A comparison of neck injuries in fatal rollover crashes to equivalent cadaver tests. Implications for neck injury criteria in rollover testing

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Abstract
A fundamental issue in developing a valid test protocol to assess occupant safety system performance is identifying relevant biomechanical injury criteria. Head, neck, thorax and lower limb injury criteria have evolved over many decades and are mandated in vehicle safety standards and test protocols. Agreement on head and neck injury criteria for rollover crash tests has not been reached. The specific injury presentations of people retained in the vehicle, but fatally injured in rollover crashes were analysed using NCIS and related files. The biomechanical literature on cadaver tests that involved inverted or largely axial loads to the human neck was reviewed. The injury presentations on a case-by-case basis from the literature were collated. Five papers reporting on 49 cadaver tests were selected. The proportion of in vitro fractures from cervical vertebra 1 to thoracic vertebra 4 was similar, but intervertebral disc, ligament and dislocation injuries were greatest around cervical vertebra 5 (C5). In contrast, the real world injury pattern was bimodal, with injuries occurring both at the occipito-atlantal joint, where the neck articulates with the head, and around C5, in the lordotic region of the cervical spine. This suggests that there may be different injury mechanisms present in the real world than in laboratory impact tests. This needs to be considered in developing a test protocol. Severe traumatic brain injury is another injury that occurs frequently in rollover crashes. Issues around injury mechanisms, taking into account the head and cervical spine, are presented.

Introduction

Serious to catastrophic neck injury arising from rollover crashes remains a road safety and public health challenge.[1 2 3] Recent research on fatal rollover cases has shown that serious to catastrophic head injury is an additional concern, one that may have been overlooked in debates of the mechanism of cervical spine injury.[4 5 6] The evolution in motor vehicle and occupant safety over the last two decades has been influenced strongly by design rules and new car assessment programs, such as ANCAP[*]. Fundamental to the success of performance tests are reliable and valid biomechanical measures of injury risk. The Head Injury Criterion, Viscous Criterion, femur loads, chest compression and Nij are examples of biomechanical variables that are either measured directly on an Anthropomorphic Test Device (ATD) or derived from ATD measurements during a crash test. The magnitude of each variable has been assigned an injury risk, often in terms of injury severity and likelihood[7]. There is a long history behind the development of these variables. This typically has involved accident investigation, biomechanical research on cadavers or animals, numerical modelling and scaling/extrapolation to wider populations[8]. In an ideal situation, the biomechanical measure (injury criteria) will reflect closely the injury mechanism and the permissible level (injury assessment reference value) for a specific injury; often adjusted for the ATD characteristics[7 8]

There has been controversy and debate regarding the mechanism of cervical spine injury in rollover crashes. On one side of the debate there is a theory that cervical spine injury arises from the occupant "diving" into the roof that is in contact with the roadway during the rollover[9]. In this theory, the residual roof crush is a measure of the crash severity, not of itself an injury risk factor. On the other side of the debate there is the theory that all injuries are caused by roof failure and intrusion[9]. In this theory, roof crush will be influenced by crash severity, crash characteristics and roof strength. The reality may be complex, with combinations of 'diving', roof crush and partial occupant ejection contributing to the resultant occupant injuries, depending on many factors specific to the crash[1 4 9].

[*] Australian New Car Assessment Program. See http://www.howsafeisyourcar.com.au/

The strength of a dynamic vehicle rollover and occupant safety test is that the 'right' test will be sensitive to the majority of predicable and unpredictable occupant loading scenarios and be able to identify safe occupant environments. The development of a dynamic rollover test protocol is presented schematically in Figure 1. This highlights the areas of research and development that are required to develop the protocol.

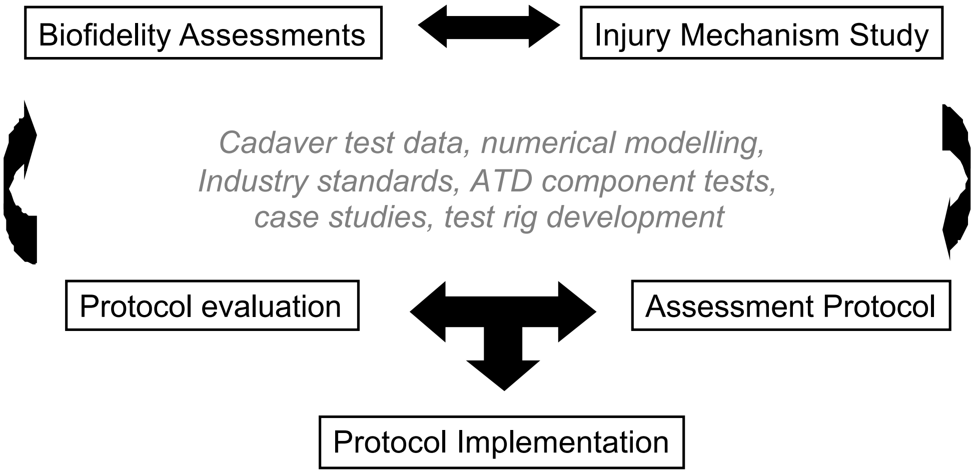

Figure 1: Schematic of dynamic rollover crash test development

From a biomechanical perspective, both 'diving' and roof crush induced loading may result in a combination of axial neck compression and bending moment. This combination is known to lead to vertebral and spinal cord injury [7 8 10]. A neck injury criterion for rollovers should in theory function equally well to assess neck injury risk for an ATD or person unrestrained who dives onto the very rigid roof of a vehicle and a well restrained ATD or person whose head is loaded as a result of rapid and significant roof crush. The question that this paper intends to consider is the extent to which current relevant *in vitro* biomechanical cadaver tests produce injuries that are similar to those observed *in vivo* in rollover crashes. If the injuries are similar this would lend support to the use of criteria and tolerance values derived from those tests in the development of rollover specific injury criteria and Injury Assessment Reference Values (IARVs). In addition, a detailed examination of the characteristics of spinal injury in rollovers may help identify the range of injury mechanisms experienced in rollover crashes.

Methods

Published impact tests to full-body cadavers were selected for comparison with post mortem reports of occupants involved in lateral rollovers from the National Coroners Information System (NCIS)[4]. Injuries from each individual were coded according to the Abbreviated Injury Scale (AIS)[11]. The anatomical region of the spine was coded in more extensive detail; consistent with the focus of this study. Only NCIS derived case series data from non-ejected, restrained occupants in lateral rollovers were included this study.

The published biomechanical literature used was:

1) Nusholtz et al, Response of the Cervical Spine to Superior-Inferior Head Impact, 1981 [12]

2) Nusholtz et al , Cervical Spine Injury Mechanisms, 1983 [13]

3) Alem et al, Head and Neck Response to Axial Impacts, 1984 [14]

4) Yoganandan et al, Experimental Spinal Injuries with Vertical Impact, 1986 [15]

5) Nusholtz et al, Kinematics of the Human Cadaver Cervical Spine in Response to Superior-Inferior Loading of the Head, 1986 [16]

When multiple injuries occurred at the same anatomical region, the highest AIS severity for that specific region was recorded. For example, if the vault sustained 3 fractures, only the most severe fracture (highest rated AIS) was recorded. The vertebrae were coded more specifically in terms of location of vertebral fractures, given that the detailed information was available. Injuries to the area surrounding each vertebra such as posterior and anterior ligaments, vertebral artery, and the surrounding muscles were also coded, regardless of AIS severity. Other superficial injuries (AIS 1) such as minor lacerations and bruises were not recorded. Dislocations/subluxations were also noted.

The frequency of injuries by severity and distribution at each level of the head and spinal column were analysed. For this paper a descriptive analysis is presented.

Results

The number of fatally injured cases analysed from the NCIS data set was 105. Thirty percent (30%) of the cases were aged between 21 and 30 years. All other age groups were between 5 and 15% of the total. The average age was 38 years compared to the *in vitro* test object age of 65 years. There were 281 injuries coded for the 105 occupants.

The number of *in vitro* cases was 49 (Table 1). In the experiments unembalmed cadavers were impacted on the crown either with an impact device or in inverted tests. The impact velocity was varied as was the impact surface in those tests to change the impact severity.

Summary	Response of the Cervical Spine to Superior-Inferior Head Impact	Cervical Spine Injury Mechanisms	Head and Neck Response to Axial Impacts	Experimental Spinal Injuries with Vertical Impact	Kinematics of the Human Cadaver Cervical Spine in Response to Superior-Inferior Loading of the Head
No. of subjects injured	11	8	10	15	5
Sex	NA	NA	Male	Male	Male
Mean height (cm)	174.17	174.25	174.09	177	174.6
Mean weight (kg)	71.54	64.63	63.42	71.67	80.2
Mean age (yrs)	68.6	60.8	61	69.5	63.4
Test type	56kg impactor	Drop test	10kg impactor	Drop test	56 kg impactor

Table 1: In vitro test characteristics

Figures 2 to 5 show the distribution of injury by level and by level and nature of injury.

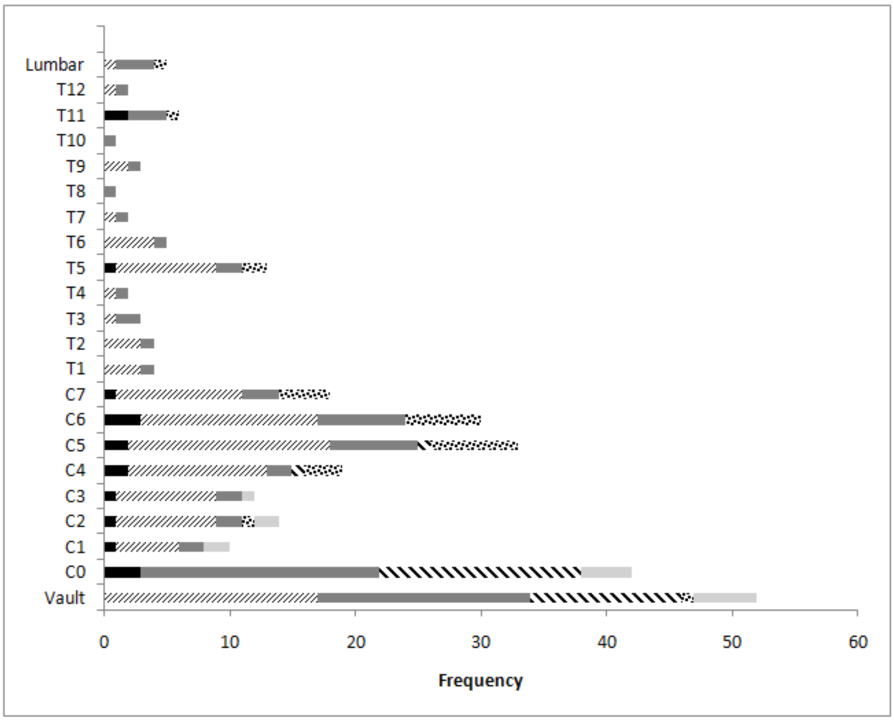

Figure 2: Distribution of injuries by AIS severity and level in spine - real world cases

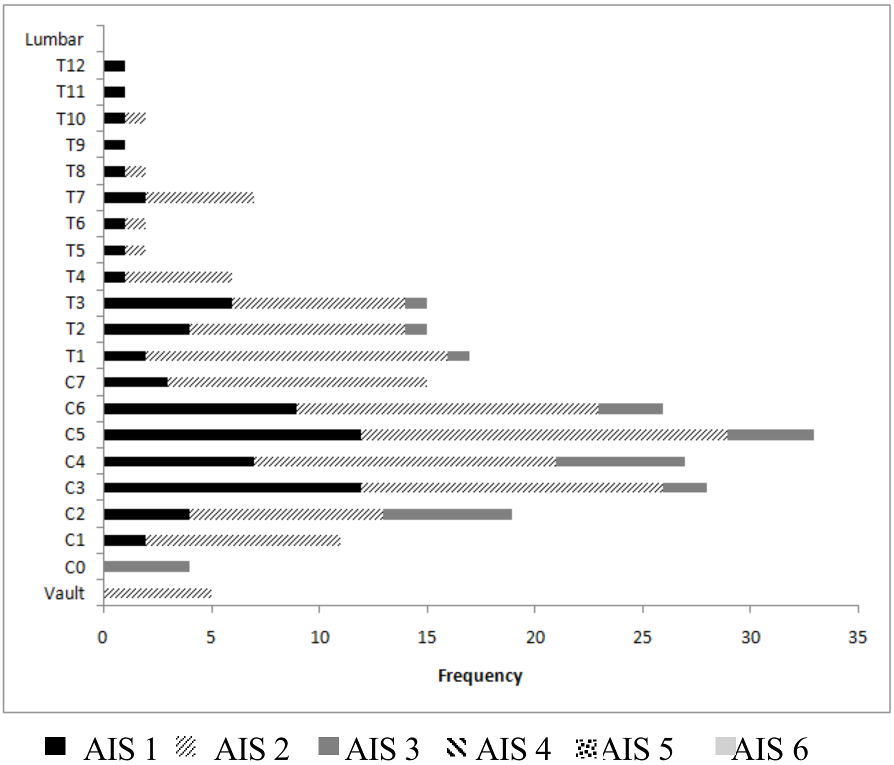

Figure 3: Distribution of injuries by AIS severity and level in spine - in vitro cases.

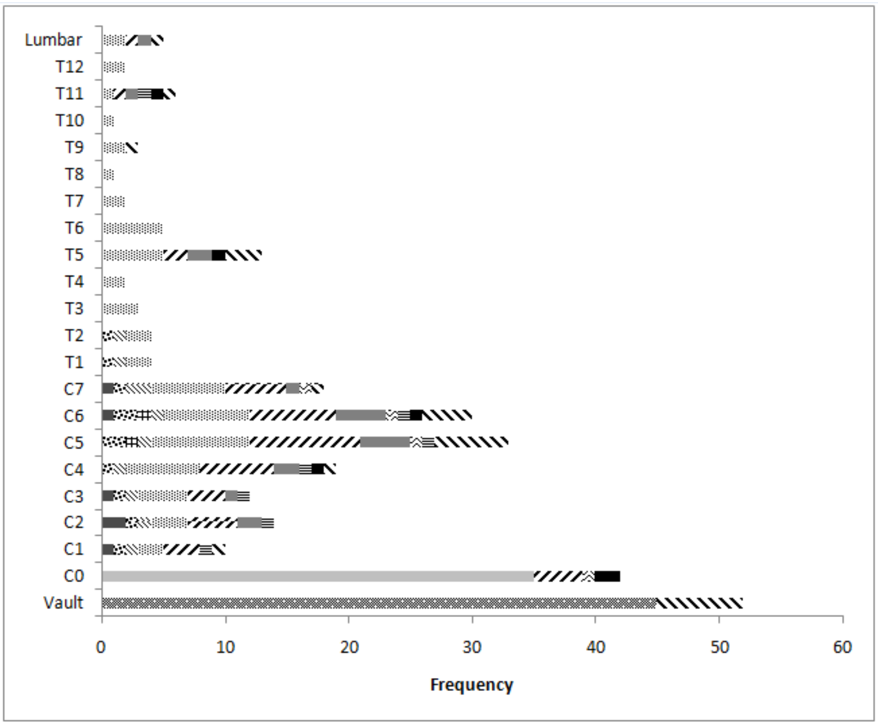

Figure 4: Distribution of injuries by type and level - real world cases.

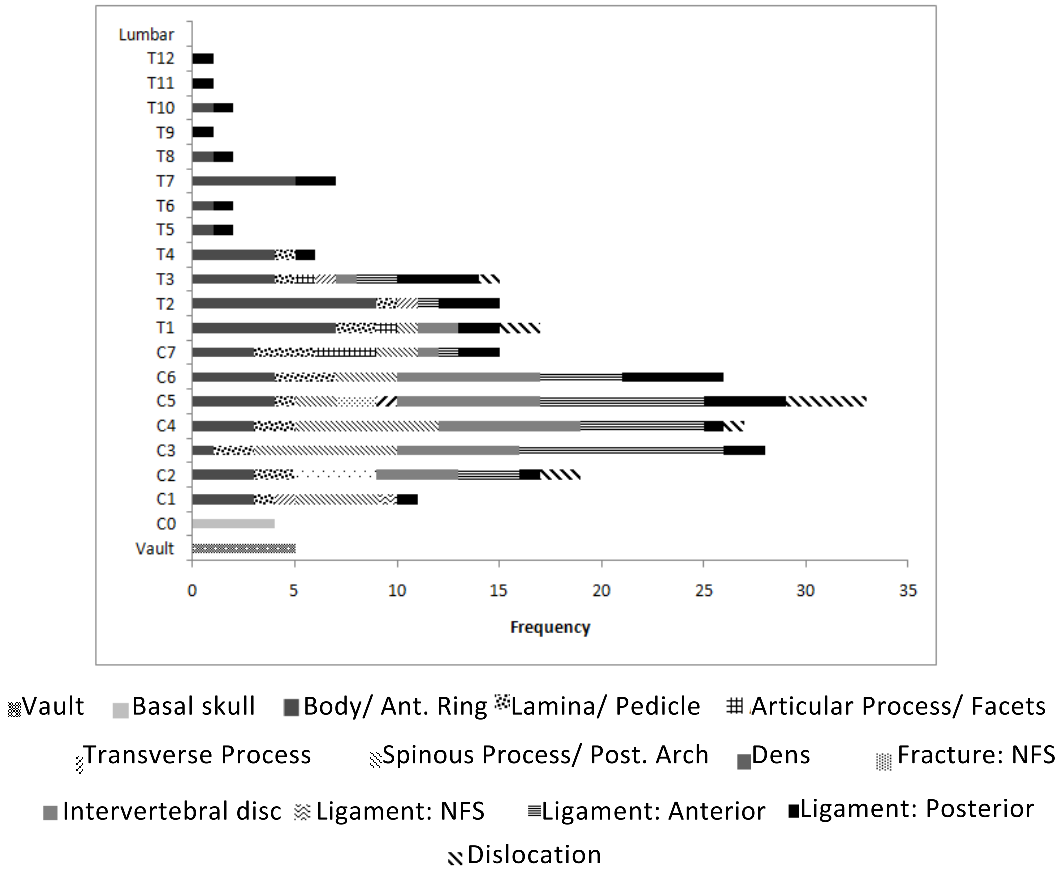

Figure 5: Distribution of injuries by type and level – in vitro cases.

Discussion

Figures 2 to 5 show that the neck injuries in real world rollover crashes are more severe, with a higher proportion of AIS 3+ injuries compared to the laboratory tests. The distribution differs too, with there being a high proportion of severe cranial vault and occipital injuries in the real world cases compared to the laboratory tests. One important difference is the age of the deceased in the NCIS data set and the cadavers used in the tests. Age affects biomechanical properties.

In the laboratory tests the injuries, including fractures, ligament tears and spinal cord lesions, were focussed between C4 and C6. The base of skull injuries are more common in the real world rollover crashes. In our previous study of injury patterns in rollover crashes, we reported that 45% of fatally injured contained and belt restrained occupants in single vehicle rollover crashes had suffered a fatal head injury and 25% a fatal neck injury[4]. The more detailed analysis presented here suggests that the head and neck are not simply two distinct body regions from an injury mechanism perspective, but the interaction between the two at the base of skull needs careful consideration. The loads applied at the base of the skull might be considered in the development of a rollover test protocol, in addition to more conventional criteria such as the Head Injury Criterion. The difference in the injury patterns suggests that the occupants in real world crashes are being subjected to more than just a combination of axial neck compression and flexion bending moments. This is consistent with our work on roof failure and related head/neck loading mechanisms in rollover crashes[9]. In consideration of the above points, there is an argument that lateral loading patterns applied to the head of the inverted occupant contribute to head injury as well as shearing or lateral bending loads on the neck. This occurs in combination with axial compression and either flexion or extension bending moments. In short, the loading and biomechanical responses are complex. In our earlier assessment of the Hybrid III in inverted impacts, we concluded that utilisation of the upper six axis load cell and the lower neck bending moment would account for the majority of loading conditions and facilitate the use of injury criteria similar to Nij[10]. The use of the upper neck forces in combination with headform acceleration or the Head Injury Criterion to assess the risk of base of skull, cranial vault fractures or crushing injuries is another area worthy of review.

Conclusions

A preliminary comparison between real world head and spine injury and injury induced in laboratory tests indicates differences in injury patterns. Reasons for these differences include age and loading mechanisms. The analysis adds one new element to our understanding of rollover injury mechanisms. Consideration for the causation of head injuries, in particular base of skull/vault fractures, needs to be given in the development of biomechanical protocols for a dynamic rollover crash test, in addition to neck loads such as axial compression and flexion bending moments.

Acknowledgments

The authors would like to thank the Australian Research Council for providing funds to carry out this research through the Discovery Projects grants scheme (No: DP0663834). The authors would like to thank the Victorian Institute of Forensic Medicine (VIFM) as the source organisation of the National Coroners Information System from which rollover crash data was extracted for the statistical analysis presented in this paper. In particular the authors would like to thank Ms Marde Hoy from VIFM for her assistance. Ms. Jee Yong worked on this project during her honours degree in Mechanical Engineering under the supervision of A/Prof Andrew McIntosh. Professor Raphael Grzebieta and A/Prof. Andrew McIntosh are Chief Investigators of the ARC Rollover project.

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