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Seriously injured occupants of passenger vehicle rollover crashes in NSW

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Abstract

This study uses linked police-reported road crash and hospitalisation datasets to establish the patterns of serious injury sustained by occupants of passenger vehicle rollover crashes in New South Wales, 2001 to 2011. A total of 10,876 casualties were identified that were injured in crashes where rollover was the primary event. The injury patterns are compared with in-depth rollover crash investigations using United States data, where injury mechanisms were identified in an effort to establish rollover crash test protocols and identify appropriate areas for vehicle improvements to ameliorate serious injuries. The aim of the present study is to establish similarities between patterns of serious injury to the head, spine and thorax between Australia and the United States, such that the lessons learned with regards to injury mechanisms, test protocols and vehicle performance requirements may be shared and used to improve vehicle rollover crashworthiness in both countries. General descriptors of rollover crash incidence, characteristics and determinates of serious injury in NSW are also reported.

Keywords

Rollover, Serious injury, Injury mechanisms, Rollover crashworthiness

Introduction

Rollover crashes are known to be relatively rare, yet particularly injurious events. Studies of Australian road fatalities have shown that one in every three to four vehicle fatalities involved a rollover of the vehicle [1]. Such studies have shown that head, spine and thoracic injuries feature highly as causes of death amongst fatally injured rollover occupants [2]. However, detailed studies of injury mechanisms resulting from rollover crashes have not been reported in Australia, and retrospective rollover investigations have concentrated on fatal crash cases [1-3]. This is partly due to the fact that vehicle rollovers cannot be identified in hospital data (wherein injury data are available), while injury data are not available in police-reported road crash data (wherein vehicle rollovers can be identified).

While the incidence of rollover fatalities has been reported to be substantial, vehicle performance testing for rollover crashworthiness in the Australasian New Car Assessment Program (ANCAP) is not scheduled to begin until 2014 [4]. The vehicle performance will be measured with a quasi-static roof crush test; however such a test has been noted as insufficient in replicating real-world crashes since the dynamic response of the roof, the kinematics of the occupant and the performance of the vehicles' safety features such as side and curtain airbags are not assessed [5]. In an effort to improve the understanding and assessment of the rollover performance of vehicles, a consortium of university and industry partners in both Australia and the United States (US) established a research program to develop a dynamic rollover occupant protection (DROP) crash test protocol [6]. Aside from the possible application of a consumer new car assessment protocol, a valid rollover crash test protocol will be an important research tool for understanding injury potential in rollover crashes, developing occupant protection systems, and thereby assisting in reducing road trauma related to this crash mode.

An important step in the development of a protocol is the identification of an Anthropomorphic Test Device (ATD) capable of replicating the injury mechanisms, for which accurate real-world data of relevant injury mechanisms are required. Due to the aforementioned difficulty of sourcing such detailed rollover crash data retrospectively in Australia, the authors previously used data from the US National Automotive Sampling System (NASS) Crashworthiness Data System (CDS). Rollover crash occupants relevant to the DROP protocol were identified, being contained (not ejected) and restrained (wearing a seatbelt) occupants in single-vehicle rollover crashes where no impacts with objects occurred either before, during or after the rollover. The major injury mechanisms were identified in these studies for the head [7], spine [8] and thorax [9]. Research is currently ongoing with regards to an appropriate ATD and DROP protocol that is capable of replicating these injury mechanisms, using a dynamic test apparatus that has been commissioned at the NSW CrashLab (UNSW Jordan Rollover System) [5,6]. Similar apparatuses have been established in the US at the Center for Injury Research [10] and the University of Virginia [11].

An important consideration for Australian researchers and ANCAP is that the injury mechanisms identified from US data are relevant to Australian conditions. The aim of the present study is to establish similarities between patterns of serious injury to the head, spine and thorax between Australia and the US, such that the lessons learned with regards to injury mechanisms, test protocols and vehicle performance requirements may be shared and used to improve vehicle rollover crashworthiness in both countries. A retrospective study of linked police-reported road crash and hospitalisation data identified occupants of rollover crashes and the injuries sustained. The characteristics of general rollover crashes (termed 'rollover crashes') were established in order to describe the overall rollover crash problem in NSW. A subset of occupants in these crashes were then identified that were seat-belted, non-ejected and in rollovers with no additional impacts (termed 'pure rollovers'). These are occupants specifically relevant to rollover crash testing and their injury patterns may be directly compared with the US studies [7-9], which only considered such occupants. Implications for rollover crash testing in Australia are discussed.

Methods

Data collections

The Admitted Patient Data Collection (APDC) includes information on all inpatient admissions from all public and private hospitals, private day procedures, and public psychiatric hospitals in NSW. The APDC contains information on patient demographics, source of referral, diagnoses, external cause(s), separation type and clinical procedures. Diagnoses and external cause codes are classified using the International Classification of Diseases, 10th Revision, Australian Modification (ICD-10-AM) [12]. Ethics approval was obtained from the NSW Population and Health Services Research Ethics Committee and was ratified by the UNSW Human Research Ethics Committee.

The CrashLink data collection contains information on all police-reported road traffic crashes where a person was unintentionally fatally or non-fatally injured, or at least one motor vehicle was towed away and the incident occurred on a public road in NSW. Information pertaining to the crash and conditions at the incident site, the traffic unit or vehicle, and the vehicle controller and any casualties resulting from the crash are recorded. Each individual is identified as being non-injured, injured or killed (died within 30 days). Data were extracted for occupants of passenger vehicles (car/4WD/utility/van/light truck) in crashes for which the number of traffic units involved was one, the first impact type was identified as a vehicle rollover and the occupant was identified as either injured or killed. These occupants are hereafter termed ‘rollover casualties’. Contained and restrained occupants in rollovers for which no secondary collisions with objects occurred were identified where the crash record further indicated the occupant was wearing a seatbelt, was not ejected from the vehicle and the first object impacted was null. These occupants are hereafter termed ‘pure rollover casualties’. Data were extracted from both datasets from 1 January 2001 to 31 December 2011. To compare the incidence rate of casualties in the rollover crash mode with those in other modes, data were then extracted in a similar manner for all passenger vehicle crashes.

Data linkage

The APDC was linked to CrashLink by the Centre for Health Record Linkage (CHeReL). The CHeReL uses identifying information (e.g. name, address, date of birth, gender) to create a person project number (PPN), for each unique person identified in the linkage process. The record linkage used probabilistic methods and was conducted using ChoiceMaker software [13]. A successful link of the APDC with CrashLink was defined as when the PPN matched in both data collections, and the admission date in the APDC was on the same or next day as the crash date.

Injury identification

Two types of injury severity were considered; KSI and major injury. KSI refers to rollover casualties that were either killed or seriously injured. A seriously injured casualty was a casualty that was admitted to hospital, as identified by a hospital record that linked to the police-reported road crash record for that individual. Major injury refers to pure rollover casualties that sustained one or more head or spine injuries with an Abbreviated Injury Scale (AIS) score of 2 to 6 (AIS 2+), or thoracic injuries with an AIS score of 3 to 6 (AIS 3+). The major injury analysis was restricted to pure rollover casualties in order to make comparisons with the US data [7-9], which only considered such occupants. The time period for the US studies was 2000 to 2009, and injuries were coded to the AIS [14], thus the Australian injuries had to be converted to the AIS scheme such that severity levels matched. Major injury was identified as AIS 2+ for the head and spine (some skull fractures and vertebral fractures considered as major injury were scored as 2) and AIS 3+ for the thorax (where a score of 3 is the typical definition of a serious injury in the AIS). A map of head, spine and thoracic injuries from the ICD-10-AM to the AIS coding scheme was generated and used to convert the injuries coded in the hospital records (considering only the AIS2+ or AIS3+ injuries described above). This process involved manually identifying the closest AIS injury corresponding to each individual ICD-10-AM injury, for example lung contusion (ICD-10-AM S27.31) was matched to lung contusion NFS (AIS 441402.3). Where insufficient detail was provided, injuries were matched conservatively to the lowest AIS severity level.

Statistical analyses

Descriptive analyses of rollover casualties were performed using various variables available in the police-reported road crash records and shown in Table 1 (shown on page 35). Logistic regression analysis was then performed considering the outcome of KSI, for each variable individually (univariate analysis) and considering all variables (multivariate analysis). The method of purposeful selection was used in order to select the variables for the multivariate logistic regression model [15], where statistical significance and confounding were assessed at the 0.05 and 0.15 levels, respectively.

Results

Rollover crash casualties

A total of 10,876 rollover casualties were identified amongst police-reported road crashes in NSW between 2001 and 2011 (inclusive). Of these, 3,365 (31%) were identified as either killed or seriously injured (KSI), of which 454 were killed. The remaining casualties were either treated at an emergency department and subsequently not admitted to hospital, were treated by a general practitioner or other health professional, or were self-treated. The proportion of rollover casualties that were KSI is compared with other crash modes in Figure 1a, where the rate of KSI in rollovers is greater than the average of 27.4%, while less than the rates for multi-vehicle head-on collisions (43.9%) and single-vehicle fixed object collisions (37.2%). The proportion of total KSI casualties in all crash modes is depicted in Figure 1b, where single-vehicle rollovers accounted for 7.2% of all KSI casualties during the study period (n = 47,380).

The annual number of rollover casualties are plotted in Figure 2, where it is clear that numbers of rollover casualties have decreased substantially over the study period; casualties decreased from 1,197 to 723, KSI casualties decreased from 310 to 229 and fatalities decreased from 49 to 19. The location of rollover crashes resulting in casualties and KSI casualties is presented in Figure 3, where it is clear that rollover casualties predominantly occur in regional areas of NSW. This finding is also highlighted in Table 1 where 85.3% of rollover casualties occurred in rural areas. Of these rural crashes, around three quarters occurred in rural non-urban areas.

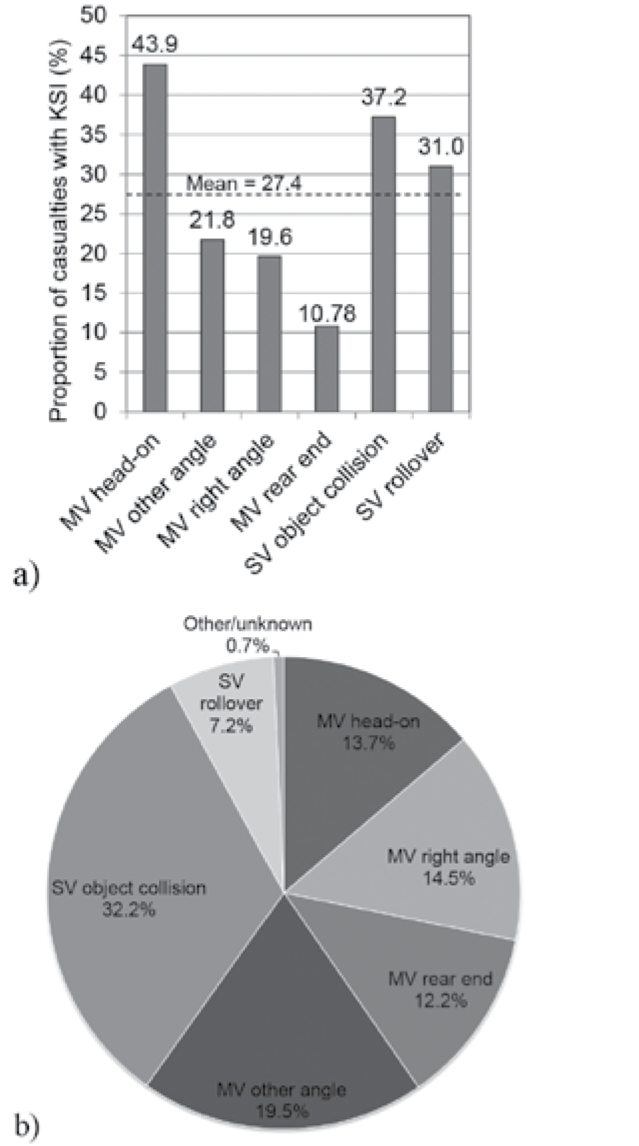

Figure 1. KSI casualties in all passenger vehicle crash modes, NSW 2001-2011. a) KSI rates, b) proportions of all KSI casualties (n = 47,380) (MV = multiple vehicle crashes, SV = single vehicle crashes)

Other descriptive results of note in Table 1 include: casualties were predominantly wearing a seatbelt (86.7%), were not ejected (96%), were seated in the front (87.1%) and were male (56.4%); the crashes predominantly did not involve a secondary object impact (91.6%), were in speed zones of 100km/h or more (63.4%), were in a car (57.9%), occurred in dry conditions (76.5%) in the daytime (59.4%) on a sealed roadway (81.2%), and did not occur at an intersection (91%) nor on highways or freeways (70.3%). The majority of crashes occurred on two-way undivided roads (79.4%). The driver was typically not driving with a BAC greater than 0.05g% (89.9%), while 32.3% of crashes were speeding-related and 10.6% were fatigue-related. The mean vehicle occupant age was 33 years.

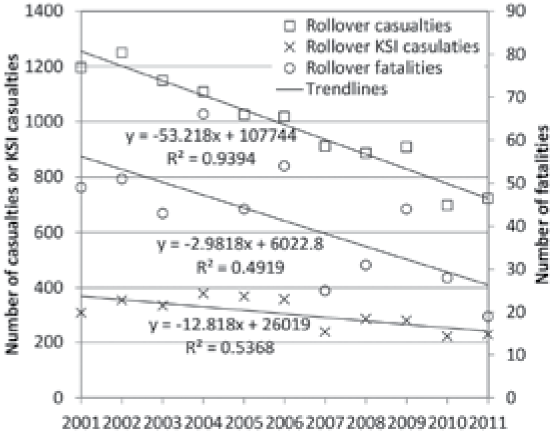

Figure 2. Temporal results, NSW 2001-2011

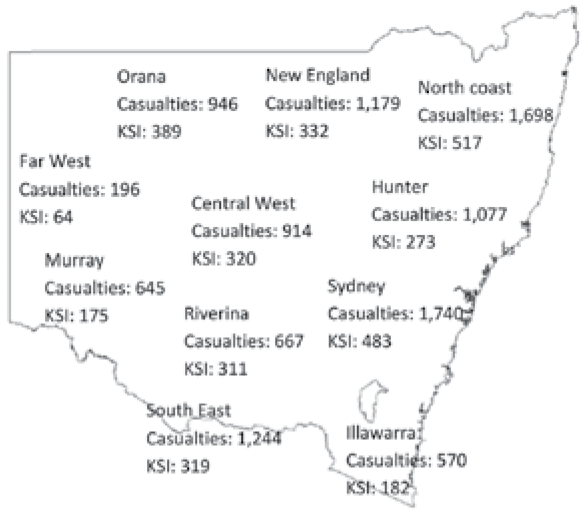

Figure 3. Location of rollover crashes, NSW 2001-2011

Factors involved in the initiation of the rollover crashes involving the 10,876 casualties were identified from the police-reported crash records and are summarised in Figure 4. Around three quarters of rollovers were run-off-road crashes, with the majority departing from the travelling lane (i.e. off the left side of the roadway). Embankments/cuttings were involved in 18.3% of rollover crashes, with ditches/drains/culverts and steep grades/crests also frequently involved, and these factors combined accounted for nearly one half of all rollover crashes. Other factors involved included avoiding an animal or vehicle, loose gravel on the shoulder or a rough surface, the driver was distracted or asleep/drowsy, and a tyre fault/failure.

The multivariate statistical results for the outcome of an occupant sustaining serious or fatal injury (KSI), and conditional upon the occupant being involved in a police-reported rollover crash where the police recorded that they were injured (casualty), are tabulated in Table 1. The results indicate that, assuming all other factors remain the same, the following factors were associated with increased odds of KSI (OR; 95% CI); ejection (3.15; 2.52-3.93), secondary fixed object impacts (1.70; 1.47-1.96), speed zones of 100km/h or more (1.35; 1.14-1.61), occupants aged above the mean of 33 years (1.52; 1.39-1.66), drivers with a BAC over 0.05 (2.22; 1.94-2.54), and crashes that occurred on sealed roadways (1.18; 1.05-1.31) and dry roadways (1.29; 1.16-1.43). Factors that were associated with reduced odds of KSI included wearing a seatbelt (0.56; 0.49-0.64) and crashes that occurred at an intersection (0.78; 0.66-0.93).

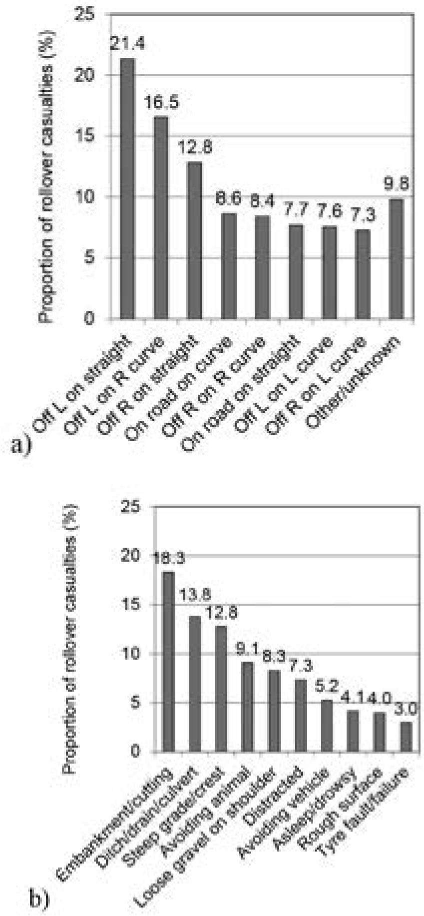

Figure 4. Proportion of rollover casualties amongst; a) rollover initiation locations and b) contributing factors to the rollover initiation (n=10,876), NSW 2001-2011

Pure rollover casualty major injuries and comparison with the US

Of the 3,365 rollover casualties that sustained KSI, 2,204 were identified as pure rollover casualties, and of these 450 sustained one or more major injuries. Of these, 227 pure rollover casualties sustained a total of 285 major head injuries (AIS 2+). Specific major head injuries are summarised in Figure 5a, where concussion and unconsciousness occurred most frequently, followed by fractures to the base of the skull and vault and brain injuries. The major injury results are compared with those identified amongst pure rollover occupants in the US study [7] in Figure 5b, where concussions and unconsciousness were excluded (n = 86 for the present study). It is noted that in the present study the ICD-10-AM code for 'unspecified intracranial injury' was used frequently, while this was not the case in the AIS-coded US study. These cases are included in Figure 5b.

A total of 198 pure rollover casualties sustained 351 major spine injuries (AIS 2+). These were predominantly vertebral fractures, and also included dislocations and spinal cord injuries. The frequency of injuries at the various levels of the spinal column are shown in Figure 6a, where fractures were sustained throughout the column, however predominantly in the lower cervical and upper thoracic spine (C5 to T4), with peaks also at C2 and T11/T12. Dislocations predominantly occurred at the C5/C6 levels, while spinal cord injury occurred in a small number of cases predominantly between C3 and C6. For comparison with the US pure rollover cases [8], the injury types were grouped and injuries to the level T4 were considered (n = 217 for the present study) (Figure 6b).

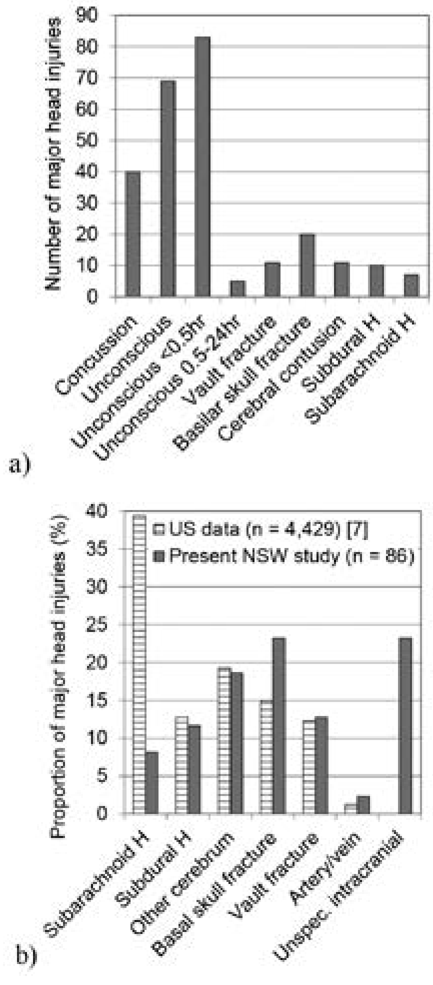

Figure 5. Major head injury in pure rollovers;
a) NSW, 2001-2011 and b) comparison with US data
(excludes concussions and unconsciousness) (H = haemorrhage)

Table 1. Descriptive and multivariate logistic regression results for rollover casualties, NSW 2001-2011

	Total rollover casualties		Rollover casualties not KSI		Rollover casualties KSI		Multivariate logistic regression Outcome = KSI			
	n	%	n	%	n	%	OR	CL_L	CL_U	p
Seatbelted	9431	86.7	6759	90.0	2672	79.4	0.56	0.49	0.64	<0.01
Not	1445	13.3	752	10.0	693	20.6	1			
Ejected	431	4.0	146	1.9	285	8.5	3.15	2.52	3.93	<0.01
Not	10445	96.0	7365	98.1	3080	91.5	1			
FO impact	918	8.4	534	7.1	384	11.4	1.70	1.47	1.96	<0.01
Not	9958	91.6	6977	92.9	2981	88.6	1			
Speed limit - 0-50	891	8.2	646	8.6	245	7.3	1			
60	1194	11.0	868	11.6	326	9.7				
70-90	1892	17.4	1365	18.2	527	15.7				
100-110	6899	63.4	4632	61.7	2267	67.4	1.35	1.14	1.61	<0.01
Vehicle - car	6297	57.9	4468	59.5	1829	54.4				
4WD	1772	16.3	1205	16.0	567	16.8				
light truck	2134	19.6	1390	18.5	744	22.1				
Ute	270	2.5	185	2.5	85	2.5				
Van	403	3.7	263	3.5	140	4.2				
Age > mean	4030	37.1	2583	34.4	1447	43.0	1.52	1.39	1.66	<0.01
≤ mean	6846	62.9	4928	65.6	1918	57.0	1			
Infringement	2	0.0	2	0.0	0	0.0				
Not	10874	100.0	7509	100.0	3365	100.0				
BAC ≥ 0.05	1095	10.1	540	7.2	555	16.5	2.22	1.94	2.54	<0.01
< 0.05	9781	89.9	6971	92.8	2810	83.5	1			
Front seated	9478	87.1	6549	87.2	2929	87.0				
Not	1398	12.9	962	12.8	436	13.0				
Male	6133	56.4	4080	54.3	2053	61.0				
Female	4743	43.6	3431	45.7	1312	39.0				
Intersection	975	9.0	721	9.6	254	7.5	0.78	0.66	0.93	0.01
Not	9901	91.0	6790	90.4	3111	92.5	1			
Metropolitan	1604	14.7	1162	15.5	442	13.1				
Rural	9272	85.3	6349	84.5	2923	86.9				
Curve	5508	50.6	3866	51.5	1642	48.8				
Not	5368	49.4	3645	48.5	1723	51.2				
Highway/freeway	3234	29.7	2220	29.6	1014	30.1				
Not	7642	70.3	5291	70.4	2351	69.9				
Sealed roadway	8831	81.2	6064	80.7	2767	82.2	1.18	1.05	1.31	0.01
Not	2045	18.8	1447	19.3	598	17.8	1			
Dry roadway	8322	76.5	5611	74.7	2711	80.6	1.29	1.16	1.43	<0.01
Not	2554	23.5	1900	25.3	654	19.4	1			
Daytime	6456	59.4	4562	60.7	1894	56.3				
Not	4420	40.6	2949	39.3	1471	43.7				

	Total rollover casualties		Rollover casualties not KSI		Rollover casualties KSI		Multivariate logistic regression Outcome = KSI			
	n	%	n	%	n	%	OR	CL_L	CL_U	p
Equipment fail	562	5.2	415	5.5	147	4.4				
Not	10314	94.8	7096	94.5	3218	95.6				
Speeding-related	3510	32.3	2418	32.2	1092	32.5				
Not	7366	67.7	5093	67.8	2273	67.5				
Fatigue-related	1151	10.6	710	9.5	441	13.1	1.24	1.15	1.42	<0.01
Not	9725	89.4	6801	90.5	2924	86.9	1			

KSI = killed or seriously injured (admitted to hospital), OR = odds ratio, CL_L = lower 95% confidence interval, CL_U = upper 95% confidence interval, FO = fixed object, BAC = blood alcohol content

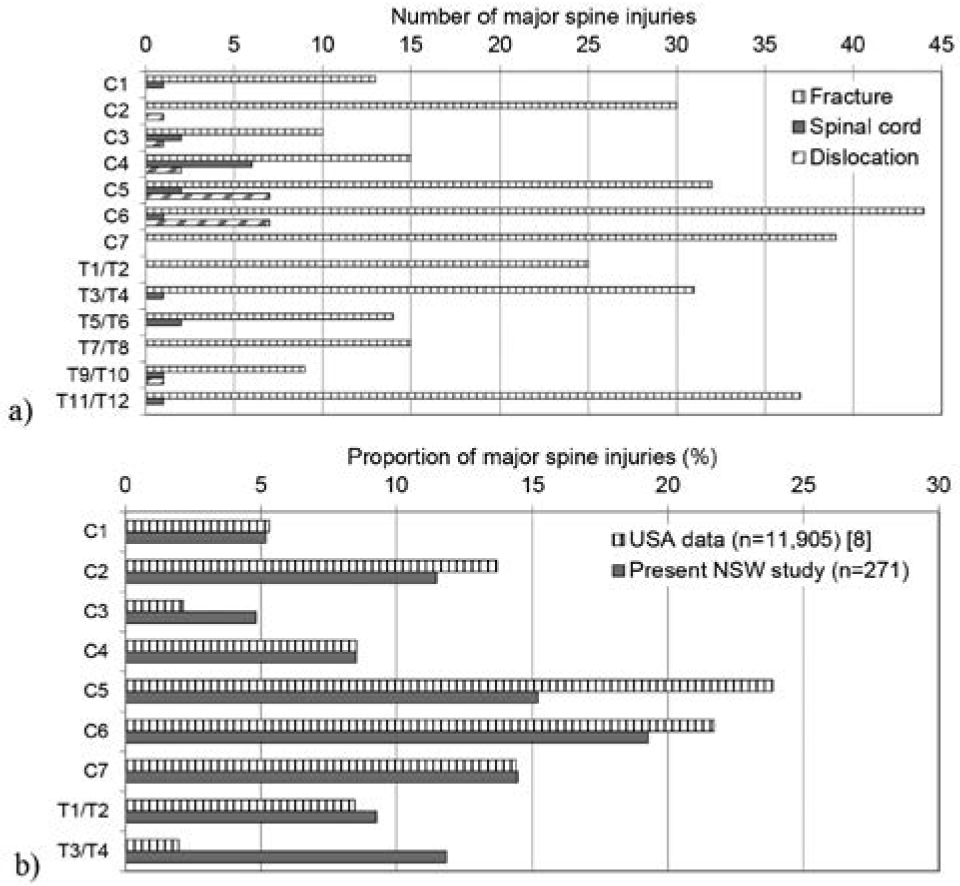

Figure 6. Major spine injury in pure rollovers; a) NSW, 2001-2011 and b) comparison with US data (C# = cervical spine vertebrae, T# = thoracic spine vertebrae)

A total of 86 pure rollover casualties sustained 98 major thoracic injuries (AIS 3+). These were predominantly lung contusions and fractures of the ribs (Figure 7a). The occurrence of contiguous injuries is also shown in Figure 7a, where pneumo/haemo/haemopneumothorax occurred in all cases of lung contusions, while major rib fractures occurred amongst only around one quarter of casualties with lung contusions. The major thoracic injury cases are compared with the US pure rollover cases [9] in Figure 7b.

Discussion

Around 7% of seriously injured passenger vehicle occupants in NSW resulted from rollover crashes during the study period. While this crash mode had a higher proportion of seriously injured occupants than the average of all crash modes, multi-vehicle head-on crashes and single-vehicle fixed object collisions had the highest rates. Around one in

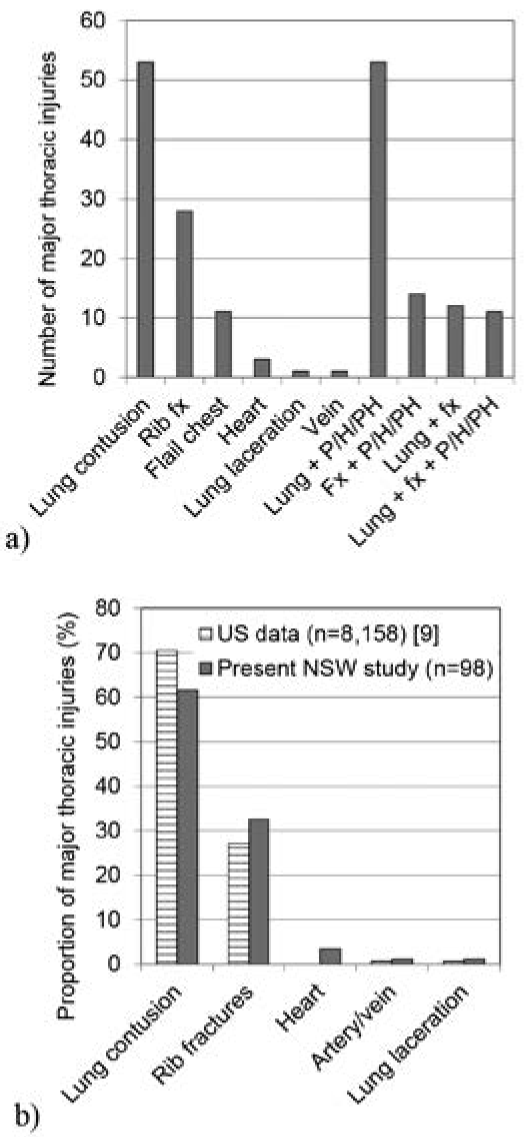

Figure 7. Major thoracic injury in pure rollovers; a) NSW, 2001-2011 and b) comparison with US data (fx = fractures, P/H/PH = pneumo/haemo/haemopneumothorax)

three rollover casualties were seriously injured or killed. These results indicate that while rollover crashes are relatively rare, they are particularly injurious crashes.

It should be noted that these results exclude other crash modes where the crash was initiated by a collision event (eg. with another vehicle or a fixed object), and the vehicle subsequently underwent a rollover event. In such cases the secondary rollover may have contributed to the occupants' injuries, thus the present study under-enumerates rollover-related occupant injuries. These crashes cannot be identified in CrashLink; regardless, in such cases it is very difficult to discern the relative contribution of the different crash modes to the occupants' injuries.

The temporal analysis indicated that the number of rollover casualties in NSW substantially decreased over the study period. This result was true for all levels of injury; casualties, KSI casualties and fatalities. This might result from vehicle improvements such as electronic stability control, which might reduce the incidence of rollovers, and structural and safety improvements such as stronger roofs and side/curtain airbags, which might reduce the incidence or severity of injuries during rollovers. This might also have resulted from improvements in the roadside environment such as shoulder sealing, roadside barriers and other general infrastructure improvements. It is also possible that occupant behaviour may have changed over the study period, such as less people not wearing a seatbelt, driving under the influence of alcohol/drugs and/or speeding.

The analysis of the location of rollover crashes indicated that they predominantly occurred in regional NSW (85.3%), and of these around three quarters occurred in non-urban regional areas. The typical rollover scenario was a vehicle on a two-way undivided road in a non-urban rural location that ran off the road and subsequently underwent a rollover. In nearly one half of cases an inclined surface was involved in the initiation of the rollover, including embankments, cuttings, ditches, drains, culverts, steep grades and crests. These results indicate that rollover is predominantly a regional problem in NSW and occurs infrequently in metropolitan areas. This indicates that roadway countermeasures to reduce rollover-related road trauma should be directed to regional NSW areas, and might include shoulder sealing and roadside barriers near slopes, for example.

The multivariate statistical results indicated that while not wearing a seatbelt, being ejected and secondary fixed object collisions occurred relatively infrequently, they were significantly associated with increased odds of KSI (Table 1). Occupants not wearing a seatbelt undergo large movements relative to the vehicle during rollover events, exposing them to injuries resulting from impacts with the vehicle interior, cargo and other occupants, or being fully or partially ejected from the vehicle. Vehicle ejection provides substantial opportunity for injury from contacts with the roadway and/or being crushed between the vehicle and the roadway. Increased odds of injury from not wearing a seatbelt and/or being ejected during a rollover have also been reported in studies of US data [16, 17]. Similarly, several authors have noted increased risk of injury from secondary fixed object collisions [18, 19].

Other factors associated with increased odds of KSI included increased age, which is a well known physiological result, and drivers who were either fatigued or had a BAC greater than 0.05g%. Fatigue and alcohol use have also been shown to increase the risk of injury in other crash modes [20, 21]. The association of KSI with higher speed zones (100km/h or greater) is likely a result of the fact that vehicles would likely be driving at higher speeds in these zones, resulting in greater crash kinetic energy which is well known to be related to injury outcome [21]. Additionally, sealed and dry roadways were associated with increased odds of KSI, a result which might be related to increased friction of the roadway resulting in a higher initial roll rate and consequently more severe rollover event, and/or an increased deceleration upon ground contact. A similar result was found in studies of US data, where dry roadways were associated with increased odds of major spine [8] and thoracic [9] injuries.

The analysis of major injuries sustained by pure rollover casualties in the head, spine and thorax body regions indicated that the results for Australian casualties closely matched those reported for US pure rollover casualties [7-9]. For the head, brain injury and haemorrhage accounted for the majority of major injuries, with the remaining attributed to fractures of the skull (base and vault). In comparison with the study of head injury in the US [7], a point of difference was in the incidence of subarachnoid haemorrhage. However, in the Australian data a substantial number of cases were coded as 'unspecified intracranial injury' while none were coded as such in the US data, which might account for some of this discrepancy. For the spine, fractures accounted for most of the major injuries and the level of injury correlated well with the US spine injury data [8]. Similarly, correlation of major thoracic injury with the US data [9] was evident, where lung contusions and rib fractures were predominant. In both the Australian and US studies lung contusions typically occurred in the absence of major rib fractures (77% and 69% of lung contusions, respectively). Overall, the differences between the proportions of particular injuries in the Australian and US data were (mean; standard deviation); head injuries (7.2%; 12.2%), spine injuries (3.0%; 3.7%) and thoracic injuries (3.8%; 3.5%); indicating close correlation between the two datasets.

The high level of correlation between major injury sustained by pure rollover casualties in both Australia and the US suggests that the injury mechanisms are similar between these casualties. The much more detailed crash investigations and reconstructions performed by the US NASS CDS afforded detailed studies of injury mechanisms and causation in these studies [7-9]. The spine fractures sustained by US pure rollover casualties resulted from interactions with the vehicle roof structure during vehicle inversion [8]. Detailed analysis of the spine fractures indicated a predominance of vertebral body fractures (typical to compression-based spine trauma), and lamina, pedicle, facet and transverse process fractures typically in the absence of spinous process fractures. These asymmetric fracture patterns indicated compression postero-laterally, which suggested an injury mechanism of compression with combined extension and/or lateral bending. These results led the authors to conclude that the predominant spine injury mechanism in pure rollovers was inverted impact with the roof structure while the head was orientated with lateral bending, and in around one third of cases this impact was further exacerbated by roof intrusion.

Major brain injuries sustained by US pure rollover casualties were predominantly to the cerebrum, including haemorrhages, haematomas and contusions [7]. Basal skull fractures without concomitant vault fractures typically result from impacts to the vertex of the head, producing predominantly axial loading, and were found to involve fracturing of the occipital condoyles without concomitant brain injury in the pure rollover cases. Basal skull fractures with concomitant vault fractures typically result from impacts to the side of the head creating a fracture of the vault that extends to the base of the skull, and were found to involve fracturing of the temporal bones that extended into the middle or anterior fossae in the pure rollover cases. Vault fractures in isolation were located in the frontal and parietal bones. Casualties with vault fractures (with or without basal skull fractures) mostly sustained concomitant brain injury, which led the authors to conclude that the principle brain injury mechanism was lateral and/or frontal loading to the head. Analysis of scalp injuries (as a proxy for head impact locations) indicated that nearly one half of head impacts occurred to the side of the head, while a further one third occurred to the front of the head, and typically resulted from contact with the roof structure or pillars. These results led the authors to conclude that the predominant head injury mechanism in pure rollovers was inverted impact with the roof structure and/or pillars while the head was orientated with lateral bending and/or extension, and in around two thirds of cases this impact was further exacerbated by roof intrusion.

The most common major thoracic injury sustained by US pure rollover casualties was a unilateral lung contusion (often in the absence of rib fractures), located on the side of the occupant adjacent to the vehicle door [9]. Lung contusions are well known to be a rate-dependant injury, and can occur in the absence of rib fractures when the ribs do not compress sufficiently to fracture, however compress the lung dynamically at a rate sufficient to contuse the lung. Major thoracic injuries predominantly resulted from direct contact with the interior door panel (57% of injuries) and in the absence of door intrusion (93% of injuries). These results led the authors to conclude that the predominant thoracic injury mechanism in pure rollovers was a result of the occupant moving laterally into the interior door panel.

These analyses of injury mechanisms led to the identification of several implications with regards to vehicle rollover performance requirements and crash test protocols that replicate and evaluate the potential for major injuries to the head, spine and thorax [7-9]. The head and spine studies identified the possibility of a lateral component to the inverted impact with the roof structure, which has implications for the selection of an appropriate ATD and injury assessment reference values (IARVs). The current neck injury criterion does not assess lateral bending loads [22] while the head injury criterion has not proven a reliable indicator of head injury in lateral impacts [23, 24]. There is a paucity of research on the applicability of the Hybrid III for lateral loads to the head and neck and associated IARVs, and some studies have questioned the validity of the Hybrid III neck for inverted loading [25,26]. Meanwhile, the Hybrid III does not measure lateral deflections of the chest which limits its applicability in assessing the thoracic injury mechanism of lateral impact with the door, in which case a side impact ATD might be more appropriate. However, validation of the head and neck of the EuroSid or WorldSid for the abovementioned inverted loadings has not been reported. Further research on the biofidelity of ATDs and associated IARVs for the identified rollover injury mechanisms is clearly required.

Additionally, roof intrusion was not associated with the thoracic injury mechanism and was a factor in around one third of spine injury and two thirds of head injury [7-9]. Since AIS3+ head, spine and thoracic injuries occur in roughly equal proportions in pure rollovers [7, 9]; roof intrusion is thus associated with only around one third of such injuries. Limiting roof intrusion by itself will therefore not reduce the majority of rollover-related injuries. These results indicate that improvements in vehicle restraints (i.e. seatbelts) and protective devices (i.e. padding, side and curtain air bags, etc.) will be required to assist in the amelioration of injuries. Moreover, assessing a vehicle's rollover crashworthiness using a quasi-static roof crush test will not address the majority of major injuries that occur in rollover crashes. The implications for the development of a rollover occupant protection test protocol are that the kinematics of the occupant (and associated impacts with interior components of the vehicle) and the vehicle performance need to be assessed dynamically, using an appropriately biofidelic ATD. Given the apparent correlation between injury patterns and mechanisms between rollover casualties in Australia and the US, it is reasonable to assume that such considerations are equally valid in both countries, and the development and implementation of a rollover crash test apparatus and protocol should proceed concurrently.

Limitations

There are a number of limitations of the study that should be noted. Not all crashes are reported to police, thus the casualties examined in the present study are under-enumerated and are a sample of all rollover casualties that occurred during the period. There may be discrepancies between the manner in which different police jurisdictions record different particulars of a crash. The designation of injured (casualty) in the police-reported crash data is subjective and not clearly defined, and is based on the discretion of the reporting police officer. The statistical method used determines associations with injury; however, it does not conclusively imply causality. There may be additional variables that are associated with injury that were not available in the data, of which notable examples include the vehicle speed and number of rolls. The probabilistic linkage method is not without possible linkage errors, however false positives and false negatives were estimated to be 0.4% and 0.5%, respectively. The sample sizes between the Australian and US data were substantially different, which reflects the substantially larger road user and rollover crash populations in the US.

Conclusions

This study identified 10,876 rollover casualties in NSW between 2001 and 2011, of which around one in three were seriously injured or killed. Rollover has been identified as primarily a regional problem in NSW, where casualties typically occurred on two-way undivided roadways in rural non-urban areas. Patterns of major injury to the head, spine and thorax were closely correlated between the present study and those of US data. Presuming this also indicates a correlation between injury mechanisms and causation, this suggests that strategies to reduce rollover-related road trauma may be aligned between the two countries. This includes techniques to measure and improve vehicle performance related to rollover, including the establishment of a dynamic rollover crash test protocol. Several recommendations for such a protocol have been identified and discussed, and it is envisaged that the development and implementation of a valid dynamic rollover crash test will help reduce road trauma related to this injurious crash mode.

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Abbreviations

AIS – Abbreviated Injury Scale

ANCAP - Australasian New Car Assessment Program

APDC - Admitted Patient Data Collection

ATD - Anthropomorphic Test Device

BAC – Blood Alcohol Content

DROP - Dynamic Rollover Occupant Protection

IARV - Injury Assessment Reference Value

ICD-10-AM - International Classification of Diseases, 10th Revision, Australian Modification

KSI – Killed or Seriously Injured

NASS CDS - US National Automotive Sampling System, Crashworthiness Data System

PPN – Person Project Number

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