MECHANISMS AND PATTERNS OF HEAD INJURIES IN FATAL FRONTAL AND SIDE IMPACT CRASHES

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ABSTRACT

Postmortem evidence on head injuries was used in conjunction with data on vehicle damage and crash circumstances to describe the mechanisms of head injury in a group of 30 fatal car crashes. The experience of a neuropathologist was linked with that of an accident investigator to explore the possibilities for improving understanding of how loading is transmitted through the car structure to the head. The load paths within the head were also traced to provide insight into the mechanism of injury, and to assist in linking injury tolerance work with accident reality. Accident selection was aimed at crash situations similar to those frequently evaluated with dummies. This was a pilot study to explore the possible benefits of this technique.

The sample was structured to contain equal numbers of frontal and side impacts. In the frontal impacts studied, loading to the skull was usually transmitted via the facial bones. In both crash types, basal skull fractures were more common than fractures of the vault. There were differences in the patterns of loading to the head and the injuries suffered in frontal as opposed to side impacts. The loading conditions in both crash types were different from those used to establish the original tolerance curves that underpin the Head Injury Criterion calculated from dummy accelerations. Improved methods of recording the information from routine postmortem investigations would aid future injury tolerance work.

INTRODUCTION

Head injuries are the leading cause of death for drivers in frontal crashes[1] and are also responsible for a large percentage of the deaths in side impact crashes[2,3]. The Head Injury Criterion (HIC) is widely used to gauge the risk of head injury in frontal impacts using dummies in laboratory conditions. This criterion is based on the Wayne State Tolerance Curve, derived in part from cadaver studies of forehead impacts on flat metal plates[4]. Criteria suitable for head injury risk assessment in side impacts are currently under development[5]; however, there is no dummy that is designed to have a biofidelic head in side impacts.

The mechanisms of head injury in both frontal and side crashes must be better understood if criteria suitable for use in these two crash conditions are to be developed. Such criteria are fundamental to vehicle designs that will reduce the risks of head injuries in crashes. This pilot study was undertaken to explore whether improved interpretation of postmortem data routinely collected in the United Kingdom in combination with field accident data could produce greater understanding of head injury mechanisms in car crashes. In many multidisciplinary crash investigations, injuries are coded to the Occupant Injury Classification to describe body region, lesion, and system/organ of the injury and to the Abbreviated Injury Scale (AIS) to describe severity, and this coding is used for analysis[6]. This limits the information available to study injury mechanisms. In this study, the skills of engineering and neuropathology were combined to form description of how an injury occurred in a car crash. Just as a vehicle engineer views a crashed car to deduce the load paths that gave rise to the bodyshell damage, a neuropathologist uses the same type of thinking to explain how loads applied externally to the face and skull gave rise to a particular pattern of injury.

Two further basic questions were considered in the present study. The first concerned the extent to which the loading conditions used to establish tolerance curves for frontal impacts were in fact observed in frontal accidents. The second examined if there were differences in the patterns of head injury in side and frontal impacts. If differences exist, careful thought needs to be given to what type of criterion would be suitable for use with dummies in side impact testing.

METHOD

A previous study[1] resulted in a database describing the experiences of 571 fatally injured car occupants in the United Kingdom. For each fatality there were a postmortem report, police and witness statements, and photographs of the vehicle and scene. Injury severity in the database was coded using the Abbreviated Injury Scale[6].

A subset of 30 cases was selected to cover a range of severe head injuries. In marked contrast to most other detailed studies of head injury, cases for evaluation were chosen according to the crash configuration. The intention was to select accident cases that were as similar as possible to currently proposed front and side impact test conditions. Fifteen frontal crashes with direction of force between 11 and 1 o'clock were selected in which the fatalities were restrained drivers with head injuries coded AIS 4 or above. Preference was given to cases where the source of the head injury lay within the case vehicle. The same number of side impacts were selected. For this group of cases the fatalities were struck side occupants with head injuries of AIS 3 or above. Preference was given to crashes that were broadly similar to the situation described by the United States side impact standard that applies beginning with 1994 models (49 *CFR* § 571.214). The level of detail in the description of the pathological findings varied from case to case and reflected the range of descriptions encountered in the basic material.

Each autopsy report was first reviewed independently by the neuropathologist to examine the details of the injury without knowledge of the crash. In a second review, involving the accident investigator as well as the neuropathologist, the injury description was assessed against the background of knowledge about the crash circumstances. Head injury data, previously summarized by use of AIS values for the face, brain, and skull, was expanded to record the following items:

- Deduced position of first blow to head;
- Fractures to the facial bones, vault, and base of skull;
- Positions of contusions, subdural, and extradural haematomas;
- Positions of subarachnoid haemorrhages;
- Positions of internal brain damage (ie damage to the substance of the brain);
- Dominant mechanism of injury; and
- Comment on the source of injury and the way in which the whole injury picture tied in with the vehicle information.

RESULTS

By sample definition, all the occupants in the frontal impacts were restrained drivers in accidents with a direction of force between 11 and 1 o'clock. Intrusion was a feature of these crashes with five fatalities experiencing reduced ride down distance, and a further seven being effected by distortion that reached their original seating positions. The steering wheel was the source of the head injury for nine of these drivers, with the windshield frame and the hood of their own car being responsible for two injuries each. The remaining injuries were associated with contact with structures that came into the case vehicle.

Two people had head injuries rated as AIS 4, 12 had AIS 5 injuries to the head, and there was just one example of an AIS 6 injury.

For side impact cases, struck side casualties were selected from crashes with directions of force of 2-4 o'clock and 8-10 o'clock. Six of these people were known to be restrained by three-point seat belts. Head injury AIS ranged from 3-6.

As indicated in Table 1, there were differences in the site of loading in the frontal and side impact crashes. Loading via the facial bones is frequent in the frontal impacts, but it is seen less often in the side impact crashes. Loading via the parietal and temporal bones and through the vertex was a feature of the side impact rather than frontal crashes.

Facial bone fracture was seen primarily among the frontal cases, as shown in Table 2. For this group, the mandible was involved in six cases. The orbit, maxilla, and nasal bones were each fractured on three occasions and a single fracture of the zygoma was recorded. Fractures of the vault were not frequent in either crash type, but basal fractures were more common. Fractures of the sphenoid were seen in eight frontal impact casualties and two side impact victims. The bones of the orbit, temporal, and occipital regions were also fractured in both crash types. Also shown in Table 2, contusions of the brain were common with the frontal and temporal lobes being most frequently involved.

The mechanisms of head injury, as deduced from the nature of the head injury, are described in Table 3. It is apparent that while mechanisms involving translational accelerations are common, other mechanisms of injury are seen, including rotational acceleration and crush. It seems likely that in any impact to the head there will be a mixture of translational and rotational accelerations. The categorization of the mechanisms given in Table 3 are considered to be the primary type of acceleration associated with each injury. It is not intended to imply that translational acceleration took place with no rotational acceleration present, or vice versa.

The group of nine restrained drivers who impacted the steering wheel in frontal impacts were considered further. This type of impact is seen frequently with seat belt restrained drivers but has not been widely reported as resulting in fatal injury. The mechanism of loading in every case was via the facial bones. The loads were applied in an upwards direction. As this loading condition is modelled by many dummies in crash tests, it is worth emphasizing that interpretation of the dummy head accelerations by criteria based on forehead impacts with a steel plate is questionable. It seems unlikely that the tolerance of the skull and brain are identical in these two very different situations. In the crash data, there is often brain damage overlying a basal skull fracture. In this group of cases it would seem that the particular load path within the facial bones and skull is critical in determining the threshold for injury. The following case study helps illustrate the type of loading and load transmission seen in these crashes. A second case study helps to illustrate the type of situation seen in side impacts.

Case Study 1: Full Frontal Crash

This was a full overlap, 12 o'clock frontal impact between two cars. The change in velocity of the case vehicle was estimated, on the basis of the damage sustained to both cars, to be of the order of 30 mph. The 36 year-old driver of the Ford Mk IV Cortina was wearing a three-point inertia reel seat belt. He was 6 feet tall and described as "obese". He experienced some dashboard and footwell intrusion into his ride down space. There was limited vertical movement of the steering wheel. His head contacted the steering wheel, with initial loading being applied to the right side of his jaw. The load path within his skull is illustrated in Figure 1. There was fracturing of his mandible and maxilla (AIS 2) with loads strutting through to the base of the skull. This produced extensive comminuted fracturing of the middle and posterior cranial fossae (AIS 4).

Extensive brain contusions (AIS 5) were noted, but their position was not specified. There were no subdural or extradural haematomas and no subarachnoid haemorrhage. There were small petechial haemorrhages in the white matter, suggestive of diffuse axonal injury and tearing of blood vessels. The brain would have experienced primarily translational accelerations in these circumstances. He was dead on arrival at hospital. In addition to his head injuries he suffered fractured ribs and lung contusions (AIS 5) and a fractured left patella (AIS 2).

Case Study 2: Side Impact Crash

This was a car-to-car side impact with a direction of force on the case vehicle of 3 o'clock. Direct loading from the front of the striking car was applied to both side doors on the right of the case vehicle's passenger compartment. The right rear passenger of the Chrysler Alpine was a 50 year old unrestrained female. There was considerable intrusion into the seating space that she originally had occupied. She received a blow to the right temporal region thought to be due to contact with the intruding window pillar. Her injuries, including facial abrasions and lacerations, are illustrated in Figure 2. She suffered no skull or facial fractures. There was a subdural haematoma over the right temporal lobe (AIS 5) with subarachnoid haemorrhage in the same area (AIS 3). No internal brain damage was recorded. The mechanism of this head injury is considered to be primarily rotational acceleration. She was dead on arrival at hospital. In addition to her head injuries, she had a tear in the left coronary artery (AIS 4) and a fractured right tibia and fibula (AIS 2).

DISCUSSION

The small sample size used in this study dictates that care should be taken in generalizing the results. The intention of this pilot study was to illustrate the types of benefits available from this enhanced analysis technique, rather than to produce a definitive description of the mechanisms of head injuries in all frontal and side impacts.

The historical development of the head injury criterion (HIC) required by Federal Motor Vehicle Safety Standard 208 has been described in detail by various authors[4,7,8]. The HIC is partly based on the Wayne State University Cerebral Concussion Tolerance curve, which describes a relationship between acceleration and duration of impact, and the severity of injury. The data defining the curve come from several sources, including cadaver studies of short duration impacts against hard plane surfaces, cadaver and animal studies of medium duration impacts, and volunteer studies of long duration acceleration without impact. The threshold of severe injury was set at concussion, assumed to be correlated with skull fracture for short duration pulses. In the cadaver material, concussion could not be measured but fracture could.

A review of the skull fracture database was done by the United States delegation to the ISO Working Group 6[9]. The four sources consisted of cadaver head drop tests on flat, rigid, and padded surfaces, cadaver windshield impacts in sled tests, and drop tests with helmeted cadavers. Unfortunately, the earlier studies did not provide data on the severity of skull fracture. For example, in the drop tests by Hodgson and Thomas, outcome was reported as skull fracture or no skull fracture[10]. These fractures were mostly linear and involving the frontal bones, with one reported as linear fracture into the orbit.

It is apparent that the experimental emphasis on impacts to the frontal bones is not typical of the impact sites seen in this pilot study. It is notable that with restrained drivers in frontal impacts, the situation in which the HIC results from test dummies are currently relied upon, the crash picture appears to be at variance with the test assumption. In these crashes, facial bone loading seems to be the norm, rather than the assumed frontal bone impacts reproduced when the tolerance data were established. This is not a criticism of the early work. It must be remembered that the three-point seat belt restrained driver was not anticipated when the original tolerance work was carried out. Lap belted occupants striking their heads on the instrument panel were the focus of this work. However, the three-point belt restrained occupant is now the usual test condition and the most frequent crash situation, particularly in Europe.

This study suggests that the time is right to re-examine the fundamental assumptions behind the use of HIC. Its suitability for assessing the severity of driver's impact with the steering wheel needs to be reconsidered. Further, this study reinforces the need to periodically review the biomechanics underlying all motor vehicle safety standards in the light of new knowledge because many of the standards were first developed at a time when only limited biomechanics information was available. As this study shows that there are probably important differences between the way loads are applied to the head in side and frontal impacts, the extension of the use of HIC directly to the side impact regulations needs very careful review. Even if such an extension is determined to be a reasonable first regulatory step, it should not be the last.

The crash sample confirms what has been known for some time that there is a group of injuries that are produced mainly by rotational accelerations. These occur in both frontal and side impacts and their correct control presents a further challenge. This study has demonstrated that important additional insights into crash injuries can be obtained by combining the skills of the vehicle engineer and neuropathologist. Such cooperative work could be eased by the development and use of a simple protocol to assist in the accurate recording of neuropathological observations during routine postmortem. It is striking that this form of cooperation between vehicle engineers and pathologists is merely an extension of the role pathologists have played in the development of modern medicine. In hospital medicine they have provided the vital feedback to clinicians. In the crash research field, they can provide an equally important feedback to ensure that the mechanisms of injury observed in practice are well understood. This knowledge in turn helps ensure that there is the most relevant possible basis for experimental work. Without such a base, there is a risk that inadvertent differences between laboratory and field conditions will be overlooked, with serious consequences for subsequent design effectiveness.

Application of these multidisciplinary techniques to other data sources would be useful. For example, modern imaging techniques would allow the same type of approach to be used with survivors.

CONCLUSIONS OF PILOT STUDY

1. Close cooperation between a neuropathologist and a vehicle engineer allows improved interpretation of routinely collected data on fatal crashes.

2. A protocol for recording neuropathological observations during routine post mortem examinations would help such work.

3. Selection of cases for analysis on the basis that they are somewhat similar to current test conditions helps link the world of crashes with that of the test laboratory.

4. In the frontal impacts studied, loading was usually applied to the head via the facial bones. This differs from the majority of tests that underpin head injury tolerance curves, where the loading is typically applied to the frontal bone.

5. Basal skull fractures are seen more often than vault fractures in the crashes studied. The early tests from which the HIC was derived tended to produce mainly vault fractures.

6. For the restrained drivers who struck their heads on the steering wheel, loading tended to be applied in an upward direction via the facial bones. Loads can be strutted through the facial bones to the base of the skull, and brain damage often overlies resulting basal fractures. It is not established that head injury tolerance to this form of loading is similar to that deduced from forehead impacts onto flat metal plates.

7. There were differences in the patterns of loading on the head and the resultant injuries in the frontal and side impact cases. This suggests that simple extension of any frontal impact head injury criterion for use in side impacts may be incorrect.

8. In both frontal and side impacts, some cases were seen where the head injuries were primarily associated with rotational as opposed to translational accelerations.

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Table 1
Site of Loading for Head Injury in Frontal and Side Impact Crashes

Site of Head Injury Loading	Frontal Crashes (N=15)	Side Impact Crashes (N=15)
Loading via facial bones	13	5
Loading via frontal bone	1	0
Loading via parietal bone	1	3
Loading via temporal bone	0	3
Loading via vertex	0	3
Loading position not known	0	1

Table 2
Type of Fracture and Brain Injury in Frontal and Side Impact Head Injury Crashes

	Frontal Crashes (N = 15)	Side Impact Crashes (N = 15)
Fracture		
Facial bone fracture	8	1
Vault fracture	2	2
Basal fracture	9	6
Brain Injury		
Contusions of brain	10	7
Subdural Haematomas	5	4
Extradural haematomas	0	0
Subarachnoid haemorrhage	4	5
Internal brain injury	9	5

Table 3
Primary Head Injury Mechanism in Frontal and Side Impact Crashes

Primary Injury Mechanism	Frontal Crashes (N = 15)	Side Impact Crashes (N = 15)
Translational accelerations	11	8
Rotational accelerations	3	4
Crush	0	2
Hyperextension	1	0
Not known	0	1

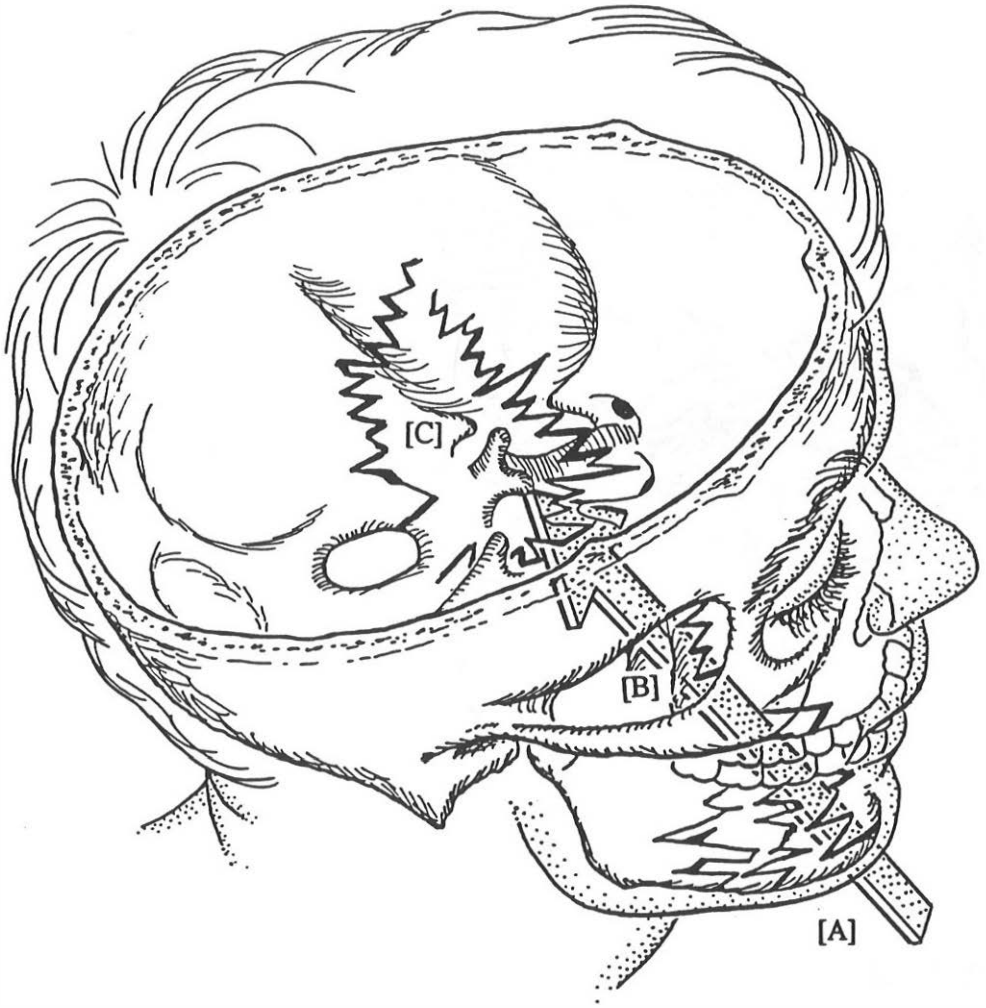

Figure 1

Diagram to show the pattern of fractures. The arrow shows the suggested loading pathway on the skull passing through the fractured mandible [A], the fractured maxilla [B] to the fracture in the base of the skull [C].

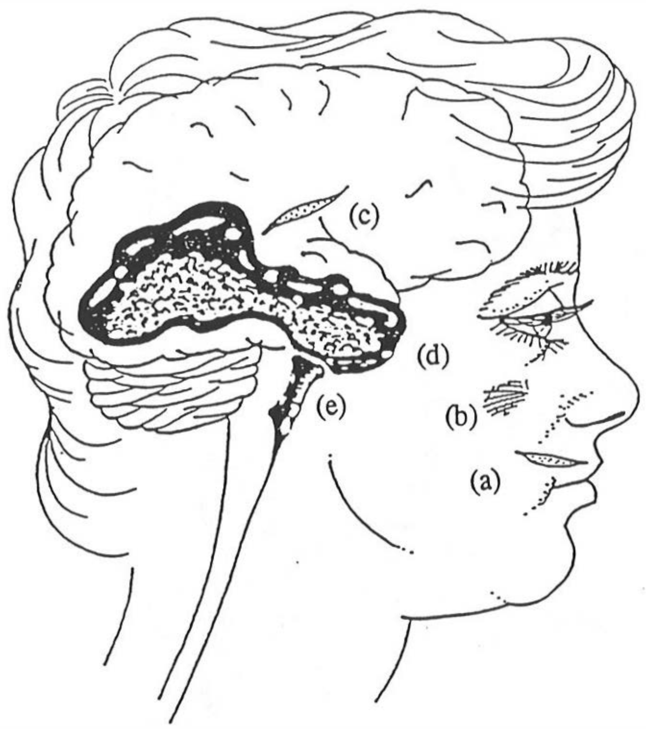

Figure 2

Diagram to show the pattern of facial and intracranial injury.

a) Laceration of lip
b) Abrasion of cheek
c) Laceration over the right temporal bone
d) Subdural haematoma over the right temporal lobe and
e) Subarachnoid haemorrhage over the front of the brain stem