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Children in crashes: mechanisms of injury and restraint systems

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Objectives: To explore the levels of protection offered to children involved in motor vehicle collisions. **Design:** A joint study by the Children's Hospital of Eastern Ontario (CHEO) and Transport Canada, Ottawa, conducted in 2 phases: retrospective from 1990 to 1997 and prospective from 1998 to 2000. **Setting:** CHEO, a university affiliated tertiary care centre. **Patients:** Children admitted to CHEO between 1990 and 2000 with spinal trauma due to motor vehical crashes (MVCs). Phase 1 of the study involved analysis, in a series of 45 children after MVAs, by location of spinal injury versus belt type. Phase 2 was a prospective study of 22 children injured in 15 MVAs. **Interventions:** A biomechanical assessment of the vehicle and its influence on the injuries sustained. **Main outcome measures:** The nature and extent of the injuries sustained, and the vehicle dynamics and associated occupant kinematics. **Results:** The odds ratio of sustaining a spinal injury while wearing a 2-point belt versus a 3-point belt was 24 (95% confidence interval 2.0–2.45, $p < 0.1$), indicating a much higher incidence with a lap belt than a shoulder strap. **Conclusions:** Proper seat-belt restraint reduces the morbidity in children involved in MVCs. Children under the age of 12 years should not be front-seat passengers until the sensitivity of air bags has been improved. Three-point pediatric seat belts should be available for family automobiles to reduce childhood trauma in MVCs.

Objectifs : Étudier les niveaux de protection assurée aux enfants victimes de collisions de véhicules à moteur. **Conception :** Étude conjointe réalisée par l'Hôpital pour enfants de l'est de l'Ontario (HEEO) et Transports Canada à Ottawa, en deux volets : étude rétrospective de 1990 à 1997 et étude prospective de 1998 à 2000. **Contexte :** HEEO, centre de soins tertiaires affilié à une université. **Patients :** Enfants admis à l'HEEO entre 1990 et 2000 qui ont subi un traumatisme à la moelle épinière causé par une collision de véhicules à moteur. La phase 1 de l'étude a consisté à analyser, dans une série de 45 enfants victimes d'une collision, le point du traumatisme à la moelle épinière par rapport au type de ceinture de sécurité. L'étude prospective de la phase 2 a porté sur 22 enfants victimes de 15 collisions. **Interventions :** Évaluation biomécanique du véhicule et de son effet sur les traumatismes subis. **Principales mesures de résultats :** La nature et l'étendue des traumatismes subis, ainsi que la dynamique du véhicule et la cinématique connexe des occupants. **Résultats :** Le coefficient de probabilité d'un traumatisme à la moelle pendant que le sujet portait une ceinture à deux points plutôt qu'une ceinture à trois points s'est établi à 24 (intervalle de confiance à 95 %, 2,0–2,45, $p < 0,1$), ce qui indique une incidence beaucoup plus élevée dans le cas de la ceinture abdominale que dans le cas du baudrier. **Conclusions :** Une bonne ceinture de sécurité réduit la morbidité chez les enfants victimes de collisions de véhicules à moteur. Les enfants de moins de 12 ans ne devraient pas prendre place sur le siège avant tant qu'on n'aura pas amélioré la sensibilité des sacs gonflables. Des ceintures de sécurité pédiatriques à trois points devraient être disponibles pour les véhicules familiaux afin de réduire les traumatismes chez les enfants victimes de collisions de véhicules à moteur.

Motor vehicle crashes (MVCs) are the leading cause of injury, disbility and death in Canadian children.[1] A number of reports have documented the role restraint systems play in the mechanism of injury, with solitary lap belts being clearly implicated in injuries to the lumbar spine.[2–7] Airbag-induced injuries have also been well documented even in properly restrained children.[8–14] A pilot study first demonstrated the feasi-

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bility of identifying children injured in MVCs in a hospital emergency department setting by the medical authors with concurrent analysis of involved vehicles and investigation of the crash scenes by the engineering authors. The purpose of the present study was to demonstrate the feasibility of a trauma-based crash study of children's injuries, to describe in detail the mechanism of specific injuries involving lap-belt trauma to the lumbar spine and air-bag induced injury to children occupying the front-seat position, based on a correlation of the medical injuries with an engineering analysis of the crash site and the crash vehicle.

Methods

The study was conducted in 2 phases. Phase 1 was a retrospective review of all children admitted to our institution with MVC-induced spinal trauma between 1990 and 1998. Information collected included the details of injury, vehicle travelling speed and type of restaint used.

Subsequently, a prospective consecutive study of all children admitted to the emergency department at our institution between 1998 and 2000 was undertaken (phase 2). Inclusion criteria included involvement in an MVC with an injury severe enough to require hospital admission. Medical data were collected prospectively, in a structured fashion, with priority given to the damage to the "case vehicle" (the vehicle in which the patient was a passenger) and the injuries of its occupants.

The engineering team personnel obtained early notification of the occurance of such a collision from the hospital-based medical personnel. When possible, investigators responded to the accident at the scene. In all cases, scenes were examined for physical evidence, (tire marks, gouges, fluid spills). This information was used to reconstruct vehicle dynamics and collision configurations. A full investigation of the vehicle included photographic documentation after its removal from the scene. Critical dimensions and location and extent of the crash profiles were recorded. In collisions that involved several vehicles, external damage of vehicles coming into contact with the case vehicle were similarly documented. The interior of the case vehicle was inspected for physical evidence: seating geometry, evidence of restraint use, including seat-belt loading and airbag deployment, and physical evidence indicating contact points of passengers that were related to injuries sustained.

All occupants of the case vehicle were contacted and interviewed. Information pertaining to the pre-crash seating positions, posture of occupants, and the manner in which restraints were used were also obtained.

Collision severity was determined using 2 methods. First, the barrier equivalent velocity (BEV) was determined from the measurements of structural damage to the vehicles, using a variant of the CRASH program.[15] Second, the change in velocity (ΔV) was determined from momentum-based calculations.

Both injury data and crash information were then used to determine crash dynamics, occupant kinetics and specifics of injury mechism. This process was undertaken jointly by the medical team and engineers experienced in studying crash dynamics.

The χ^2 test was used for statistical analysis. BEV and ΔV (change of vehicular velocity during the crash) values were obtained from the CRASH software program and momentum calculations.

The crash site and vehicular assessment data were correlated with the child's injury in an attempt to formulate the mechanism of injury and the role of the restraints in the injuries.

Results

Phase 1

The cases of 45 children, ranging in age from 3 to 19 years, were reviewed retrospectively. Children were divided into groups based on site of injury and belt type (Table 1). A total of 9 children sustained cervical spine injuries; 31 children sustained lumbar spine injury; and the remainder (5) sustained thoracic spine injury.

Phase 2

Prospective data included a series of 26 children injured in 15 MVCs (Fig. 1), including 5 children with distraction spinal injuries (Chance fractures). Four children with Chance fractures wore 2-point belts, 1 wore a 3-point belt. Twenty-one children without a Chance fracture included 3 with 2-point belts and 18 with 3-point belts. The odds ratio of sustaining a Chance fracture while wearing a 2-point belt versus a 3-point belt was 24 (95% confidence interval 2.0–245, $p < 0.1$).

Ilustrative case reports

The cases presented below were drawn from data compiled from the 15 cases investigated prospectively to date. Cases were selected to illustrate specific injury mechanisms.

Case 1. Lap belt injuries secondary to malposition of the belt

A severe head-on highway crash occurred between a 1998 Honda Accord and a 1998 Nissan Maxima (case vehicle) after the Accord drifted over the centre line. The BEV was 82 km/h. The 3 occupants were a 30-year-old man restrained with a 3-

Table 1

Summary of Spinal Injury by Location and Belt Type in 45 Children

	Fracture type	
Belt type	Cervical spine	Lumbar spine
2-point	3	21
3-point	1	3
Not specified	3	9
No belt	2	4

point belt and airbag, a 6-year-old girl with lap belt and a 4-year-old boy with lap belt. The man sustained displaced fractures of the forearm and tibia. The girl sustained a lumbar spine fracture with paraplegia, iliac artery and jejunal tears. The 4-year-old boy sustained a lumbar spine fracture (Fig. 2), paraplegia, jejunal tear and a cranial nerve VI palsy. Data obtained from car measurements and the patients' extremity lengths demonstrated a discrepancy in seat depth to lower extremity length. Examination of their abdomens revealed belt loading marks at the umbilical level indicating malposition of the belt (Fig. 3).

This case represents a severe deceleration injury. The discrepancy between lower extremity length and seat depth forced the children into a slouch position in order to bring the lower leg over the edge of the seat. This in turn brought the lap belt into a more proximal position on the abdomen creating a direct load to the lumbar spine rather than to the iliac wings of the pelvis during the crash, resulting in a flexion-distraction fracture of the lumbar spine and paraplegia.

Case 2. Appropriate belt function

A frontal impact occurred between a Chevrolet S10 pickup and a Toyota Celica that had turned left into the truck's path. BEV was 48 km / h. The 2 occupants were a 35-year-old man and a 5-year-old boy each wearing a 3-point belt. The adult sustained a mild concussion as well as cuts to the forehead and knee. The child sustained a concussion, a laceration to the left brow and a fracture of the left iliac wing.

The force of the crash, sufficient to fracture the iliac wing, was successfully transmitted to the pelvis by a well-fitting floor-mounted seat belt. In contrast to the injuries sustained by the patient in case 1, a patient can recover fully from this injury primarily because the lap belt was correctly positioned over the pelvis and not the abdomen.

Case 3. Two-point versus 3-point seat-belt restraint

A 1993 Honda Accord crossed the centre line to crash head-on with a 1994 Suzuki Swift. The BEV was 26 km / h. The 5 occupants included an 18-year-old girl wearing a 3-point belt with airbag deployment, a 17-year-old girl wearing a 3-point belt, an 18-year-old boy with a 3-point belt, a 17-year-old girl with a 2-point belt (seated in the centre position, second row) and an 18-year-old boy with 3-point belt. The 4 passengers wearing 3-point belts left the scene with minor injuries. The 17-year-old girl wearing the 2-point belt sustained a lumbar spine fracture that necessitated spinal fusion (Fig. 4), and a small-bowel injury that required laparotomy.

This represents the difference in injury severity with identical deceleration force due to the type of seat belt worn. Examination of the centre lap belt revealed that a proper fit was impossible owing to the high position of the belt "stalks" combined with the passenger's slouched position, resulting from inadequate leg room. Both factors allowed the belt to sit near the umbilical level rather than remain on the pelvis during collision, resulting in spinal injury.

Case 4. Airbag deployment trauma

A 1997 Suzuki Swift struck a stopped tractor trailer. The BEV was 31 km / h. There was no evidence of compartment intrusion. The 2 occupants were a 27-year-old woman wearing a 3-point belt with airbag and a 4-year-old boy wearing a 3-point belt with airbag. The child sustained a fracture to the left orbital roof and maxilla with bruising to the

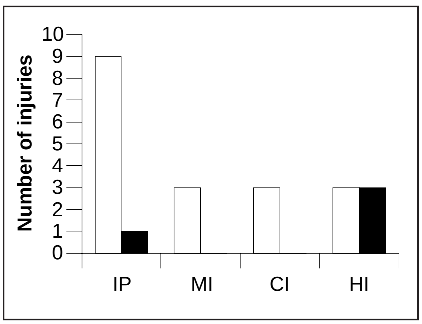

FIG. 1. Associated injuries in 22 children studied prospectively between 1999 and 2000 who suffered a spinal injury in a motor vehicle crash. White bars = 2-point belt, black bars = 3-point belt. IP = intestinal perforation, MI = musculoskeletal injury, CI = chest injury, HI = head injury.

FIG. 2. Chance fracture in a 4-year-old boy.

FIG. 3. Malposition of the lap seat belt causing bruising.

right arm, as well as a right brachial plexus palsy at C5–C7 from airbag deployment.

This small child was not kept out of the zone of airbag inflation by the seat belt. Both direct and indirect injury resulted from airbag deployment. The brachial plexus injury occurred from direct impact of the airbag over the neck and shoulder. The orbital fracture occurred from direct injury to the left side of the head against the gearshift knob secondary to acceleration from the air bag. This mechanism has been previously described to cause fatal injury.[12] The child's low body mass made him susceptible to small changes in body position at the time of airbag deployment. Potential preventive strategies include placing the child in the back seat or depowering the airbags.

Case 5. Influence of infant seat positioning on trauma sustained

A 1996 Suzuki Sidekick was struck on the driver's side by a 1988 Jeep Cherokee after the latter vehicle ran a stop sign. The Sidekick rolled onto its right side. Barrier speed was not applicable. The 2 occupants were a 29-year-old woman wearing a 3-point belt with airbag and a 3-month-old infant in a rear-facing carrier in the front passenger seat. An airbag deployed into the child's carrier seat.

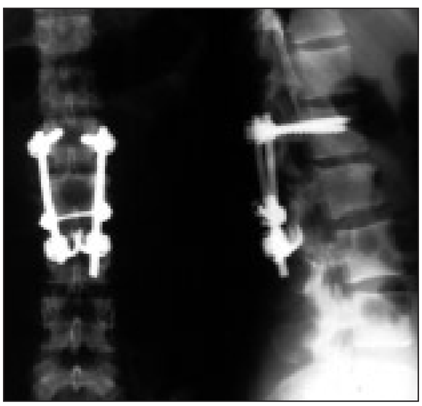

FIG. 4. Spinal instrumentation used in the treatment of a lumbar spine fracture to a 17-year-old girl who was wearing a 2-point belt.

The adult sustained fractures of the left clavicle, humerus and wrist and a laceration to the scalp. As the airbag deployed, it initially displaced the seat toward the centre of the car. The child sustained injuries to both sides of the head: a bruise to the left scalp from the inflating airbag and a right skull fracture and subdural hematoma from acceleration into the car interior or seat handle once it came to rest (Fig. 5). The airbag therefore contributed to the total force displacing the car seat and thus the severity of the child's injury. Having the infant in the rear seat would have avoided the airbag impact as part of the injury forces.

Discussion

We have shown that a trauma study in which a hospital emergency department recruitment strategy is combined with an engineering team assessment is feasible. The inherent weakness exists in the selection bias built into the protocol. Detailed mechanisms of injury secondary to restraint failure have been identified. However, this protocol does not include crashes in which severe injury has not occurred. Thus, the full preventive impact of restraint use cannot be studied using this protocol.

It has been hypothesized that the addition of a third-point belt to the 2-point lap belt would have the effect of displacing the injury proximally into the cervical spine. High cervical spine injuries are more common in infants and young children owing to multiple factors, including a larger head, laxity of ligaments, weak cervical muscles and flat articular facets.[16] Review of our retrospective data does not support this hypothesis: a single cervical spine injury occurred in a child restrained in a 3-point belt, compared with 3 seen in children with 2-point belts.

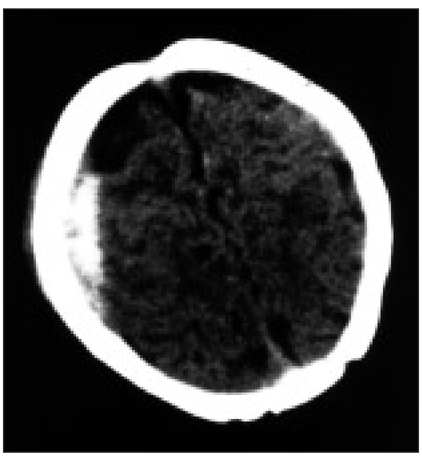

FIG. 5. Subdural hematoma associated with a skull fracture in a 3-month-old infant.

It has been suggested that the "lap belt syndrome" injury complex occurs when very large forces are applied during vehicle collision, and that this injury pattern is not preventable. Contrary to this theory, all Chance fractures in our series were associated with a poorly fitting lap belt. The ideal position for the belt is on the anterior inferior iliac spines. The mechanism of submarining, during which the occupant slides under the belt thus producing intra-abdominal and spinal injury has been described in human mechanical surrogates.[17] We have confirmed that this also occurs in vivo. In case 2 there is evidence of a well-fitting belt transmitting enough force to the pelvis to cause fracture (a fully recoverable injury). Case 3 described 4 passengers in 3-point belts with minor injury, and a fourth in a 2-point belt who suffered a flexion-distraction injury and intra-bdominal injuries.

We have determined that proper belt fit with a lap belt is sometimes impossible to achieve. This occurs when seat depth is greater than femur length, forcing the child into a slouched position. We propose that a booster seat would allow better fit of the belt across the bony pelvis, using either 2-point or 3-point devices, preventing a slouched position. We also found that significant variation occurs in the geometry of 2-point belts across different vehicles, sometimes making appropriate belt fit impossible. We propose that the addition of a crotch strap would prevent submarining and maintain the belt on the pelvis in the younger child.

Although we know that airbags used as supplemental restraints have worked to prevent injury, they have also been implicated in its cause. Children positioned close to the airbag have been shown to be at greater risk.[9,12] Case 4 in our series describes a 4-year-old child who suffered injury both directly from airbag inflation and indirectly by contact with the gear shift rise after being pushed into it. Case 5 describes injuries sustained in a child seated in a rear-facing infant carrier in the front seat. Both direct (from the airbag) and indirect (from striking the interior of the vehicle) injury occurred. Potential solutions include depowering airbags or the use of "smart" airbags, which detect the presence of a car seat in the passenger position and assess the size of the front seat passenger, adjusting the deployment force of the bag accordingly.

In conclusion, proper use of passenger restraint reduces morbidity for children involved in MVCs. However, current restraint systems are not designed to safely restrain young children under 12 years of age. We have shown that these children should not be seated in the front passenger seat until air bags are rendered more sensitive to smaller occupants. As well, booster seats are recommended for small children seated in the back to ensure proper positioning of the lap belt over the iliac crests. Finally, improved 3-point pediatric belt restraint systems should be developed for the family automobile to reduce childhood automotive trauma.

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