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Thoracic Injury Mechanisms in Rollover Crashes

J. R. Kerrigan, J. H. Ash, D. Bose, M. Sochor, J. Crandall, J. Funk, J. Cormier, S. Manoogian, S. Ridella, M. Scarboro, S. Summers

This paper has not been screened for accuracy nor refereed by any body of scientific peers and should not be referenced in the open literature.

ABSTRACT

The goal of this study was to identify and provide a detailed description of thoracic injury mechanisms, loading directions, and injury sources for rollover crash-involved occupants. As part of a larger effort to investigate dynamic rollover crash testing as a means of evaluating vehicle-specific occupant injury risk, the types, mechanisms and sources of thoracic injuries need to be well defined to provide metrics for evaluating injury risk in rollover crashes and computational simulations and to evaluate the ability of existing injury criteria to predict thoracic injuries. The thorax was found to be the most commonly injured body region, at the AIS 3+ level, for belted, not-ejected occupants involved in rollover crashes where the rollover was the most harmful event. Thoracic injuries are typically the result of direct lateral (impact) loading to the thorax by the interior of the vehicle, which results from when the right or left sides of the vehicle impact the ground during the crash.

INTRODUCTION

In 2008, 22% of fatal crashes involved rollover, whereas only 2.7% of all crashes involved rollover. When considering passenger cars and light trucks only, 36% of all vehicle occupant fatalities occurred in the only 3% of vehicle crashes that involved rollover. Despite the plethora of rollover crash injury research and testing that has been performed, there is still no dynamic crashworthiness assessment that is widely accepted or used (Chou et al. 2005). This study is part of a larger study aimed at determining whether a dynamic assessment of vehicle crashworthiness in rollover crashes can be feasibly made by measuring occupant injury risk with an ATD in a controlled, laboratory test. In this effort, to identify targets for biofidelity assessment and injury risk prediction, the most common injuries and injury mechanisms for rollover-involved occupants need to be clearly identified.

Thoracic trauma is the principle causative factor in 30% of road traffic fatalities (Mulligan et al. 1994). However, for rollover crashes, spinal injuries receive more focus from the research community due to the incidence of associated spinal cord damage. Despite the well-documented frequency of and risks associated with spinal injuries in rollover crash-involved occupants, the frequency and severity of thoracic injuries is often overlooked. Digges et al. (2005) showed high frequency and HARM associated with injuries to the trunk (including thoracic and abdominal injuries) in rollover occupants, but offered little discussion of the mechanisms, sources and conditions surrounding the incidence of thoracic injuries.

The aim of the current study is to investigate thoracic injury in rollover to a greater depth by (1) performing an additional NASS/CDS analysis aimed at identifying the crash, vehicle and occupant factors that influence thoracic injury including the occurrence of injuries to other body regions, and (2) analyzing in-depth crash investigation cases to identify specific sources and mechanisms of crashes. This study is broken up into three major parts. The first part was aimed at identification of the frequency of thoracic injuries relative to injuries to other body regions by examination of injury patterns using a population-based dataset. The second part of the study was to examine the specific injuries to the thorax to determine the targeted injuries for the detailed mechanism/direction/source analysis. The last part of the study involved identification of rollover crash cases from the CIREN database, biomechanical analysis of the thoracic injuries sustained, and a detailed reporting of the results.

METHODS

Injury Patterns Analysis

The National Highway Traffic Safety Administration's (NHTSA) National Automotive Sampling System Crashworthiness Data System (NASS CDS) database was queried to identify rollover crash cases for this analysis. NASS CDS provides nationally representative data regarding motor vehicle crashes based on a weighted annual sample of approximately 5,000 police reported tow-away crashes (NHTSA, 2008). The dataset includes detailed information about the occupant, vehicle, crash kinematics, restraint usage and injury outcome including incidence of fatality and injury severity codes for each individual injury based on the 1990 Abbreviated Injury Scale (AIS) for cases before 1998, and the 1998 AIS for cases 1998 and later (AAAM, 1990). The selection criterion for the sampled cases was that:

- the rollover crash must have occurred between 1995 and 2008;
- the rollover crash must involve at least one quarter turn of lateral roll and come to a rest within 16 or less quarter turns. End-over-end rollovers (rotation about vehicle pitch axis) were excluded in the selection due to their low frequency (< 1% of all rollover crashes) and substantially different kinematics compared to the lateral rollovers.
- The crash must involve adult (>=16 years) occupants in the first three seating rows only;
- and the occupant must be properly belted,
- and non-ejected (no complete or partial ejections were included),
- and the occupant must have sustained at least one AIS 2+ injury.
- Additionally the vehicle must have been of the type car, SUV, light van or pick-up truck (with mass less than 5000 kg),
- and the crash could have involved multiple events, but only cases where the highest severity event was coded as non-collision overturn were included.

The survey selection criteria yielded 713 rollover cases, representing approximately 119,581 weighted samples at the national level available for the retrospective descriptive analysis.

Specific Injury Identification

Ridella et al. (2009) presented the results of a different analysis of the NASS-CDS database aimed at determining the distributions of specific injury types in rollover crashes for belted, non-ejected, occupants. Cases describing crashes that occurred between 2003 and 2007 involving adult, front-row, outboard, non-ejected occupants involved in rollovers of eight quarter turns or less were used for the study. The results included injury distributions for both pure (single event) rollovers and multi-event rollover crashes. Specifically, the study presented, the top five most frequent AIS 3+ thoracic injuries sustained by occupants meeting the criteria in pure rollover crashes. The current study utilized the dataset developed for the Ridella et al. (2009) study to determine the top 10 most frequent AIS 3+ thoracic injuries for occupants in pure rollover crashes. Further, the frequency of each injury is presented as a proportion of all of the top 10 most frequent AIS 3+ thoracic injuries.

In-Depth Crash Case Analysis

This portion of the study was performed using information drawn from the NHTSA-sponsored Crash Injury Research and Engineering Network (CIREN) database. This database contains information collected from approximately 4,000 crashes of late model year vehicles where at least one serious (AIS => 3) or two moderate (AIS = 2) injuries occurred to one of the vehicle occupants. Other selection criteria are employed, but the crashes are selected based upon injury severity of the occupant. A complete list of CIREN inclusion criteria may be found in the United States Federal Register (2004). For each case, the following information is compiled to construct the case file:

- Crash Information-scene diagram, scene photos, crash description (from a crash reconstruction analysis);
- Occupant Information-anthropometry, injuries (with AIS codes), injury photographs, occupant-to-vehicle contacts (with certainty level);
- Vehicle Information-make, model, year, interior and exterior photographs, deformation measurements (measured as intrusions into the occupant compartment) and directions,
- Medical Records: radiological images and reports, clinical progress, notes during treatment, operating room reports, clinical photographs, occupant interviews, discharge reports, one year follow-up recovery assessment and detailed descriptions of the injuries.

In the current study, the CIREN database was queried for cases that involved belted occupants in single-event rollover crashes involving 8 quarter turns (two complete rolls) or less. A total of 41 cases were identified and reviewed. The review process consisted of a group of biomechanical engineers, accident reconstruction experts and physicians reviewing the available case data and identifying qualifying injuries, which were defined as AIS 2 fractures and AIS 3+ injuries to the head, spine and thorax (Figure 1). For each case, the review team used the case information to identify the vehicle kinematics during the crash and the certainty with which those kinematics could be determined. Then the vehicle kinematics were used to identify the occupant kinematics and the certainty with which those kinematics could be determined. Then the case information was used with the vehicle and occupant kinematics to identify the particular injury causation scenario for each of the AIS 3+ injuries to the thorax including the perceived loading direction, injury mechanism, rollover phase in which the injury was assumed to have occurred, and any other details associated with the injury. Additionally, using all of the case information, the likelihood that the occupant was partially ejected from the vehicle during the rollover crash was determined.

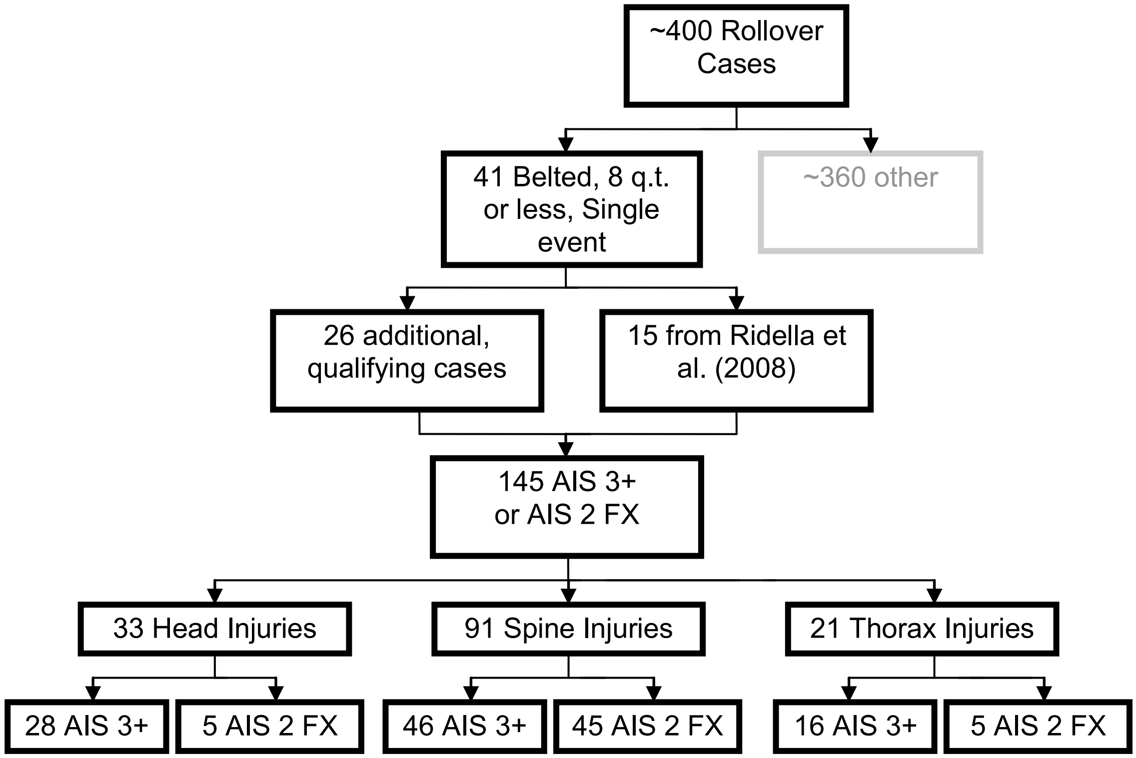

Figure 1. Tree diagram depicting the numbers of injuries in each category from the CIREN cases reviewed.

RESULTS AND DISCUSSION

The NASS-CDS database was queried for rollover (at least one quarter turn) crashes occurring between 1995 and 2008, with less than 16 quarter turns, where the driver was at least 16 years old, belted, not-ejected, and sustained at least one AIS 2+ injury, and the vehicle was a passenger car, light truck, SUV or van. After grouping injuries by body region according to the first digit of their AIS codes, the data showed that the thorax ranked the third most commonly injured body region by number of AIS 2+ injuries (4th most common counting unweighted cases). However, when considering only AIS 3+ injuries (35% of all MAIS 2+ cases were MAIS 3+), occupants were found to be most likely to sustain a thoracic injury (16% of AIS 2+ cases), with the proportion of AIS 3+ thoracic injuries greater than the sum of AIS 3+ head and AIS 3+ spine injuries (Table 1). The data showed thoracic injuries to be more severe overall: 59% of all AIS 2+ thoracic injuries are AIS 3+, compared to 47% for spine injuries and 33% for head injuries. Furthermore, when considering patterns of injuries at the AIS 3+ level, the most common pattern of injuries was AIS 3+ injuries to the thorax only (13.3% of all MAIS 2+ cases), without injuries at the AIS 3+ level to other body regions. When considering HARM (injury cost weighting factor applied to each AIS level), Digges et al. (2005) found that trunk injuries accounted for 30% of AIS 3+HARM (35% and 12% for head and spine injuries, respectively) for belted occupants involved in rollovers (NASS 1995-2003). However, Digges did not divide trunk injuries into thoracic and abdominal injuries. Digges et al. (2005) also found that trunk injury HARM was greater for occupants on the leading or near-side relative to the rollover direction, whereas for injuries to the head, spine, and extremities HARM was greater for the far-side occupants.

Using the data from Ridella et al. (2009), the most common thoracic injuries are lung contusions with unilateral and bilateral contusions accounting for 40% and 34% of the 10 most common injuries, respectively (Table 2). After contusions, rib fractures with hemothoraces or pneumothoraces are the second most common injuries (16.9% of the top 10). The remaining injuries involve the lung, multiple rib fractures and hemothoraces/pneumothoraces.

Table 1. Proportion (weighted) of all MAIS 2+ cases belted, not-ejected occupants in rollover crashes with the listed injury and raw (unweighed) sample sizes.

Injury	Raw Sample Size	Proportion Mean	95 % LB	95 % UB	Injury	Raw Sample Size	Proportion Mean	95 % LB	95 % UB
Thorax AIS 2+	177	27.9	13.2	42.6	**Thorax AIS 3+**	124	16.4	1.9	31
Head AIS 2+	309	40.3	25.2	55.3	**Head AIS 3+**	103	6.9	2.7	11.1
Spine AIS 2+	195	18.4	10	26.8	**Spine AIS 3+**	92	7.2	1.9	12.4
Up. Ext AIS 2+	230	28.8	21.3	36.3	**Up. Ext. AIS 3+**	63	6.7	3.5	9.8

Table 2. Top 10 most frequent AIS 3+ thoracic injuries sustained by adult, front-row, outboard, non-ejected occupants involved in single-event rollover crashes. Frequency is the percentage of top 10 AIS 3+ thoracic injuries (sums to 100%).

Rank	Code	Description	Frequency
1	441406.3	Lung contusion unilateral with or without hemo-/pneumothorax	40.0%
2	441410.4	Lung contusion bilateral with or without hemo-/pneumothorax	34.1%
3	450222.3	Rib cage fracture 2-3 ribs any location with hemo-/pneumothorax	6.7%
4	450252.4	Rib cage fracture open/displaced/comminuted with hemo-/pneumothorax	5.9%
5	450232.4	Rib cage fracture >3 ribs on one side and <4 ribs on either side with hemo-/pneumothorax	4.3%
6	441499.3	Lung NFS	3.6%
7	450230.3	Rib cage fracture >3 ribs on one side and <4 ribs on either side	2.3%
8	442202.3	Thoracic cavity injury with hemo-/pneumothorax	1.3%
9	441456.5	Lung laceration bilateral with or without hemo-/pneumothorax with blood loss > 20% by volume	1.0%
10	450266.5	Rib cage flail chest bilateral with or without lung contusion (OIS Grade V)	1.0%

Injury mechanisms, loading directions, and injury sources were investigated by performing a detailed analysis of in-depth crash investigation cases acquired from the Crash Injury Research and Engineering Network (CIREN) database. Of the 41 reviewed cases, 16 AIS 3+ thoracic injuries were found in 12 of the case occupants (four occupants had two injuries). Since 28 and 46 AIS 3+ head and spine injuries were also found in the 41 case set, it is clear that the distribution of injuries between the NASS and CIREN databases for rollover-involved occupants are not the same. However, since CIREN and NASS databases do not have the same case selection criteria, and the CIREN database is not a nationally representative dataset, the representativeness of the cases from the CIREN database was evaluated by comparing the 16 CIREN case injuries to the 10 most common injuries (from NASS) reported in rollover crashes (Table 3). Eleven of the injuries were AIS 3, four were AIS 4 and one was an AIS 5. Eleven of the 16 injuries sustained by the CIREN case occupants were represented by the top 10 most frequent AIS 3+ thoracic injuries to rollover-involved occupants. The other 5 injuries were very similar to injuries ranking in the top 10: one occupant sustained the lung laceration without a hemo-/pneumothorax, which is a similar injury to injury 6 and injury 9, two occupants sustained 1 rib fracture with a pneumothorax (incidentally, only pneumothoraces and no hemothoraces were found among the CIREN population), which is similar to injuries 3-5 and 8, and two occupants sustained more than three rib fractures on each side (with and without a pneumothorax), which are similar to injuries 5, 7 and 10. While the representativeness of the CIREN cases cannot be verified, the types of injuries in the CIREN cases are the same as those of the NASS population.

Table 3. CIREN Comparison of top 10 most frequent thoracic injuries (Table 2) with injuries seen in the CIREN cases.

NASS Rank	AIS Code	Detail	# of CIREN Injuries
1	441406.3	Lung contusion unilateral with or without hemo-/pneumothorax	6
2	441410.4	Lung contusion bilateral with or without hemo-/pneumothorax	1
3	450222.3	Rib cage fracture 2-3 ribs any location with hemo-/pneumothorax	0
4	450252.4	Rib cage fracture open/displaced/comminuted with hemo-/pneumothorax	0
5	450232.4	Rib cage fracture >3 ribs on one side and <4 ribs on either side with hemo-/pneumothorax	2
6	441499.3	Lung NFS	0
7	450230.3	Rib cage fracture >3 ribs on one side and <4 ribs on either side	2
8	442202.3	Thoracic cavity injury with hemo-/pneumothorax	0
9	441456.5	Lung laceration bilateral with or without hemo-/pneumothorax with blood loss > 20% by volume	0
10	450266.5	Rib cage flail chest bilateral flaill with or without lung contusion	0
-	441414.3	Lung Laceration NFS without hemo-/pneumothorax	1
-	450214.3	Rib cage fracture 1 rib with hemo-/pneumothorax	2
-	450240.4	Rib Cage Fracture > 3 ribs on each of two sides, with stable chest or NFS	1
-	450242.5	Rib cage fracture >3 ribs on each of two sides, with hemo-/pneumothorax	1

The twelve occupants in the CIREN cases varied in age from 18-75, in stature from 1.57 m to 1.88 m, in mass from 61 kg to 130 kg, and four were female (Table 4). Nine of the occupants were drivers, two were right front passengers and one was seated on the right side of the second row. Six of the occupants were in SUVs, one was in a truck, and five were in sedans. Half of the occupants were involved in far-side rollovers, with seven of the 12 cases involving two roof impacts, and the other five only had one roof impact.

Considering the rollover crash kinematics, one vehicle rolled over into an embankment, while in two cases the vehicle drove up a roadside embankment and then rolled back down (Table 5). In two cases, the vehicles tripped and landed on the near-side roof rail, and in the other five cases, the vehicle sustained a high energy roll with one or more lateral impacts to the vehicle. Two of the crashes occurred in the rain, one occurred on a snowy day, but the other 9 occurred in clear weather conditions.

Eleven of the 12 occupants' injuries were the result of direct lateral loading of the thorax, however in four of the cases, the loading was applied obliquely from the anterior or posterior side (Table 6a and Table 6b). In one case (number 9), it appeared as though the occupant sustained a thoracic injury due to belt loading, which resulted when the front left corner of the vehicle made contact with the ground causing the occupant's frontward/outboard kinematics. In half of the cases, the injury was sourced to contact with the door panel, with two cases sourced to armrest, two cases sourced to the B-pillar, one case sourced to the center console and one case sourced to the belt. None of the occupants under age 40 sustained rib fractures (n=5), except the occupant in case 2, who sustained some of the most severe injuries of the group. All of the occupants over 40 sustained rib fractures. Five of the occupants' most severe injuries were thoracic injuries, whereas four of the occupants sustained more severe injuries to the cervical or thoracic spine, two of the occupants sustained head/brain injuries as their most severe injuries, and one occupant sustained a series of severe upper extremity injuries (due to partial ejection). Partial ejection was found likely to have occurred in three of the cases, possible in four cases, doubtful in two cases, and no evidence of partial ejection was found in three of the cases. Evidence for partial ejection included broken side glass at the occupant's seating position with upper extremity or head injuries involving severe abrasions, lacerations, or when debris was found in the injury. In most cases, the injury could be sourced with certainty to a single impact (one particular quarter turn), but in four of the cases certainty of the particular impact in which the injury occurred could not be achieved.

Table 4. CIREN case information pertaining to the occupant

#	CIREN ID	Height [m]	Weight [kg]	Age	Gen.	Make	Model	Year	Occ. Pos.	Roll Dir.	Near/ Far	Quarter Turns
1	103304	1.8	82	76	M	Chev-rolet	Impala	2004	R Fr. Pass.	L	Far	6
2	100112055	1.57	68	34	F	Ford	Taurus	2000	Drv.	R	Far	8
3	590144150	1.85	77	26	M	Honda	Element	2004	Drv.	R	Far	8
4	852177768	1.8	77	28	M	Ford	F150 Super-Crew	2008	Drv.	R	Far	8
5	591155321	1.6	113	75	F	Nissan	Altima	2008	R. Fr. Pass.	L	Far	2
6	965066489	1.73	61	18	M	Jeep	Liberty	2002	Drv.	R	Far	6
7	138319	1.75	82	64	M	Volvo	C70 Conv.	2004	Drv.	L	Near	4
8	160135188	1.88	130	63	M	Ford	Explorer	2005	Drv.	L	Near	4
9	286035678	1.82	70	35	M	Honda	Accord	2003	Drv.	L	Near	2
10	378083996	1.65	69	30	F	Chev-rolet	Trail-blaizer	2003	Drv.	L	Near	8
11	591153886	1.75	83	50	M	Ford	Explorer Sport-Trac	2004	Drv.	L	Near	7
12	852124349	1.57	72	57	F	Chev-rolet	Sub-urban	2006	R 2nd Row	R	Near	4

Table 5. CIREN case information pertaining to the crash.

#	QT	Roll Dir.	Yaw	Cond.	Pre-Roll Vehicle Kinematics	Roll Kinematics	Crash Character
1	6	L	Clock	Day/ Rain	Begins clockwise yaw to keep vehicle in road, but slides into median and trips at access road, down and then up to trip at access road	One contact with passenger side roof rail, and most deformation at vehicle rear…assuming pitch causes rearward/outboard kinematics of passenger	Footballing causes rear loading on QT3
2	8	R	Counter Clock	Day/ Clear	Yaws into median grass, down hill, trips in median, rolls up smaller hill onto road on other side	Roof Tented in Middle, which looks like flat landings on both roof rails that include top half of door. Probably misses roof and lands at 200+ degrees on first roll (or on second)	Massive roof/door to ground impact in high energy roll
3	8	R	Counter Clock	Dark/ Dry	Leaves Road to left, yaws and trips on gravel berm on relatively flat ground	Very high intrusion on center of roof. Roll direction is not clear from vehicle, driver a-pillar def suggests far side roll, head contact on left/pos side…not so much frontal	High energy roll, multiple impacts
4	8	R	Counter Clock	Clear/ Dry	Lost control on off ramp, overcorrected to left, then left road and tripped in level grassy area	Vehicle Deformation suggests one roll across hood, and one on roof	High energy roll, with footballing-multiple lateral impacts
5	2	L	Clock	Clear/ Dry	Drifted to left, steers right to reenter, yaws, slides across road, trips off right side at curb, rolls	Almost no right side damage, possibly rolls to 3, but then back to 2…With a lot of pitch b/c right side damage is on qrtr panel…high energy front left quarter panel hit gives passenger forward and left vector	High energy first impact on left front during trip
6	6	R	Counter Clock	Night/Dry	Steers right, then back left, overcorrecting, causing yaw. Trips and rolls on wide road	At least one roll gets to hood on both sides (PITCH)	High energy roll, one bad impact
7	4	L	Clock	Day/ Snow/ Icy	Loses control in snow and begins yaw…Trips at road edge and rolls into upward embankmentq	Lots of Driver side deformation…Hard Hit 1st QT, Lots of Contacts On Driver Door, and lots of cracking of the door panel	Roll Into Embankment-Hard Impact 1st QT
8	4	L	-	Day/ Dry/ Clear	Drives up steep Right side embankment, and rolls down back to road	Classic Embankment-No great image, but assume hard hit on left side at QT1 (driver door is off)	Up Embankment and Roll Down
9	2	L	-	Wet/ Rainy	Left Road to Right, Steered Up Embankment Rolled Back Down-More like a corkscrew test	On 1st QT, car lands on A-Pillar/RoofRail/Window Area…flattens A-pillar/roof rail into single line…Damage shows frontal component	Up Embankment and Roll Down/Off-Like Corkscrew
10	8	L	Clock	Clear/ Dry	Leaves Road to left, and steers back on, causing yaw, Trip is on road, so is roll…Flat, Straight	Typical Barrel, possibly one roll footballed to the rear of vehicle on the far side	High energy barrel roll-Multiple Impacts
11	7	L	Clock	Clear/ Dry	Steers left, goes off road, steers right to come back on, induces yaw, rolls on road/shoulder	First roll gets the hood, causing matchboxing at the hood, second roll gets the rear (B+Cpillars) giving occupant left+Post (+ some up) vector	High energy roll, with footballing
12	4	R	Counter Clock	Clear/ Dry	Steers right to avoid stopped truck, steers left to reenter road, begins sliding/yawing, trailer goes up embankment, trips/rolls on road	Hard Hit on 1st qt	High energy first qt

Table 6a. CIREN case information pertaining to the occupant injuries (Cases 1-6).

#	Thor. Inj. AIS	Additional Description	Notes	Source	QT	Loading Direction	Other Injuries	Partial Ejection?	Most Sig Inj
1	450230.3 /// 450230.3	Posterolateral R9-R12 Fx /// Ant-R1, Ant-L1, Post L2	Rearward/Outboard kinematics on QT3 /// L2 Assoc. with T2 Trans Proc Fx	Arm Rest/ B-Pillar /// Head-to-Roof	3 /// 2 or 6	Postero-Lateral /// Cspine Extension	Ant/Sup Head Contact on Roof, Axial Compression+Extension of Cspine=C1-C4 Fx + Dens	No-Window Intact	Cspine
2	450242.5 /// 441406.3	L3-5 Post, L6-8, R8, R2-3 Fx /// Left Upper/Lower Contusions, Left Small Pneumo	R8-T8 Comp Fx, L-Upper Ribs through shoulder (w/Clav), right fxs inertia, or roof when left side is out /// Door-to-ground impact causes compression, contusions and Rib Fx	Door/ Ground /// Door/ Ground	2.5 /// 2.5	Lateral /// Lateral	T8-Cord Lac Complete, T4 Comp fx, Cspine Axial/C1 Comp, and C7 Comp, T6,T9, T10 Trans Proc, T7-t8 Comp fx, Left Humerus/Deglov, Pancreatic/Splenic Contusion, BilatMid Clav Fx	Likely: UpExt Fx, Abd. Contus.	Tspine / Cspine
3	441406.3	Right, No Pneumo, no fx YOUNG	Severe Roll, Door-to-Ground impact causes compression, contusion. Possibly second contusion on left	Door	3 or 7	Lateral	C5 facet w/assoc arterial occlus, Right UpExt Abras/Lac, Scalp Abras Left	Possible,	Cspine
4	441406.3	Left, w/ Chest skin abrasion/contusion, no fx YOUNG	Hard impact on door in one of the rolls	Door	3 or 7	Lateral	C7 Facet, C5/6 Disc herniation, Tib Fx Displ, Fib Fx	Possible,	Cspine
5	450240.4	Left Lat 4-7, Right Lat 4-6	Forward and left vector, Contact with Center console causes compression of chest, age and extra thoracic mass are factors...Sternum Contus possibly by belt, Right Side Lung Contusion (possible)	Center Console	1	Lateral, Ant-Lat	Ankle Fx Multiple, Concussion,	Doubtful	Thorax
6	441410.4	No Pneumo, Both Upper w/Chest Contus, no fx YOUNG	Head out window to get avuls, chest loads door hard, High enough energy/compression to get bilat contus	Door	3	Lateral	Cspine Trans Proc (only), Unconscious, Scalp Avuls, Chest/Abd contus	Likely-;scalp lac	Thorax

Table 6b. CIREN case information pertaining to the occupant injuries (Cases 7-12).

#	Thor. Inj. AIS	Additional Description	Notes	Source	QT	Loading Direction	Other Injuries	Partial Ejection?	Most Sig Inj
7	450214.3	Bilateral Pneumothoraces, Ant-Lat L9 Fx	Rib Fx from Arm rest/Door Contact, and Pneumo from high rate of loading	Door	1	Lateral	SDH-Left, SAH-Bilat, SkullFX-LEFT-ANT, Spleen Lac, Adrenal Gland Contusion, Kidney Contus, LEFT Scalp Lac Major, Left Chect Contus	Likely, convertibl e	Brain
8	450214.3	L 10 Fx-Lat/PostLat, Left Small Pneumo	Hard Left side impact with door (they have armrest contact	Door/ Armrest	1	Lateral	Scalp Contu, Up Ext Abras, Fac Abras/Contus	Doubtful	Thorax
9	441406.3	RIGHT Side, no fx YOUNG	His vector is up, left and forward…belt loading causes contusion	Belt	1.5	Anterior, Ant-Lat	Large EDH, Vault Fx, Scalp Lac,	Possible	Brain
10	441406.3	Left Side, Minor, no fx YOUNG	Arm out the door, thorax loaded by door frame	Door	1 or 5	Lateral	Left Up Ext-Disp Sup Hum Fx, Ulna Fx, Wrst Disloc, Elbow Dislc, Abras/Lac, T1 Trans Proc Fx	Possible: Left Arm	Left Up Ext
11	450232.4 /// 441406.3	L Ant 2, L Post-Lat 3-5-Comminuted, Large Left Pneumo /// Left Side	Not sure about Left Ant 2 /// Left Chest Contusion, Scapula Fx	B-Pillar /// B-Pillar	7 /// 7	Postero-Lateral /// Postero-Lateral	Scapula fx	No Evidence	Thorax
12	450232.4 /// 441414.3	R 2-8, Lat and Post, Also R Clav, Pneumo /// result from Rib Fxs, There are Multiple Lacs	Hard 1st QT impact causes chest compression resulting in Fx ///	Door/ Armrest /// Door/ Armrest	1 /// 1	Lateral, Post-Lat /// Lateral, Post-Lat	L2 Compression Fx, L1 SpProc, Right Clav	No Evidence	Thorax

In most cases, the thoracic injuries resulted from direct lateral (or antero-/posterolateral loading) loading to the thorax, however, in some cases the vehicles did not sustain any lateral intrusion to side with the case occupant. In cases 1 and 11, almost no lateral deformation/intrusion to right front passenger and driver's side doors were noted, respectively (Figure 2 and Figure 3). In both cases, the occupants sustained thoracic injuries resulting from posterolateral loading and in both cases the thoracic injuries were sourced to either the B-pillar or arm rest. Occupant contact to this area occurred as a result of lateral impacts to the rear of the vehicle that gave the occupant rearward and outboard trajectories. However, in some cases, the thoracic injuries were combined with significant lateral deformation of the vehicles and intrusion into the occupant compartment (Figure 4 and Figure 5).

Figure 2. Vehicle images from case number 1. Case occupant was right front passenger in a far-side rollover.

Figure 3. Vehicle images from case number 11. Case occupant was the driver in a near-side rollover.

Figure 4. Vehicle images from case number 2. Case occupant was the driver in a far-side rollover.

Figure 5. Vehicle images from case number 7. Case occupant was the driver in a near-side rollover.

The details of one of the 12 cases is included as an example (Figure 6). In case 11, a 50 year old male was the sole occupant of a 2004 Ford Explorer Sport Trac. He was driving on a straight and level five lane concrete roadway in clear conditions during daylight hours. The driver steered left to avoid slowing traffic, steered right to re-enter the road way, lost control, began a clockwise yaw and tripped on the road in a left-side (driver's side) leading seven quarter turn roll (Figure 6-A). Images depicting broken wheel rims on the left side coupled with the deformation of the vehicle roof on the right side (Figure 6-C) confirm that the roll direction was driver's side leading. Furthermore, deformation to both the vehicle front and rear on the left side (without damage to the middle) suggest that the vehicle was in at least 5 quarter turns (two left side impacts) (Figure 3). A rounding off of the roof (Figure 6-C) and the hood (Figure 3) on the right side suggest that the vehicle was pitched forward as it's right side contacted the ground on the second-third-fourth quarter turn. Front right damage, and rear (C-pillar) left damage suggest the vehicle reverse pitched (rear down)as it loaded the driver's side and roof the second time (quarter turns 5 and 6). The severe damage and deep scratches to the C-pillar (Figure 6-B) suggest that this impact was significant. Identified contact between the occupant and the B-pillar (Figure 6-G) is consistent with rearward/outboard occupant kinematics, which are consistent with a significant impact to the C-pillar on the left side. Fractures of the left scapula (Figure 6-D), left-side postero-lateral ribs (Figure 6-E) and a left pneumothorax and lung contusion (Figure 6-F) suggest the occupant sustained postero-lateral loading, likely during the B-pillar impact.

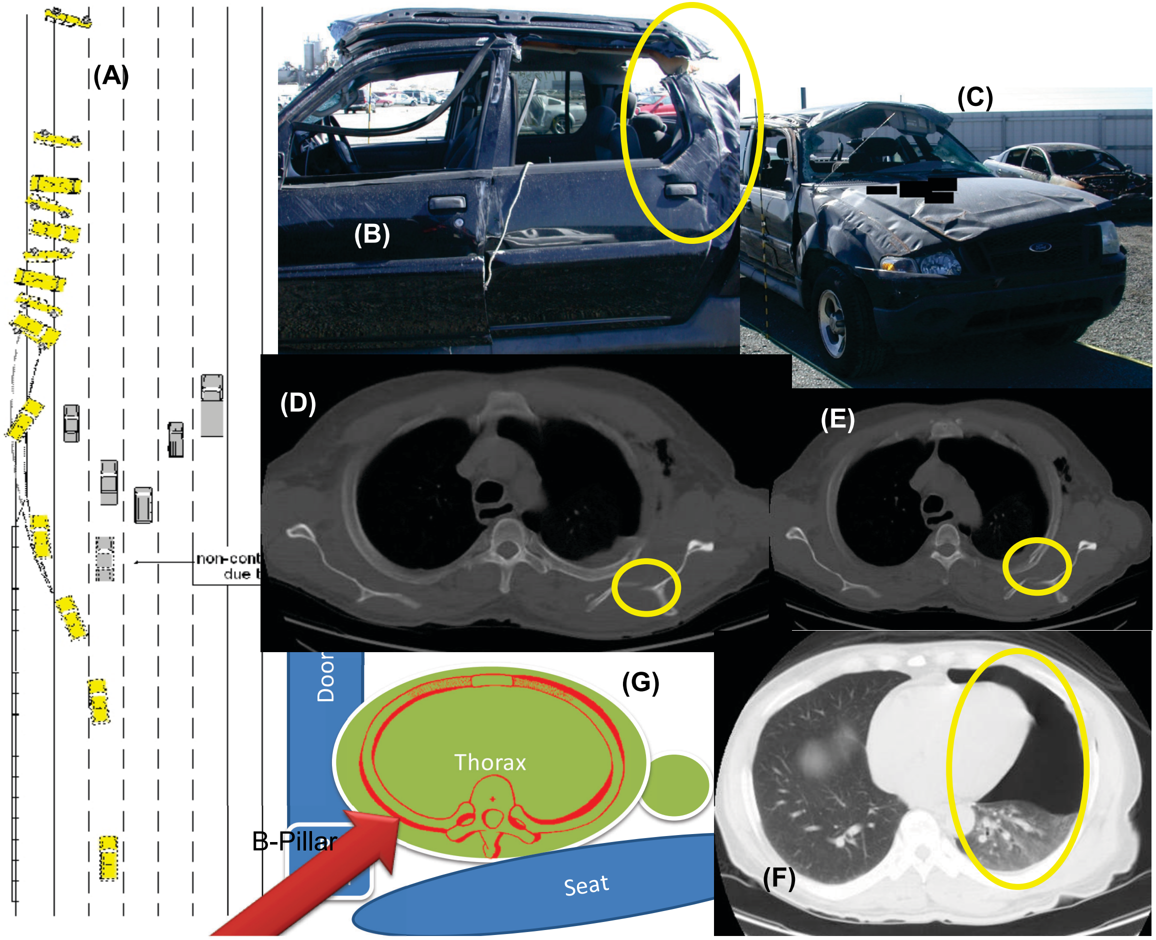

Figure 6-Images and diagrams from case 11. (A) crash reconstruction diagram, (B) lateral view of vehicle showing damage from a lateral impact to the C-pillar, (C) front view of the vehicle showing the sloped roof on the far (passenger) side, (D) CT image showing the left scapula fracture, (E) CT image showing left-side postero-lateral rib fractures, (F) CT image showing a large left pneumothorax and left lung contusion, and (G) a diagram showing how the occupant's thorax loaded the B-pillar during the C-pillar impact.

CONCLUSIONS

This study examined the incidence and types of thoracic injuries sustained by rollover-involved occupants using NASS-CDS, and it examined thoracic injuries and their mechanisms in detail using cases from the CIREN database. Thoracic injuries were found to be the most common AIS 3+ injury for belted not-ejected occupants involved in single-event rollover crashes. Thoracic injuries actually accounted for more AIS 3+ injuries than those to the head and spine combined. Most of the thoracic injuries appear to be due to direct lateral impact loading of the thorax from the vehicle interior either in combination with or in the absence of significant lateral vehicle deformation/intrusion. In most cases, the thoracic injuries are believed to occur when the vehicle impacts the ground on either the right or left sides, and not during roof-to-ground impact. This study highlighted the frequency and severity of thoracic injuries for rollover-involved occupants, and it identified the need for lateral impact biofidelity in computational models and ATDs to be used in evaluating rollover crash injury risk.

REFERENCES

ASSOCIATION FOR THE ADVANCEMENT OF AUTOMOTIVE MEDICINE (AAAM). The abbreviated injury scale, 1990. Association for the Advancement of Automotive Medicine, Des Plaines, IL.

CHOU, C., MCCOY, R., AND LE, J. (2005) A literature review of rollover test methodologies. Int. J. Vehicle Safety 1(1/2/3).

DIGGES K, EIGEN AM, DAHDAH S. (2005) Injury patterns in rollovers by crash severity. Paper 05-0355. Proceedings of the Nineteenth International Technical Conference on the Enhanced Safety of Vehicles (ESV). http://www-nrd.nhtsa.dot.gov/departments/esv/19th/

MULLIGAN, G.W.N., PIZEY, G., LANE, D., ANDERSSON, L., ENGLISH, C., KOHUT, C. (1994) An introduction to the understanding of blunt chest trauma. In Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex, ed. Backaitis, S., pp. 11-36, Society of Automotive Engineers publication PT-45.

NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION (NHTSA). (2008). National Automotive Sampling System Crashworthiness Data System -Analytical user's manual, 2008 File, U.S. Department of Transportation. Available online at http://www.nhtsa.gov/NASS

RIDELLA SA, EIGEN AM, KERRIGAN, JR, CRANDALL J. (2009) An Analysis of Injury Type and Distribution of Belted, Non-Ejected Occupants Involved In Rollover Crashes. Proceedings of the 53rd Annual Conference of the Association for the Advancement of Automotive Medicine (AAAM).

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