PREDICTORS AND PATTERNS OF PEDIATRIC HEAD INJURY IN MOTOR VEHICLE CRASHES

Kristy B. Arbogast*+, Jessica S. Jeramian*, Yoganand Ghati*, Rebecca Smith*, Matthew R. Maltese*, Rajiv A. Menon*

* Trauma Link, The Children’s Hospital of Philadelphia
+ The University of Pennsylvania School of Medicine

ABSTRACT

Traumatic brain and skull injuries are the most common serious injuries sustained by children in motor vehicle crashes. To address head protection for children, regulations typically use the Head Injury Criterion (HIC), scaled from adult and subhuman primate data and based on tolerance for skull fracture. It is unclear whether the spectrum of head injuries sustained by children in motor vehicle crashes is adequately addressed by a fracture-based criterion. To provide insight into this question, this paper evaluated patterns and predictors of pediatric head injuries using a large US population-based surveillance system and clinical data from a large pediatric trauma center. Predictors of elevated AIS2+ head injury include lap belt only (1.2%), right front seat position (1.4%), rollovers (4.6%) and struck-side crash (1.6%). Examination of non-concussive head injuries showed similar relationships. Increasing age was associated with increasing non-concussive head injury risk except for the children less than 1 year whose injury risk was slightly higher than their older counterparts. Review of the trauma registry data revealed that approximately 60% of the head injuries sustained by children age 1-12 years were intracranial injuries in absence of skull fractures. Consideration of the known mechanisms of the specific head injury diagnoses illustrated a potential gap in regulation by highlighting the substantial fraction of injuries that may be better correlated with a head injury metric derived from a measure of head rotation than the current HIC measurement.

Key words: head injury, child injury, HIC

TRAUMATIC BRAIN AND SKULL injuries are the most common serious injuries sustained by children in motor vehicle crashes regardless of age group or crash direction. (Arbogast et al. 2002; Durbin et al. 2003; Howard et al. 2003; Orzechowski et al. 2003; Arbogast et al. 2004) In particular, the single most common anatomic injury resulting in a child occupant death following a motor vehicle crash is a head injury, responsible for fully one-third of all injury deaths (Adekoya et al. 2002; Thompson and Irby 2003). These head injuries range from mild brain injury (defined as concussion or brief loss of consciousness) to skull fractures and more severe intracranial injuries. In the United States, traumatic brain injury in children age 0-14 years results in over 3000 deaths, 29,000 hospitalizations, and 400,000 Emergency Department visits annually (Centers for Disease Control 2000). Prevention of these injuries are especially important in children as the effects of traumatic insult to the nervous tissue at an early age are still not fully understood and are a focus of clinical concern.

To address head protection for motor vehicle occupants, regulations have implemented the Head Injury Criterion (HIC) as the metric by which the risk of head injury is assessed. As reported in NHTSA’s Recent Upgrade to FMVSS No. 208 (Eppinger et al. 2000), the HIC was based originally on the Wayne State Tolerance Curve (WSTC) (Lissner et al. 1960), which was developed by dropping embalmed cadaver heads onto rigid flat surfaces. The WSTC provided a relationship between peak acceleration, pulse duration, and concussion onset. In its final form (Gurdjian 1963; Patrick 1963), the WSTC was developed by combining results from a wide variety of pulse shapes, cadavers, animals, human volunteers, clinical research, and injury mechanisms. Skull fracture and/or concussion was used as the failure criterion, except for the long duration human volunteer tests in which there were no apparent injuries. Later, the Gadd Severity Index (GSI) was developed to fit the WSTC, with a value greater than 1000 considered to be life-threatening (Gadd 1966). The GSI was based not only on the original Gurdjian data, but also upon additional long pulse duration data obtained by Eiband (Eiband
Versace was first to propose the HIC (Versace 1971), and in 1972, NHTSA proposed to introduce a HIC requirement into FMVSS No. 208 Frontal Crash Protection. Today, a variety of HIC formulations exist in motor vehicle regulations. In regulations that apply to children, HIC in FMVSS No. 208 (Frontal Crash Protection) has a 15 msec time limit and scaled tolerance limits ranging from 700 for the 6 year old to 390 for the 12-month-old dummy. Conversely, HIC is limited to 1000 regardless of age, with a 36 msec time limit in FMVSS No. 213, NHTSA’s standard for Child Restraint Systems. To obtain the scaled values of HIC for children implemented in FMVSS 208, factors such as age, physical dimension, and tissue elastic modulus are considered (Irwin and Mertz 1997). While anthropometric studies have been published to establish mass and size for scaling (Irwin and Mertz 1997), current data on variations in brain tissue modulus with age (Thibault and Margulies 1998) have not been incorporated into the regulated scaled values of HIC. Some researchers have attempted to account for such material differences in the scaling such as using pediatric tendon stiffness as a surrogate for cranial suture stiffness when scaling the HIC (Eppinger et al. 2000).

Regardless of the debate on the accuracy of these scaling techniques, our current means of assessing the value of technological interventions to mitigate head injury in child occupants relies on the assessment of HIC and other head injury metrics such as head excursion in controlled laboratory test environments. If real world reductions in head injuries are to be achieved, the accuracy of HIC in predicting actual pediatric head injury risk must be ensured. The first step in determining whether the spectrum of head injuries sustained by child occupants is adequately addressed by a fracture-based criterion is to define the clinical picture of pediatric motor vehicle crash head injury. For this reason, the objective of this work was to evaluate patterns and predictors of pediatric head injury and to determine what fraction of head injuries sustained by children occur in the absence of skull fracture and thus potentially not assessed using the traditional HIC evaluation.

METHODS

Two datasets were used: 1) a probability sample of 25,209 child occupants (weighted to represent 345,610) in motor vehicle crashes from a surveillance system involving insured vehicles in three large US regions, 12/1/98 to 12/31/04 where data were collected via insurance claim records and validated telephone survey, and 2) a census of children admitted to a Level 1 pediatric trauma center from 2001-2003 with an AIS2+ head injury sustained in a motor vehicle crash. Each data set is described below.

PARTNERS FOR CHILD PASSENGER SAFETY: The data were drawn from the Partners for Child Passenger Safety (PCPS) program, collected from December 1, 1998 to December 31, 2004. A description of the study methods has been published previously (Durbin et al. 2001). PCPS consists of a large scale, child-specific crash surveillance system: insurance claims from State Farm Insurance Co. (Bloomington, IL) function as the source of subjects, with telephone survey and on-site crash investigations serving as the primary sources of data.

Vehicles qualifying for inclusion were State Farm™-insured, model year 1990 or newer, and involved in a crash with at least one child occupant ≤15 years of age. Qualifying crashes were limited to those that occurred in fifteen states and the District of Columbia, representing three large regions of the United States (East: NY, NJ [until 11/01], PA, DE, MD, VA, WV, NC, DC; Midwest: OH, MI, IN, IL; West: CA, NV, AZ, TX [starting 6/03]). After policyholders consented to participate in the study, limited data were transferred electronically to researchers at The Children’s Hospital of Philadelphia (CHOP) and University of Pennsylvania (Penn). Data in this initial transfer included contact information for the insured, the ages and genders of all child occupants, and a coded variable describing the level of medical treatment received by all child occupants (no treatment, physician’s office or emergency department only, admitted to the hospital, or death).

A stratified cluster sample was designed in order to select vehicles (the unit of sampling) for the conduct of a telephone survey with the driver. In the first stage of sampling, vehicles were stratified on the basis of whether they were towed from the scene or not, and a probability sample of both towed and non-towed vehicles was selected at random, with a higher probability of selection for towed vehicles. In the second stage of sampling, vehicles were stratified on the basis of the level of medical treatment received by the child occupant(s). A probability sample from each tow status/ medical treatment stratum was selected at random with a higher probability of selection for vehicles in which a child occupant died, was admitted to the hospital, or evaluated in a physician’s office or emergency department only.
department. In this way, the majority of injured children would be selected while maintaining the representativeness of the overall population. If a vehicle were sampled, the “cluster” of all child occupants in that vehicle were included in the survey.

Drivers of sampled vehicles were contacted by phone and screened via an abbreviated survey to verify the presence of at least one child occupant with an injury. Surveys were conducted only in English. All vehicles with at least one child who screened positive for injury and a 10% random sample of vehicles in which all child occupants screened negative for injury were selected for a full interview. The full interview involved a 30-minute telephone survey with the driver of the vehicle and parent(s) of the involved children. Only adult drivers and parents were interviewed. The median length of time between the date of the crash and the completion of the interview was six days.

The eligible study population consisted of all 663,266 children riding in 447,924 State-Farm-insured vehicles newer than 1990 reporting a crash claim between December 1, 1998 and December 31, 2004. Claim representatives correctly identified 96% of eligible vehicles, and 70% of policyholders consented for participation in this study. Of these, 18% were sampled for interview and an estimated 81% of these were successfully interviewed.

For a subset of cases in which child occupants were admitted to the hospital or killed, in-depth crash investigations were performed. Cases were screened via telephone to confirm the details of the crash. Contact information from selected cases was then forwarded to a crash investigation firm (Dynamic Science, Incorporated, Annapolis, MD), and a full-scale on-site crash investigation was conducted using custom child-specific data collection forms. For this analysis, these data were used only to validate the surveillance data. Among 528 children for whom paired information on seating position (front versus rear) was available from both the telephone survey and crash investigations, agreement was 99% between the driver report and the crash investigator (kappa=0.98, p<0.001). Among 511 children for whom paired information on type of restraint use was available from both the telephone survey and crash investigations, agreement was 87% between the driver report and the crash investigator (kappa=0.77, p<0.001).

Separate verbal consent was obtained from eligible participants for the transfer of claim information from State Farm to CHOP/Penn, for the conduct of the telephone survey, and for the conduct of the crash investigation. The study protocol was reviewed and approved by the Institutional Review Boards of both The Children’s Hospital of Philadelphia and The University of Pennsylvania School of Medicine.

Seating location and restraint use of each child was determined from a series of questions in the telephone survey. Direction of first impact was derived from a series of questions regarding the vehicle parts that were involved in the first collision. Crash severity was determined by driver report of the presence of intrusion into the occupant compartment of the vehicle via the telephone survey. A reliable measure of delta V is not available via the survey methodology. The presence of intrusion (a dichotomous yes/no variable) was reported by the driver as intrusion anywhere in the vehicle not just in the case occupants’ seating location. Tow-away status of the vehicle was reported in the insurance claim file.

Survey questions regarding injuries to children were designed to provide responses that were classified by body region and severity based on the Abbreviated Injury Scale (AIS) score (AAAM 1990). The ability of parents to accurately distinguish AIS 2 or greater injuries from those less severe has been previously validated for all body regions of injury (Durbin et al. 1999). Children were classified as injured if they had an injury with an AIS score of 2 or greater which for the head includes all injuries except for soft tissue scalp/head injuries. Analyses were conducted on two levels of head injury severity: all AIS2+ injuries including concussions and non-concussive head injuries. The non-concussive head injury dataset is a subset of the concussive injury dataset specifically excluding those children with mild traumatic brain injuries. This includes those who were excessively sleepy, difficult to arouse, or unsure of their surroundings, those whose only diagnosis from medical personnel was a concussion and those whose loss of consciousness was less than 5 minutes.

Because sampling was based on the likelihood of an injury, subjects least likely to be injured were underrepresented in the study sample in a manner potentially associated with the predictors of interest. The SAS-callable SUDAAN®: Software for the Statistical Analysis of Correlated Data, Version 9.0 (Research Triangle Institute, Research Triangle Park, NC, 2004) was used for the weighted analyses to account for the stratification of subjects by medical treatment, clustering of subjects by vehicle, and
the disproportional probability of selection. Analyses based on the PCPS data determined the population-based risk of head injury (as defined above) by key child, vehicle, and crash predictors.

TRAUMA REGISTRY: Detailed clinical data were obtained from all children age 0-15 years admitted to CHOP from 2001-2003 as a result of injuries sustained in a motor vehicle crash from the CHOP Trauma Registry, an electronic database of detailed medical diagnoses, procedures, and clinical data. Specific medical diagnoses based on AIS codes were analyzed to determine the percentage of children in each age group and restraint type who sustained intracranial injuries alone versus brain injuries with accompanying skull fracture.

Each brain injury was then classified as occurring through rotational, translational or rotational and translational mechanisms according to the classification developed by Martin et al (Peter Martin, personal communication). This taxonomy was based on assessment from the literature of the mechanism of particular brain and skull injuries (Gennarelli 1993). Specifically, all 229 unique AIS codes for brain injuries and skull fractures from the AIS coding manual (AAAM 1990)) were reviewed and placed into three categories: those caused by translation only (i.e. focal injuries such as skull fractures, contusions, and extradural, subdural, or intracerebral hemorrhages) and those caused by rotation only (diffuse axonal injury and deep inertial strains) and those caused by both mechanisms. Approximately 15% of the AIS head injury codes were attributed to rotational mechanisms, 10% to translational mechanisms and the remainder to both mechanisms.

RESULTS

PARTNERS FOR CHILD PASSENGER SAFETY DATA: The distribution of child, vehicle, driver and crash characteristics in the study sample is described in Table 1. The overall risk of AIS2+ head injury and non-concussive head injury for the total sample was 0.86% (95% CI: 0.77-0.97%) and 0.11% (95% CI: 0.10-0.13%) respectively. Figure 1 shows head injury risk for both levels of head injury severity by age group. Those 13-15 years of age had the highest risk of both AIS2+ and non-concussive head injury. Although those <1 year of age had the second lowest AIS2+ head injury risk, they sustained the second highest non-concussive head injury rate. Reasons for this shift may lie in biomechanics or differences in methodology for the non-concussive questions in the youngest children. See Discussion for further comments.

Figure 2 shows the risk of head injury by restraint type. As expected, those unrestrained had the highest risk of both AIS2+ and non-concussive injury. Among those restrained in seat belts, head injury risks were similar; with those in lap belts showing a slight increase. Of note, the injury risk in the two child restraints (forward-facing and rear facing child restraints) showed injury risks on average 83% lower than the two belt conditions.

Figure 3 presents the risk of head injury by seat position. The front row demonstrates elevated risk of injury with similar injury risks across all three seat positions in the rear row(s). This finding held for both levels of head injury severity.

Figure 4 shows the head injury risk by crash direction. Elevated AIS2+ and non-concussive head injury risks were seen in struck-side and rollover crashes. “Other” crashes include those crashes with multiple impacts too complex to be classified as a single impact direction.

Figure 1: Head injury risk (AIS2+ and non-concussive) by age group from the PCPS population based data set. n=unweighted number of children with AIS2+ head injury.
The PCPS data allow a further division of children with head injuries into those involving skull fracture and those involving intracranial injury alone. Figure 5 shows the relative percentages by age group of these two types of AIS2+ head injuries. The data in this graph exclude concussions. For all age groups except for those less than 1 year, intracranial injury represented the overwhelming majority of the injuries sustained.

Figure 2: Head injury risk (AIS2+ and non-concussive) by restraint type from the PCPS population based data set. n= unweighted number of children with AIS2+ head injury.

Figure 3: Head injury risk (AIS2+ and non-concussive) by seat position from the PCPS population based data set. n= unweighted number of children with AIS2+ head injury. 94 children did not have a defined seat position and thus are excluded from these injury risk calculations.

Figure 4: Head injury risk (AIS2+ and non-concussive) by crash direction from the PCPS population based data set. n= unweighted number of children with AIS2+ head injury.
TRAUMA REGISTRY DATA: Data were obtained on 192 children age 0-15 years admitted to CHOP from 2001-2003 as a result of injuries sustained during a motor vehicle crash. 39% (n=74) of them sustained an AIS2+ head injury and 30% (n=57) sustained an AIS3+ head injury. Overall, 58% of the 192 were restrained and that percentage dropped slightly in the AIS2+ head injured sub group (50%, n=37). Of those who sustained an AIS2+ head injury, 55% (n=41) sustained an intracranial injury alone – no skull fracture was present. The types of intracranial injuries were subdural hematoma, subarachnoid hematoma, brain stem hemorrhage, cerebral concussion, diffuse axonal injury, intracerebral hematoma, and cerebral contusion. Skull fractures occurred to the vault as well as to the basilar skull. Figure 6 shows the relative percentage of intracranial injury alone versus intracranial injury with skull fracture among those children restrained. Although concussions (mild traumatic brain injuries) were not specifically excluded from this dataset, because it is limited to those children admitted at least overnight to the trauma center, most mild brain injuries, which do not require hospital admission, are thus not included. In this data set, a larger percentage of children sustained skull fractures compared to the PCPS data set, however for those from age 1 to 12 years, intracranial injuries alone represented 60% of the injuries. Similar to the PCPS data, this percentage was smaller for those less than 1 year (37%).

![Figure 5: Relative percentage of children with AIS2+ head injuries that were intracranial alone versus skull fracture (with and without intracranial injury) by age group from the PCPS population based data set. Concussions were excluded. n = unweighted number of children.](image1)

![Figure 6: Relative percentage of children who sustained AIS2+ head injuries that were intracranial alone versus intracranial and skull fracture by age group from the trauma registry data set. n= number of children.](image2)

Using Martin’s methods of classification of head injuries as described in the methods, restrained children with head injuries were classified as sustaining injuries due to mechanisms of rotation,
translation, or both. (Figure 7). Except for three children in the 4-8 year old age group, no children sustained only translation-induced injuries. Most children sustained injuries due to both mechanisms and approximately 20% of those 0-12 years of age sustained only rotational injuries.

Figure 7: Relative percentage of restrained children with AIS2+ head injuries that were rotational, translational and both by age group from the trauma registry data set. n= number of children.

DISCUSSION

The analyses contained in this manuscript provide population-based head injury risks for child occupants based on a contemporary set of vehicles and restraints as well as detailed clinical data that allow for the determination of the relative proportion of skull fractures versus intracranial injuries in these children. The population-based data provide context for future research in this area by highlighting areas of priority for prevention while the trauma registry data point to patterns of head injury that suggest future research into pediatric head injury mechanisms and their implications for current regulatory metrics. The analyses examined the variability of injury risk with age, restraint type, seat position and crash type. Each will be discussed in detail below.

Overall, those 1-3 years of age had the lowest head injury risk, which can be attributed to the high level of effectiveness of forward-facing child restraints, the most common restraint in this age group (Arbogast et al. 2004). The injury risk to the head increases as children get older. Although 4-8 year olds are recommended to be in booster seats, most of these children are restrained in adult seat belts (Winston et al. 2004), a restraint condition that has been previously identified as leading to elevated head injury risk (Durbin et al. 2003). Those 9-12 years of age show a similar risk of head injury as those 4-8 years. For this age group, front seating is more common and injury risks associated with that seat row such as air bag injury risk and simply being closer to the impact in frontal crashes likely leads to the elevated injury risk (Braver et al. 1998; Durbin et al. 2001; Durbin et al. 2004). Thirteen to fifteen year olds had the highest risk of both AIS2+ and non-concussive head injury. This is likely related to characteristics of the vehicle environment and crash type that children of this age are in rather than difference in biomechanical tolerance. These children are almost exclusively in the front seat, have a lower restraint use than younger children, ride with their peers and are involved in crashes of higher severity (Chen et al. 2005).

Although those <1 year of age had the second lowest AIS2+ head injury risk, they sustained the second highest non-concussive head injury rate. Reasons for this shift may lie in biomechanical characteristics of the skull and brain for infants or differences in methodology for obtaining data on the presence of concussion in the youngest children. One of the questions in the survey for determining the presence of AIS 2+ injury asks about the presence of sleepiness or altered consciousness in the child passenger after the impact. This mental state, although a true clinical predictor of mild traumatic brain injury, is difficult for parents to assess, particularly in the youngest children. For that reason, we do not currently ask that question on any child occupant less than 4 years and as a result, the AIS2+ injury rate for the youngest children may be artificially low. Thus, caution
should be exercised when interpreting the specific value of head injury risks for the youngest age groups.

The findings with regard to restraint type follow the findings described above for age. Unrestrained children, as expected, had the highest risk of head injury. Among those children restrained, AIS 2+ head injury risk was reduced by approximately two-thirds in all of the child restraint types as compared to seat belts. This pattern did not follow when examining the non-concussive injury risk. Those children in belt-positioning booster seats and forward-facing child restraints had the lowest non-concussive injury risk, however among the remaining restraint types (rear-facing child restraints, shield boosters, lap belts, and lap shoulder belts) the risk was similar and two to three times higher than the other child restraints. Small sample sizes should caution over-interpretation of this finding.

AIS2+ head injury risk in the front seat was twice as high as all three rear seating positions. This finding remained, although not as strong, for non-concussive head injuries as well. Elevated injury risk in the front seat has been demonstrated by several researchers (Braver et al. 1998; Durbin et al. 2001; Durbin et al. 2004) and is likely due to the presence of air bags and proximity to the impact in the frontal crash direction. Of note, all three rear seat positions showed similar risk of AIS2+ and non-concussive head injury. This finding, in contrast to the traditional thought that the center rear seat position is associated with a lower risk of injury (Howard et al. 2003), has recently been documented by several researchers. On a seat belt restrained sample of the PCPS population, Maltese et al has demonstrated the similarity of injury risk between center rear child occupants and those on the struck side in side impact crashes (Maltese et al. 2005). Lund evaluated the effect of seat position on injury to all body regions using the US NASS data set for children restrained in child safety seats and found that all three seat positions in the rear row have similar injury risks (Lund 2005).

Injury risk by crash type pointed to the high risk of head injury (both AIS2+ and non-concussive) in rollover crashes. Both levels of head injury risk were over 5 times higher in rollovers than the average of other crash types. This finding specific to head injury confirms previous research on all body regions of injury using the US FARS and NASS data sets that determined that rollover crashes resulted in two times the risk of death and injuries for child occupants compared with non-rollover crashes (Rivara et al. 2003). In addition to rollovers, struck-side crashes were associated with a high risk of head injury. The involvement of injuries to the head in this crash scenario has been previously highlighted by several researchers (Arbogast et al. 2001; Hillary et al. 2002; Howard et al. 2003; Orzechowski et al. 2003; Arbogast et al. 2004; Bazarian et al. 2004). In this crash type, children are often impacting their head on the interior vehicle surface, particularly below the belt line, or for rear seat occupants, on front seat components intruding into the rear occupant space (Arbogast et al. 2001; Arbogast et al. 2004).

When examining the patterns of head injury for the entire age group, 55% and 51% of the children sustained intracranial injuries alone, from the PCPS data and Trauma Registry data, respectively. For the PCPS data set, this value increased with age to over 70% of 13-15 year olds sustaining intracranial injuries alone. This trend with age was similar in the trauma registry data except for the 13-15 year olds of whom 38% sustained isolated intracranial injuries; however there were only 3 subjects in this age group in that dataset so that percentage is likely unstable. These data suggest that in order to properly assess the effect of technology on mitigating head injuries in children, we need to ensure that our metric accurately predicts the occurrence of intracranial injuries in the absence of skull fracture. This point is reinforced below in the analysis of the data using the Martin taxonomy.

Of interest, our data showed an increase in the proportion of skull fractures in children less than 1 year old as compared to children older than 1; this was reflected both in the PCPS (Figure 5) and the Trauma Registry (Figure 6) data. This finding has been observed in at least one other trauma center setting. Muñoz-Sánchez et al, in a Spanish study of almost 2000 pediatric head injuries from all sources (including traffic crashes, falls, and other impact scenarios), found that children under two years of age were 2.9 times more likely to receive a skull fracture as compared to children aged 2 to 13 (Munoz-Sanchez et al. 2005). The fact that this finding was evident in a sample of injured children from a variety of mechanisms, mostly non-automotive, strengthens the suggestion that it is a biomechanical characteristic of young children and not a product of how the injuries occurred. Biomechanically, the skull of the young child is thin, pliable, and characterized by deformable sutures (Smith et al. 1975; Berney et al. 1994; Zimmerman and Bilaniuk 1994). Material testing of human
and porcine infant skull tissue has determined that it possesses a lower ultimate stress but a higher strain to failure (Margulies and Thibault 2000). These somewhat conflicting characteristics suggest that the young child’s skull can experience large deformation without fracture, injuring the brain tissue beneath the deforming skull; however the thinness of the skull itself and its low ultimate stress suggests it might fracture at lower forces. The data support this second hypothesis – the non-concussive head injury rate in infants is higher than their older counterparts and when injured, they sustain a pattern of injuries that more likely includes skull fracture with and without intracranial injury. This finding suggests that the current head injury metric in US FMVSS 213 designed to protect the youngest children in rear facing restraints is not serving that purpose. It draws attention to the HIC (36 millisecond time window) limit of 1000 implemented in this regulation and suggests that future regulatory actions should incorporate documented differences in skull and brain material properties into a more accurate head injury metric.

The debate on the relative importance of rotational versus translational mechanisms as the primary cause of head injury in motor vehicle occupants and the relevance of the HIC as an appropriate metric has been ongoing for decades. A complete review of the data supporting these conflicting hypotheses was presented recently by King et al (King et al. 2003). Briefly, the one hypothesis is that if angular acceleration is the primary mechanism of head injuries such as subdural hematoma and diffuse axonal injury, then HIC, developed with skull fracture as the failure criterion, may not be adequate for assessing the risk of common head injuries such as these. In contrast, those that advocate for the appropriateness of the HIC, point to the success of helmets, which reduce translational not rotational acceleration, in mitigating brain injury. This debate takes on additional complexity when discussing the implications for children due to the biomechanical difference in their skull and brain described above.

The analyses contained herein cannot conclusively answer that debate; however by classifying the injuries sustained by the children in the Trauma Registry dataset into rotational, translational, or both, the importance of rotational acceleration for pediatric head injuries is highlighted. For all age groups except the 13-15 year olds, 20% of head injured children sustained injuries due to rotation alone; only 3 children in the 4-8 year old age group sustained injuries due to translational mechanisms only. (Figure 6) This result emphasizes the need to develop pediatric head injury metrics that incorporate a measure of head rotation. The taxonomy used was developed for adult head injuries and may not be completely applicable to pediatric head injuries; however it provides insight into the relative importance of rotational mechanisms of head injury in children.

Part of this research is conducted on crashes involving State Farm Insurance Co. policyholders. State Farm is the largest insurer of automobiles in the United States, with over 38 million vehicles covered; therefore, its policyholders are likely representative of the insured public in this country. The surveillance system is limited to children occupying model year 1990 and newer vehicles insured in 15 states and the District of Columbia. Our study sample represents the entire spectrum of crashes reported to an insurance company including property damage only, as well as bodily injury crashes. While our sample included a significant number of vehicles with intrusion into the occupant compartment, it is possible that we do not have a representative sample of the most severe crashes. This limitation was addressed with the addition of the second dataset.

Nearly all of the data for the PCPS study were obtained via telephone interview with the driver/parent of the child and is, therefore, subject to potential misclassification. On-going comparison of driver-reported child restraint use and seating position to evidence from crash investigations has demonstrated a high degree of agreement. In addition, our results on age-specific restraint use and seating position are similar to those of other recently reported population-based studies of child occupants (Edwards and Sullivan 1997; Wittenberg et al. 1999). Therefore, it is unlikely that errors in reporting restraint use or seating position would substantially alter the results of this study.

For the PCPS study, data on the injuries sustained have been obtained via a validated telephone survey – more specific details from medical records may provide insight regarding the mechanisms of injury. Thus, it is important to note, however that these comparisons only look at injury risk and do not assume similar mechanisms of injury. For example, although the head injury risk in frontal crashes and non-struck side crashes are similar, the mechanisms and patterns of injuries sustained in those impact directions may be different. Further the injury risks presented are for AIS2+ injury. These surveillance data cannot detect if those in frontal crashes are sustaining primarily AIS3-4 injuries.

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while those in non-struck side crashes are experiencing only AIS2 injuries. Further, detailed measures of crash severity such as delta v (not available in these two data sets) and their effect on injury risk and injury pattern should be explored. These questions will be examined in future work involving the crash investigation component of the PCPS data set.

The trauma center data, although a small data set, represent a more severe subset of injuries children sustain as a result of motor vehicle crashes. These data represent the experience at a single Level 1 pediatric trauma center and may not be representative of all pediatric trauma hospitals. Future studies combining detailed clinical data from several trauma centers, such as that collected as part of the CIREN study, may help further explain these findings.

CONCLUSIONS

Based on population-based data, AIS2+ head injury risk varied by age, seat position, restraint, and crash type. Predictors of elevated AIS2+ head injury include lap belt only (1.2%), right front seat position (1.4%), rollovers (4.6%) and struck-side crash (1.6%). Examination of non-concussive head injuries showed similar relationships. Increasing age was associated with increasing non-concussive head injury risk except for the children less than 1 year whose injury risk was slightly higher than their older counterparts. Review of the trauma registry data revealed that approximately 60% of the head injuries sustained by children age 1-12 years were intracranial injuries in absence of skull fractures. This percentage was slightly less for those <1 year of age who show an increased proportion of skull fractures compared to other age groups. Consideration of the known mechanisms of the specific head injury diagnoses illustrated that approximately 20% of the head injuries may be better correlated with a head injury metric derived from a measure of head rotation than the current HIC measurement.

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REFERENCES


Table 1: The distribution of child, driver, vehicle, and crash characteristics in the study sample

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<tr>
<th>Child characteristics</th>
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<th>Weighted %</th>
<th>Mean S.E.</th>
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<td>7.9 ±0.03</td>
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Note: Due to missing data, the unweighted n by subgroup does not add up to the total unweighted n