CHARACTERIZING DIFFUSE BRAIN INJURIES FROM REAL-WORLD MOTOR VEHICLE IMPACTS

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ABSTRACT

This study characterized brain injuries with a focus on diffuse axonal injuries using the Crash Injury Research Engineering Network (CIREN) database, developed by the National Highway Safety Administration (NHTSA). Tier one and tier two medical- and crash-related data from 1997 to 2006 were used in the retrospective analysis. Diffuse axonal injuries injuries were assessed using the 1990 version of the Abbreviated Injury Scale. In addition, other brain injuries and bony trauma to this body region were extracted. Potential head contact data were determined based on an evaluation of medical information such as x-rays and CT scans. Crash-related variables such as change in velocity, principal direction of force, and impact modality were obtained.

Case-by-case analyses were grouped as a function of the number head injuries sustained by each occupant. Out of the 3,178 medical cases from 2,823 crashes, 67 occupants, 11 months to 85 years of age, sustained diffuse axonal injuries. Change in velocity ranged from 4 to 24 m/s. Twenty-eight passengers and 39 drivers and were involved in 49 lateral, 15 frontal, and three rear impacts. There were 32 female and 35 male occupants. In no case two occupants sustained diffuse axonal injuries in the same crash. Head contact was identified in a majority of occupants. Airbags were not attributed to be the cause of injury in more than 90% of the cases, implying its minimal role in severe head trauma. These preliminary findings appear to support the hypothesis that diffuse axonal injuries occur with impact loading to the head. In addition, this type of injury occurs more in side crashes than frontal impacts. Furthermore, these results suggest a decreasing trend for the incidence of diffuse axonal injuries in modern vehicular environments, possibly with newer technologies and increased restraint usage.

INTRODUCTION

Motor vehicle impacts continue to be a source of unintentional injury to the human head [1-4]. The recent brain injury symposium held in Washington, DC, in February 2007, emphasizes the importance of trauma to this region of the human body in vehicular environments. In neurosurgical and other clinical literatures, head injuries are commonly classified as open or closed depending on the integrity of the dura. Another classification is based on whether the injury is focal or diffuse [5]. Although national and international databases such as the Cooperative Crash Injury Study, CCIS, in England, and the National Automotive Sampling System, NASS, and Fatal Analysis Reporting System, FARS, in USA have been developed in the past, CIREN database provides opportunities to conduct detailed analyses of trauma from medical and clinical perspectives. Studies have begun to appear in published literature using this database. For example, a study on fractures of the second cervical vertebra was reproted using CIREN and NASS databases [6]. Injury mechanisms were derived based on the analysis of medical- and crash-related data from CIREN [7] Outcomes were correlated with clinical and laboratory studies [7, 8]. Recent presentations at CIREN meetings and the Society of Automotive Engineers – Government Industry conferences held in the United States have adopted a similar approach for analyzing injuries and injury mechanisms to other body regions. Chest injuries and injury mechanisms from pole-induced lateral impacts were described in 2006 [9].

Because head injuries continue to have significant societal impact and are a byproduct of motor vehicle crashes, similar analyses are needed. To the best of our knowledge, such studies for this body region are lacking in published literature. With this as a focus, the present preliminary study was designed to characterize brain injuries. Specifically, diffuse axonal injuries were characterized at the occupant

level using case-by-case analysis of crash- and medical-related information from CIREN database.

METHODS

All occupants with diffuse axonal injuries were included. Brain injuries were classified based on AIS 1990 definition [10]. This included both hemispheres of the cerebrum, cerebellum, and brainstem regions. No limit was placed on the principal direction of force or impact, the magnitude of change in velocity, occupant seating position, restraint availability or use, and occupant demographics. However, rollovers and ejections were excluded.

Medical information in the database included several evaluations. Pre-hospital data included emergency medical technician reports and trauma nurses notes. In addition, emergency room records, immediate and follow-up scans such as computed tomography and magnetic resonance images, operating room records, radiology/neuroradiology findings, and neurological status were included.

Each case was analyzed with a focus on injuries to the head. Case-by-case analyses at the occupant level were grouped into factors such as impact mode, i.e., frontal, side, and rear, and injury severity. Although injuries to other body regions were available, the current study focused on the head. Potential head contact suggesting impact load transfer was included in the characterization. In order to be consistent, the same team of clinical, biomechanics, and crash investigation personnel conducted the analysis. In the following sections, case and occupant are synonymously used.

DATA SOURCES

Information from CIREN database was used in the study. Tier one and tier two data were analyzed for the years 1997 to 2006. It should be noted that CIREN teams have been gathering data since 1996. Although current year data are available, because quality control and other requirements have not been completed, these data were omitted from the analysis. The number of head injuries sustained by each occupant was used as a basis in the analysis.

RESULTS

Between 1997 and 2006, 2,823 “structured case vehicles” and 3,178 “medical cases” were logged into the database. However, 2,618 structured vehicle cases were coded with digital information for data retrieval and analyses. The number of cases post quality control was 1823.

Out of the 3,178 cases in the database, 67 occupants were identified with diffuse axonal injuries with an incidence rate of 2.1%. No crash resulted in diffuse axonal injuries to more than one occupant.

Thirty-nine were drivers and 28 were passengers in the ensemble. Thirty-two were female and 35 were male occupants. Pregnant occupants were not involved. Occupant age ranged from 11 months to 85 years. Fifteen out of the 28 passengers were under 16 years of age and one was an eleven-month old occupant. Fourteen occupants sustained fatal injuries, and 53 were survivors. The cause of death was attributed to be head injury in 11 (79%) cases, aortic trauma in two cases, and internal trauma in one case.

Fifteen were frontal, 49 were lateral, and three were rear end impacts. Figure 1 shows the percentage distribution of these data. Of the 49 lateral impacts, one side impact involved the youngest occupant in the center-rear seating position, and 38 were near side and ten were far side impacted occupants.

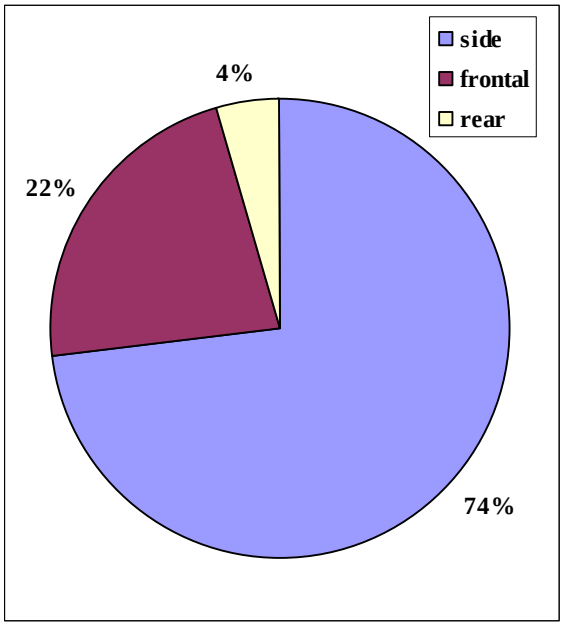

Figure 1: Distribution of injuries by impact mode.

The mean change in velocity was 11.2 m/s (standard deviation: ± 3.8, range 4.4 to 24.7 m/s) for the entire

ensemble. The average change in velocity for the frontal, side, and rear impacts were 11.5 ± 5.5, 10.9 ± 3.4, and 15.1 ± 2.5 m/s.

Out of the 67 occupants, six (9.0%) sustained single diffuse axonal injury. Three were frontal and three near side impacts in this subgroup. All diffuse axonal injuries were to the right or left cerebrum region. One side impact resulted in a fatal injury to the passenger, and noncontact was identified as the injury source for this occupant. Injury severity scores ranged from 26 to 66 in this subgroup. Table 1 summarizes other data.

Table 1.
Summary of data

# of injuries per occupant	# of occupants	# of fatalities	# of occupants with skull fracture	# of occupants with head contact	ISS range	# of impacts		
						frontal	side	rear
1	6	1	0	5	26 to 66	3	3	0
2	13	1	0	11	26 to 43	2	11	0
3	19	3	0	16	26 to 59	6	12	1
4	11	2	1	11	25 to 57	2	7	2
5	4	2	2	4	43 to 50	0	4	0
6	5	2	0	5	35 to 45	0	5	0
7	5	2	1	5	30 to 57	0	5	0

The remaining 59 (91%) occupants sustained at least one diffuse axonal injury and other brain injuries or bony trauma to the head. Table 1 shows the distribution of injuries and associated variables including head contact and skull fracture.

Thirteen (19.4%) out of the 67 occupants sustained two different types of head injuries. The first head trauma was a diffuse axonal injury to the cerebrum (12 cases) or cerebellum (one case). Out of the 13 cases, two were frontal, four were far side, six were near side, and one was an occupant in the center seat with side impact involvement. Rear end impact occupants were absent in this sub group. A far side driver was fatal and all other occupants were survivors. Head contact was identified in 11 (85%) cases. The diffuse axonal injury in one case was attributed to noncontact, and in the other case it was unknown. Injury severity scores ranged from 26 to 43 (Table 1).

Nineteen (28.4%) out of the 67 occupants sustained three different types of head injuries. The first head trauma was a diffuse axonal injury to the cerebrum in 17 cases, one was brain stem, and the other case involved the cerebellum. Head contact was identified in 16 (84%) cases. In one case the diffuse axonal injury was attributed to noncontact, and in the remaining two cases, head contact information was unknown. Three occupants sustained fatal injuries. Injury severity scores ranged from 26 to 59 (Table 1).

Eleven (16.4%) out of the 67 occupants sustained four different types of head injuries. The first head trauma was a diffuse axonal injury to the cerebrum in ten cases and cerebellum in another case. Although skull fractures were not identified in any case, AIS 3 severity orbit fracture occurred to one occupant. Out of the 10 cases, two were frontal, two were rear, and seven were side impacts. Head contact was identified in all cases. This included occupant-to-occupant contact in one case. Injuries to two occupants resulted in fatality. Injury severity scores ranged from 25 to 57 (Table 1).

Four (6.7%) out of the 67 occupants sustained five different types of head injuries. The first head trauma was a diffuse axonal injury to the cerebrum in all cases. Skull fracture occurred in two cases. All occupants sustained side impacts with head contact. Two occupant injuries were fatal. Injury severity scores ranged from 43 to 50 (Table 1).

Five (7.5%) out of the 67 occupants sustained six different types of head injuries. The first head trauma was a diffuse axonal injury to the cerebrum in all cases. Skull fractures were not identified in any case. All occupants sustained side impacts with head

contact. Two occupant injuries were fatal. Injury severity scores ranged from 35 to 45 (Table 1).

Five (7.5%) out of the 67 occupants sustained seven different types of head injuries. The first head trauma was a diffuse axonal injury to the cerebrum in all cases. Skull fracture occurred to one occupant. All five occupants sustained side impacts with head contact. Two occupant injuries were fatal. Injury severity scores ranged from 30 to 57. Figure 2 shows the cumulative distribution as a function of number of head injuries sustained by each occupant. More than one-half of the occupants sustained three or less head injuries (Table 1).

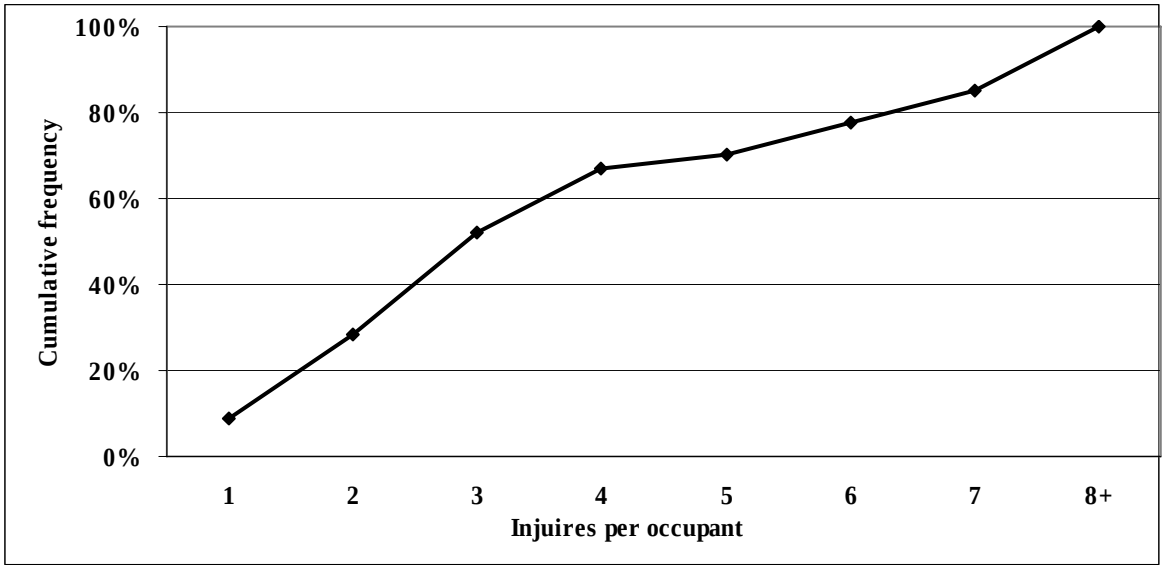

Figure 2: Injury distribution as a function of the number of head injuries sustained by each occupant.

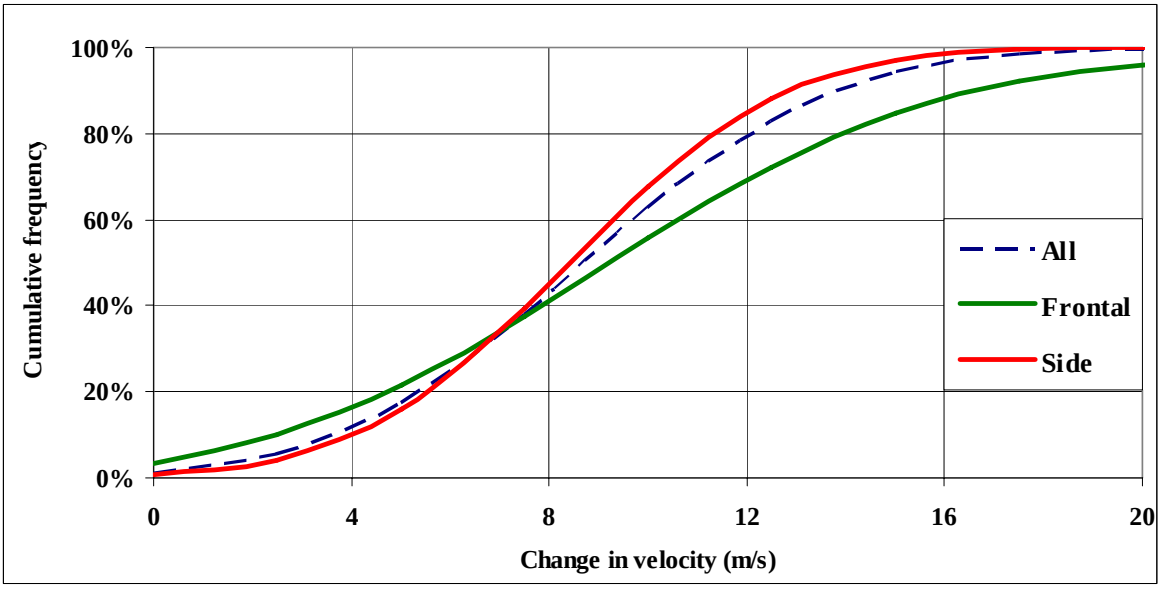

Figure 3: Cumulative frequency of the change in velocity as a function of impact mode.

Figure 3 shows the cumulative frequency distribution of the change in velocity for the entire ensemble, and for frontal and side impacts. More than one-half of the crashes had a change in velocity of 10 m/s or less.

DISCUSSION

As described in the earlier section, more medical cases than case vehicles were logged in the database. The database consists of two main components, i.e., structured case vehicles and individual medical cases. A case vehicle may include more than one occupant. Data entry is done through CIREN and NASSMAIN applications. The former focuses on medical aspects and the latter focuses on crash and vehicle data. A case can be initiated by entering data in either application. However, the two applications remain segregated until a medical case is linked to the corresponding crash case. Thus, a crash case can be associated with more than one medical case. The potential for a 'one-to-many' relationship between a crash case and multiple medical cases explains differences between the number of crash and medical cases in the database.

The quality control of a medical case in this database is involved because of the availability of clinical information such as x-rays and CT. The availability of actual images in the database, along with medical records such as operating room documents and radiology reports, facilitates a more comprehensive analysis (example, injury type) of crash- and clinical-related information. As emphasized, the present study characterized diffuse axonal trauma on an occupant-to-occupant basis, a first step in such analysis. Further analyses such as determining the most commonly associated brain injury with the diffuse axonal trauma and potential variations as a function of impact mode and change in velocity are needed for a more comprehensive understanding of the injury biomechanics.

One of the criteria for case selection is the vehicle model year (less than seven years at the time crash). The current data selection process limits to six years. Although this feature may bias data collection, it has advantages for gathering and analyzing data from recent model years, examining effects of potential crashworthiness improvements, and continuing prospective evaluations of US Federal government Standards. From this viewpoint, gathering of such data is necessary. Presently, eight nation-wide teams are developing a comprehensive, i.e., clinical and crash database with this as a basis, and its uniqueness should assist in assessing performance of more recent model year vehicles. It should however be noted that, because data are gathered from few teams, and are not population based, general estimates cannot be obtained. A more conventional database such as NASS should be used to analyze data from an epidemiological perspective. However, a distinct limitation of NASS is the limited availability of medical records, a critical aspect in studying brain trauma, especially diffuse axonal injuries.

As indicated in the Introduction, the present analysis is limited to the characterization of diffuse axonal injuries. Thus, cases were selected only if an occupant sustained this type of injury. While it is possible and necessary to analyze injury data based on factors such as restraint use/availability, crash severity and mode, being a preliminary study, the analysis is focused mainly at the occupant level. This was achieved by describing other head injuries in association with diffuse axonal trauma.

A small percentage of occupants (less than ten) sustained this type of brain injury without any other accompanying head trauma (Table 1). All occupants with the exception one fatality sustaining the injury due to head contact indicate that single diffuse axonal injury in the motor vehicle environment is most likely associated with contact loading to the head in both frontal and side crashes.

In occupants sustaining more than one head injury associated with diffuse axonal injury as the most severe trauma, as shown in table 1, head contact was again identified in a significant majority of the cases, further emphasizing the role of contact loading. Therefore, it can be hypothesized that diffuse axonal injuries occurs with the transfer of impact loading during the dynamic event, and this observation is independent of crash modality. In addition, the occurrence of minimal number of skull fractures, despite direct loading to the head, suggests that the impact force transmitted is below bony tolerances while exceeding the threshold of diffuse axonal trauma [11]. The presence and increased use of modern restraint systems may account for the decrease in bony pathology.

It is important to include crash-related engineering and medical records in the assignment and evaluation of diffuse axonal injuries as this terminology has been used somewhat loosely in clinical practice. Although the injury has been described, defined, and investigated in the laboratory by the clinical author of this paper and others in the literature, and identifiable on imaging, patient evaluation is critical [5, 12-24].

The present characterization relied on injury coding according to AIS 1990 version. The coding scheme has changed since 2005 as the Injury Scaling team headed by Genneralli has incorporated procedures that include clinical correlation in conjunction with radiological data [25]. From this perspective, no single clinical discipline can conclusively determine and report that the injury belongs to the diffuse axonal type. The next logical step would be to process current data with the new coding scheme. With continuing addition of cases to the database and recoding current data, a more appropriate analysis of head injuries can be made. This is considered as a future research topic.

Although NASS and FARS databases have been in vogue before CIREN and are population-based, these databases were not used because of the lack of required medical records to conduct the retrospective analysis. From a biomechanical perspective, injuries associated with head contact found in significant majority of cases imply the role of direct impact load transmission as a potential trauma mechanism. This is supported by laboratory studies wherein direct load transmission is necessary to reach the high angular acceleration level associated with this type of injury [26]. The study, using first generation mathematical simulations, showed the importance of impact loading of the head to attain injury threshold levels reported in published experimental research. Contact loading mechanism has also been supported by international epidemiological studies [27]. The present characterization from a more recent database and modern vehicle environments further reinforces this conclusion. In addition, because of sample size constraints, the characterization underscores the need to gather similar data from other countries for epidemiological interpretations.

In this limited database, the present preliminary findings appear to support the hypothesis that diffuse axonal injuries occur with impact loading to the head. In addition, this type of injury occurs more in side crashes than frontal impacts. Airbags are not the injury causal agent in a considerable majority of cases (more than 90%), implying its minimal role in severe head trauma. These results suggest a decreasing trend for the occurrence of diffuse axonal injuries in modern vehicular environments, possibly with newer technologies and increased restraint usage.

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