

Motor vehicle collision factors influence severity and type of TBI

FRANK G. HILLARY[†], PHILIP
SCHATZ[‡], STEPHEN T. MOELTER[§],
JODY B. LOWRY[§], JOSEPH H. RICKER[†]
and DOUGLAS L. CHUTE[§]

[†] University of Medicine and Dentistry, Newark, NJ, USA

[‡] Department of Psychology, Saint Joseph's University, Philadelphia, PA, USA

[§] Neuropsychology Programme, Drexel University, Philadelphia, PA, USA

(Received 23 April 2001; accepted 4 December 2001)

Primary objective: To analyse the relationship between motor vehicle collision factors and TBI.

Research design: Retrospective design analysed the difference between the types of brain injuries sustained in distinct collision configurations.

Methods and procedures: Medical charts and police accident reports were reviewed for individuals sustaining TBI in 168 motor vehicle collisions between 1985–1998.

Main outcomes and results: Lateral collisions and collisions involving contact with a fixed object were associated with the most severe brain injuries. Analysis of safety restraints revealed that seatbelts not only reduce the probability of injury, but they also mediate the severity of brain injury when it is sustained.

Conclusions: Future research should focus the prevention of injury by better defining the minimum physical thresholds at which brain injury might be sustained and the mechanisms by which these thresholds are achieved during natural collisions.

Introduction

Traumatic brain injury (TBI) has been defined as an injury to the brain resulting from an external source, which may lead to significant impairment in the individual's physical, cognitive and psychosocial functioning [1]. Motor vehicle collisions (MVCs) are the most common cause of TBI in the USA [2]. Each year, 3–5 million people sustain brain injury due to motor vehicle collisions [3], resulting in a large number of individuals who endure life-long impairment and disability. As a result, analysing the motor vehicle collision factors that influence incidence, severity and outcome in TBI is of considerable importance.

Investigators of MVCs have focused their study on the initial angle of impact of the vehicles and its relationship to occupant injury. Such research has revealed an increased incidence of TBI during lateral collisions [4, 5] and collisions where compartmental intrusion is significant [4–6]. Similarly, in studies of motor vehicle occupant fatality, occupants of 'struck' vehicles were significantly more likely to be

Correspondence to: Frank G. Hillary, Kessler Medical Rehabilitation Research and Education Corporation, 1199 Pleasant Valley Way, West Orange, NJ 07052, USA. e-mail: fhillary@kmmrrec.org

killed during MVCs compared to occupants of 'striking' vehicles [7]. Moreover, when comparing lateral and frontal collisions, seatbelt efficacy is reduced [4] and brain injury occurs at lower closing speeds and with less vehicle deformation [8] during lateral collisions. When considered together, these findings implicate lateral collisions as particularly threatening to the motor vehicle occupants involved. In fact, in one investigation of lateral collisions, the protection from TBI offered by seatbelts was considered negligible [4].

In addition to the study of the angle of impact, velocity change is a factor that mediates the affects of other collision variables such as angle of impact and seatbelt use and is a primary determinant of occupant injury [9]. Velocity change is the change in speed the vehicle undergoes during the collision and should not be confused with the 'speed' of the vehicle prior to the collision. In analyses of natural collisions, approximations of velocity change have been used to support the diagnosis of mild TBI [10] and to study brain injury and outcome in motor vehicle related injuries (i.e. injuries to motor vehicle occupants, pedestrians, and bicyclists) [11]. Because velocity change interacts with most collision variables, ideally it should be included in all collision analyses. However, velocity change is often cumbersome to approximate following real world collisions and requires assumptions regarding the physical nature of each collision. For this reason, velocity change may be 'impractical' for collision reconstruction and, to overcome this problem, investigators have used surrogates for velocity change, such as a measurement of vehicle deformation [8].

Analysis of seatbelt use has indicated that, when brain injury is sustained, seatbelts influence the severity of brain injury and the sites of brain lesions [12]. Although collisions were not analysed, a greater incidence of sub-cortical lesions was observed in belted individuals compared to unbelted individuals sustaining brain injury. The between group differences were attributed to the differential expression of energy for belted individuals during an MVC (upward from the neck, as opposed to downward from the skull). In addition, a greater incidence of posterior cortical lesions was noted in unbelted occupants (i.e. parietal, occipital) compared to those with seatbelts, due to the increased opportunity for posterior skull versus obstacle contact for unbelted individuals. Separately, investigation revealed that individuals who did not use a seatbelt at the time of injury show greater difficulty on neuropsychological tests of executive functioning when compared to a restrained group [13]. These findings indicate that seatbelts are affecting the physical environment in which brain injury is sustained and, subsequently, influencing brain lesion sites. These findings are not surprising, considering that differing physical mechanisms (e.g. inertial and contact phenomenon) are responsible for dissociable brain lesions [14]. Because the type of brain injury sustained often influences the acute recovery course [15], understanding the relationship between the mechanism of injury and resultant lesion sites may, eventually, be useful to rehabilitation specialists.

Collision analyses in the areas of angle of impact, deceleration and safety restraint use have typically studied the frequency of occupant injury, including TBI. The necessity for continued analysis of natural collisions and their effect on occupant injury has been emphasized for some time [16]. An important aim in this study is to analyse the relationship between MVC factors and their influence on qualitative differences in the types and degree of TBI sustained.

Study aims and anticipated results

It is anticipated that, when brain injury does occur, the frequency of sub-cortical and brainstem injuries would increase in the case of seatbelt use due to the propagation of physical energy from the neck up, instead of from the skull down. It is also anticipated that, when brain injury occurs, the frequency of posterior cortical lesions would increase when a seatbelt is not used, due to the increased opportunity for posterior skull versus obstacle contact. Based on the relationship between 'oblique' head movements and diffuse axonal injury [17], it is anticipated that lateral collisions will result in a greater frequency of white matter shear injuries and will be associated with more severe brain injury when compared to frontal collisions. Based on the importance of velocity change in mediating occupant injury, occupants in vehicles striking fixed objects would sustain the most severe injuries (when compared to struck and striking vehicles) due to the presumed rapid deceleration. It is anticipated that seatbelts would not only reduce the likelihood of sustaining TBI, but they would reduce the severity of brain injury when TBI occurred. Finally, in accordance with previous findings [4], it was anticipated that protection from TBI afforded by seatbelts would be reduced during lateral collisions.

Methodology

Participants

Those included in the study were 168 individuals admitted to one of three local medical facilities and were occupants of a motor vehicle collision between 1985–1998. Although police accident reports were sought for all cases, a match between the patient and their accident report was required for consideration in the study. Access to medical records followed IRB approval across three separate facilities and access to police accident reports was granted following approval from city officials.

Individuals in this study were divided into four groups. Individuals were included in Group 1 (moderate-to-severe brain injury, $n=75$) if neuroimaging results for brain lesion were positive or if they had a GCS score of less than 12 in the emergency room. In addition, individuals with a skull fracture were included in Group 1, even in the absence of documented brain lesion. Individuals in Group 2 (mild brain injury, $n=38$) included patients whose GCS scores ranged from 13–15 in the emergency room, who experienced a period of loss of consciousness at the scene, and who had negative neuroimaging results for the skull and brain. Individuals with evidence of facial fracture (in the absence of a skull fracture) and with only a short period of loss of consciousness at the scene of the accident were also included in Group 2. Individuals in Group 3 (no brain injury, $n=30$) experienced no documented period of loss of consciousness or acute confusion and there was no noted treatment for head injury or concussion. For those with CT scans, evidence of skull or facial fracture eliminated the patient from Group 3; however, patients with soft tissue swelling or lacerations on the neck or face were included.

Variables definitions

Injury severity

Injury severity was measured through analysis of three separate variables: Glasgow Coma Scale (GCS, 18) scores in the emergency room (ER), duration of loss of

consciousness (LOC), and the number of acute care days spent in the hospital. Duration of LOC was adapted from an ordinal level scale [19] and was determined from medical charts as follows:

- (1) no appreciable confusion and no LOC at the time of the collision,
- (2) initial disorientation or confusion with no reported period of LOC,
- (3) very brief LOC at the time of the collision, yet the individual was reportedly lucid at the scene,
- (4) a longer period of LOC at scene that cleared prior to arrival in the ER and a GCS of greater than 12 in the ER,
- (5) LOC lasting for greater than 1 hour but no longer than 1 day,
- (6) LOC lasting for greater than 1 day but less than 1 week,
- (7) LOC lasting for greater than 1 week but less than 3 weeks,
- (8) LOC lasting for greater than 3 weeks but less than 5 weeks, and
- (9) LOC lasting for greater than 5 weeks.

Lesion analysis

Computerized tomography (CT) or magnetic resonance imaging (MRI) results were taken from radiologic reports or discharge summaries from acute care records. All abnormalities noted on CT or MRI, including haematomas and haemorrhagic and non-hemorrhagic infarctions were classified as brain injury, or 'lesions'. Lesions were coded dichotomously (irrespective of the number or size in any given region) across 15 anatomical regions. These 15 regions were collapsed into six primary regions. The primary regions included each of the four cortical lobes, a group of sub-cortical structures (corpus callosum, internal capsule, basal ganglia, thalamus), and a group of brainstem structures (pons, medulla, fourth ventricle haemorrhage).

Collision types

From 168 police accident reports, two basic collision types (frontal and lateral) were first determined. Separate from these two basic collision types, three categories were developed according to the *direction of energy* during the collision (striking, struck, fixed), as described below. Based on the differential fatality rates between the 'striking' and the 'struck' vehicle during two car collisions [5], these two categories were used (i.e. Striking, Struck). A third group involving single car collisions with fixed objects was referred to as the 'Fixed' group. These categories did not include collisions in the analyses in which the physical nature of the collision was difficult to determine (i.e. rollover collisions, collisions with multiple contacts) or collisions that were too unique to fit into the groups developed (e.g. telephone pole falling onto a moving vehicle). This resulted in a total of 132 collisions for collision analyses. In police accident reports, the point of contact is logged through the use of a clock analogy (e.g. the front of the vehicle is 12 o'clock). For consistency, the clock analogy was used in this study.

Frontal

This group of collisions ($n = 75$) was composed of any collision involving single or multiple contact between 11–1 o'clock. This group included two car collisions and single vehicle collisions that involved contact with fixed structures within the range of specified impact points.

Lateral

This group of collisions ($n=38$) was composed of any collision involving single or multiple contact between 2–4 and 8–10 o'clock. This group includes contact with other vehicles or contact with fixed objects.

Striking

This group of collisions ($n=26$) was composed of two-car collisions that included single or multiple contact to the front of the vehicle (11–1 o'clock), followed by a change in direction and dissipation of the vehicle's energy over a period greater than 10 feet prior to coming to a controlled or uncontrolled stop.

Struck

This group of collisions ($n=47$) involved only two-car collisions, and the vehicle of interest was struck by another vehicle. This group did not include 'head-on' collisions. After a change in direction, struck vehicles continued along a new vector. Although the overlap between the lateral and struck collision groups is significant (29 collisions), struck vehicle collisions included non-lateral contact.

Fixed

This group of collisions ($n=44$) involved one-car collisions that included a lateral or frontal impact with a fixed object (e.g. building, parked tractor trailer) resulting in very little movement in the direction of the original vector (typically 3 m or less).

Data analysis

For all statistical analyses, the data were initially compiled in an Excel 2000 spreadsheet and later transferred to the SPSS statistical package version 10 for Windows. Both parametric and non-parametric analyses were conducted with the use of this statistical package.

Descriptive statistics

Descriptive statistics were used to provide a context by which further data analysis may be conducted. These statistics included mean, median, mode, standard deviation, variance and kurtosis. Through the use of descriptive statistics, the distribution and range of the data for each variable was observed prior to statistical analysis.

Location of injury and injury severity

One purpose of this study was to analyse the relationship between collision factors and the resultant lesion location. Because location of neurological injury (anatomical structures affected) was coded as a dichotomous variable, non-parametric statistics (χ^2) were used for this analysis. In addition, the relationship between collision factors and injury severity was analysed. Due to the non-normality of variables describing injury severity (e.g. LOC scale and GCS scores), χ^2 analyses were conducted. Finally, to analyse the influence of vehicle factors on the number of acute hospital days, independent sample *t*-tests were used.

Results

Due to multiple statistical comparisons, the traditional p -value of 0.05 was not recognized as statistically significant in all cases. Holm's sequential Bonferroni procedure was used to correct for multiple comparisons [20]. This procedure determines alternate and hierarchical α -levels based upon the number of comparisons.

Demographics

Collision variables and injury and outcome data were analysed for 75 individuals with moderate-to-severe TBI (Group 1), 38 individuals with mild TBI (Group 2) and 30 individuals who sustained non-brain injuries (e.g. arm fractures, abdominal laceration) (Group 3). Motor vehicle drivers made up the largest percentage of the total sample ($n=120$; 71.4%), with the remainder being front seat passengers ($n=35$; 20.8%), backseat passengers ($n=9$; 5.4%), and individuals whose position was unable to be determined ($n=4$; 2.4%). Individuals in the study were predominantly male (73.7%) and the average age for the entire sample was 36.5 years (SD = 17.2). For those collisions with definitive determinations for seatbelt use (67% of total population), 70.9% of the patients were unrestrained by a seatbelt. Female occupants employed their seatbelt 40% of the time, versus 22.9% for male occupants. Use of alcohol or illicit drugs at the time of injury was associated with reduced seatbelt use (14.3%). Alcohol and/or illicit drugs were used by just over one-fifth (21.4%) of the individuals included in the study.

Clinical data

For the moderate-to-severe TBI group (Group 1), the mean acute care hospital stay was 28.3 days ($n=67$, SD = 19.1), the mean Glasgow Coma Scale score was 7.0 ($n=61$, SD = 3.9), and the mean score on the LOC scale was 6.0 ($n=55$, SD = 1.4). In mild TBI (Group 2), the mean acute care stay was 5.3 days ($n=36$, SD = 12.4), the mean Glasgow Coma Scale score was 14.5 ($n=34$, SD = 0.66), and the mean score on the LOC scale was 2.7 ($n=24$, SD = 1.0). For individuals without brain injury (Group 3), the mean acute care hospital stay was 2.7 days ($n=29$, SD = 2.1), the mean Glasgow Coma Scale score was 15 ($n=28$, SD = 0), and the score on the LOC scale was 1.1 ($n=11$, SD = 0.4).

Analysis of collision types (significance at $p < 0.05$)

When considering the direction of energy for only those occupants sustaining TBI, individuals were unconscious in the ER 37.5% of the time in the striking group ($n=16$), 59.4% in the struck group ($n=32$), and 78.6% in the fixed group ($n=28$). Periods of unconsciousness for longer than 1 day occurred in 23.1% of the striking group ($n=13$), 50% of the struck group ($n=22$), and 63.2% of the fixed group ($n=19$). Analysis of the effect of direction of energy on duration of LOC revealed non-significant differences ($\chi^2=2$, $p=0.077$). While the use of safety restraints (seatbelts or airbags) was different between groups (Fixed = 17.2%, Striking = 55%, Struck = 40.6%), the average GCS score for the seven unrestrained occupants of striking collisions remained quite high (12.8). The influence of direction of energy on duration of LOC is illustrated in figure 1.

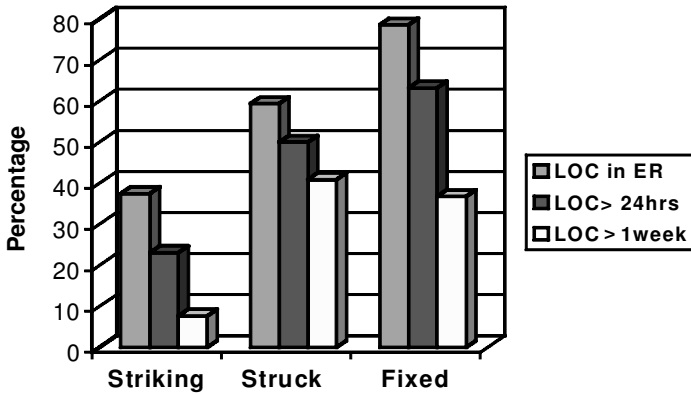


Figure 1. Relationship between duration of LOC and the direction of energy at the time of the collision.

Lesion analysis (significance determined at $p < 0.007$ – 0.05 sequentially)

Results did not support the hypothesis that subcortical/brainstem damage would be more common in restrained vs unrestrained individuals with brain injury (restrained = 21%, unrestrained = 18%) ($\chi^2 = 0.127$, $p = 0.72$). For all unrestrained occupants with positive CT scans, lesions to either posterior cortical lobe (parietal or occipital) were sustained 42.5% of the time ($n = 40$) vs 30% for restrained motorists ($n = 13$). Unrestrained occupants sustained lesions solely to the occipital lobe 20% of the time ($n = 40$) vs 7% for restrained motorists ($n = 13$). As expected, comparisons between the occupants of frontal and lateral collisions revealed no effect on the likelihood of sustaining frontal lobe lesions ($\chi^2 = 446$, $p = 0.336$). Contrary to the hypotheses, white matter shearing injury was no more likely to occur in lateral collisions (23%, $n = 30$) compared to frontal collisions (22%, $n = 53$) ($\chi^2 = 0.005$, $p = 0.943$). When comparing lateral and frontal collisions for the incidence of injuries indicative of more severe types of TBI, occupants of lateral collisions were significantly more likely to sustain skull fractures ($\chi^2 = 4.13$, $p = 0.04$), haemorrhagic lesions ($\chi^2 = 14.1$, $p < 0.001$), and temporal lobe damage ($\chi^2 = 10.97$, $p = 0.001$). In addition, individuals involved in lateral collisions were significantly more likely to undergo surgical interventions (craniotomy, draining or evacuation of subdural, lobectomy, ICP bolt placement, or ventriculostomy) ($\chi^2 = 7.38$, $p = 0.007$) compared to occupants of frontal collisions.

Seatbelt use (significance determined at $p < 0.16$ – $p < 0.05$ sequentially)

Comparisons of belted and unbelted individuals sustaining TBI (irrespective of airbag deployment) revealed between group differences for injury severity variables. For example, the difference in length of acute care stay for belted occupants ($M = 15.6$, $SD = 18.9$, $n = 22$) and unbelted occupants ($M = 25.9$, $SD = 19.4$, $n = 55$) approached significance [$t(75) = 2.1$, $p = 0.039$]. Similarly, difference in GCS scores for belted occupants ($M = 11.1$, $SD = 5.0$, $n = 19$) and unbelted occupants ($M = 8.2$, $SD = 4.4$, $n = 49$) also neared significance ($\chi^2 = 4.7$, $p = 0.03$). Finally, the scores between LOC scale scores for belted ($M = 4.1$, $SD = 1.9$, $n = 20$) and unbelted occupants ($M = 5.7$, $SD = 1.6$, $n = 20$) were significantly different ($\chi^2 = 11.2$, $p = 0.001$). Figures 2 and 3 provide a breakdown of the

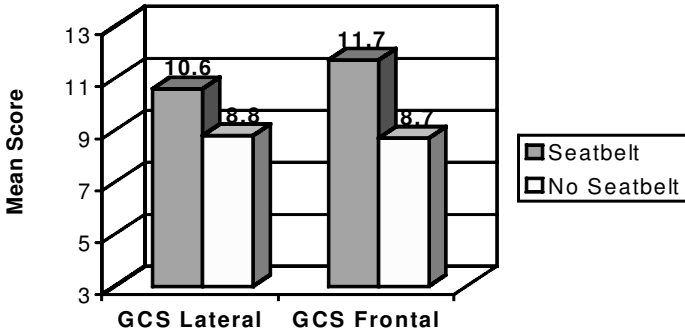


Figure 2. Comparison of mean GCS scores between groups of belted and unbelted motor occupants involved in frontal and lateral collisions.

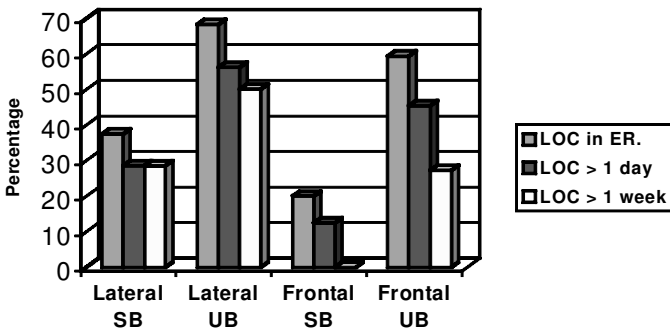


Figure 3. Comparison of duration of LOC scores between groups of belted and unbelted motor occupants involved in frontal and lateral collisions.

relationship between lateral and frontal collisions, seatbelt use, and injury severity variables.

Discussion

Collision analysis

Analysis of MVCs revealed relationships between specific collision variables and the nature and magnitude of TBI. For example, lateral collisions were associated with reduced seatbelt efficacy and more severe brain injury. When considering the entire sample, patients were more likely to arrive unconscious at the ER following lateral collisions (54.3%, $n = 35$) compared to frontal collisions (44.8%, $n = 58$) and were more likely to be unconscious after 24 hours when comparing the two groups (48% and 38.5%, respectively). As noted, injuries indicative of severe brain injury (e.g. skull fractures, intracranial haemorrhage, and the requirement of neurosurgical intervention) were significantly more common following lateral collisions. It is concluded that occupants are of greater risk for severe TBI in lateral collisions due to the reduced energy absorption that is typically afforded when the side of the vehicle is struck and because the occupant potentially maintains closer proximity to the point of impact.

It appears that prior research of MVC fatality [7] is consistent with the current findings for brain injury; occupants of the 'struck' vehicle sustain more severe brain injuries when compared to individuals in 'striking' vehicles. For struck vehicles, the deleterious effects on their occupants were attributed to the significant transfer of energy from one vehicle to another and the abrupt change in direction following contact. Occupants of struck vehicles, like occupants of vehicles involved in lateral collisions, are also more likely to be adjacent to the point of impact.

Fixed collisions were also associated with severe TBI. It is concluded that the increased incidence of severe TBI for occupants of fixed collisions is due to the expression of significant kinetic energy upon the vehicle and the occupant as 'work'. During any collision, energy is lost to either 'work' or to 'heat'. In fixed object collisions, the energy transferred to heat (e.g. friction during skidding) is minimized and the remaining kinetic energy must be transferred, or used-up, for the vehicle to come to a stop. For example, when a car strikes a local diner on a city corner (a collision included in this sample), the amount of energy lost to heat (friction) is likely to be much less than if the car strikes an object of less resistance (e.g. another vehicle) and subsequently slides to an uncontrolled stop. Therefore, the energy not expressed as friction is expressed as work on the building (if the building sustains recognizable damage). The remainder of the collision's energy is absorbed by the vehicle and, subsequently, the vehicle occupant. Therefore, when a vehicle stops abruptly, the occupant continues forward and may strike his/her head against an unyielding structure such as the windshield. In this case, there is direct expression of kinetic energy (work) on the occupant's skull and/or the brain tissue.

In sum, brain injury severity was influenced by specific collision configurations. The physical circumstances predictive of injury severity are most evident during lateral collisions or collisions where the patient's vehicle is struck (where there is presumably diminished safety restraint efficacy and less absorption of energy by the vehicle), and collisions with fixed objects, where deceleration occurring over very short distances forces the occupant to absorb a majority of the collision's kinetic energy.

Lesion analysis

The incidence of frontal lobe lesions was similar across collision types. These data are consistent with literature suggesting that the incidence of frontal lobe lesions are common, irrespective of the side of the head that is struck [21]. Contrary to the hypothesis, the incidence of sub-cortical white matter lesions (or shear injury) was not more likely to occur in lateral collisions when compared to frontal collisions. However, one interesting finding should be noted: increased incidence of shear injury was observed in collisions involving significant change in the vehicle's direction after the initial contact. That is, when considering both frontal and lateral collisions involving individuals who sustained diffuse petechial haemorrhaging, or sub-cortical white matter injury, six-to-12 maintained a post-collision angle change (i.e. change in vehicle direction following initial contact) greater than 50°. By contrast, occupants sustained the same pattern of injuries only 11% of the time when the post-collision angle change was less than 50° (one out of nine collisions). Significant post-collision angle change may create a similar angular or 'oblique' head movement, which has been determined to contribute to shear injury in non-human primates [17]. This relationship is intriguing and should be more rigorously

investigated through on-site collision analysis and the employment of advanced neuroimaging techniques that maintain increased sensitivity to measuring white matter lesions, such as magnetic transfer imaging (for review see [22]) or magnetic resonance spectroscopy (for review see [23]). In addition, because head vs obstacle contact reduces the amplitude of energy required to cause DAI [24], instances of head contact must be accounted for in order to better delineate the relationship between change in vehicle direction, potential head rotation, and white matter shear injuries.

During lesion analysis of cortical and sub-cortical injuries, it was noted that of the 64 individuals with positive CT findings in this study, 12 maintained sub-cortical or brainstem (or both) lesions in the absence of any gross cortical lesion. These data are important for two reasons. First, these findings have been reported to be rare [25] and, secondly, deep brain lesions have been correlated with poor patient outcome [26]. Of these 12 collisions, six involved lateral impact and four involved striking a fixed object and, in this investigation, these collision types were associated with severe brain injury. Furthermore, in the lateral collisions where the post-collision angle change could be determined (four of six), all values were greater than 60° (e.g. 64, 67, 100, 153°). Although this finding requires further investigation of a greater number of collisions, it appears that isolated sub-cortical lesions can occur in nearly one out of five of those individuals sustaining moderate or severe brain injury in MVCs. Furthermore, isolated subcortical/brainstem lesions may be more likely to occur when there is significant post-collision angle change or deceleration over a short distance (e.g. fixed object collisions).

Use of seatbelts

In this study, the incidence of seatbelt use for individuals sustaining brain injury (Groups 1 and 2, 27.7%) was lower than has been reported as the national average (68%, [28]). The overall rate of seatbelt use in this group of individuals with brain injury is consistent with prior research of seatbelt use in another investigation of individuals with moderate and severe TBI [12]. Safety restraints (seatbelts and airbags) were associated with lower incidence of brain injury and less severe TBI when brain injuries occurred. For example, disparities in seatbelt use were evident when comparing individuals with moderate and severe TBI (Group 1, 21.3%) and individuals with mild TBI (Group 2, 45.5%). Thus, an important conclusion to be drawn is that safety restraints not only reduce the probability of sustaining TBI, but they also moderate the severity by which injuries may be sustained. When considering both TBI groups, use of a seatbelt resulted in a reduction of scores for all injury severity variables, irrespective of the angle of impact. This reduced injury severity was somewhat greater in frontal collisions, but there remained an appreciable protective affect offered by seatbelts during lateral collisions (see figure 1). For example, when considering the eight lateral collisions where a seatbelt was used in the absence of airbag deployment, the number of individuals who arrived to the emergency room unconscious was three (37.5%). This number is compared to the 13 out of 19 (68.4%) unbelted individuals without airbags who were unconscious in the emergency room following lateral impact. These data are not consistent with previous findings concluding that seatbelts do not provide significant protection during lateral collisions [4].

The average 'year of manufacture' for the vehicles in this sample was 1986 (SD = 5.99). Because airbags were not standard in most new vehicles until ~1991 (this year varied for major motor vehicle companies), many of the motor vehicle occupants in this sample did not have this passive restraint system available in their vehicle. Future analyses will allow for examination of airbag efficacy in reducing the incidence and severity of brain injury.

Hypotheses regarding the effects of seatbelt use on brain lesion location were partially supported in this study. Consistent with a previous study, lesion analysis indicated a difference in the incidence of posterior cortical injuries between restrained and unrestrained groups. However, lesion analysis of sub-cortical/brain-stem lesions did not reveal a significant between group differences for restrained and unrestrained motor vehicle occupants. These data are inconsistent with those observed in a group of individuals with moderate-to-severe brain injury. The apparent inconsistencies in these data may be attributable to the small size of the restrained sample with positive CT findings in this study ($n=13$). In addition, the mean injury severity (e.g. LOC scale score and GCS score) was less severe in this sample compared to those in a previous study. For example, the typical restrained motor vehicle occupant in this study experienced a period of altered consciousness briefly at the scene and became more lucid in the emergency room or within 1 hour of admission (LOC score of 3.8). The typical duration of LOC for restrained motor vehicle occupants in a previous study was 1–3 weeks. The difference in brain injury severity between these two groups is considerable and may have influenced the replicability of these results. Therefore, to determine the influence of safety restraint use on the incidence of specific brain lesion types, investigations analysing distinct collision configurations, varying degrees of collision severity, and varying resultant degrees of brain injury severity (e.g. mild, moderate and severe) will be important. This will allow investigators to determine if the use of a safety restraint influences the incidence of sub-cortical brain lesions.

Conclusion

The data indicated that motor vehicle collision factors are useful predictors of the type and severity of TBI. Analysis of safety restraints revealed that seatbelts not only reduce the probability of injury, but they also mediate the severity of brain injury when it is sustained. In addition, specific collision configurations such as lateral collisions, struck vehicles, and collisions involving contact with a fixed object were associated with the most severe brain injuries. Admittedly, the physical conditions present in motor vehicle collisions are chaotic and can be cumbersome to determine. The fact that each collision may create a distinct physical environment only increases the difficulty in cataloguing the parameters necessary to cause TBI. Moreover, important collision factors such as velocity change and the degree of vehicle deformation are difficult to measure and often require approximations. Continued efforts should work to reduce this 'chaos' through the on-site reconstruction of each collision, brain lesion analysis with advanced neuroimaging techniques, and neuropsychological assessment of cognitive dysfunction. By integrating these sources of information, the physical circumstances responsible for disparate forms of brain injury and the subsequent cognitive outcomes may be profiled.

In acute brain trauma, traditional neuroimaging techniques such as CT or MRI may be negative for hours following brain injury or may not reveal gross pathology

at all [28]. In these cases, patients must be carefully monitored early on and determinations regarding the severity of injury and necessity for neurosurgical intervention (e.g. intracranial monitor placement) may be difficult to ascertain. It is during this time period that treating specialists might benefit from specific information regarding the physical conditions responsible for the patient's TBI. These data may eventually have important implications for acute care treatment as well as for the development of the next generation of vehicle safety devices.

Limitations of this investigation support the need for on-site collision analysis to better understand the specific physical conditions involved in collisions and their effect on brain injury. Continued research should focus on TBI prevention by better defining the minimum physical thresholds that brain injury might be sustained in and the mechanisms by which these thresholds are achieved during real-world collisions.

Acknowledgements

The authors wish to thank Drew Nagele, Stephanie Wingate-Gardner and Kelli Williams for their efforts throughout this study. We thank Henry Browning and Edwin Chiu for offering their expertise in physics and collision analysis. In addition, we want to thank Deputy Commissioner David Weinberg and the people of the Research and Planning Division, Records Department, Philadelphia, PA. Finally, we thank Scott Millis for sharing his considerable expertise in the area of statistical analysis.

References

1. National Institutes of Health: Rehabilitation of persons with brain injury. *NIH Consensus Statement*, **16**: 1–41, 1998.
2. KRAUSE, J. F. and McARTHUR, D. L.: Epidemiologic aspects of brain injury. *Neuroepidemiology*, **14**: 435–450, 1996.
3. BERKER, E.: Diagnosis, physiology, pathology and rehabilitation of traumatic brain injuries. *Journal of Neuroscience*, **85**: 195–220, 1996.
4. SIEGAL, J. H., MASON-GONZALEZ, S., DISCHINGER, P. C. *et al.*: Safety belt restraints and compartment intrusions in frontal and lateral motor vehicle crashes: mechanism of injuries, complications, and acute care costs. *Journal of Trauma*, **34**: 736–758, 1993.
5. SIEGAL, J. H., MASON-GONZALEZ, S., DISCHINGER, P. C. *et al.*: Causes and costs of injuries in multiple trauma patients requiring extrication from motor vehicle crashes. *Journal of Trauma*, **35**: 920–931, 1993.
6. LOO, G. T., SIEGAL, J. H., DISCHINGER, P. C. *et al.*: Airbag protection versus compartment intrusion effect determines the pattern of injuries in multiple trauma motor vehicle crashes. *The Journal of Trauma Injury, Infection, and Critical Care*, **41**: 935–950, 1996.
7. EVANS, L. and FRICK, M. C.: Safety belt effectiveness in preventing driver fatalities versus a number of vehicular, accident, roadway, and environmental factors. *Journal of Safety Research*, **17**: 143–154, 1986.
8. JONES, I. A. and CHAMPION, H. R.: Trauma triage: vehicle damage as an estimate of injury severity. *The Journal of Trauma*, **29**: 646–653, 1989.
9. JONES, I. S. and SHAIBANI, S. J.: A comparison of injury severity distributions and their application to standards for occupant protection. *Proceedings of the 1982 IRCOBI Conference*, Cologne, Germany, pp. 1–16, 1982.
10. VARNEY, N. R. and VARNEY, R. N.: Brain injury without head injury. Some physics of automobile collision with particular reference to brain injuries occurring without physical head trauma. *Applied Neuropsychology*, **2**: 47–62, 1995.

11. VIANO, D., VON HOLST, H. and GORDON, E.: Serious brain injury from traffic-related causes: priorities for primary prevention. *Accident Analysis and Prevention*, **29**: 811–816, 1997.
12. HILLARY, F. G., MOELTER, S., SCHATZ, P. *et al.*: Seatbelts contribute to location of lesion in moderate to severe head trauma. *Archives of Clinical Neuropsychology*, **16**: 171–181, 2001.
13. SMITH-SEEMILLER, L., LOVELL, M. R., FRANZEN, M. D. *et al.*: Neuropsychological function in restrained versus unrestrained motor vehicle occupants who suffer closed head injury. *Brain Injury*, **11**: 1735–1742, 1997.
14. MCINTOSH, T. K., SMITH, D. H., MEANEY, D. F. *et al.*: Neuropathological sequelae of traumatic brain injury: relationship to neurochemical and biomechanical mechanisms. *Laboratory Investigation*, **74**: 315–342, 1996.
15. LEVIN, H. S.: Prediction of recovery from traumatic brain injury. *Journal of Neurotrauma*, **12**: 913–922, 1995.
16. VIANO, D.: Perspective on head injury research. *Paper presented at the IRCOBI conference, Goteberg, Sweden*, pp. 24–26, 1985.
17. GENNARELLI, T. A., THIBAUT, L. E., ADAMS, J. H. *et al.*: Diffuse axonal injury and traumatic coma in the primate. *Annals of Neurology*, **12**: 564–574, 1982.
18. TEASDALE, G. and JENNETT, B.: Assessment of coma and impaired consciousness: a practical scale. *Lancet*, **2**: 81–83, 1974.
19. RIMEL, R. W., GIORDANI, B., BARTH, J. T. *et al.*: Disability caused by minor head injury. *Neurosurgery*, **9**: 221–228, 1981.
20. HOLM, S.: A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics*, **6**: 65–70, 1979.
21. WHYTE, J., HART, T., LABORDE, A. *et al.*: Rehabilitation of the patient with head injury. In: J. A. Delisa (editor) *Rehabilitation Medicine: Principles and Practice*, 3rd edn (Philadelphia, PA: J.B. Lippincott Publishing, Co.), pp. 1191–1240, 1998.
22. MASSIMO, F., GROSSMAN, R. I. and COMI, G: Magnetic transfer imaging in multiple sclerosis. *Neurology*, **53** (supplement 3): 1999.
23. BROOKS, W. M., FRIEDMAN, S. D. and GASPAROVIC, C.: Magnetic resonance spectroscopy in traumatic brain injury. *Journal of Head Trauma Rehabilitation*, **16**: 149–164, 2001.
24. OMMAYA, A. K. and HIRSCH, A. E.: Tolerances for cerebral concussion from head impact and whiplash in primates. *Journal of Biomechanics*, **4**: 13–20, 1971.
25. OMMAYA, A. K. and GENNARELLI, T. A.: Cerebral concussion and traumatic unconsciousness: correlation of experimental and clinical observations on blunt head injuries. *Brain*, **97**: 633–654, 1974.
26. LEVIN, H. S., WILLIAMS, D., CROFFORD, M. J. *et al.*: Relationship of depth of brain lesions to consciousness and outcome after closed head injury. *Journal of Neurosurgery*, **69**: 861–866, 1988.
27. FEDERAL REGISTER: Presidential initiative for increasing seatbelt use nationwide; recommendations from the Secretary of Transportation. *Pres Doc*, **62**: 1997.
28. BIGLER, E. D.: Quantitative magnetic resonance imaging in traumatic brain injury. *Journal of Head Trauma Rehabilitation*, **16**: 117–134, 2001.