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AORTIC INJURIES IN SIDE IMPACTS: A PRELIMINARY ANALYSIS

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ABSTRACT

Injuries to the aorta are among the more serious injuries that result from vehicle impacts, and may often be fatal. This paper examined the incidence of aortic injuries in the US and UK using real-world crash data. The main outcome of interest was the level of risk associated with each principal direction of force for drivers and front seat passengers with respect to sustaining aortic injuries. The results indicate that the risk of sustaining an injury to the aorta is greater for near side crashes than for far side crashes. Further, it is apparent that given a near side crash, the risk of an aortic injury is greater on the left side of the body (and left side of the vehicle) than on the right. It was also found that the delta-V of crashes where occupants sustained an injury to the aorta was considerably higher than crashes where occupants did not sustain aortic injuries. It was speculated that the anatomical asymmetry of the thorax might play a role in the differences seen in injury risk associated with different impact directions. Limitations and further planned research are discussed.

Injuries to the aorta, though infrequent, represent a serious threat to life. The aorta is the main vessel emerging from the heart and supplies blood to the vasculature. A tear or rupture of the aortic wall can result in extensive blood loss, haemorrhagic shock and death. Motor vehicle crashes are seen to be the largest cause of laceration or rupture of the aortic wall. In a study of non-penetrating injuries of the aorta, Parmley et al. (1958) reported that motor vehicle collisions account for approximately 57% percent of such injuries, while airplane crashes and pedestrian impacts account for 16% and 6% of aortic ruptures respectively.

Estimates of the incidence of traumatic ruptures of the aorta (TRA) have largely relied on autopsy studies. In a study of traffic fatalities in the United Kingdom between 1979 and 1981, Newman and Rastogi (1984) found TRA to be the principal cause of death in 17% of cases. In a similar study conducted in Toronto, Canada, between 1991 and 1995, Katyal and colleagues (1997) reported evidence of TRA in 21% of persons involved in crashes. Katyal et al. (1997) reported that lateral and frontal impacts each accounted for 50% of TRA cases respectively. Of the occupants sustaining TRA in lateral impact crashes, 80% were associated with being struck on the near side (where near side refers to an impact to the side of the vehicle closest to the occupant, and far side refers to an impact to the side of the vehicle furthest from the occupant). In frontal impact crashes, 76% of drivers and 24% of passengers sustained a TRA. Hunt et al. (1996) reported the overall incidence of TRA in North Carolina, US to be 0.23%

The life-threatening nature of injuries of the aorta has been well documented. Smith and Chang (1986) estimated that 80% - 85% of motor vehicle occupants who sustain ruptures of the aortic wall die at the scene of the crash. Of the remaining victims, approximately one third die within the first six hours of having sustained the injury and, if left untreated, ninety percent die within three months of the collision. Similarly, Hunt and colleagues (1996) reported that 70% - 90% of TRA victims die at the scene, while 44% of TRA victims who survive to the emergency room eventually died.

Studies have demonstrated that there are three primary locations of TRA: (1) in the ascending aorta, (2) in the aortic root and (3) in the descending aorta, immediately distal to the left subclavian artery. A number of authors have demonstrated that the most common location is distal to the subclavian artery where the lumen narrows and forms the aortic isthmus (Parmley et al., 1958; Smith et al., 1986; Newman et al., 1984; Hunt et al., 1996 and Katyal et al. 1997). Ben-Menachem (1993) suggested that the lesser curvature of the aorta is subject to particular involvement in side impacts.

Aortic tears typically involve the tunica intima (innermost layer) and the tunica media (middle layer) (Strassman 1947; Cammack et al. 1959). In some cases, an incomplete tear of the tunica adventitia (outermost layer) may occur. If the incomplete tear is not diagnosed early and the victim is left untreated, a secondary rupture usually occurs within weeks of the injury. Such an injury is defined as aortic dissection (Lansman et al., 1999).

In order to ensure accurate computer modelling and the development of effective side impact countermeasures, there is a need to understand the anatomical location and direction of force in the occurrence of TRA. Laboratory studies and the analysis of real-world crash data offer a means to further understand the mechanisms of TRA injuries. To date, however, laboratory experiments designed to reproduce aortic rupture by blunt impact loading have met with limited success (Kroell et al., 1974; Viano, 1989; Cavanaugh et al. 1990; Cavanaugh et al., 1993).

Analysis of in-depth crash databases provides an opportunity to examine the incidence and mechanisms of TRA in real-world motor vehicle crashes. However, few studies using mass data have attempted to determine the incidence and mechanisms of TRA. In one such study of UK occupants, Richens et al. (2002) reported that TRA was more common in lateral impacts than frontal impacts. Furthermore, it was demonstrated that the use of seatbelts and airbags did not reduce the risk of TRA. A recent study by Thakone et al. (2001) investigated impact direction and injury outcomes. Although the research did not focus on aortic injuries, it was concluded that the incidence of injury from blunt trauma was influenced by occupant position. In the sample of occupants studied, the authors demonstrated that most drivers suffered a right side diaphragmatic rupture and most FLP's a left side diaphragmatic rupture in a country where vehicles travelled on the left side of the road.

This research aims to examine the incidence and mechanisms of injuries to the aorta using real-world crash data from the US (where drivers sit on the left side of the vehicle and the vehicle travels on the right side of the road) and the UK (where the driver's seating position and vehicle travelling side is the reverse to the US). The primary goal of this paper is to examine the risk of sustaining injuries to the aorta by principal direction of force and seating position of the occupant. The use of the US and UK data sets allows a comparison to be made in relation to near-side and far-side impacts on different sides of the body for both drivers and front seat passengers. Given that the thoracic cavity is asymmetric with respect to internal organs (the aorta runs largely to the left of the midline), it is plausible that impact direction relative to the occupants' seating position and the side of the vehicle struck influences the risk of sustaining injuries to the aorta.

METHOD

Data Sources

i. The National Automotive Sampling System (NASS), US.

For right side travelling vehicles, crash data collected between 1993 and 2000 inclusive was used from the NASS (National Automotive Sampling System) CDS (Crashworthiness Data System), which is compiled by the National Highway Traffic Safety Administration (NHTSA) in the US. The NASS CDS is a probability sample of police-reported tow-away crashes in defined primary sampling units. Occupants who were dead at the scene were included.

A comparison set of data, which excluded collisions involving non-horizontal impacts or collisions in which no event occurred (for example, a bridge collapsing under the weight of a vehicle), was created for the NASS CDS database and used for the analysis. A subset of data containing details of only those occupants with aortic injuries was then produced from the comparison data. The analysis of the CDS data was conducted using the recommended weighting system.

ii. The Co-operative Crash Injury Study (CCIS), UK.

For left side travelling vehicles, crash data from 1983 to 2001 inclusive was extracted from the CCIS (Co-operative Crash Injury Study) database, which contains information on crashes in the UK. The information is collected by the University of Birmingham, Loughborough University, and the Vehicle Inspectorate Agency on behalf of the industry and the UK government, while the Transport Research Laboratory (TRL) manage the project. The criteria for inclusion in the CCIS study are:

- The collision must be in a predefined geographical region;
- The case vehicle must be less than 7 years old;
- The case vehicle must be towed from the scene, and
- The case vehicle must have at least one injured occupant.

Approximately 1,500 vehicles are investigated each year. Occupants who were dead at the scene were included. A random stratified sampling system is used based on injury severity. The weighting system of the CCIS was not appropriate for this analysis.

Data Analysis

In addition to TRA, injuries of the thoracic aorta include aortic tears and lacerations of varying degrees of severity. According to the 1998 update of the Abbreviated Injury Scale (AIS), 1990 revision, these injuries cover the codes of AIS 4 to AIS 6. The analysis in this study used aortic injuries coded as 4202xx.4, 4202xx.5 and 4202xx.6, where the 4202 refers to a thoracic aorta injuries and the xx is a number that codes the type of aortic injury.

Statistical analyses were conducted in Statistical Analysis Software (SAS) 4, Version 8.2 and Statistical Package for the Social Sciences (SPSS), Version 10. The overall incidence of aortic injury for the UK and the US was calculated. The age, weight and height of those occupants sustaining aortic injuries and those who did not were calculated. The observed probability of sustaining an injury to the aorta, given that an occupant was injured, was calculated for frontal (PDOF 11-1), left lateral (PDOF 8-10), right lateral (PDOF 2-4), and rear impact crashes (PDOF 5-7) for both data sets. This analysis was conducted for cases where the delta-v was known. A detailed analysis of the probability of sustaining an aortic injury controlling for risk factors, such as delta-V, age and weight was beyond the scope of the present study.

RESULTS

ANALYSIS OF ALL OCCUPANTS - Table 1 presents the incidence of both aortic injuries and other injuries as a function of occupant position in the vehicle. The data shows that the incidence of aortic injury in the US was 0.18% and in the UK the frequency was 1.73%. The majority of the occupants were drivers, while FSP only comprised approximately 20% of the occupants.

Table 1: The incidence of aortic injury against all injuries for the various occupant seating positions.

Country	Position in vehicle	Number of occupants with aortic injuries	Number of injured occupants	Incidence of aortic injury	Percentage of aortic injuries
US (weighted)	Driver	15,002	7,911,502	0.19%	74.8%
	FRP[#]	4,262	2,180,739	0.20%	21.2%
	Other	772	1,032,865	0.07%	3.80%
	Total (US)	20,036	11,125,106	0.18%	100%
UK	Driver	198	10,251	1.93%	68.3%
	FLP[##]	67	3,842	1.74%	23.1%
	Other	25	2,645	0.94%	8.6%
	Total (UK)	290	16,738	1.73%	100%

Note: FRP – front right passenger; FLP – front left passenger

The average age, height and weight of occupants with aortic injury and occupants with injuries other than that of the aorta are presented in Table 2. The mean age and weight of both male and female US occupants with aortic injuries was higher than the mean age and weight of occupants with injuries other than that of the aorta, whereas the heights for both groups were similar. On the other hand, the mean anthropometric characteristics of UK occupants with and without aortic injuries were similar.

Table 2: The anthropometric characteristics for male and female occupants with aortic injuries.

		US OCCUPANTS				UK OCCUPANTS			
Sex		**Aorta**		**Other injuries**		**Aorta**		**Other injuries**	
		N	**Mean**	**N**	**Mean**	**N**	**Mean**	**N**	**Mean**
M	Age (years)	327	41.2	89021	34.3	213	38.6	9246	34.5
	Height (m)	315	1.76	76494	1.74	106	1.77	4410	1.75
	Weight (kg)	314	87.6	77434	79.6	61	78.8	4291	75.0
F	Age (years)	196	48.0	77611	36.9	75	43.7	6622	36.4
	Height (m)	188	1.64	67852	1.61	35	1.64	3599	1.61
	Weight (kg)	187	75.2	68462	65.6	19	60.9	3548	60.9

Note: M – males; F – females

ANALYSES OF THE WEIGHTED NASS DATABASE (US) – In the analysis of the NASS CDS data, only crashes involving horizontal impacts were considered. Using the weighting system for the US NASS database revealed that there were 33,259,162 collisions involving 11,131,373 injured occupants recorded from 1993-2000 inclusive. There were 20,034 occupants who suffered an aortic injury. The overall incidence of aortic injury was 0.18%.

To examine the role of crash severity in the probability of sustaining an aortic injury, cases where the delta-V was unknown were excluded. Table 3 shows the number of aortic injuries and mean delta-V as a function of the total number of injuries for each impact direction. For both driver and front seat passenger and all impact directions, the mean delta-V associated with aortic injuries was seen to be higher than that associated with other injuries. In the case of the driver, the observed probability of sustaining an injury to the aorta is higher for near side impacts (left lateral impacts) compared to far side (right lateral impacts) despite the fact that the near side collisions involved vehicles having a lower mean delta-V. For the FRP's, right lateral impacts are still the most injurious even though the mean delta-V from this impact direction is similar to that of other impact directions.

Table 3: Number of aortic injuries in the US as a function of the total number of injuries for each impact direction (only cases where delta-V known are included).

Occupants' Seating position	PDOF	Injury Type	Frequency	Observed Probability	Mean Delta-V (km/h)	SD
Driver	2-4	Other injury	1795486.9		25.1	11.3
	Right lateral	Aortic injury	762.0		56.4	12.5
		Total	1796248.9	0.00042		
	5-7	Other injury	1070652.0		26.8	12.5
	Rear	Aortic injury	361.6		66.0	0.0
		Total	1071013.6	0.00034		
	8-10	Other injury	2145241.6		23.3	11.8
	Left lateral	Aortic injury	2159.8		42.2	10.0
		Total	2147401.4	0.00101		
	11-1	Other injury	9992791.8		29.1	14.7
	Frontal	Aortic injury	4023.6		53.3	19.9
		Total	9996815.4	0.00040		
FRP	2-4	Other injury	608189.1		25.6	11.3
	Right lateral	Aortic injury	770.1		42.9	10.9
		Total	608959.2	0.00126		
	5-7	Other injury	347396.6		24.8	10.5
	Rear	Aortic injury	0.0			
		Total	347396.6	0.00000		
	8-10	Other injury	399078.4		23.8	11.1
	Left lateral	Aortic injury	93.7		45.4	3.7
		Total	399172.2	0.00023		
	11-1	Other injury	2661909.2		27.5	12.9
	Frontal	Aortic injury	2898.1		46.9	15.5
		Total	2664807.4	0.00109		

Note: FRP – front right passenger

ANALYSIS OF THE CCIS DATABASE - In the years 1983 to 2001 inclusive, a total of 24,832 injured occupants in 18,575 vehicles involved in 15,378 collisions were recorded. There were 101,246 injuries as a result of these collisions. Eliminating non-horizontal and unknown events gave a subset of comparison data that contained 11,309 collisions involving 13,324 vehicles where all 20,456 occupants sustained at least one injury. There were 84,824 injuries in total.

Table 4 shows the number of aortic injuries and mean delta-V's as a function of the total number of injuries for each impact direction. It can be seen that left lateral impacts were the most injurious in terms of aortic injury to the UK driver, followed by frontal impacts. For the FLP, left lateral impacts are also most injurious, followed by right lateral impacts. It should be noted, however, that the mean delta-V's for left lateral and frontal impact types were considerably higher than the mean delta-V for right lateral impacts. Furthermore, it is interesting to observe that although the delta-V was highest for frontal impacts, both for the driver and the FLP, the observed probability of aortic injuries was lower for this impact type compared to the other impact types. Hence it can be concluded that a near side impact is most detrimental for the UK FSP in terms of aortic injury, whereas it is not clear if this is also the case for the UK driver.

Table 4: Number of aortic injuries in the UK as a function of the total number of injuries for each impact direction (only cases where delta-V known are included).

Occupants' seating position	PDOF (o'clock)	Injury Type	Frequency	Observed Probability	Mean Delta-V (km/hr)	SD
Driver	2-4	Other injury	1885		34.79	15.46
	Right lateral	Aortic injury	19		45.11	14.21
		Total	1904	0.00998	34.90	15.47
	5-7	Other injury	396		33.31	14.28
	Rear	Aortic injury	0		0	0
		Total	396	0	33.31	14.28
	8-10	Other injury	1285		41.54	19.20
	Left lateral	Aortic injury	17		60.06	13.58
		Total	1302	0.01306	41.78	19.25
	11-1	Other injury	11872		45.88	19.82
	Frontal	Aortic injury	39		64.67	21.96
		Total	11911	0.00327	45.94	19.85
FLP	2-4	Other injury	458		29.47	15.30
	Right lateral	Aortic injury	3		46.67	9.71
		Total	461	0.00651	29.58	15.33
	5-7	Other injury	144		33.06	14.54
	Rear	Aortic injury	0		0	0
		Total	144	0	33.06	14.54
	8-10	Other injury	853		39.67	16.95
	Left lateral	Aortic injury	20		54.70	12.76
		Total	873	0.02290	40.01	17.01
	11-1	Other injury	3535		43.85	19.26
	Frontal	Aortic injury	6		58.33	18.26
		Total	3541	0.00169	43.87	19.26

Note: FLP – front left passenger

OVERALL PATTERNS OF AORTIC INJURIES

Table 5 shows the observed probability of sustaining aortic injuries and associated characteristics for UK and US drivers and front seat passengers in rank order. It is evident from this table that for both UK and US occupants, the observed probability of sustaining an injury to the aorta is greater for near side crashes than for far side crashes. Further, it is apparent that, given a near side crash, the risk of an aortic injury is greater on the left side of the body (and vehicle) than on the right side of the body.

Table 5. Observed probability of sustaining aortic injuries and associated characteristics for UK and US drivers and front seat passengers in rank order

Side of vehicle struck	Seating position	Country	Crash type	Observed Probability (of 1000)	Delta-V (km/h)	Rank
Left	FLP	UK	Near	22	54.7	1
Left	Driver	UK	Far	13	60.1	2
Right	Driver	UK	Near	9	45.1	3
Right	FLP	UK	Far	6	46.7	4
Right	FRP	US	Near	1.3	42.9	6
Left	Driver	US	Near	1.0	42.2	7
Right	Driver	US	Far	0.4	56.4	8
Left	FRP	US	Far	0.2	45.4	9

Note: FRP – front right passenger; FLP – front left passenger

In examining the probability of sustaining an injury to the aorta in the US and UK, it is apparent that there are large differences in risk between the two data sets. This result may possibly suggest differences between the two data sets with respect to crash severity, crash type, vehicle type, collision partner, and the demographic characteristics of occupants. Table 5 also shows the mean delta-V for crash configurations for US and UK drivers and passengers. It is evident that the probability of sustaining an injury to the aorta likely to be related to crash severity, as indexed by delta-V. Without further modelling, however, it is difficult to draw any definitive conclusions from these data.

DISCUSSION

The results presented in this paper demonstrated that the incidence of aortic injury in both the US and the UK is low. However, as noted in the Introduction, such injuries represent a serious threat to life and are often fatal. Consequently, an improved understanding of the mechanisms associated with aortic injuries is important to ensure the development of occupant protection countermeasures.

In the analysis of the US and UK databases it was evident that the risk of sustaining an injury to the aorta is greater for near side crashes than for far side crashes. It was also seen that the risk of sustaining an aortic injury in a near side crash was greater when the vehicle was struck on the left side rather than the right side. The risk of sustaining an injury to the aorta was found to be associated with crash severity, as indexed by delta-V. In every crash configuration in the both the US and the UK samples, the delta-V associated with sustaining an injury to the aorta was higher than the delta-V associated with other injuries. This finding has important implications for both modelling and for the development of occupant protection countermeasures.

As indicated above, the risk associated with sustaining an injury to the aorta is highest for near side crashes. Such a result is not surprising given the velocity of the collision partner and the forces applied directly to the occupant within the cabin. It was also reported that the risk of sustaining an aortic injury was higher for left near side collisions than for right side near impact collisions. It might be speculated that this finding is partially due to the asymmetric configuration of the thorax. The aorta arises from the anteriorly located left ventricle, channelling upward and to the right before the aortic arch descends on the left side of the body. Hence, it would be reasonable to conclude from the current study that a factor contributing to the likelihood of sustaining an aortic injury is a strike to the left side of the thorax. As previously mentioned, of the three regions where TRA occurs, the most frequent location is in the descending aorta, just below the left subclavian artery. The ascending aorta arises from the left ventricle, is protected by other tissues of the heart and ascends towards the right. On the other hand, the aortic arch and descending aorta are both exposed to the left side of the body and hence may be at greater risk from impact.

The conclusions here are speculative to some extent. In approximating the risk of aortic injuries in the UK and the US, this study does not correct for potential confounding variables such as size of vehicle, impacting object, delta-V, and occupant characteristics. While the results presented here are interesting and novel, without controlling for confounding variables, it is difficult to draw definitive conclusions from the data. It was evident, however, that there were significant differences in the risk of aortic injuries between the US and UK occupants. This result highlights the difficulties associated with comparing injury patterns across international databases. The next stage of this research is to use logistic regression modelling to control for various risk factors. In doing so it will be possible to determine the risk of aortic injuries on the left and right of the body in near and far side crashes by using US and UK drivers and passengers. On the basis of the data presented in this study, it is reasonable to conclude that occupants struck on the near side are at greater risk of sustaining an injury to the aorta than occupants struck on the far side. Furthermore, a left lateral impact is more injurious than a right lateral impact.

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