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Air Bag–Related Deaths and Serious Injuries in Children: Injury Patterns and Imaging Findings

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BACKGROUND AND PURPOSE: **As of November 1, 1997, automotive air-bag deployments occurring in low-speed collisions had resulted in the deaths of 49 children and in the serious injuries of 19 children in the United States. The purpose of this study was to investigate the patterns of injury occurring in this new mechanism of pediatric trauma.**

METHODS: **In search of common patterns of injury, three pediatric radiologists retrospectively evaluated the available autopsy and imaging studies in 11 such cases not previously reported in the medical literature, in addition to three published case studies.**

RESULTS: **The cause of death or serious injury in every case was the direct result of neurologic injury. Injury patterns differed according to the child's age and type of restraint used at the time of collision. Crush injury to the skull predominated in infant victims traveling in rear-facing child safety seats, and both cranial and cervical spine trauma occurred in older children traveling restrained, improperly restrained, or unrestrained in the vehicle's front passenger seat.**

CONCLUSION: **Air-bag systems pose a potentially fatal threat to the front-seat child passenger. This is directly related to the biomechanics at impact placing the child closer to the deploying air bag. An understanding of the biomechanics provides the radiologist insight into the two types of injury patterns observed.**

Motor vehicle accidents are the leading cause of injury-related deaths in the United States, accounting for more than 600 deaths each year in children under the age of 5 years (1). In an effort to decrease motor vehicle accident–related fatalities, Federal Motor Vehicle Safety Standard (FMVSS) 208 (Occupant Crash Protection) was issued in 1984 by the National Highway Traffic Safety Administration (NHTSA) requiring inclusion of automatic occupant protection devices (ie, air bags or automatic safety belts) to be phased into passenger cars during the 1987 to 1990 model years (2). By 1994, NHTSA had information on 614 injuries related to air-bag deployment affecting 279 people in 272 separate incidents (3). With the introduction of the passenger-side air bag in the 1993 model year, injuries involving the front-seat passenger (including children) began to be reported. By November 1, 1997, 49 child deaths and 19 serious injuries had been attributed to passenger-side air-bag deployments occurring in low-speed collisions that were deemed otherwise survivable by investigating authorities (4).

Although numerous case reports have appeared in the medical literature describing air bag–related injuries primarily involving the adult population (5–26), no formal study detailing the observed injury patterns in a cohort of pediatric passengers has been performed to our knowledge. The purpose of this study was to investigate the patterns of injury occurring with this type of pediatric trauma and to correlate the observed patterns with the biomechanics of injury production at the time of air-bag deployment.

Methods

Our study includes a cohort of pediatric patients who sustained fatal or serious injuries as the direct result of passenger air-bag deployments occurring in low-speed collisions (average speed of collision, 11 mph; range, 5–24 mph) The patients were located with the assistance of victim advocacy groups, the media, and institutional networking, in addition to collection of local cases. A letter requesting participation in the study was mailed to victims' families whose location was known. Approximately half the families or their legal council were contacted. Eleven child victims who, to our knowledge, have not previously been described in the medical literature were included in

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this study. Three previously published pediatric air bag–related trauma case reports were also reviewed (27–29).

Copies of the patients' pertinent radiologic studies were obtained. In each case, radiologic studies reviewed included one or more of the following: plain film examinations of the cervical spine, CT scans of the brain or upper cervical spine, MR examinations of the brain or cervical spine, nuclear medicine brain death studies, or postmortem radiographs. One pediatric radiologist and two pediatric neuroradiologists retrospectively reviewed the radiologic studies blinded to the initial interpretation rendered at the originating institutions. In each case, the observed radiographic abnormalities were documented. Patients were then stratified by age and type of restraint used at time of collision into two groups: the infant traveling in the rear-facing child safety seat and the older child facing forward in the vehicle's passenger seat. Each patient was then compared with other patients within the subgroup to ascertain any commonality of injury patterns.

The three patients (two boys, one girl) in the rear-facing child safety seat cohort had an age range of 1 month to 5 months (average age, 2.3 months). CT examinations of the brain were available for review for all three patients. The eight patients (three boys, five girls) in the forward-facing older child group had an age range of 3 years to 10 years (average age, 6.4 years). Examinations reviewed in this cohort included CT scans of the brain (four cases), CT scans of the cervical spine (two cases), cervical spine plain films (three cases), brain MR images (two cases), cervical spine MR images (one case), a nuclear medicine brain death study (one case), postmortem radiographs/autopsy reports (three cases), and extremity/nonneurologic plain films (two cases). For the remainder of the pediatric victims reported nationwide by November 1, 1997 (including the three published case reports), the data summarizing autopsy results detailing the cause of death or serious injury in each case was acquired through NHTSA's Special Crash Investigation Program and reviewed to assess similarity of injury patterns with our described cohort. Radiologic studies were not reviewed in this final group of patients.

Results

The child victims can be stratified into two distinct groups according to age and type of restraint system used at the time of collision. The first pediatric victim group is the infant traveling in the rear-facing child safety seat. The second pediatric victim group is composed of the older child traveling restrained, unrestrained, or improperly restrained facing forward in the vehicle's front passenger seat. The patterns of observed injury differ markedly between these two groups.

Infant in Rear-Facing Child Safety Seat

Twenty infant victims of air-bag deployment occurring during low-speed impacts nationwide were reported to NHTSA by November 1, 1997. The cause of death (n = 12) or serious injury (n = 8) in every case was the result of skull fractures and direct brain contusion/hemorrhage (Table 1). Three cases of this pattern of injury were reviewed.

The patterns of observed injury varied from a simple linear skull fracture seen in a child who survived without sequelae, to massive crush injury of the skull resulting in complex skull fractures, brain hemorrhage, and extrusion in a child who was fatally injured (Fig 1).

Forward-Facing Older Child in Front Passenger Seat

The observed pattern of injury is different in the forward-facing older child victim traveling in the ve-

TABLE 1: Infants in rear-facing child safety seats who sustained fatal or serious injuries in minor or moderate severity air bag deployment crashes

Case	Date	State	Age/Sex	Vehicle	Change in Velocity (mph)	Child Injuries	Driver Injuries
1	11/94	CA	3 mo/F	94 Toyota Corolla	Low	Nonfatal skull fxs	Wrist fx
2*	7/95	PA	3 wk/F	95 Ford Escort	20–25	Skull fxs, brain	Extremity fx
3*	9/95	CA	5 mo/F	94 Toyota Camry	<10	Skull fxs brain	Minor
4*	10/95	LA	4 mo/M	95 Saturn	12–14	Skull fxs, brain	None
5	10/95	CA	6 mo/M	95 Ford Escort	<10	Nonfatal skull fxs	Minor
6	11/95	CO	3 mo/M	94 Ford Aspire	9	Nonfatal skull fxs	None
7	11/95	WI	7 wk/M	96 Dodge Caravan	12–17	Nonfatal skull fxs	Minor
8*	1/96	NJ	4 mo/M	95 Isuzu Trooper	15	Skull fx	Minor
9*	5/96	FL	8 mo/F	94 Toyota Camry	10	Brain	Minor-none
10*	4/96	FL	3 mo/M	95 Hyundai Accent	Moderate	Head injuries	Minor-none
11*	6/96	IL	7 d/F	95 Ford Escort	8	Head injuries	Minor
12	9/96	GA	6 mo/M	96 Saturn	<10	Nonfatal skull fxs, brain	Minor
13*	9/96	OH	1 mo/M	95 Mazda Protege	12–14	Skull fxs, brain	Unknown
14*	10/96	FL	7 wk/F	96 Dodge Caravan	12–14	Skull fxs, brain	None
15	11/96	NH	3 wk/F	95 Ford Escort	24	Nonfatal skull fxs, brain swelling	Nonfatal skull fx
16	12/96	CO	7 mo/F	96 Ford Escort	12	Nonfatal brain hemorrhage	None
17	12/96	VA	3 mo/M	95 Ford Escort	Low	Nonfatal skull fx	Minor-contusions
18*	5/97	CA	5 mo/M	94 Mazda 626	7	Skull fxs, brain	Minor-contusions
19*	5/97	NC	5 mo/M	95 Ford Crown Victoria	13	Skull fxs, brain	Contusions/abrasions
20*	6/97	CO	3 mo/M	97 Ford Escort	16	Skull fxs, brain	Minor

Source: U.S. Department of Transportation, National Highway Transportation Safety Administration, National Center for Statistical Analysis.
* Fatality.
Note.—Fx indicates fracture.

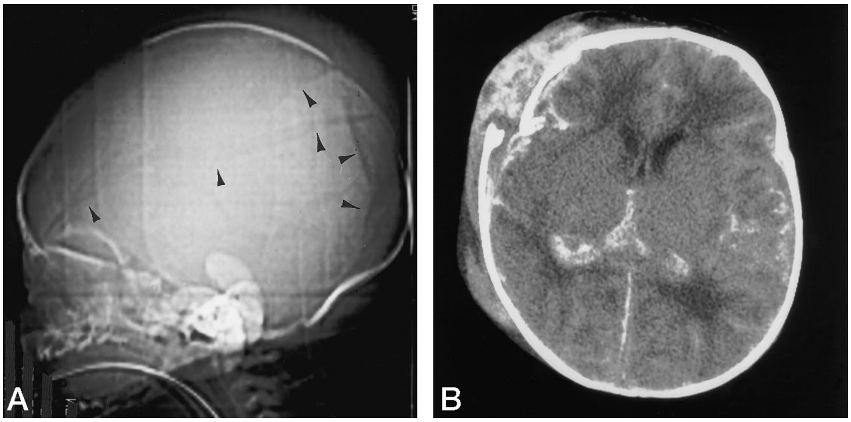

FIG 1. Fatally injured infant in rear-facing child safety seat.

A, Lateral CT scout reveals multiple complex skull fractures (*arrowheads*).

B, Axial CT scan shows subarachnoid, intraventricular, and parenchymal hemorrhage with edema. Frank extrusion of brain parenchyma through diastatic right parietal fracture site was identified on higher sections.

hicle's passenger seat. Of the 48 victims reported to NHTSA by November 1, 1997, the cause of death (n = 37) or serious injury (n = 11) was no longer limited to cranial trauma alone, as seen in the rear-facing infant cohort. Cervical spine injuries ranging from nonfatal fractures to frank decapitation (n = 2) have been identified in 30 of the 48 recorded cases (Table 2). Eight cases in this patient cohort were reviewed.

Of the eight patients, two were properly restrained with three-point safety belts, and the remaining six were improperly restrained or unrestrained at the time of collision. Of the two properly restrained children, one sustained "minor" injuries resulting in multiple upper extremity fractures, and the other was fatally injured as a result of atlantooccipital dissociation, brain stem herniation, and cord transection that was documented at the time of autopsy (Fig 2).

The vulnerability of the pediatric cervical spine in the event of air-bag deployment was clear in our review. Of the eight patients, two had imaging or autopsy findings of atlantooccipital dissociation (Fig 2), one sustained a "near decapitation" injury (Fig 3), two had fatal cervical spine fracture distraction injuries of C2 and C4, respectively, and two suffered nonfatal cervical spine injuries resulting in left-sided brachial plexus avulsion (Fig 4) and atlantooccipital instability, respectively (Fig 5).

The cervical trauma observed was superimposed on craniofacial trauma documented in five of the eight reviewed cases. Facial trauma included ocular injury/blowout fracture (n = 1), depressed frontal skull fractures (n = 1), and lacerations with or without fractures noted in the mental/submental region (n = 2). Intracranial injury varied from minor subarachnoid hemorrhage (n = 2) to subdural, intraventricular, and parenchymal hemorrhage with associated edema (n = 3).

Discussion

On December 18, 1991, the United States Congress passed the Intermodal Surface Transportation and Efficiency Act, which mandated that all passenger cars manufactured after September 1, 1997, and light trucks, vans, or sport utility vehicles manufactured after September 1, 1998, must include driver and passenger air bags as standard equipment (30). At that time, NHTSA's FMVSS 208 required air bags to protect a 5 ft. 8 in., 165-lb, unbelted occupant in a 30-mph full-face impact into a rigid barrier. In response to these mandates, automotive manufacturers developed and installed single-chamber air-bag deployment systems in passenger vehicles beginning in the 1980s, with design specifications varying among automakers (Table 3).

After implementation of the driver-side air-bag safety systems, NHTSA began collecting reports of injuries sustained solely as a result of air-bag deployment. The majority of the initial driver-side air bag–related injuries involved forearm fractures, ocular injury, contact burns, abrasions, lacerations, and contusions, all of which have been well described in the medical literature on a case report basis (5–26). In 1990, the first driver fatality related to air-bag deployment was documented occurring in a 56-in. female driver positioned with the driver seat in the forward position, placing the victim in close contact to the deploying air bag. As of November 1, 1997, 38 adult deaths (35 drivers, three passengers) had been attributed to air bags (4). Case reports describing both adult-related deaths and serious injury have begun to appear in the trauma literature (17–26).

Studies have shown that proper use of a three-point restraint (lap/shoulder belt combination) is 41% effective in preventing fatality in front-seat occupants, and the addition of the driver-side air bag provides 16% to 24% further reduction in fatality rates (31, 32). Unfortunately, United States seat belt usage rates are estimated at only 68% (33). As of November 1, 1996, NHTSA estimated that driver-side air bags had saved a net of 1481 lives, and passenger-side air bags had saved a net of 164 lives among the 13 years and older age group (34). For young children, properly installed safety seats or booster seats remain the most effective restraint system, having reduced fatal injury by as much as 69% (35). Among the 13 years

TABLE 2: Older children (not in rear-facing child safety seats) who sustained fatal or serious injuries in minor or moderate severity air bag deployment crashes

Case	Date	State	Age/Sex	Vehicle	Change Velocity (mph)	Restraint	Child Injuries	Driver Injuries
1*	4/93	OH	6 yr/F	93 Volvo 850	7	No	Brain	Minor
2*	9/94	UT	4 yr/F	94 Chrysler Minivan	8	No	Skull fxs	Minor
3*	7/94	VA	4 yr/M	94 Ford Mustang	10–12	No	Brain, neck	None
4*	3/95	TX	9 yr/M	95 Chrysler Minivan	16	Lap belt	Brain, neck	Minor
5*	3/94	TX	7 yr/F	93 Lexus LS400	Low	No	A/O	None
6*	10/95	UT	5 yr/M	94 Chev. Camaro	10	No	C-spine	Minor
7*	10/95	MD	7 yr/F	95 Chrysler Minivan	12–14	Lap belt	Closed head injury	None
8	10/95	PA	3 yr/M	95 Jaguar	<10	Booster	Nonfatal brain injury	None
9*	5/95	MI	5 yr/F	95 Ford Contour	10–15	No	C-spine, A/O, brain	Minor
10*	4/95	VT	5 yr/F	93 Dodge Intrepid	12–18	No	Brain, neck	None
11*	12/94	MS	6 yr/F	95 Toyota Camry	<10	No	Closed head injury	Minor
12*	1/96	MI	9 yr/M	95 Chrysler Minivan	12–18	No	Fx/dislocation A/O	Minor
13*	4/96	MD	3 yr/F	95 Geo Metro	10–15	No	A/O, cord, skull fxs	Minor-none?
14*	12/94	VA	4 yr/F	94 Ford Aspire	<20	No	Brain, neck	Arm fx
15*	5/96	NC	4 yr/F	94 Chrysler Minivan	9–13	No	Brain, neck	None
16*	5/96	NY	7 yr/M	95 Ford Contour	<15	No	Neck transected	Minor
17*	6/96	KS	5 yr/M	95 Chev. Lumina	12–18	No	Broken neck	Minor-none
18*	6/96	MO	4 yr/M	95 Dodge Caravan	15–20	No	Basal skull fx	Minor, wrist fx
19*	9/96	TN	5 yr/F	96 Dodge Caravan	12	Yes	Brain	Minor
20*	9/96	NH	5 yr/M	95 Hyundai Sonata	12–14	No	Cord, C-spine	None
21	9/96	PA	4 yr/M	95 Ford Contour	TBD	Lap belt	Nonfatal liver	Unknown
22	8/96	MI	3 yr/M	96 Escort Wagon	22	Lap belt	Nonfatal brain	Liver laceration, fxs
23*	6/96	OK	5 yr/M	96 Mitsubishi Galant	12	Yes	Closed head injury, skull fx	None
24*	10/96	MS	6 yr/M	95 Ford Mustang	TBD	No	Neck fx	Minor
25	10/96	OH	4 yr/F	95 Chev. Camaro	8–10	No	Nonfatal brain, skull fx	None
26*	7/96	NM	6 yr/F	96 Plymouth Neon	Low	No	Cervical fx	Minor
27	11/96	UT	4 yr/M	95 Pontiac Grand Prix	13	Lap belt	Nonfatal brain, arm fx	None
28*	11/96	ID	1 yr/F	95 VW Jetta	7	No/FFCSS	Decapitation, arm fxs	Minor
29	12/96	NE	6 yr/M	95 Plymouth Voyager	8	No	Nonfatal neck fx	None
30*	12/96	KY	4 yr/M	95 Geo Metro	Low	No	Neck fx	Minor
31*	12/96	NM	4 yr/F	96 Oldsmobile Cutlass	12	No	Head injuries	Minor chest injuries
32*	12/96	TX	2 yr/M	95 Geo Metro	10	No/on lap	Decapitation	None
33*	1/97	PA	23 mo/F	94 Ford Aspire	Low	No/on lap	Head and neck injuries	Minor
34*	12/96	GA	18 mo/M	96 Saturn SL	10–12	No/on lap	Closed head injury	Minor
35	1/97	ME	3 yr/M	94 Dodge Caravan	12	Booster	Nonfatal skull fx, brain	Minor
36*	2/97	OH	4 yr/M	97 Hyundai Accent	13	No	Cervical fx	Minor
37	1/97	CO	7 yr/M	95 Dodge Caravan	14	Yes	Nonfatal blunt head trauma	Minor
38*	4/97	PR	18 mo/F	96 Hyundai Accent	Low	No	Neck fx	None
39	2/97	CA	6 yr/F	96 Dodge Caravan	9	Yes	Nonfatal blunt head trauma	Unknown
40*	4/97	FL	2 yr/M	95 Saturn SL2	13	No/on lap	C-spine transection	None
41*	5/96	IL	4 yr/F	94 Plymouth Voyager	13	Lap belt	C1–C2 subluxation, brain	None
42*	8/97	NC	8 yr/F	94 Jaguar	19	No	Fracture A/O dislocation	None
43	2/97	FL	3 yr/F	97 Geo Metro	21	Yes	Nonfatal brain, skull fx	Minor
44	11/96	WI	8 yr/F	96 Plymouth Voyager	24	No	Nonfatal C-spine, A/O, brain	Fx hip and rib
45*	8/97	NM	2 yr/F	95 Hyundai Accent	12	Lap belt	C-spine transection	None
46*	8/97	OK	2 yr/F	95 Mitsubishi Galant	13	Yes	A/O dislocation	Minor
47*	5/97	TX	4 yr/F	97 Chevrolet Camaro	12	No	Fx/dislocation C1 with cord injury	Minor
48*	7/97	AZ	5 yr/M	97 Mercury Tracer	5	No	Fx/dislocation C-spine, cord injury	Minor

Source: U.S. Department of Transportation, National Highway Transportation Safety Administration, National Center for Statistical Analysis.
* Fatality.
Note.—A/O indicates atlantooccipital; Fx, fracture; TBD, to be determined; FFCSS, forward-facing child safety seat.

and younger age group, however, it is estimated that passenger-side air bags are killing more children than they are saving, with an estimated 128 child deaths each year expected after the full phase-in of the Intermodal Surface Transportation and Efficiency Act mandatory air-bag legislation (36). This study serves to reinforce the lesson that the safest place for a child passenger is secured in an approved safety restraint device placed in the rear seat of the vehicle.

The cases presented here are graphically illustrative of the danger that air bags pose to the front-seat pediatric passenger, even in the event of low-speed collisions in which the driver sustains no or minor injuries. Analysis of the radiologic and autopsy find-

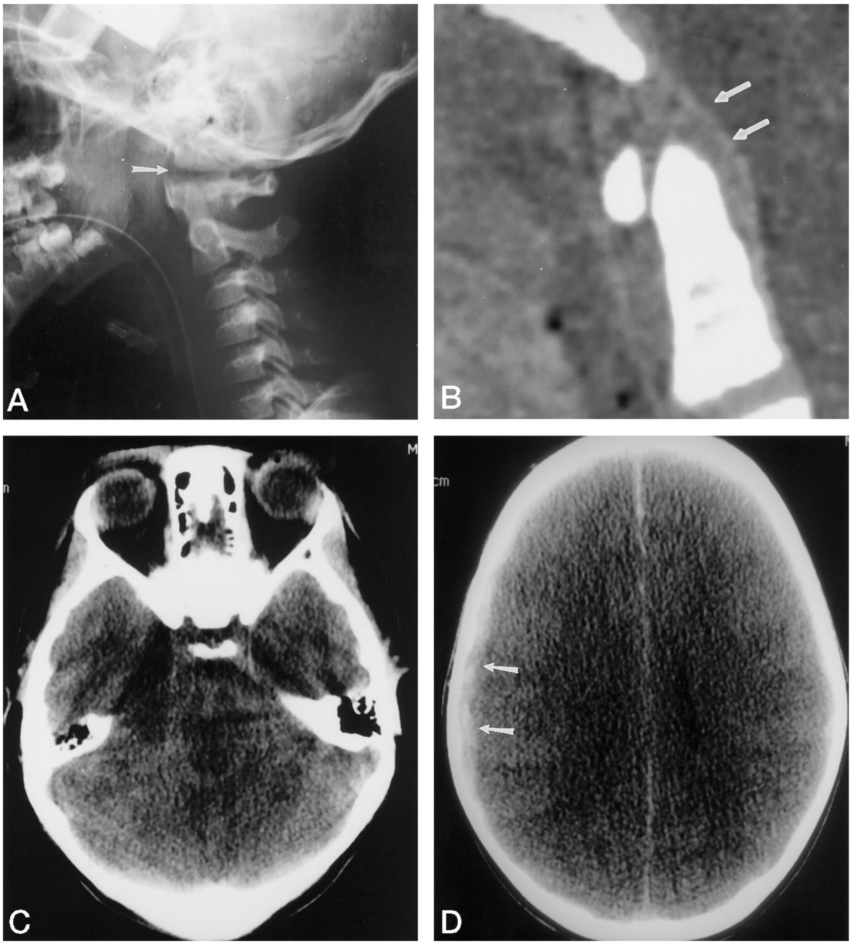

FIG 2. Fatally injured, three-point restrained child passenger.

A, Lateral cervical spine radiograph with prevertebral soft-tissue swelling noted from the skull base to C3 level, with reversal of lordotic curvature and distraction of the atlantooccipital joints also present (*arrow*).

B, Sagittal CT reconstruction at the craniocervical junction reveals ligamentous thickening and increased attenuation suggestive of hemorrhage involving the tectorial membrane and cruciform ligaments (*arrows*).

C and *D*, Axial CT scans of the brain reveal extensive parenchymal edema, effacement of the sulcal markings and basilar cisterns, and right parietal subdural hematoma (*arrows*).

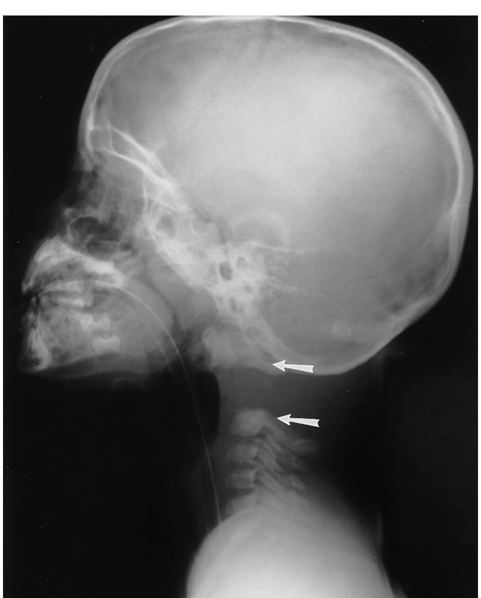

FIG 3. Fatally injured, unrestrained forward-facing child passenger. Postmortem radiograph shows fracture distraction injury through the C2 subdental synchondrosis (*arrows*).

ings in each of the two pediatric victim groups provides insight into the biomechanics that are operating at the time of impact to produce the injury patterns described. Observed injury patterns differed according to the child's age and the method of restraint at impact.

Infant in Rear-Facing Child Safety Seat

Because infants lack head control, safety seats designed with a 45° recumbent angle were developed to provide a safe traveling position at which the infant's airway would not be compromised because of a slumped head posture. To adequately secure these seats into a vehicle in the recumbent angle, the child must be positioned facing the rear. Often, parents will mistakenly place the rear-facing child safety seat in the front-seat passenger position to have visual and physical access to the child while driving. This placement within the vehicle situates the child closer to the dashboard and at extreme risk in the event of passenger-side air-bag deployment.

At deployment, the air bag, inflating at speeds approaching 200 mph, impacts against and collapses the back of the infant seat, striking the posterior cranium and thrusting the child toward the rear of the vehicle, thereby compressing the infant against the back of the vehicle's passenger seat. This action creates a "nutcracker" force, impinging the child's head

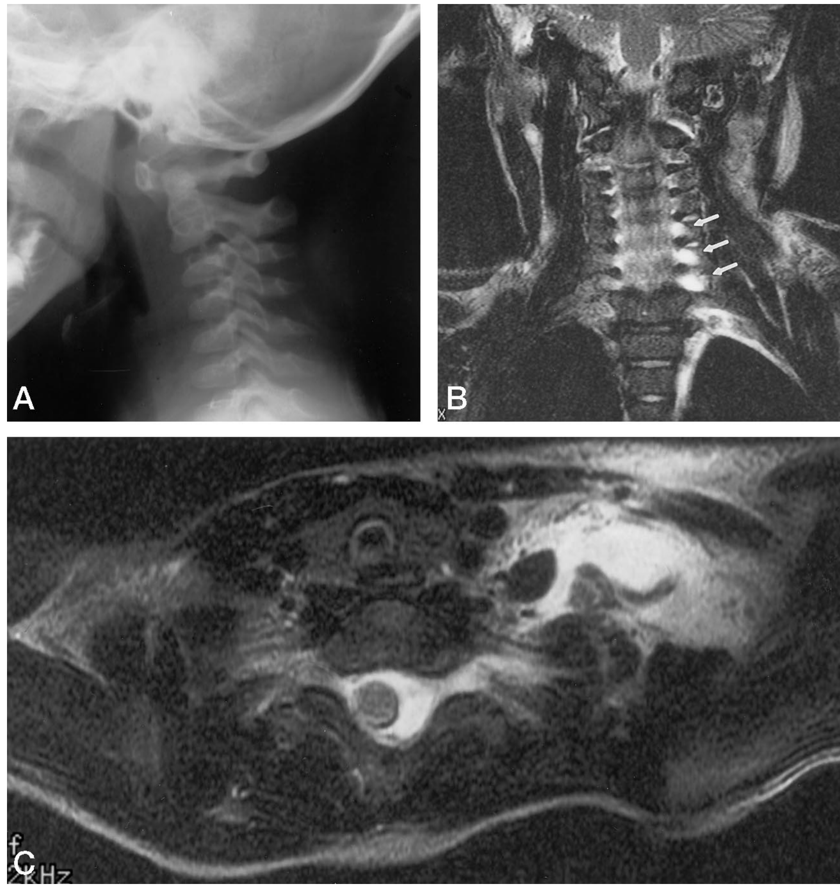

FIG 4. Nonfatally injured, unrestrained forward-facing child passenger.

A, Lateral cervical spine radiograph shows prevertebral soft-tissue swelling and reversal of cervical lordotic curvature without evidence of fracture or subluxation.

B and *C*, T2-weighted fast spin-echo MR coronal (*B*) and axial (*C*) images with imaging parameters of 5000/126/2 (TR/TE/excitations) show left-sided cervical nerve root avulsion resulting in pseudomeningocele formation (*arrows*) at the C4–T1 levels, rightward eccentric positioning of the spinal cord within the cervical canal, and frank extravasation of CSF into the soft tissues of the left shoulder. Subcutaneous edema anterior to the left clavicle, associated with the air-bag impact site, and chemical burns were noted on physical examination.

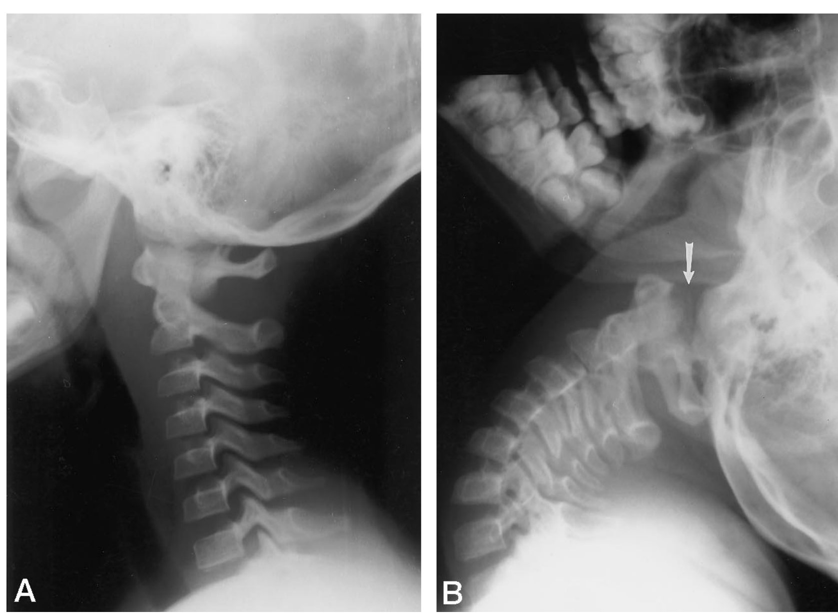

FIG 5. Nonfatally injured, unrestrained child passenger.

A, Plain radiograph of lateral cervical spine reveals prevertebral soft-tissue swelling from the skull base to C3 level.

B, Plain radiograph of cervical spine extension shows abnormal increased mobility at the atlantooccipital joints, with the anterior joint space splayed open to a distance of 11 mm (*arrow*).

between the infant seat (with posterior momentum produced by the inflating air bag) and the passenger seat (with anterior momentum produced by the crash impact). The child's head is effectively placed within a vice (Fig 6). Resultant injury is limited to skull fractures, direct brain contusion, and hemorrhage. The trauma sustained at the time of the air bag's impact with the rear of the infant safety seat is shown in Figure 7, in which a depressed occipital skull fracture resulted from collapse of the rear-facing child safety seat against the child's skull.

Forward-Facing Older Child in Front Passenger Seat

The forward-facing front-seat child victim experiences a different mechanism of injury. Before impact, the driver usually anticipates the accident and uses

TABLE 3: Air bag design specifications

Deployment threshold	6–18 mph
Deployment speed	96–200 mph
Extension from dashboard	12–20 in.
Air bag effluents	Sodium azide solid rocket propellant ± compressed gas
Time for inflation/deflation	<1/10 s, inflation force transmitted in 15–20 ms

Note.—Source: Sanders (36).

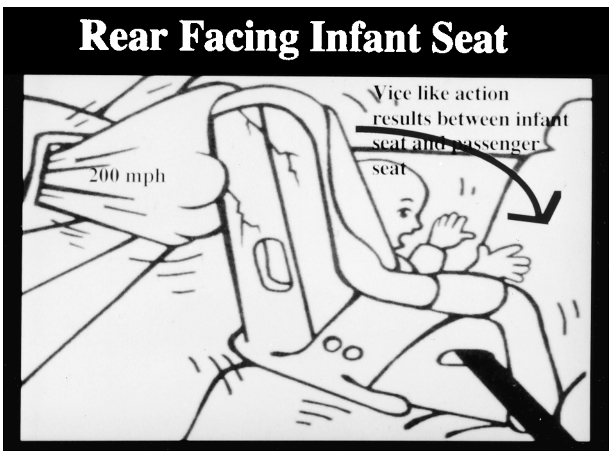

FIG 6. Schematic representation of the "nutcracker" biomechanics of injury production involving the infant traveling in the rear-facing child safety seat at air-bag deployment. (Cartoon edited and reproduced with the permission of the American Academy of Pediatrics).

what is referred to as "preimpact braking." Obeying Newton's first law of physics (ie, an object in motion will stay in motion until it encounters a force or object that impedes it), the improperly restrained child is propelled forward toward the dashboard during preimpact braking, and, at the time of collision, is therefore closer to the air-bag module when it deploys. The unbelted child may achieve a near-standing posture. If the child has slipped off the shoulder strap of the three-point restraint, he or she will instead be flexed forward with his or her head or face positioned adjacent to the deploying air-bag module (Fig 8). With deployment, the face and frontal cranium receive first impact, followed by violent hyperextension of the head and neck as the air bag inflates and propels the child toward the rear of the vehicle. The child may also be subjected to upward-directed forces associated with the angle of deployment from the dashboard, resulting in thrusting of the head against the compartmental beams, windshield, and so on. Of the 48 children reported to NHTSA nationwide in this victim category by November 1, 1997, 40 were unrestrained or improperly restrained. However, eight children (three fatalities, five with serious injuries) were properly restrained with either approved forward-facing child safety seats/booster seats or three-point seat-belt restraints (Table 3).

In this cohort of patients, injuries are no longer confined to the cranium. Cervical injury was observed in over half the reported cases, ranging from nonfatal fracture or ligamentous injury to frank decapitation occurring in low-speed collisions deemed otherwise survivable (Figs 2–4).

It is unknown to us how many of the nationally reported child victims actually survived long enough to be imaged. Although we had access to and have reported NHTSA's Special Crash Investigation Program statistics, we did not review the imaging findings of all the cases reported to that agency. Obstacles to collating all the imaging data were encountered in the form of ongoing litigation preventing inclusion and governmental privacy issues preventing release of detailed victim information.

In addition to the 11 cases mentioned above, three pediatric air-bag injury cases reported in the medical literature were analyzed to see whether the injury patterns described differed from those outlined in this study. One case, reported by Hollands et al (28), involved a 3-week-old infant restrained in a rear-facing child safety seat at the time of impact who sustained "massive subgaleal hematoma and bilateral parietal fractures as well as massive cerebral edema with compression of the ventricles and loss of the gray white junction." This case again reinforces the vice-like crushing biomechanics of injury production.

Two other published case reports described the forward-facing older child injury pattern. Hollands et

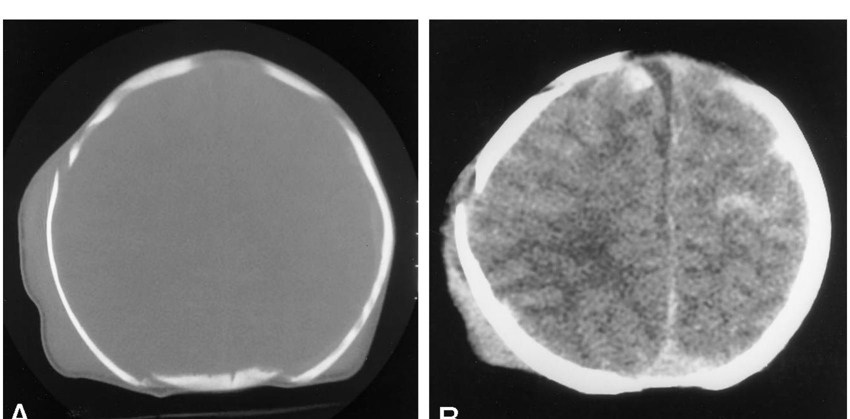

FIG 7. Fatally injured infant in rear-facing child safety seat.

A, Axial bone window image shows depressed occipital fracture component with associated diastatic right parietal linear fracture and parietooccipital soft-tissue swelling.

B, Brain window image reveals subarachnoid hemorrhage, hemorrhagic parenchymal contusions, and right hemispheric brain edema.

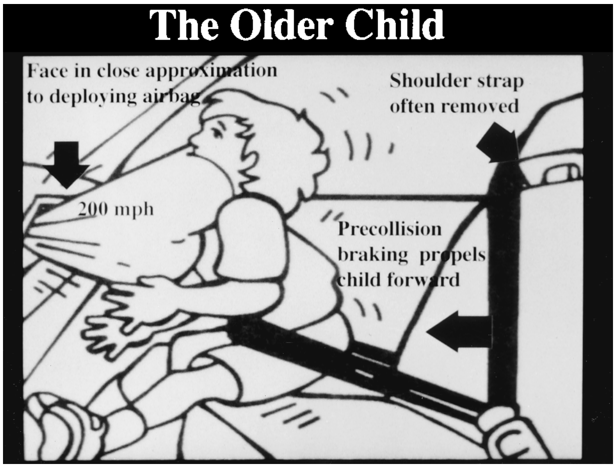

FIG 8. Schematic representation of the biomechanics of injury production affecting the forward-facing child victim at air-bag deployment. (Cartoon edited and reproduced with the permission of the American Academy of Pediatrics).

al (27) reported a case of a properly restrained 3-year-old child traveling in an approved booster seat. This child suffered severe facial trauma, a small right-sided subdural hematoma, and diffuse axonal injury, but did survive. Willis et al (29) described the case of a 5-year-old who was fatally injured, sustaining C2–C3 dislocation/distraction cervical trauma, resulting in cord transection in addition to severe facial lacerations, intracranial subarachnoid hemorrhage, brain parenchymal edema, and resultant descending herniation. The injuries observed in each of these forward-facing victim cases are concordant with the biomechanical epidemiology described previously. Craniofacial trauma is sustained at initial impact with the deploying air bag, with cervical injury occurring in association with subsequent hyperextension that takes place during continued air-bag inflation.

Barring changes in governmental protection guidelines, air-bag design specifications, or public awareness, the magnitude of the problem will continue to increase as passenger-side air bags become mandatory in all vehicles by 1999. In response to increasing media and public awareness, the government has responded to the "air-bag crisis" with a number of temporary and long-range solution plans.

1. Education: Warning Labels, Notification Letters, and Public Information Campaigns

On November 27, 1996, NHTSA passed an addendum to FMVSS Part 571, mandating brightly colored warning labels explicitly stating the potential danger of serious injury or even death for a front-seat child passenger (37). These labels were required on vehicles as of February 25, 1997, and on child restraints as of May 27, 1997.

2. Smart Air Bags: The Future . . .

Automakers have acknowledged the need to make the current "dumb" single-chamber deployment air-bag systems "smarter." Although some automobiles are already equipped with "smart air-bag design," it is estimated that design, testing, and implementation of these intelligent systems may take at least 5 years to complete. NHTSA currently plans to issue a policy addendum to FMVSS 208 requiring implementation of smart air bags and establishing performance requirements for those air-bag systems. The next generation of air bags will use sensors to detect occupant size and weight and will automatically adjust passenger seat position to optimize proper distance between the occupant and the steering wheel and dashboard. Air bags will likely have a multichamber design and variable inflation speed capability that differs according to the severity of the crash. Infrared and acoustic sensors will determine and dynamically monitor the position of the occupant as preimpact braking and crash impact occur, and then prescribe an appropriate deployment strategy to the air-bag system. Finally, sensors may be able to detect the use of a child safety seat and which direction it is facing, and automatically adjust the deployment guidelines.

3. What Are the Options Now?

Safety Belt Pretensioner/Tensioner.—This system actively removes any slack in the passenger shoulder strap before the crash activated by preimpact braking. Once it deploys, it must be replaced. Ninety-two percent of all vehicles in Europe (including United States makes) will have this system by the year 2000, as compared with implementation in only 6% of cars driven in the United States by that same time. To be effective, however, the seat belt must be worn and, as stated above, current United States usage remains less than optimal.

Voluntary Deactivation.—Currently, federal law prohibits dealers or repair shops from disabling air bags. Furthermore, state inspection laws may require air bags to be fully functional. On January 6, 1997, NHTSA issued a *Federal Register* notice of a proposed rule to permit motor vehicle dealers and repair businesses, on the request and consent of the consumer, to deactivate driver and passenger air bags. The proposal was open for comments through February 5, 1997, and a final ruling has not yet been rendered. Until such time, NHTSA is considering individual petitions allowing exemption from the prohibition against disabling air bags, if it makes a determination that the exemption is "consistent with safety" (34).

On-off Switches.—Automakers have strongly opposed deactivation of air bags and have proposed instead the installation of on-off switches. As of January 6, 1997, NHTSA published a final rule, extending until September 1, 2000, allowing a provision in FMVSS 208 for vehicle manufacturers to offer manual cutoff switches (38). This feature is allowed only in new vehicles that have no rear-seat position or a rear seat that is too small for a rear-facing infant seat. No cutoff switches are permitted for the driver-side air bag in any vehicle.

Depowering.—NHTSA issued a final rule amending FMVSS 208, permitting automotive manufacturers to depower air bags as a temporary measure until smart air bags are in place (39). This recent proposal will permit air bags to be depowered by 20% to 35% of capacity. NHTSA estimates that the depowering will save 39 (20% depowering) to 83 (35% depowering) of the 128 expected child deaths, at the cost of 487 to 1203 adult deaths each year. If smart air bags are, in fact, 5 years away, depowering could result in the deaths of 2435 to 6015 adults in the interval (36).

Conclusion

The passenger-side air bag poses a serious fatal threat to the child passenger traveling in the vehicle's front passenger seat, even in the event of a low-speed impact. With the mandatory implementation of driver- and passenger-side air-bag systems in all vehicles manufactured after the 1999 model year and the public's continued practice of placing children in the vehicle's front passenger seat, the number of pediatric air bag–related deaths and serious injuries is likely to increase. Stratification of the victims into two groups according to age and type of restraint at impact provides the informed radiologist with insight into the expected injury patterns and imaging findings. Reports of cases of the infant traveling in the rear-facing child safety seat provide evidence of direct crush injury to the skull because of the vicelike biomechanics at air-bag deployment. The older child victim is in close approximation to the dashboard and air-bag module at the time of deployment because of preimpact braking and often improper use of restraints at the time of collision. With passenger-side air-bag deployment, craniofacial trauma is initially sustained, with violent hyperextension occurring with continued air-bag inflation. Therefore, a detailed evaluation of the cervical spine must be included in the imaging workup of this patient population in addition to the imaging studies needed to exclude intracranial trauma.

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