

Head injury patterns in Australian rollover fatalities from the National Coronial Information System

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Abstract

An analysis of the head injuries sustained by fatally injured occupants in rollover crashes was conducted using the available online data from the Australian National Coronial Information System. All available autopsy, police reports, and findings were reviewed. Cases were selected for inclusion in the study if they could be identified as properly restrained and contained occupants in single event passenger vehicle rollovers. All head injuries were coded using the Abbreviated Injury Scale, 1990 update. The required online data were available from New South Wales, Northern Territory, Queensland, Tasmania and Victoria. Eighty-three cases were identified between 2000 and 2011 that met all inclusion criteria. The study was undertaken as part of a project with the aim of developing a dynamic test protocol to assess injury in the rollover crash mode, with specific interest in serious head injuries. The patterns and types of head injury were identified and cross referenced with known rollover conditions and occupant factors. The patterns of head injuries appear to differ based on many factors such as seat position and head contact location. Head injuries were the most frequently occurring serious injury among fatally injured occupants with a presence in 67 % of all cases. Of the cases that sustained a serious head injury 50 % had a serious thorax injury and 20 % had a serious spine injury. The findings help to identify which countermeasures may be effective in mitigating serious head injuries in rollover crashes as well as appropriate test methods that could assess the safety of a vehicle in the rollover crash mode.

Introduction

This study is part of a project with the aim of determining a dynamic rollover occupant protection (DROP) crash test protocol (Grzebieta et al., 2012). In the context of this project restrained and contained occupants 16 years and older in pure rollover crashes are of interest. Restrained and contained occupants are defined as those who are appropriately belted and remain inside the vehicle during the duration of the event. Pure rollovers, for the purpose of this study, are those in which the rollover is the only harmful event in the crash. Multi-event rollovers, and those in which the occupants are unrestrained or ejected, are outside the scope of the project as they produce more severe and different injury patterns (Bedewi et al., 2003; Bose et al., 2011; Funk et al., 2012).

Crashes involving rollover are responsible for approximately one-quarter and one-third of all occupant fatalities in Australia and the United States (US), respectively (Grzebieta et al., 2009; NHTSA, 2011c). Serious head injuries (SHI), defined as having a post-dot score from 3-6, inclusive, in the head chapter of the Abbreviated Injury Scale 1990 update (AIS 1990 update), account for 37 % of all serious (AIS 3-6) injuries and are a contributing cause of death for 45 % of fatally injured occupants in rollovers of all types (Bedewi et al., 2003; Fréchéde et al., 2011). With regard to restrained and contained occupants in pure rollover crashes, approximately 20 % of serious injuries are coded to the head (Bambach et al., 2013b) and 21 % of seriously injured occupants have an SHI (Mattos et al., 2013b). The frequency and distribution of specific SHIs for predominantly non-fatal crashes has been described previously (Atkinson et al., 2004; Hu et al., 2005; Mattos et al., 2013b; Patel et al., 2004) with brain injuries occurring more frequently than skull fracture. The relationships between certain occupant, vehicle, and environmental factors and SHI have also been investigated (Funk et al., 2012; Hu et al., 2007). A previous study of SHI in

pure rollover crashes in the US identified a relationship between occupant seat position and location of head injury as well as three patterns of basilar skull fracture (Mattos et al., 2013b).

The NCIS database, which includes records of deaths reported in Australia, has been used previously to investigate the general characteristics of rollover fatalities (Fréchède et al., 2011) as well as the detailed characteristics of spine injuries sustained by occupants in rollover (McIntosh et al., 2010). This study will investigate the patterns and characteristics of SHIs that occurred to fatally injured occupants of pure rollover crashes in Australia. The aim of which is to provide information to aid in the selection of an appropriate anthropometric test device (ATD) and test protocol to replicate and evaluate the potential for SHI in a dynamic rollover test.

Methods

The National Coronial Information System (NCIS) is an online database, available to authorised users, which includes records of every death reported to participating coronial offices in Australia beginning in July 1, 2000 for all states and territories except Queensland which commenced in January 2001. Depending on the circumstances of the case investigation each record may include police accident reports (PAR), autopsy and toxicology reports, and/or coronial findings. The database can be queried using a set of core data variables such as case demographics and cause of death (COD) details (NCIS, 2010). Further information not included in the core data set must be determined via case-by-case review of available reports. Ethics approval was sought and obtained prior to the study from the Victorian Department of Justice Research Ethics Committee (Reference No. CF/12/22070) and from the UNSW Human Research Ethics Committee (Reference No. HC11445).

Cases were extracted from the NCIS database following a procedure similar to that used by Fréchède et al. (2011). The inclusion criteria for the study is summarised in Table 1. The initial query yielded 4,171 cases which were output to an excel spread sheet to be filtered further, shown in Figure 1. The first phase of the filtering process used NCIS coding variables to remove irrelevant cases. Cases were removed if the crash involved an impact with a fixed object or if there was insufficient information available to identify the necessary crash characteristics. The second phase involved a manual check of the PAR and/or coronial findings to determine specific information pertaining to the characteristics of the crash. At this point each case was reviewed to confirm that it complied with the inclusion criteria. A conservative approach was taken in identifying occupant restraint and containment as well as the characteristics of the rollover. Cases were removed if seat belt use and containment could not be confirmed by PAR, findings, or autopsy records. Pure rollovers were defined as crashes in which the only harmful event was determined to be the rollover itself. Cases in which the rollover was preceded, initiated or interrupted by an impact or for which too little detail was available were removed. Overly severe rollovers such as end-over-end, high speed (>150km/h), or those involving steep terrain, fire, or submersion were also removed. Out of the remaining cases 351 were identified as restrained and contained in a rollover crash, of which 190 were classified as pure rollovers. A further 107 cases were removed because either an autopsy report was not available or adequate or further inspection identified other characteristics, such as ejection status, that were previously unidentified.

The autopsy reports for each of the 83 cases that met the inclusion criteria were reviewed and all head injuries were coded using the Abbreviated Injury Scale (AIS), 1990 update (AAAM, 1990). This version was used to allow for direct comparison with previous work. AIS 1-2 head injuries, such as abrasions, contusions, and lacerations, were used to estimate locations of head contact. Brain and skull injuries were defined as those falling under the “Internal Organs” or “Skeletal” section of the head chapter in the AIS90 dictionary, respectively. All serious spine and thorax injuries were coded for occupants that sustained a SHI. Additionally, AIS 2 spine injuries, mainly fractures, were identified and coded.

Table 1. Case inclusion criteria

Initial NCIS query	
Age	16+ years
Date range	1/7/2000 to 31/12/2011
Primary injury mechanism	Blunt Force
Secondary injury mechanism	Transport injury event
Tertiary injury mechanism	Vehicle occupant
Mode of transport 1	Light transport vehicle
Counterpart	Single vehicle
States/territories	NSW, NT, QLD, TAS, VIC
Manual document check	
Restraint	Seatbelt
Containment	Not ejected
Crash type	Pure, single-vehicle rollover
Vehicle type	Passenger vehicle

**Figure 1. Case selection flowchart**

For each case an attempt was made to collect additional information about the event from the available reports, see Table 2. The seat position relative to the direction of roll (near- or far-side), an important factor in head injury location and patterns (Mattos et al., 2013b), was determined for each occupant whenever possible. Near-side occupants were defined as seated adjacent to the direction of roll and far-side occupants opposite to the direction of roll. The designations inboard and outboard were used to differentiate between the halves of the body, divided by the mid-sagittal plane, nearest to the centre or door of the vehicle, respectively. Chi-squared tests were used to determine if any significant correlations existed between crash parameters and outcomes.

Table 2. Additional information collected from reports

Vehicle / Crash characteristics	Occupant / Injury characteristics.
Vehicle make/model/year	Age
Speed limit / estimated travel speed	Weight
Roll direction	Height
Final rest position	Seat location
Airbag deployment	AIS 1-2 head/face injury location
Roll distance / quarter turns	Blood alcohol level

Results

Descriptive Results

Eighty-three cases met the inclusion criteria of this study. The general empirical results are described in Table 3. Fifty-six cases with a serious head injury (SHI) were identified. Among the cases with SHI, the primary cause of death (COD) was cited as the SHI in 45 and positional asphyxia in 3 with the remainder split between spinal and thoracic injuries. For those cases without SHI, the primary COD was identified as spinal (12), thoracic (7), and abdominal (1) injuries. Additionally, 7 occupants without further identified serious injuries died due to positional asphyxia

(6) and heart attack (1). The group with SHI were an average of 16 years younger than those without and included nearly equal counts of males and females. Cases with and without SHI were identified as having concomitant serious spine injury (SSI) or serious thoracic injury (STI) with similar frequencies. Roll direction could be identified for 50 cases (35 with SHI). A significantly higher percentage of occupants with SHI were seated on the far-side than the near-side ($p < 0.05$). Except for one crash, all occurred on roads with a speed limit greater than 80 km/h with 80 % occurring on roads with a speed limit greater than 100 km/h. The distribution of vehicles and vehicle model years was similar for both groups. Although information on the presence of airbags for each vehicle was not available, only seven vehicles had airbags deploy during the crash.

Table 3. General empirical results

	SHI n=56 [%]	No SHI n=27 [%]
Age-mean, median, std. dev.	36, 34, 16	52, 52, 21
Height-average (cm)	172	173
Weight-average (kg)	81	89.7
Male	32 [57]	21 [78]
With serious thorax injury	28 [50]	13 [48]
With serious spine injury	11 [20]	8 [30]
Far- / near-side / unknown (?)	27 [48] / 8 [14] / 21 [38]	6 [22] / 9 [33] / 12 [44]
Driver / Front passenger / other	40 [71] / 11 [20] / 5 [9]	15 [56] / 11 [41] / 1 [4]
Sedan / SUV / Pickup / ?	20 [36] / 13 [23] / 9 [16] / 14 [25]	9 [33] / 8 [30] / 6 [22] / 4 [15]
Average vehicle year	1996	1998

Minor head/face injuries

For all occupants, 56 had minor (AIS 1-2) injuries to the face and 71 had minor injuries to the scalp. Nineteen occupants were identified as having deep, ragged, or degloving type lacerations, all with SHI. The distribution of AIS 1-2 head/face injuries for all occupants is shown in Figure 2 with respect to their seat position relative to the direction of roll. The overall distribution was similar for the SHI and non-SHI groups. For an occupant seated on the near-side, minor head injuries were distributed fairly evenly between the inboard and outboard side of the head. For occupants seated on the far-side, AIS 1-2 head injuries occurred to the inboard region of the head almost twice as often as to the outboard region. A significantly higher proportion ($p < 0.001$) of far-side occupants sustained minor injuries to the forehead than near-side occupants. The only major difference in contact location between occupants with and without SHI was in the occipital region where minor injuries were observed for 36 % and 11 % respectively.

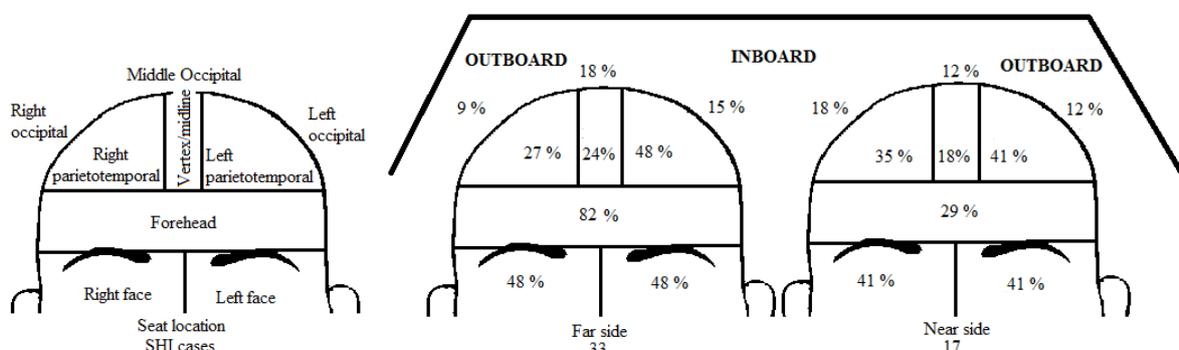


Figure 2. Location of minor (AIS 1-2) head injury locations by seat position relative to roll direction for all occupants with known roll direction.

Skull Fractures

Twenty-six occupants were identified as having a skull fracture, three of which were linear or comminuted fractures of the vault. The remaining 23 fractures were complex and involved both the vault and base of the skull. Roll direction could be identified for 16 of the cases with skull fracture, 14 of which were far-side. Due to the complex nature of some of the skull fractures the location of impact could only be identified for 17 cases, 11 of which had roll direction identified. Eleven cases had skull fractures identified to the inboard side of the head, seven of which with known roll direction (all far-side). Four cases had skull fractures to the outboard side of the head, three of which with known roll direction (2 near- and 1 far-side). The foramen magnum was involved in two cases, one of which had extensive comminuted fractures of the vault and basal skull. The occipital condyles were not identified as being involved in any of the cases. Eight cases with skull fracture also experienced a fracture of the spine. The spinal fractures were located at the cervical (4), upper thoracic (3), and in both the cervical and upper thoracic spinal regions (1). The cervical spine fractures occurred at the first, third, fourth, sixth, and seventh vertebrae. All skull fracture cases had serious brain injuries.

Serious Brain Injuries

There were 170 SHIs sustained by 56 occupants. The average number of SHIs for near and far-side occupants was 3.3 and 2.3 respectively. The distribution of SHIs in this study is compared to that of predominantly non-fatal cases and is shown in Figure 3. Cerebral subarachnoid haemorrhage (SAH) was the most common SHI with 59 observed for 37 cases. Twenty-six occupants had SAHs on both hemispheres, six had unilateral SAHs, and five were of unknown location. Seventeen of the occupants with SAH, of which all but one had bilateral SAH, had a skull fracture. For the five occupants with unilateral cerebral SAH and no skull fracture all but one had subgaleal hematomas noted to the front of the head. Twelve of the 15 occupants with bilateral SAH, and no skull fracture, showed evidence of lateral head impact. Twenty-five hematomas were identified for 21 occupants, five of which sustained multiple hematomas, and 10 of which had an attendant skull fracture. The hematomas most frequently occurred unilaterally (nine on the left and eight on the right) with only four occurring bilaterally. Those that were sustained with a skull fracture were observed in the same location of the fracture for six cases and on the opposite side for four cases. There was no discernible relationship between impact location and position of hematoma for occupants without skull fracture. The distribution of hematomas by depth is shown in Figure 4. Hematomas most frequently occurred at the subdural level and decreased in frequency with distance from the subdural layer. Twenty cerebral contusions were observed for 13 occupants, five of which received multiple contusions, and all but two had a concomitant skull fracture. Thirteen of the contusions were sustained on the same side as the skull fracture while five occurred on the opposite side. Cerebrum contusions were more frequently located on the frontal (7) or temporal (7) poles than on the occipital poles (3).

Diffuse axonal injury (DAI) was noted in two of the autopsy reports. For the remaining reports DAI was not able to be positively identified. This was due to the fact that most of the cases died at the scene and that no hospital information was available for those that did not. This precluded the diagnosis of coma which is necessary to identify DAI, as per AIS coding guidelines (AAAM, 2005). There were, however, five additional cases which exhibited brain injury that is commonly associated with DAI.

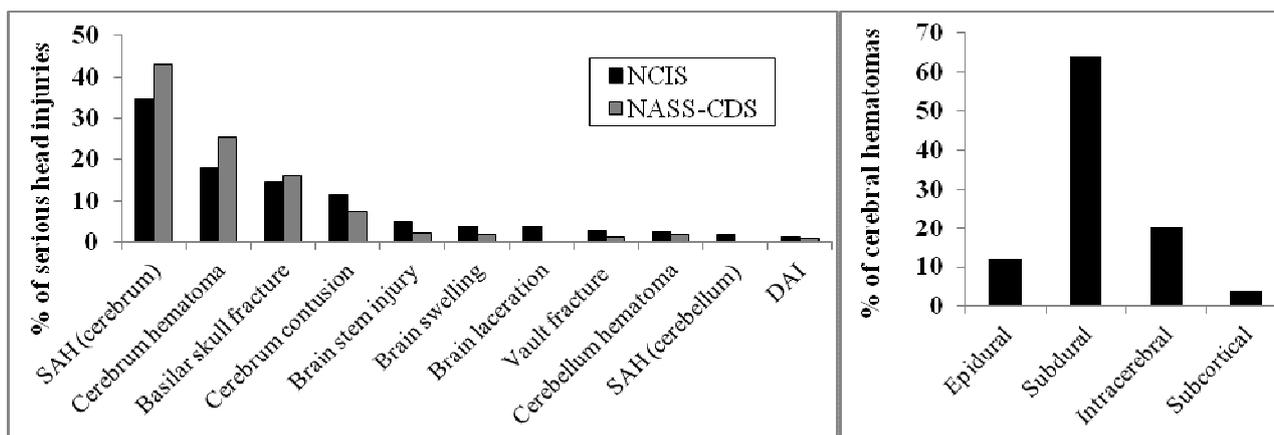


Figure 3. Distribution of serious head injuries [n=170] for fatal (NCIS) and all occupants (NASS-CDS, after Mattos et al. 2013) in pure rollover crashes.

Figure 4. Distribution of cerebrum hematomas by location.

Multi-region Serious Injuries

Half of the occupants with SHI had a serious thorax injury and one in five had a serious spine injury. An additional nine occupants with SHI were identified as having AIS 2 spine injuries; seven at the level of the cervical spine and two at the thoracic spine. Six cases with SHI sustained serious injuries to both the spine and thorax. The SSIs were distributed among the cervical (7), thoracic (3) and lumbar spine (1). All serious cervical spine injuries involved fracture and/or dislocation of the vertebrae with spinal cord injury. The distribution of AIS 2+ spine injuries for occupants with SHI are shown in Figure 5 along with results from other studies. For occupants with SHI, spine injuries were observed to occur in the lower cervical spine about twice as often as the upper cervical spine. Dislocation of the atlanto-occipital joint was only observed for cases in the current study. The serious brain injuries sustained by occupants with cervical spine injuries were generally similar to the entire SHI group with the exception that haemorrhages at the base of the brain were more common in cases with cervical spine injury.

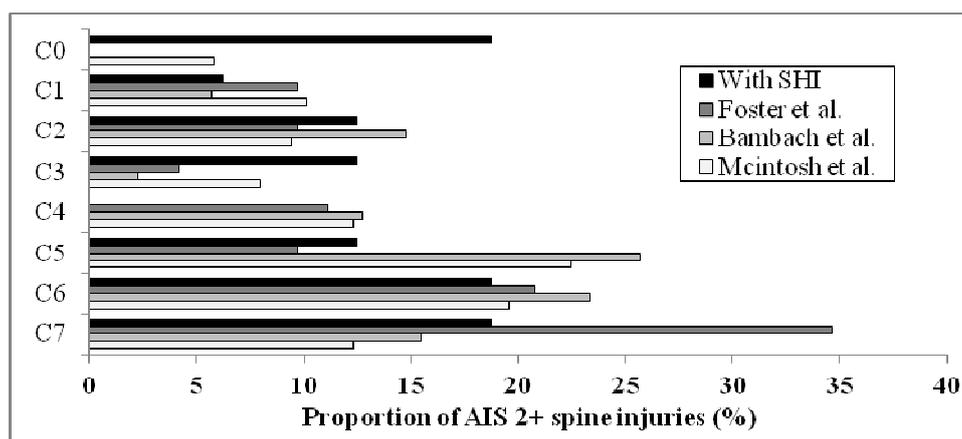


Figure 5. Proportion of AIS 2+ spine injuries for occupants with serious head injury according to location [n = 16]. Results from studies of AIS 2+ spine injury in similar rollover crashes using CIREN (Foster et al., 2012) and NASS-CDS (Bambach et al., 2013a), as well as from a study of spine injury for all fatally injured occupants in all severity of rollovers using NCIS (McIntosh et al., 2010) are also shown.

Discussion

The results of this study were similar, but with an overall increase in severity, to those found by previous work using non-fatal data. For instance, although the distribution of SHIs was similar to that reported by others (Atkinson et al., 2004; Hu et al., 2005; Mattos et al., 2013b), fatal occupants tended to have more complex skull fractures, typically including the base of skull, and brain injuries. As has been documented elsewhere (Funk et al., 2012; Mattos et al., 2013b) the far-side occupants in this study were more likely to sustain a SHI, and had more SHIs on average, than near-side occupants. Due to the increased severity inherent in fatal crashes the ratio of occupants with SHI as well as the average number of SHIs sustained per occupant was higher than reported for non-fatal cases. The over representation of far-side occupants in the SHI group and their increased frequency of injury is most likely a result of the difference in occupant kinematics and roof performance between the near- and far-side. This result has been observed by Jehle et al. (Jehle, 2007) who noted that the fatality rate for far-side occupants was more than 50 % greater than it was for near-side occupants and that far-side occupants suffered serious injury 5 times more often. This is due to a combination of the more severe impact, and greater roof crush, that generally occurs on the far-side as well as the increased energy and motion of the far-side occupant (Gloeckner et al., 2007; Mattos et al., 2013a; Parenteau et al., 2001; Thorbole et al., 2009; Viano et al., 2009) . The danger of roof crush is further demonstrated by the 10 cases in which occupants perished due to positional asphyxiation caused by intrusion of the roof into the occupant compartment. Roof deformation was commonly noted in PARs as an obstruction in the extrication process.

The location of AIS 1-2 head injuries and AIS 2+ skull fractures were used to identify head contact locations and were noted on every region of the head. The results correlated well with previous research (Mattos et al., 2013b) confirming that head injury location is dependent on seat position relative to roll direction. Far-side occupants suffered impacts more frequently on the inboard and frontal regions of the head than near-side occupants. The locations of head impact were most frequently in the temporoparietal region for all occupants and in the frontal region for far-side occupants. Impacts were observed occasionally in the occipital region of the head and relatively rarely to the vertex. The distribution of head contact locations highlights the complexity of the rollover crash mode and indicates that the occupant does not maintain an upright seated posture during the rollover event. This information can assist in determining the initial positions of ATDs in dynamic tests that will result in observed contact locations.

The most common serious brain injuries for rollover occupants, bleeds and contusions, are generally described as resulting from relative motion between the brain and skull due to direct impact to the head from nearly any direction (Bandak, 1996; Goldsmith, 2001). For this reason specific types and locations of brain injuries cannot generally be traced back to specific impact locations. This was the case for the brain injuries that were observed. However, certain characteristics were noted that are relevant to the rollover crash mode. Impact to the head in the lateral direction, with or without skull fracture, was not only more frequent but was also observed to occur in higher severity SAH while evidence of anterior-posterior impact accompanied unilateral SAH. The increased severity of impact in the coronal plane, resulting in brain injury and skull fracture, as compared to impacts in the sagittal plane has been documented experimentally (Gennarelli et al., 1987; McIntosh et al., 1993; Zhang et al., 2009) and in real world crashes (Yoganandan et al., 2010; Yoganandan et al., 2009). Skull fracture was appeared to be a prerequisite for cerebral contusions which occurred most frequently at the frontal and temporal poles. Although the contusions were most often on the same side of the head as the skull fracture, their location is most likely due to the irregularities of the internal bone structure at those locations, not necessarily because impact has occurred there (Goldsmith, 2001). This is not to say that the fracture is not related to the injury. The occurrence and characteristics of cerebral hematomas did not appear to be related to the location of head impact nor the existence of skull fracture.

The presence of skull fractures and scalp lacerations can be used to estimate the severity of head impact. Experiments indicate that basilar skull fractures can be produced from impacts to the vault in the order of 7.5 kN (McElhaney et al., 1995) and that impacts greater than 4 kN will produce scalp lacerations and vault fractures (Sharkey et al., 2012).

The proportion of spine injuries by location for fatally injured occupants with SHI was similar to that found in other studies. The only major difference was that dislocations of the atlanto-occipital joint were only observed to occur in the current study, which is not surprising given that this type of injury is generally fatal. The similarity in the location of cervical spine injuries between all occupants with AIS 2+ spine injuries and those with concomitant SHI indicates that injury modes exist that are common to some SHIs and cervical spine injuries. Although this may be the case for a selection of SHIs the relatively low frequency of cervical spine injuries occurring with SHI indicates that the predominant modes of injury are different.

One challenge in using the NCIS data was identifying partially ejected occupants. A partial ejection occurs when one or multiple parts of an occupant's body, typically the head or upper extremities, projects through an opening such that it has the potential to contact the outside environment. Cases in which the PAR or findings identified a partial ejection were removed, yet some with no mention of partial ejection were noted as exhibiting injuries consistent with partially ejected occupants such as deep, ragged or degloving type lacerations. Although the lacerations observed are commonly sustained by ejected occupants (Turnage et al., 2000) they have also been observed to occur to fully contained occupants due to the lack of adequate interior padding (Rechnitzer et al., 1994), which would be the case for most of the vehicles in the study.

Some of the SHIs sustained could potentially be mitigated by countermeasures that are currently available. Four of the primary countermeasures currently used to mitigate head injury are increased roof strength (Brumbelow et al., 2009; Mandell et al., 2010; NHTSA, 2010), appropriate restraints (Digges et al., 2003), side air curtains (NHTSA, 2011b), and upper interior padding (NHTSA, 2011a). The first 3 countermeasures work together to help contain the occupant during the event while the interior padding reduces the severity of head impacts when contact between the head and interior structure occurs.

With regard to a dynamic rollover test the results indicate the characteristics of SHIs that a protocol would aim to reproduce. These characteristics include the types and locations of injury with respect to seat position as well as patterns of injury between body regions. This will aid in determining the combination of test conditions and ATD features which would be necessary to replicate and measure appropriate injurious head contact. The patterns of injury between body regions could prove to complicate a test protocol due to the decoupled nature of serious head, spine, and thorax injuries. All three injuries were rarely observed concurrently. If it is the goal of a dynamic test to be able to replicate serious injury in all three of these body regions, the results indicate that different test conditions may be necessary to produce an injury in each body region. Further, the differences in SHI frequency and head contact location between the near- and far-side occupants indicates that different test conditions may be necessary to produce injury in these two seat positions. At the very least multiple ATDs would need to be used.

There are limitations of this study which should be noted. The study is dependent upon the accuracy and completeness of reporting of the police and coroners. Although the NCIS data is nearly a census of all deaths, not all deaths are investigated or reported. Further, select cases were excluded from the study that lacked detailed information. There does not appear to be any reason for the exclusion of these cases to introduce a bias that would affect the study.

Conclusion

Serious head injuries (SHIs) were coded for fatally injured contained and restrained occupants of pure passenger vehicle rollover crashes. SHI is over represented in fatal rollovers. Far-side occupants are more likely to suffer SHI and were observed to sustain more impacts to the front and inboard region of the head than near-side occupants. The patterns of serious brain injury related to head contact location and skull fracture were identified. SHI was observed to occur generally independent of serious spine and thorax injury. The distribution of spine injuries sustained by occupants with SHI was similar to that found for fatal and non-fatal occupants without SHI. The characteristics of SHI observed in this study will serve as a benchmark from which prototype dynamic test protocols can be assessed to determine their appropriateness to the real world in terms of SHI prediction.

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