50,000,000 vehicles confirm effectiveness. Insurance Institute for Highway Safety Status Report 1995 Mar;30 (3):1,10.
59. National Highway Traffic Safety Administration World-Wide Web Site - http://www.nhtsa.dot.gov.
60. King AI, Yang KH. Research in biomechanics of occupant protection. J Trauma 1995;38:570–6.
61. Melvin JW, Horsch JD, McCleary JD, Wideman LC, Jensen JL, Wolanin MJ. Assessment of air bag deployment loads with the small female hybrid III dummy. Warrendale, PA: Society of Automotive Engineers, Inc.; 1993 SAE Report No.: 933119.
62. Coben LE. The risk and benefits of air bag systems: are they needlessly killing and injuring motorists? Warrendale, PA: Society of Automotive Engineers, Inc.; 1997 SAE Report No.: 970492.
63. Mertz HJ, Marquardt JF. Small car air cushion performance considerations. Warrendale, PA: Society of Automotive Engineers, Inc.; 1985 SAE Report No.: 851199.
64. Lau IV, Horsch JD, Viano DC, Andrzejak DV. Mechanism of injury from air bag deployment loads. Accid Anal Prev 1993;25:29–45.
65. Huelke DF, Moore JL, Compton TW, Samuels J, Levine RS. Upper extremity injuries related to airbag deployments. J Trauma 1995;38:482–8.
66. Martinez R. Improving air bags. Ann Emerg Med 1996;28:709–10.
67. Smith DP, Klein FA. Renal injury in a child with airbag deployment. J Trauma 1997;42:341–2.
68. Blacksin MF. Patterns of fracture after air bag deployment. J Trauma 1993;35:840–3.
69. Lancaster GI, DeFrance JH, Borruso JJ. Air-bag—associated rupture of the right atrium. N Engl J Med 1993;328:358.
70. National Highway Traffic Safety Administration: Air bag deployment characteristics. Springfield, VA: 1992 National Technical Information Service Publication No.: DOT 807 869.
71. National Highway Traffic Safety Administration: National Conference on Medical Indication for Air Bag Disconnection–July 16–18, 1997. Ann Emerg Med 1998;31:782–3.
72. Jolly BT. NHTSA notes commentary: air bags–the changing landscape. Ann Emerg Med 1998;31:783–4.
73. Collins MP, Robinson GC. Traumatic rupture of the pulmonary artery. Ann Thoracic Surg 1989;47:612–3.
74. Shkrum MJ, McClafferty KJ, Green RN, Nowak ES, Young JG. Mechanisms of aortic injury in fatalities occurring in motor vehicle collisions. J Forensic Sci 1999;44:44–56.
75. Lau IV, Viano DC. The viscous criterion–bases and applications of an injury severity index for soft tissues. Warrendale, PA: Society of Automotive Engineers, Inc.; 1986 SAE Report No.: 861882.
76. Cooper GJ, Taylor DEM. Biophysics of impact injury to the chest and abdomen. J R Army Med Corps 1989;135:58–67.
77. Lau V, Viano DC. Influence of impact velocity and chest compression on experimental pulmonary injury severity in rabbits. J Trauma 1981;21:1022–8.
78. Wilson JV, Tunbridge RE. Pathological findings in a series of blast injuries. Lancet 1943;i:257–61.
79. Pillgram-Larsen J, Geiran O. Kollisjonsputer pavirker skademonsteret ved alvorlige thoraxtraumer (Air bags influence the pattern of injury in severe thoracic trauma). Tidsskr Nor Laegeforen 1997;117:2437–9.
80. Dunn JA, Williams MG. Occult ascending aortic rupture in the presence of an air bag. Ann Thorac Surg 1996;62:577–8.
81. Prasad P, Daniel RP. A biomechanical analysis of head, neck, and torso injuries to child surrogates due to sudden torso acceleration. Warrendale, PA: Society of Automotive Engineers, Inc.; 1984 SAE Report No.: 841656.
82. Link MS, Wang PJ, Pandian NG, Bharati S, Udelson JE, Lee M, et al. An experimental model of sudden death due to low-energy chest-wall impact (commotio cordis) N Engl J Med 1998;338:1805–11.

Additional information and reprint requests:
Michael J. Shkrum, M.D.
Department of Pathology
London Health Sciences Centre
375 South Street
London, Ontario, Canada
N6A 4G5