BRAIN LESIONS IN MOTOR VEHICLE CRASHES: DIFFERENCES BETWEEN SIDE AND FRONTAL IMPACTS

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ABSTRACT

This study determined the characteristics of brain lesions as a function of frontal, lateral, and oblique impacts. Data were extracted from NASS general Crashworthiness Data System. 1,980 lesions in frontal and 1,278 lesions in side crashes were analyzed. There was a significant difference in the change in velocity (DV) between frontal, oblique, and pure lateral crashes. There appeared to be a relationship between injury type and DV needed to produce different brain lesions in frontal crashes. In side crashes, this relationship was not as clear. The mean DV required to produce any lesion was lower in oblique than pure lateral collision. These findings indicate the severity of the oblique crash vector for brain injury susceptibility, and the importance of this mode in crashworthiness.

Keywords: biomechanics, brain injury, frontal impacts, side impacts, velocity

PATTERNS OF INJURIES are different between frontal and lateral collisions. For example, it is known that injuries to the face and lower extremities are considerably greater in frontal collisions while thorax, abdominal, and pelvic injuries are more frequent in lateral collisions. Frontal and lateral collisions have different lesion risk (Dischinger et al. 1993). Therefore, information on the direction of impact has potential use for clinical decision making. As a consequence, it would be acceptable to hypothesize that the direction of force and change in velocity (DV) of impact influences the type of brain lesion. Although Motor Vehicle Crashes (MVC) are the leading cause of hospital admissions due to traumatic brain injury in the United States (Langlois et al. 2004), there is limited information about the influence of the direction of the impact in head injuries. While previous epidemiological studies have analyzed databases such as the National Automotive Sampling System (NASS) for injuries and associated variables, research focusing on brain injuries and differences in their patterns based on the direction of impact is limited. With this objective, this study determined the characteristics of brain lesions as a function of frontal, lateral, and oblique impacts.

MATERIALS AND METHODS

Data Source

The data for this study were obtained from the Crashworthiness Data System (CDS) which is part of the United States NASS database (National Automotive Sampling System). The CDS is a nationwide annual probability sample of passenger vehicles (cars, light trucks and vans) involved in police-reported tow-away collisions with property damage or personal injury. Each crash that occurs within a CDS team's area has a chance of being included in the sample. The selection of sample crashes for CDS is accomplished in stages. The first stage is the selection of primary sample units (PSUs) grouped into 12 categories described by geographic region and degree of urbanization. Two

PSUs are selected from each category. In the second stage, the police agencies in a PSU are categorized by the number and type of processed police crash reports. Sample police agencies are then selected randomly from each category. The fraction of the agencies selected increases as the number and severity of crashes reported by the agency increases. The final stage of sampling is the random selection of reported crashes from the sample police agencies.

Study Population

In this study the analysis was focused on: only front seat occupants; either drivers or passengers; with at least one injury; older than 16 years of age; frontal or side collisions; and for the years 1993 to 2005. Rollovers and full ejection events were excluded. Frontal collision was defined as an impact in which the primary direction of force was between 11 and 1 o'clock position. Lateral collision was defined as an impact in which the main direction of force was between 2 and 4, and 8-10 o'clock positions. Among these, the collision was considered as pure lateral if primary direction of force was 3 or 9 o'clock position, and oblique if the primary direction of force was 2, 4, 8 or 10 o'clock position. All side collisions were further classified as nearside or far side collision according to the sitting position of the occupant, i.e., adjacent or not to the site of impact.

Variable definitions and Statistical Analysis

The 1990 version of the Abbreviated Injury Scale (AIS) was used for injury coding. Penetrating injuries as well as scalp injuries and burns were excluded. Blunt injuries were included. All brain contusions, either not further specified, single or multiple, uni- or bilateral were grouped together (AIS codes 140602 to 140626 and 140699). Brainstem group included contusion, diffuse axonal injury, hemorrhagic lesions, laceration and massive destruction of the brainstem (AIS codes 140202 to 140214 and 140299). Subdural hematomas (SDH) (AIS codes 140650 to 40656) and traumatic subarachnoid hemorrhage (tSAH) (AIS code 140684) were analyzed separately. Skull fractures and basilar skull fractures were classified in the same group (AIS codes 150200 to 150408).

Three groups of restraint systems were analyzed: belt, frontal bag deployed and side bag deployed. Undeployed airbags were analyzed separately. The "belt" group included shoulder belt, lap belt, and lap and shoulder belt. Crash dynamics were analyzed using the DV parameter, defined as the vector velocity change during the collision phase of the crash. All lesions were compared between frontal and side crashes; nearside and far side, and oblique and pure lateral impacts. Continuous variables were expressed as mean ± standard deviation (SD) and compared with Student t-test. Categorical variables were expressed as percentage and analyzed with Pearson's chi-square test. Multiple logistic regression techniques were used to analyze difference between brain lesions in side and frontal impacts (corrected by DV and belt use). Statistical significance was set at $p<0.05$. All the analyses were performed with SAS 9.1 (SAS Institute Inc. USA) software.

RESULTS

From 1993 to 2005, 17,387 patients with at least one injury were included in the NASS data base with a mean of 1,337 (SD 120) patients per year (Table 1). 6,977 patients were front seat passengers in frontal collisions and 10,410 were front seat passengers in lateral collisions. Among the patients involved in side crashes, 5188 passengers were seated adjacent to the side of impact (nearside) and 4,274 passengers were seated opposite to the side of the impact (far side). 948 front seat passengers were involved in lateral collisions with unknown sitting position. 7,785 of all front seat passengers suffered a head injury (4,403 in frontal and 3,382 in lateral impacts). Among the patients implicated in frontal collisions, 59% were belted and 31% had airbags deployed. Of those involved in lateral impacts, 83% were belted, 19% had the frontal airbag deployed and 1.7% had the side airbag deployed. Undeployed airbags are reported in table 1.

In patients with head injury, 1,980 lesions in frontal (470 contusions, 276 SDH, 525 skull fractures, 507 tSAH, 202 brainstem lesions), and 1,278 lesions in side crashes (326 contusions, 195 SDH, 274 skull fractures, 357 tSAH, 126 brainstem lesions) were analyzed. All lesions including contusions, SDH, skull fractures, tSAH and brainstem lesions were more frequent in frontal than lateral impacts. However, when lesions were analyzed based on DV and use of seatbelt , no difference was found in the incidence of SDH, tSAH and brainstem lesions. Contusions and skull fractures continued to be more frequent in frontal impacts (Table 2).

Lesions had increasing DV in frontal crashes. The mean DV of the lesions was 45.4 km/h for contusions, 45.9 km/h for SDH, 49 km/h for skull fractures, 50.6 km/h for tSAH, and 57.9 km/h for brainstem lesions. In side crashes, no clear progression was evident (contusions 39.1 km/h, SDH 38.3 km/h, skull fractures 41.5 km/h, tSAH 40.6 km/h), with the only exception of brainstem (44.3 km/h) (Table 3). There were no significant differences between nearside and far side impacts. The major difference was seen in SDH (far side 36.1 km/h and nearside 40.5 km/h, Table 4). Mean DVs for pure side crashes (contusions 41.1 km/h, SDH 42.6 km/h, skull fractures 44.3 km/h, tSAH 44.5 km/h, brainstem 48.1 km/h) were greater than DVs for oblique crashes (contusions 38 km/h, SDH 36.1 km/h, skull fractures 39.9 km/h, tSAH 37.8 km/h, brainstem 42.5 km/h) (Table 5)

Table 1 Epidemiological data

	Frontal crash	Lateral crash	p
Mean age ± SD	37.2 ± 17.7	39.3 ± 19.7	<0.0001
Male Sex (%)	4274/6977 (61%)	4814/10410 (46%)	<0.0001
Belt used	3601/6067 * (59%)	7719/9325 #(83%)	<0.0001
Frontal Bag Deployed	2162/6977 (31%)	1948/10368°(19%)	<0.0001
Frontal Bag Undeployed	460/6977 (6.6%)	3209/10368 (31%)	<0.0001
Lateral Bag Deployed	-	144/8601@ (1.7%)	
Lateral Bag Undeployed	-	285/8601@ (3.3%)	
214 compliant	-	3184 (31%)	
Mean DV ± SD	35.1 ± 17.6	25.4 ± 11.9	<0.0001

* 910 missing (13%) # 1085 missing (10%) ° 42 (0.4%) missing @ 1809 (17%) missing

Table 2 Differences in lesions between frontal and lateral crashes.

	Frontal crash	Lateral crash	p	p corrected by DV and belt use
Contusion n (%)	470 (6.7)	326 (3.1)	<0.0001	<0.0001
SDH n (%)	276 (3.9)	195 (1.9)	<0.0001	**NS**
Skull fracture n (%)	525 (7.5)	274 (2.6)	<0.0001	<0.0001
tSAH n (%)	507 (7.3)	357 (3.4)	<0.0001	**NS**
Brainstem lesion n (%)	202 (2.9)	126 (1.2)	<0.0001	**NS**

Table 3 Delta velocity by brain lesions in frontal and lateral collisions (n= number of cases)

Mean DV (km/h)	Frontal crash (SD)	Lateral crash (SD)	P
Contusion	45.4 (21) n=288	39.1 (14.1) n=203	0.0002
SDH	45.9 (20.4) n=164	38.3 (14.9) n=133	0.0004
Skull fracture	49 (22.7) n=288	41.5 (15.2) n=158	0.002
tSAH	50.6 (24.4) n=295	40.6 (15.3) n=225	<0.0001
Brainstem lesion	57.9 (22.7) n=199	44.3 (14.5) n=74	<0.0001

Table 4 Delta velocity by brain lesions in lateral collisions. Difference between nearside and far side impacts (n= number of cases)

Mean DV (km/h)	Near side crash (SD)	Far side crash (SD)	P
Contusion	38.4 (13.8) n=118	40.5 (14.7) n=85	0.30
SDH	40.5 (14.8) n=82	36.1 (14.6) n=53	0.09
Skull fracture	41.5 (16) n=90	41.5 (14.4) n=68	0.98
tSAH	39.5 (14.6) n=135	42.4 (16.4) n=90	0.17
Brainstem lesion	44.3 (13) n=48	46.0 (16) n=26	0.64

Table 5 Delta velocity by brain lesions in lateral collisions. Difference between pure side and oblique side impacts (n= number of cases)

Mean DV (km/h)	Pure side crash (SD)	Oblique side crash (SD)	P
Contusion	41.1 (16.1) n=71	38 (12.9) n=132	0.14
SDH	42.6 (17.8) n=45	36.1 (12.8) n=88	0.02
Skull fracture	44.3 (17.9) n=55	39.9 (13.4) n=103	0.09
tSAH	44.5 (19.1) n=65	39 (13.2) n=160	0.01
Brainstem lesion	48.1 (18.7) n=23	42.5 (12) n=51	0.13

DISCUSSION

Although studies have been performed to analyze crash dynamics and injuries, this study analyzed the relationship between the primary direction of force and DV for different types of brain lesions. In the present population of only injured frontal seat passengers, head injuries were more frequent in frontal crashes than in side collisions. As the mean DV in frontal collisions was significantly higher than the mean DV in side impacts, the higher head injury incidence in the former mode was expected. Furthermore, the decreased use of seat-belts in passengers involved in frontal crashes could also influence the higher head injury rate in this crash mode. As expected, the DV needed to produce any lesion in frontal crashes was greater than that needed for side crashes. Therefore, for the same DV, lateral crashes seemed to be more severe than frontal crashes. Other authors have compared frontal and side collisions. In particular, head injuries seem to be more severe in lateral than frontal crashes (Bazarian et al. 2004; Nirula et al. 2003). According to Hillary et al, passengers involved in lateral collisions were more likely to undergo neurosurgical interventions and head injuries such as skull fractures, hemorrhagic lesions and temporal lobe damage (Hillary et al. 2002). No difference was found in the incidence of frontal lobe lesions or white matter shearing injuries. In the present population, when brain lesions adjusted by delta velocity of the impact and use of seatbelt were analyzed, no difference was found in the incidence of SDH, tSAH and brainstem lesions. Instead, contusions and skull fractures were more frequent in frontal impacts contrasting the results published by Hillary et al. However, the present study does not compare the differences in lesion severity between frontal and lateral collisions. As both types of lesions are contact injuries, it is possible that at the same DV and with the same type of restraint, contusions and skull fractures in side crashes are more severe than in frontal crashes. It is also important to emphasize that the number of passengers without lesions should be considered in further analysis. Considering that the DV needed to produce a brain lesion is the lowest in lateral impacts, it could be reasonable to presume that the incidence of head injured patients would be higher in side than in frontal collisions if all MVC are considered and not only those with property damage or personal injuries.

In the present analysis, the relationship between DV and any type of brain lesion was different for frontal and side impacts. Contusions were associated with lower DV, followed by SDH and skull fractures in frontal crashes. For the purpose of this study, all types of contusions where considered in the same group. Most contusions were coup and contrecoup types. Coup contusions are contact injuries (Gennarelli and Thibault 1985; Ommaya and Gennarelli 1974) and are produced by compressive forces operating beneath an area of skull inbending or, tensile forces generated by the negative pressure produced beneath an area of skull inbending. Acute SDH is caused by three sources: hemorrhagic contusions that break through the arachnoids, the rupture of bridging veins, and rarely by laceration of cortical arteries or veins. In autopsy series, two thirds of the SDH were associated with contusions (Maxeiner 1997). Therefore, in a great number of cases, the mechanism for SDH and contusion will be probably the same. That may be the reason of similar DV for contusions and SDH in the present study. Basilar skull fractures and skull fractures were analyzed together in the present analyses, and the mean DV needed to produce any skull fracture was higher than that needed for contusions and SDH. It is reasonable to state that the mean DV needed to produce a skull fracture in may be biased by the low rate of airbag deployment. However, according to Pintar et al, skull fractures in frontal impacts appear to be unaffected by the presence of a restraint system (Pintar et al. 2000). The brain lesions that required the highest DV in frontal crashes were tSAH and brainstem lesions, probably because both are acceleration/deceleration related lesions. Finally, it is possible that the difference in DV progression between frontal and side impacts is due to the greater number of impact lesions in frontal crashes. Further studies are needed to analyze the influence of the principal direction of force of the collision and the severity of the different types of head injury.

Another important point in the present study is that regarding the type of collision, all brain lesions seemed to occur with a mean DV higher than 40 km/h. This velocity threshold was already associated with significantly higher mortality either in frontal or lateral crashes. However, DVs greater than 40 km/h in lateral crashes have higher odds of death than in frontal crashes (Ryb et al. 2007). A possible explanation could be that in lateral collisions, occupants maintain closer proximity to the point of impact and the energy absorption by the deformable parts of the car is reduced. In addition, frontal crashes had more airbags than side crashes because frontal airbags do not always deploy in side crashes. This is confirmed by US side impact NCAP tests wherein, even under controlled laboratory conditions, not all vehicles and not all models by the same manufacturer will produce frontal airbag deployments.

In the present cohort of patients, there appeared to be a relationship between head injury type and DV needed to produce different brain lesions in frontal crashes but not in lateral collisions. Considering the type of lesion as a surrogate for injury severity (brainstem lesions are more severe than SAH and brain contusion), one can assume that the higher the velocity, the higher the severity of the lesion. Therefore, it is not surprising for different lesions to have different mean DV. In passengers involved in frontal collisions, there was a progression in the mean DV with the increasing lesion severity. Hence, contusions required less DV to occur, and lesions associated with worst outcome such as tSAH (Chieregato et al. 2005) and brainstem injuries required the highest DV. In side crashes, the relationship between DV and type of lesion was not as clear. This is perhaps due to the limited sample size compared to frontal crashes, and complexities associated with side impacts such as lesser effectiveness of seatbelt s especially with increasing intrusion to the occupant compartment and more direct exposure of the passenger. Although it has been reported that the side-bag deployment decreases the head injury severity (Yoganandan et al. 2007), in the present cohort, the side-bag system was present and deployed in only 1.7% of the cases and did not make a significant difference.

Surprisingly, in the present population, nearside and far side impacts had minor differences in the DV needed to produce a brain lesion. Previous studies had demonstrated that, in side collisions, front-seat occupants sitting adjacent to the impact (nearside) and those sitting in the opposite side of the impact had different risk of injuries specially in thoracic and abdominal districts (Newgard et al. 2005). It was reported that above an energy equivalent speed of 40 km/h, all nearside occupants, but only half of the far-side occupants, sustained severe injuries reinforcing the concept that far side are "less dangerous" than nearside impacts. However, head injuries were the second cause of death in both cohorts (Miltner and Salwender 1995), supporting the theory that the sitting position does not make a significant difference in the head injury severity. The finding that the mean DV required to produce any lesion was lower in oblique than pure lateral collision, suggests the importance of the oblique vector in lateral crashes. Oblique crashes and side airbags should be investigated more thoroughly in future studies.

Special consideration should be given to the different utilization rate of seat-belts between passengers involved in frontal and lateral collisions. According to the United States National Highway Traffic Safety administration (NHTSA) in 1994, 58% of the front seat passengers wore the seat-belt (http://www.nhtsa.dot.gov/people/injury/research/BuckleUp/ii__trends.htm) while in the year 2000, this rate rose to 71% (Solomon et al. 2001). As the analyses included patients from 1993, the increasing belt use along the years could partially explain the low rate of seatbelt use in the present cohort. However, the significant difference in seatbelt use between frontal and lateral impacts cannot be explained. This difference could influence the lack of relationship between DV and type of injury in lateral impacts. Further studies are needed with the same type of restraint system in both cohorts.

While retrospective, the current analysis from the largest and most widely used database indicate that brain injuries are crash mode specific. At the same DV, frontal impacts offer greater protection than side impacts. Oblique impacts have more detrimental consequences than impacts under any other mode.

LIMITATIONS

Analysis from one database, albeit widely used in crashworthiness. The low share of side airbags makes the present analysis somewhat preliminary from addressing their efficacy in lateral crashes, although this is the largest and most widely used database around the world.

CONCLUSIONS

While results from this retrospective study show that brain injuries are crash mode dependent, injuries continue to occur around US FMVSS regulatory speeds, and frontal crashes offer greater protection at a given change in velocity than lateral crashes. Because brain injuries occur at lower speeds in oblique than pure lateral and frontal impacts, this vector may need attention.

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