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Injury Mechanisms of Aortic Ruptures to Vehicle Occupants and Vulnerable Road Users – An In-Depth-Investigation over Time

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Abstract

A rupture of the aorta was a common injury observed in the 60ies and 70ies regarding unprotected car occupants, reported in 10% to 15% of vehicle mortalities in the past. With this study it is investigated how often the Aortic Rupture can be observed in today´s traffic accident scene and what changes happened in the course of time history regarding different kinds of traffic participation and different kinds of injury mechanisms. Based on very well documented in-depth-accident cases by GIDAS (German-In-Depth-Accident-Study) a representative sample of all traffic accidents during a 40 year period (years 1973 to 2014) is available (n>100.000 involved persons) and the cases with Aortic ruptures AR (n=142) are analyzed in detail.

The Aortic rupture can be observed in high speed accidents with high body deceleration and direct load to the thorax. Nearly always a high compression of the thorax is responsible for the load direction to the heart vessel. The analysis found load in most cases from caudal-ventral in 26.1% and from ventral 21.1%. Another high percentage could be registered from the left and the right (19.7% each) and 7.5% in roll-over events by vehicles with high thorax compression. The rupture was found mostly classical on the area of the aortic arch into pars descendens caused by a kind of scoop-mechanism and in few cases a hyper flexion mechanism, but never with deceleration effect only. Today the AR is very seldom registered for car occupants (0.1%) and also for cyclists (0.05%), more frequent for pedestrians (0.22%) and motorcyclists (0.23%). Related in the course of time history the focus of AR has to change from car occupants to vulnerable road users. Always the characteristic is linked with high thorax deformation mainly in accident situations under high impact speed, no seatbelt and direct body impact.

Keywords: Injury mechanism; Aortic ruptures; Biomechanics; Injury severity; In-Depth-accident-study; Time history of aortic ruptures; Traffic accidents

Introduction

Some decades ago the aortic rupture was a common injury in the traffic accident scene in Germany and also in other countries. Former studies showed that the aortic rupture was detected in 10-15% of vehicle mortalities and that it was the primary cause of death in a high percentage of cases [1,29,33,34]. Richens et al. [2] mentioned an occurrence of blunt traumatic aortic ruptures in 20% of all automobile fatalities and a scene survival of the victim of 2-5%. Following Pongratz et al. [3] a rupture of the descending thoracic aorta is the second most common cause of death after the most common cause, the traumatic brain injury. Most of the casualties decease at the accident location before arrival of the rescue forces, only 5-15% survive till arrival at the hospital. Of these share, another 50% decrease within 24 hours.

Voigt et al. [4,5] already investigated the mechanisms of injuries to unrestrained drivers in head-on collisions in the 1960s. The evaluation of autopsies led to an explanation of the fatal aortic rupture at the classical location, closely below the insertion of the ligature arteriosum Botalli. Most often (in 32 cases) a “shoveling effect on the thorax” could be detected. In the vehicle, the lower part of the rim of the steering wheel was bent forward, or the wheel rim together with the spoke was broken off the hub. In each case the blow was transferred to the driver’s thorax by the lower edge of the steering wheel hub or the point of bending or breaking of the spoke directed towards the driver. That is far below the site of the aortic rupture. The torso of the driver tilts around the steering wheel hub after impacting it, so that the hub of the point of bending or breaking of the spoke impresses the lower part of the anterior thoracic wall in dorsal-cranial direction and simultaneously presses upwards the organs of the mediastinum. The aortic arch is deflected and pushed upwards with a consequent strain on the ligature arteriosum Botalli. The strain causes the aortic rupture at the classical site.

Gotzen et al. [6,7] analyzed 26 aortic ruptures which were found in 107 autopsies of vehicular trauma victims; 14 car passengers, in four 4 cases of pedestrians and in two cases of cyclists. The Aortic ruptures could be correlated to a severe ventral or ventro-lateral thoracic compression trauma. The depressed anterior chest wall produces the before mentioned shoveling effect on the intra thoracic organs, especially the mediastinal structures (i.e., heart and pulmonary hila) pressing them upwards posteriorly and to the left into the aortic arch. By this movement the aortic arch then will be pushed upwards, deflected and twisted, and in this manner severe shearing and stretching at the isthmus (the area of change from the mobile to the more fixed segment of the aorta) may cause rupture beginning at the concavity of the terminal arch.

In a prospective study by Newman et al. [8] traffic accidents in Oxfordshire, limited to car occupants, were analyzed by a combined team of surgeons and engineers over a 3-year period. All persons with a thoracic aortic rupture were front passengers and most of them (9 out of 12) were not belted. The most frequent cause of the rupture was steering assembly contact.

In the study of Arajarvi et al. [9] 4,169 fatally injured victims investigated by the Boards of Traffic Accident Investigation of Insurance Companies during the period of 1972 to 1985 in Finland were analyzed. Chest injuries (26.9%) were recorded as the main cause of death whereas only 5% of the victims have worn a seat belt and aortic ruptures were found at autopsy in 2.4% of victims. Injuries in the ascending aorta were mostly found in unbelted victims and were sustained in frontal impact collisions, the injury-causing part of the car being the steering wheel. Ruptures of the distal descending part of the aorta were frequently associated with fractures of the thoracic vertebra.

Following Ben-Menachem [18] violent lateral blunt impacts to the chest, such as inflicted in broadside automobile collisions, can cause traumatic rupture of the thoracic aorta. In most of these events, quite unlike the classic isthmus rupture of deceleration accidents, the injury appears to be partial shearing of the distal aortic arch, probably just above the isthmus. The aortic injury is often part of a trauma pattern typical of a lateral collision, in which critical intra-abdominal injuries are located on the side of the patient that was on the receiving end of the impact. The author points out that seatbelts and (frontal) air bags do not protect car occupants in lateral collisions.

Shkrum et al. [10] examined 35 collisions from the years 1984-1991 in which 39 fatally injured victims sustained aortic traumata. An occupant contact with the vehicle interior surfaces was identified in most cases and especially in side collisions occupant restraints were often ineffective. The most frequent site of aortic rupture was at the isthmus and a majority of victims had rib/sternal fractures indicating significant chest compression. This study supports that predominant impression, concluding that rapid chest deceleration/compression induces torsional and shearing forces that result in transverse laceration and rupture of the aorta, most commonly in the inherently vulnerable isthmus region.

Bass et al. [19] designed *in vitro* and *in situ* tests providing aortic failure data under pressure loading in comparison to finite element models and to investigate the hydraulic pressure mechanism itself as a potential cause of traumatic aortic rupture. The rupture location was the aortic isthmus in 70% of the tested cases. The pressure mechanism may generally require some displacement component for ruptures seen in epidemiological studies. If the aorta had isotropic material properties in a cylindrical cross section, failure would invariably occur in the azimuthal direction (transverse failure). This further suggests that some relatively high rate displacement mechanism increases the stress in the axial direction relative to the pressure loading seen in this study.

Shah et al. [11] developed a model of the human thorax and used it to study the effects of internal pressure and stretch on aortic rupture due to pendulum impacts. The model predicted that, in a frontal impact, the isthmus and the root of the aorta are the two most probable sites of high stress in the aorta. In a left-sided lateral impact, the isthmus, the mid descending aorta and the aortic valve are prone to have high stress whereas in a right-sided lateral impact the isthmus, the root of the aorta and the mid descending aorta are vulnerable.

Forman et al. [12] developed a method for the experimental investigation of acceleration as a mechanism of aortic injuries. High-acceleration ATD sled tests were performed resulting in rearward x-axis sled accelerations up to 91 g to 98 g, chest center of gravity accelerations as high as 131 g (3 ms duration), mid-spine accelerations up to 102 g (3 ms duration) and thoracic deflections less than 6% to 10% of the undeformed chest depth. These tests resulted in no significant injuries to the thorax. This study did not generate any thoracic vascular trauma, where identifiable, in human cadavers exposed to chest acceleration magnitudes as high as 117 g (CFC 180).

Cavanaugh et al. [13] analyzed the traumatic rupture of the aorta in seventeen Heidelberg-style side impact sled tests using human cadavers with sled speeds of 6.7, 9.0 and 10.5 m/s. Aortic injury occurred in five cases. In all cases the tears was just distal to the ligamentum arteriosum and proximal to the descending thoracic aorta and the aortic laceration had a transverse orientation. Peak recorded pressures ranged from 5 to 119 kPa. A positive correlation between peak aortic pressure and aortic injury was not found by the authors to here.

Shah et al. [14] analyzed the biaxial mechanical properties of planar aorta tissue at strain rates likely to be experienced during automotive crashes and also the structural response of the whole aorta to longitudinal tension with thoracic aortas harvested from human cadavers. Cruciate samples were excised from the ascending, peri-isthmic, and descending regions. The aorta fails within the peri-isthmic region. The aorta fails in the transverse direction, and the intima fails before the media or adventitia layers. The aorta tissue exhibits nonlinear behavior. The aorta as complete structure can transect completely from 92 N axial tension and 0.221 axial tension. Complete transection can be accompanied by intimal tears.

Lee SH, Kent R (2007) Blood Flow and Fluid-Structure Interactions in the Human Aorta during Traumatic Rupture Conditions, Stapp Car Crash Journal, Vol. 51, P. 211-33 (October 2007) developed a numerical method by means of a mesh-based code coupling to elucidate the injury mechanism of traumatic aortic ruptures (TAR). The aorta is modeled as a single-layered thick wall composed of two families of collagen fibers using anisotropic strain energy function with consideration of viscoelasticity. The result of parametric study reveals that the maximum level of 280 kPa pressure alone might cause TAR near the ascending aorta region, but that a characteristic deformation pattern, termed "dynamic self-pinch", occurs in the presence of superimposed chest deceleration, chest compression, and blood pressure. Considering combined impact loading, the model indicates that an aortic rupture initiates from the inner wall (intima) at the classical site, the isthmus. The combined effect of chest deceleration, chest compression, and blood pressure appears to generate an aortic deformation and failure pattern that captures all the salient characteristics of clinically observed TAR.

Hardy et al. [16] studied traumatic ruptures of the aorta (TRA) using the human cadaver and different impact conditions. Clinically relevant TRA can be generated in the cadaver in situ model using simple tension whereas thoracic deformation is required for TRA, but whole-body acceleration is not. Loading of the aorta via the ligamentum arteriosum is not required for, but may contribute to TRA. The isthmus of the aorta moves dorsocranially during frontal shoveling and submarining loading modes. The isthmus of the aorta moves medially and anteriorly during impact to the left side. Dorsocranial and anteromedial motion mediastinal contents result in axial tension in the aortic isthmus. Elongation of the aorta is central to the generation of TRA. Tethering of the descending thoracic aorta by the parietal pleura is a principal aspect of TRA.

Belwadi et al. [17] analyzed high-speed racing crashes and the corresponding aortic mechanics. In order to understand aorta biomechanics in racing car drivers, three left side impact cases were used as inputs to Wayne State Human Body Model with a simulated racing buck. The driver in each case had no major injuries reported. The average maximum principal strain (AMPS) for the high-speed racing crashes were 0.1551 ± 0.0172 while the average maximum pressure (the average maximum pressure) was 110.50 ± 4.25 kPa. The average AMPS reported was significantly less than those reported in real world accident reconstructions, biaxial material testing and in whole body cadaver impacts. The shoulder support pad plays a crucial role in injury mitigation to the thorax in high-speed racing crashes.

Summarized from literature research, past studies showed a shoveling effect on the thorax [5,7]. The load was often transferred to the thorax of the car occupant by the steering wheel assembly [5,7,8,9]. Most loads to the thorax were reported from the front, but also a few studies showed risks for aortic ruptures in side impact conditions [13,18]. In the previous studies, most of the casualties with aortic ruptures were found in not belted situations. The former studies [2,10] pointed out a rapid chest deceleration as an important factor for the occurrence of aortic ruptures whereas in newer studies [15,16,35] the chest deceleration is mostly mentioned as a side effect along with chest compression and should not be the main influencing factor for such kind of severe injury.

Approach of this study

While in the past years the number of fatal and severe injured victims from traffic accidents was reduced worldwide and the safety standards of the vehicles changed dramatically, it is also interesting to analyze the effect for the occurrence of aortic ruptures in traffic accidents. Since national accident statistics are not detailed enough to get information on the characteristics of impact types, an in-depth database was used: the German In-Depth Accident Study (GIDAS). Here a representative sample of accident data was collected over many years in Germany [22,30].

In this study, the occurrence and frequencies as well as the mechanisms and the causes of aortic ruptures are analyzed over the past 40 years. Traffic accidents from the years 1973 to 2014 are included with car occupants, occupants of trucks, pedestrians and riders of motorized two wheelers as well as bicyclists. For reasons of simplification the riders of motorized two wheelers are called “motorcyclists” in this paper.

Methods

Accident sample and data structure of GIDAS

GIDAS (German In-Depth Accident Study) is a joint project of the Federal Highway Research Institute (BASt) in Germany and the German Association for Research in Automobile Technology (FAT). While the in-depth-investigation started in 1973 based on a governmental contract with BASt in the area of Hannover, GIDAS sampling began in 1999 in two research areas of Dresden and Hanover based on the established research activities of the Medical University Hannover [21]. About 2,000 accidents of all kinds of traffic participants are recorded each year in a statistical random procedure, resulting in a representative sample of the national German accident statistics [22]. The teams consisting of technical and medical experts investigate the data at the accident scene and at the hospitals. Each case is encoded in the database with about 3,000 variables. The database contains detailed information about the environment (meteorological influences, street condition, and traffic control), vehicle (deformations, technical characteristics, safety measures), the involved persons (first aid measures, therapy, rehabilitation) and injuries (severity, description, causation). For the classification of injuries the Abbreviated Injury Scale of 1998 [23] was used, because the past cases are coded in that format. The injuries are coded with medical knowledge of the reported patient history according to a combination of the information collected on scene, visiting (and questioning if possible) the injured or fatally injured traffic participants at the hospital, hospital records/reports, photo documentation of the injuries and autopsy reports. On the basis of this comprehensive information with a detailed documentation with pictures of the vehicles and the accident scene, every accident is fully reconstructed [24,31] regarding the pre- and post-crash motion of the traffic participants as well as collision speeds, delta-v and angle of impulse.

Results

For this study accidents from the years 1973-2014 were analyzed. In order to avoid any bias in the database, the data collected in the study is compared annually to the official accident statistics and all police reported accidents for estimation of weighting factors. This process explains why the data captured by the research teams can be seen as representative for their areas [30]. As reference data the official accident data of the respective year from the German National Statistics Office (Destatis 2014-Federal Bureau of Statistics) was used. As weighting factors the accident site (rural, urban), the main accident type (1 to 7) and the injury severity (slightly injured, severely injured, fatal) were used. This resulted in $2 \times 7 \times 3=42$ weighting factors for the analysis. This implies that the used absolute n-numbers in this study and the percentage numbers can't be directly converted into each other if weighting was done. In total there were 41,670 traffic accidents with personal injuries on which 104,507 persons were involved and 53,851 injured persons. There are 41,670 traffic accidents with at least one injured person. Overall there are 104,507 persons involved; 53,851 of them were injured. An aortic rupture was registered in 142 (0.26%) of the injured persons.

Injury frequency of aortic ruptures

Figure 1 shows a pie chart of the distribution of aortic ruptures for the different kinds of traffic participation. Most persons with aortic ruptures could be found in car occupants (53.5%), followed by pedestrians (19.0%), motorcyclists (16.9%), bicyclists (7.8%) and truck occupants (2.8%).

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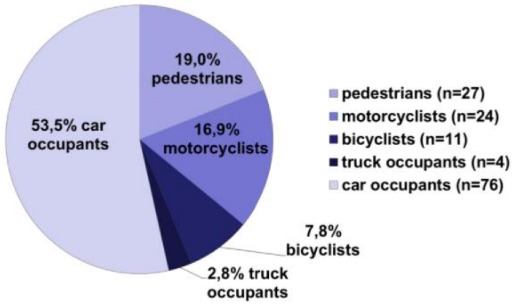

Figure 1: Pie chart of the distribution of aortic ruptures for the different kinds of traffic participation.

Table 1 shows the age distribution for the persons with aortic ruptures after traffic accidents for the different kinds of traffic participation and a comparison to the injured persons in GIDAS without AR. The distribution shows that especially the motorcyclists with aortic ruptures are very young (70% younger 30 years). This could be explained by many accidents in this age group because of little driving experience and often overestimation of the own driving skills as well as the higher driving speed of the younger motorcycle drivers. In this context common and most often occurring motorcycle accident with severe injuries (MAIS 3+) are object collisions (guardrails, trees, poles, etc.) including falls [20]. Falls of motorcyclists prior to an impact of the motorcyclist against a vehicle are also relevant. For the other vulnerable road users, pedestrians and cyclists, a shift to the older age groups can be identified, especially in bicyclists. This correlates with the higher probability of occurrence of injuries with increasing age because of the lower biomechanical tolerance of older persons [25]. This is remarkable in comparing with casualties without an aortic rupture. The distribution of truck occupants is not relevant because the n-number is very low (n=4).

Figure 2 shows the distribution of the aortic ruptures of the years for 1973 to 2014, grouped in 3-year-intervals. It is shown that the occurrence of aortic ruptures in traffic accidents was higher in the 70ies and 80ies at 0.24-0.46% of all injured casualties compared to the years above 1985. In the last 20 years, the occurrence of aortic ruptures could be registered at 0.04-0.16%.

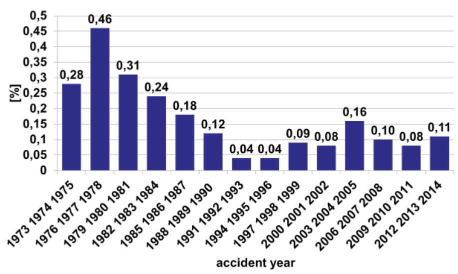

Figure 2: Percentage of aortic ruptures after traffic accidents over the past 40 years.

	with aortic rupture (n=142)	without aortic rupture (n=53,709)

		<30 years	30-59 years	>60 years	<30 years	30-59 years	>60 years
Kind of traffic participation	Car occupants n=76 with AR	48.20 %	25.80 %	26.00 %	45.00 %	43.50 %	11.50 %
	Pedestrians n=27 with AR	5.00%	59.30 %	35.70 %	46.20 %	27.50 %	26.30 %
	Motorcyclists n=24 with AR	70.30 %	28.60 %	1.10%	54.50 %	39.90 %	5.60%
	“Bicyclists” and “n=11 with AR”	16.90 %	25.70 %	57.40 %	42.30 %	39.50 %	18.20 %
	“Truck occupants” and “n=4 with AR”	-	100%	-	31.40 %	52.00 %	16.60 %
	Overall n=142 with AR	42.90 %	33.40 %	23.70 %	45.00 %	41.50 %	13.50 %

Table 1: Age distribution for the persons with aortic ruptures for the different kinds of traffic participation, cases with aortic rupture compared with cases without AR.

For all cases detailed injury documents of the traffic participants were available. In most cases the position of the aortic rupture was known. In n=46 (32.4%) cases the exact location was unknown. In the autopsy report or medical documents of these cases there was just given an aortic rupture without declaration of the location. Table 3 shows the location of the aortic ruptures for the different kinds of traffic participation. For all the analyzed kinds of traffic participation (except for truck occupants, low n-number) the descending aorta was ruptured most often (Figure 3). For car occupants the arch of the aorta is more often ruptured than the ascending aorta in contrast to all other kinds of traffic participation where the ascending aorta is more often ruptured than the arch of the aorta.

Table 2 shows a breakdown of the aortic ruptures by kind of traffic participation and calendar year grouping.

		Kind of traffic participation				
		Car occupants n=76	Pedestrians n=27	Motorcyclists n=24	Bicyclists n=11	Truck Occupants n=4
Accident years	1973-1975	8	-	1	2	-
	1976-1978	11	2	2	1	-
	1979-1981	6	2	-	-	2
	1982-1984	13	1	2	2	-
	1985-1987	3	1	3	-	-
	1988-1990	6	4	1	2	-

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	1991-1993	2	3	-	1	-
	1994-1996	3	1	-	-	-
	1997-1999	3	1	2	1	1
	2000-2002	5	4	3	-	1
	2003-2005	9	2	4	2	-
	2006-2008	4	4	3	-	-
	2009-2011	2	1	2	-	-
	2012-2014	1	1	1	-	-

Table 2: Cases of aortic ruptures by kind of traffic participation and calendar year grouping.

		Location of aortic rupture			
		Ascending	**Arch**	**Descending**	**Unknown**
Kind of traffic participation	**Car occupants n=76**	6 7.9%	15 19.7%	27 35.5%	28 36.9%
	Pedestrians n=27	4 14.8%	2 7.4%	13 48.2%	8 29.6%
	Motorcyclists n=24	3 12.5%	2 8.3%	14 58.4%	5 20.8%
	Bicyclists n=11	3 27.3%	1 9.1%	4 36.3%	3 27.3%
	Truck occupants n=4	1 25%	1 25%	-	2 50%
	Overall n=142	17 12%	21 14.8%	58 40.8%	46 32.4%

Table 3: Location of the aortic ruptures for the different kinds of traffic participation.

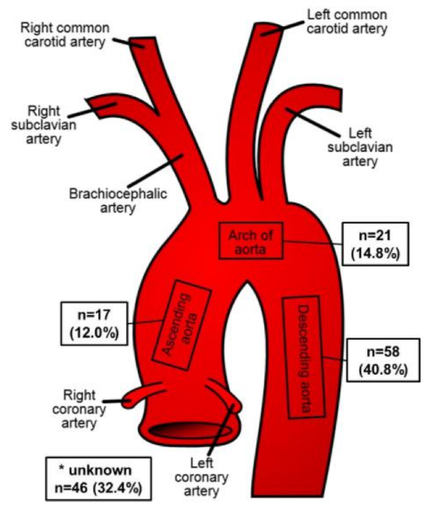

Figure 3: Shows the structure of the aorta and the distribution of the aortic ruptures for all kinds of traffic participation. Mostly the descending part of aorta was ruptured (40.8%), followed by the arch of the aorta (14.8%) and the ascending part of the aorta (12.0%).

Injury mechanisms and accident load conditions of aortic ruptures

The analysis regarding the direction of force to the aorta during the collision phase describes the mechanism that causes an aortic rupture. The analysis was carried out case by case based on the reconstructed vehicle movement, the resulting relative movement of the injured persons and the assessment of all injuries of the casualties based on the reconstructed body relative motion. This was done by an interdisciplinary team of engineers and medical specialists. Figure 4 shows the established distribution of direction of load to the thorax.

For car occupants the force vector from caudal-ventral (40.8%) and ventral (21.1%) is dominant. These mechanism is detected in frontal collisions with severe deformation of the car and was often a result of a direct impact of the thorax against the steering wheel (or airbag in new cars in combination with missing seatbelt usage) or the dashboard. Approximately 65% of car occupants, where the belt-status was known and an aortic rupture occurred, were not belted. Another high percentage of aortic ruptures were detected with forces of direction from the left or the right side (each 17.1%). This injury mechanism to the aorta was observed in side collisions with severe intrusion of the concerning side of the car. Other force directions occurred only in very seldom and severe instances. The major accident type for aortic ruptures of belted persons is related to a severe side impact event. Most of AR were found without belt (n=43), with belt (n=29) and with airbag deployments (n=10).

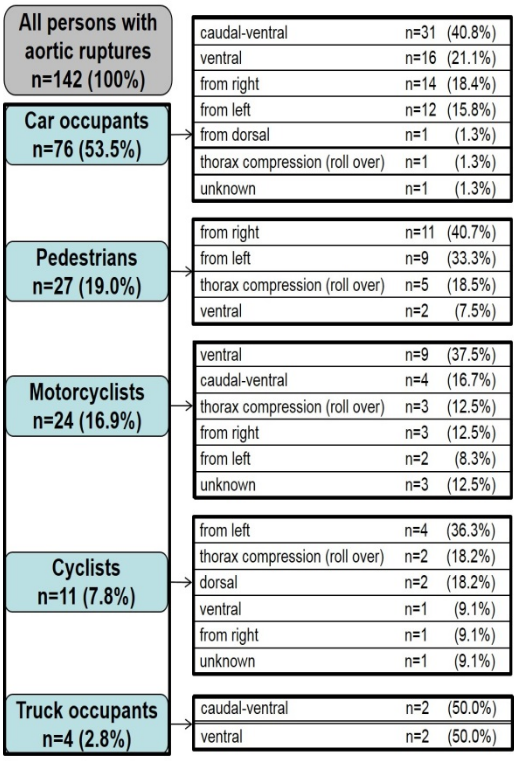

Figure 4: Direction of force to the aorta in case of an aortic rupture for the different kinds of traffic participation.

For pedestrians mainly a fronto-lateral force direction to the thorax/aorta can be detected (from right 40.7% and from left 33.3%). This injury mechanism is typically for a pedestrian crossing a street and getting impacted by a vehicle with high speed from the side of the body resulting in a fronto-lateral impact of the thorax against stiff structures of the vehicle, i.e., roof edge, bonnet, a-pillar or vehicle front (bus, tram, etc.). The body was often rotated during the wrap around movement over the bonnet to windscreen and roof structure. Another high percentage of aortic ruptures was observed in a high thorax compression from multiple sides (18.5%) as a result of a roll-over-event by a vehicle.

Related to the car occupants, the direction of force from ventral (37.5%) and caudal-ventral (16.7%) to the thorax/aorta of the motorcyclist was dominant as cause for aortic ruptures. Some motorcyclists were rolled-over by a vehicle (12.5%) after a fall before the vehicle crash or impacted to the roof of the vehicle compartment. The direction of force was mainly from frontal (37.5%), from the right side was responsible for 12.5% of the aortic ruptures and from the left side for 8.3%.

Aortic ruptures in bicyclists were most often a result of a force to the thorax/aorta from the left side (36.3%), followed by a direction of force from dorsal and a high thorax compression by a roll-over (18.2% each). A direction of force from ventral and from the right side accounts for 9.1% each. It has to be mentioned that the overall n-number of cyclists (n=11) with aortic ruptures was relatively low in comparison to car occupants, pedestrians and motorcyclists.

The aortic ruptures of the few casualties of truck occupants (n=4) were all a result of a caudal-ventral or caudal force (50% each) as a result of a direct impact of the thorax against the steering wheel or the dashboard. Only 1 of the 4 truck occupants was belted. In many cases, a large intrusion of the frontal interior can be observed.

Characteristics of typical mechanisms of aortic ruptures

A characteristically mechanisms for the aortic rupture can be found for the different kinds of traffic participation. While for car/truck occupants (Figure 5) and motorcyclists (Figure 6) the load was mainly from ventral or caudal-ventral, for the other vulnerable road user's pedestrians (Figure 7) and cyclists a more lateral load could be detected in the analyzed cases.

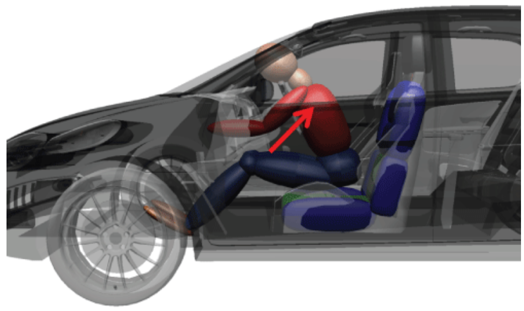

Figure 5: Typical injury mechanism of an aortic rupture for car/truck occupants: Caudal or caudal-ventral thoracic load (red arrow).

In case of car occupants the injury mechanism of the aortic rupture has to be subdivided by case scenarios, i.e., frontal or side impact, whether the occupants were belted or not and whether an airbag was available/deployed or not. The direction of force to the thorax for car occupants is shown in Figure 6.

Typically the thoracic aorta descendens is affected, directly after the outgoing circuit of the aorta subclavia where the arch of the aorta is fixed tissue-related through the ligamentum ductus botalli. Deceleration caused motions lead to torsional and shears forces because of the simultaneous motions of the organs in the mediastinum. This leads to transection of the aortic wall. As further mechanism a sudden compression of the thorax with intrathoracic or intraabdominal pressure boosting is possible. Blunt thoracic traumata, i.e., impact against a steering wheel, explosions or incarceration of the thorax are possible [3] (Figure 8).

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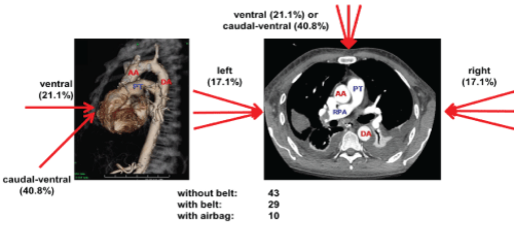

Figure 6: Direction of load to the thorax and corresponding injury mechanism for car occupants (AA: ascending aorta; DA: descending aorta; PT: pulmonary trunk; RPA: right pulmonary artery).

Figure 7: Typical injury mechanism of an aortic rupture for motorcyclists: Caudal or caudal-ventral thoracic load (red arrow) respectively a frontal or lateral impact of the thorax to the roof, A-pillar or side compartment of the car/truck.

The study can identify the typical mechanism for aortic ruptures as shown in Figure 9. The compression of the thorax leads to a movement of the heart, following to torsion of the upper part of the aorta. This relative motion leads to a laceration of the aorta descendens at the fixation point through the ligamentum ductus botalli just after the outgoing circuit of the aorta subclavian, the mechanisms showed by can be confirmed with this study.

For the majority of cases with aortic ruptures, a load to the thorax can be established from ventral or lateral-side of the body with direction from caudal to dorsal could be found. Nearly all of the analyzed accidents (except for the roll-over accidents) with aortic ruptures were marked by high speed collisions with high load and compression to the thorax. A body deceleration could be established only as secondary side effect.

Figure 10 shows the cumulative distribution of delta-v in frontal impacts for all car occupants without aortic rupture and with aortic rupture and Figure 11 for side impacts. It can be seen that the accident severity which can be measured by delta-v is much higher for collisions with resulting aortic ruptures of the occupants. This accounts for frontal impacts as well as for side impacts. More than 2/3 of car occupants suffered an aortic ruptures in accidents with delta-v values above 50 km/h, which only 10% of all car occupants suffered from.

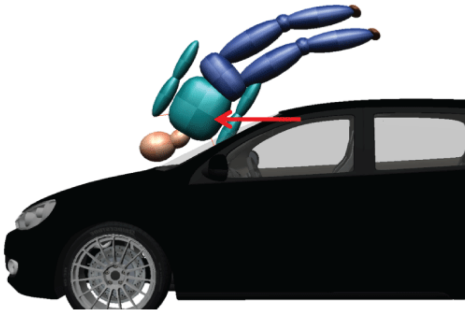

Figure 8: Typical injury mechanism of an aortic rupture for pedestrians: Lateral thoracic load (red arrow). The thorax impacted the roof structure during the wrap around movement within a rotation of the full body as a result of high speed of the car (>80 km/h).

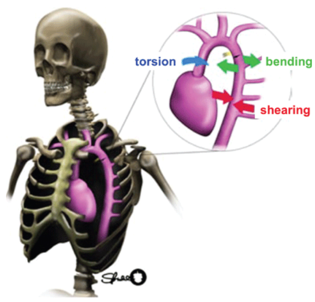

Figure 9: Typical analyzed injury mechanism of the traumatic rupture of the aorta: Torsion (blue), bending (green) and shearing forces (red) at the thoracic aorta (picture from Rückert et al.; slightly modified).

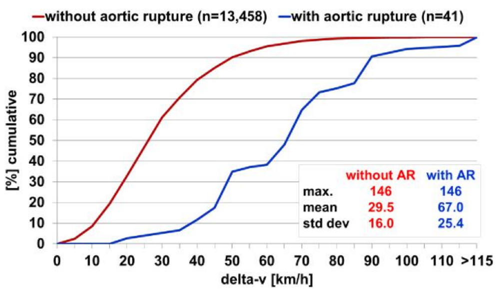

Figure 10: Cumulative distribution of delta-v in frontal impacts for car occupants with and without aortic ruptures.

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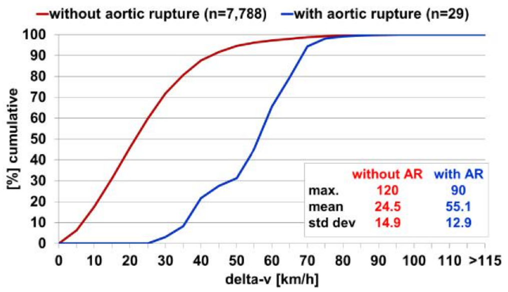

Figure 11: Cumulative distribution of delta-v in side impacts for car occupants with and without aortic ruptures.

The collision velocities of the opposing vehicles in pedestrian and bicycle accidents (Figures 12 and 13) with an aortic rupture of the vulnerable road user were much higher in comparison with accidents without aortic ruptures. 70% of pedestrians as well as cyclists suffered from an aortic rupture in accidents with impact speeds of more than 50 km/h and also 20% higher than 80 km/h.

For motorcyclists the relative speed between motorcycle and the opposing vehicle can be seen as indicator for injury severity [26]. For aortic ruptures in motorcycle crashes the relative speed in the point of collision is mainly high, 80% above 50 km/h. Compared to these cases 80% of motorcyclists without aortic rupture had a relative speed of up to 50 km/h (Figure 14).

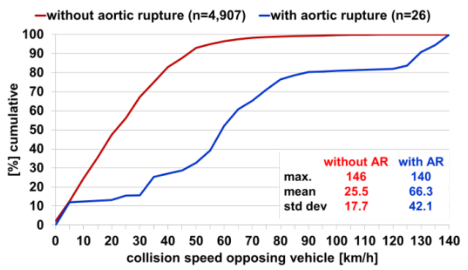

Figure 12: Cumulative distribution of collision speed of the opposing vehicle for pedestrians.

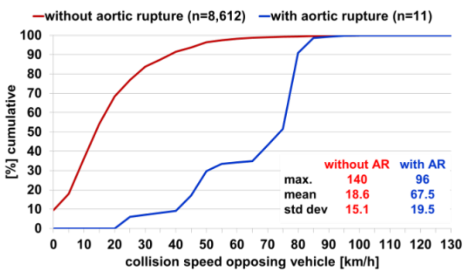

Figure 13: Cumulative distribution of collision speed of the opposing vehicle for cyclists.

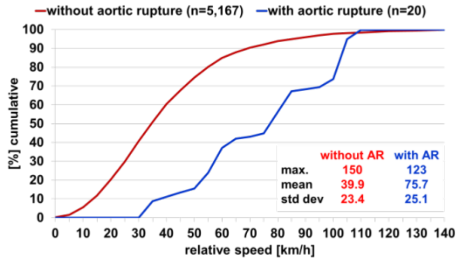

Figure 14: Cumulative distribution of relative speed for motorcyclists.

Comparison across accident years 1973-1994 / 1995-2014

The analyzed cases were split into 2 groups, accidents from 1973-1994 (called "past" cases) and accidents from 1995-2014 (called "present" cases). Two groups were built for the time history analysis from 1973 to 2014. The analysis shows, that the share of aortic ruptures was at 0.16% in the years 1973-1994 and only at 0.10% in the years 1995-2014. A year related reduction of 38% from 1973-1994 to 1995-2014 of the occurrence of aortic ruptures can be calculated from the accident sample.

A high reduction of the occurrence of aortic ruptures can be registered in Figure 15 especially for car drivers (61%) and bicyclists (50%). The decrease of aortic ruptures in car occupants (21%) and in pedestrians (13%) was lower. An increase of aortic ruptures could be detected in truck occupants (16%) and in riders of motorized two wheelers (20%). This can be explained by an increase of special collision types for motorcyclists during the last decades i.e., such accidents with impact situation of the motorcyclist against objects as guardrails, and road impacts prior to car/truck impacts [20] with high incidence of rolling over the body of the motorcyclists (17% in years 1973-1994 vs. 41% in years 1995-2014), which are 58% of all motorcycle cases with aortic ruptures. For truck occupants the cases with aortic ruptures are mainly front to rear impacts on a highway with high accident severity based on the deformation of the vehicle cabin.

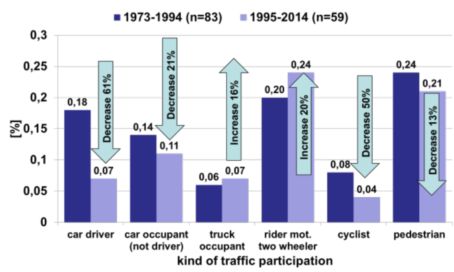

Figure 15: Distribution of aortic ruptures for the years 1973-1994 and 1995-2014 for the different kinds of traffic participation.

Figure 16 shows the cause of death for the persons with aortic rupture after traffic accidents in view of time history. In GIDAS for every injury the effect to the patient is coded, i.e., survived or dead. Additionally for every person the localization of fatal injuries is coded as (head, spine, thorax, abdomen, pelvis, extremities, and cumulative

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causes, not due to injuries or unknown). The analysis of these variables showed that the injuries at the thorax alone were responsible for 23.8% of fatalities in the years 1973-1994 and for 15.2% of fatalities in the years 1995-2014, in these cases there were no deadly injuries at other body regions. The categories "also head", "also spine" and "also abdomen" describe deadly injuries at the thorax and at the concerning other body region which is mentioned. In the past only 7.5% of the persons with aortic ruptures survived whereas 14.5% survived in present years. Nowadays the cause of death is often a result of severe spine injuries.

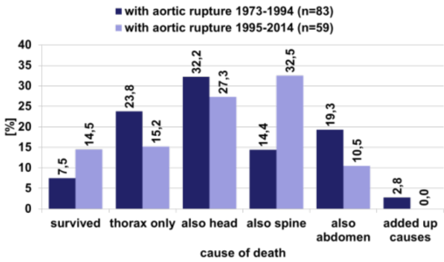

Figure 16: Causes of death for the persons with aortic ruptures for the years 1973-1994 and 1995-2014.

Table 4 shows the companion injuries at the thorax for the different kinds of traffic participants with aortic ruptures after traffic accidents.

It is shown that a high amount of companion injuries at the thorax is registered in patients with aortic ruptures after traffic accidents. That is reasonable because the accidents are characterized by high impact speeds and high accident severity. Serial rib fractures could be found in most of the analyzed cases, especially in vulnerable road users. Injuries at the spine are also often registered among the vulnerable road users. Some percentages (especially the 100%) of the bicyclists and truck occupants can only be seen with limitations because the N subject number was low in these categories.

Discussion

In this study traffic accidents of the past 40 years were analyzed based on an in-depth-investigation by GIDAS. All cases contain detailed information about the environment (meteorological influences, street condition, traffic control), vehicle (deformations, technical characteristics, safety measures), injured persons (first aid measures, therapy, rehabilitation) and injuries (severity, description, causation) and every accidents is fully reconstructed among others regarding the pre- and post-crash motion of the traffic participants as well as collision speeds, delta-v and angle of impulse.

From a total number of 104,507 involved traffic participants (car occupants, truck occupants, riders of motorized two wheelers, cyclists and pedestrians) 142 (0.14%) persons with aortic ruptures were analyzed in detail. In summary the analysis of the velocities of the traffic participants shows that the traffic accidents with the occurrence of aortic ruptures are characterized by high speed collisions with multiple body injuries and comprehensive thorax compression of the involved traffic participants. These criteria apply for all kinds of analyzed traffic participation (car/truck occupants, motorcyclists, pedestrians and cyclists). The descriptive statistics show that a large reduction of the occurrence of aortic ruptures can be registered over time during the last 40 years (approximately 38% from 1973-1994 to 1995-2014, all kind of road users included).

		Kind of traffic participation				
		Car occupants n=76	Pedestrians n=27	Motorcyclists n=24	Bicyclists n=11	Truck occupants n=4
Kind of companion injuries	lungs	60.3%	86.6%	53.0%	100%	55.0%
	series rib fracture	53.4%	93.8%	74.2%	93.9%	81.4%
	spine	49.2%	76.9%	80.8%	80.1%	51.2%
	liver	52.6%	52.5%	81.3%	52.5%	62.4%
	spleen	36.4%	34.7%	46.4%	39.7%	18.6%
	kidney	27.8%	47.6%	42.3%	28.0%	100%
	gastro-intestinal	8.6%	16.6%	17.8%	100%	100%
	pelvic fracture	49.1%	54.4%	26.0%	23.2%	100%

Table 4: Companion injuries for traffic participants with aortic ruptures after traffic accidents.

In the past, the aortic rupture was mentioned mainly for non-belted car occupants, while today a very small number of belted and airbag protected occupants, mainly in high speed collisions with high deformation characteristics of the vehicles, suffered from this kind of severe thorax injury and an aortic rupture can be seen for motorcyclists, bicyclists and pedestrians, even in a very low frequency.

The detailed analysis of the 142 cases of this study showed that the force vector to the thorax respectively the aorta is mainly from caudal-ventral and caudal fronto-lateral to dorsal and this load is expressed by a high thorax deformation – compression followed in a lateral relative movement of the aorta. This leads to bending and shearing of the aorta mainly in the region of the pars descendens.

In most cases the accident severity was high accompanied by a high deformation of the car. In the past cases a dislocation of the steering column could be registered in many cases. As a result the steering wheel was shifted up and towards the driver of the car (Figure 17).

A direct impact of the thorax against the steering wheel was the main cause of aortic ruptures for the driver and against the dashboard for the co-driver. Nowadays, in present cases with frontal car collisions of modern cars an aortic rupture occurs very rarely. This is a result of the improvement of the cars, especially an improvement of the crumple zone, the implementation of front airbags and an improved construction of the steering column. Additionally the rate of seat belt use is much higher in present cases in comparison to past cases. The seat belt wearing rate of all car drivers was at 75.5% in the years 1973-1994 whereas it was at 93.5% for the years 1995-2014. From the drivers with aortic ruptures only 34.9% were belted in the past cases and 46.8% in the present cases. That shows that the seat belt use is an important factor for reducing the risk of suffering an aortic rupture, especially in frontal collisions.

For pedestrians the force direction to the aorta from the right side (40.7%) and the left side (33.3%) was dominant. This injury mechanism is typically for a pedestrian crossing a street and getting impacted by a vehicle resulting in a lateral impact of the thorax against stiff structures of the vehicle, i.e., roof edge (Figure 18), bonnet, a-pillar or vehicle front (bus, tram, etc.).

The aortic rupture in pedestrian accidents has also decreased over the past 40 years. This is a result of the improved pedestrian safety of new cars which is also integrated in today's crash tests [28]. Modern cars are equipped with automatic brake systems which are able to avoid or at least to mitigate the accident and injury severity of the pedestrian. Another possibility is a deployable or pop-up bonnet, which is lifted in a crash involving a pedestrian to create more space between bonnet and stiff structures below the bonnet to absorb the head impact energy and reduce the injury severity. Additionally the car manufacturers are developing pedestrian airbags which could also mitigate the injury severity in a car-pedestrian accident.

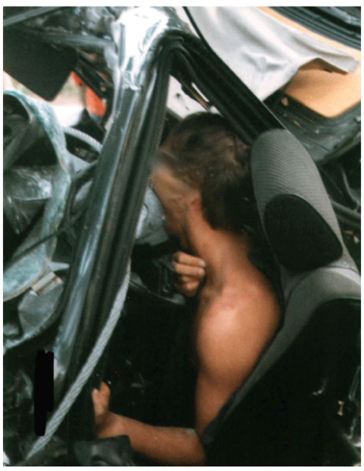

Figure 17: Example of dislocation of the steering column after frontal car collision, accident year 1991.

Related to the car occupants, the direction of force from ventral (37.5%) and caudal-ventral (16.7%) to the thorax/aorta of the motorcyclist was dominant as cause for aortic ruptures. The occurrence of aortic ruptures in motorcyclists has increased over the years. This can be explained by an increase of special collision types for motorcyclists during the last decades, i.e., such accidents with impact situation of the motorcyclist against objects (tree, guardrail) or falls on the road prior to vehicle impacts [20] with high incidence of a roll-over of the motorcyclist (17% in the years 1973-1994 vs. 41% in the years 1995-2014), which are 58% of all motorcycle cases with aortic ruptures. Additionally and in contrast to the improved safety of cars there were barely changes in the development of motorcycles regarding passive and active safety elements. Certainly it must be noted that for motorcycles the effectiveness of such safety tools and implementation of such systems is generally not available. For motorcycles there is no crush-collapse zone or a solid passenger compartment for the protection of the driver. An airbag mounted on the Steering column is a possibility to reduce such partly introduced load compression to the thorax by larger load distribution implemented in some Honda Goldwing models.

Figure 18: Example of car-pedestrian accident with thorax impact of the pedestrian at the roof edge of the car, accident year 1989.

The overall N number of bicyclists with aortic ruptures (n=11) was very low in this study. Therefore, the results have to be seen with some limitations. A load from the lateral direction can be seen as dominant force to the thorax/aorta, followed by a high thorax compression, often the case within a roll-over of the body by a vehicle. The decrease of aortic ruptures in bicycle accidents is a result of improved vehicle safety of the opposing vehicle as it could be explained for pedestrians as well.

For truck occupants the dominant cause of aortic ruptures is a force to the thorax from caudal-ventral or caudal. Similar to car occupants it is a result of direct impact against the steering wheel for the driver or against the dashboard for the co-driver. Here the deformation of the interior is often also influencing the thorax deformation.

A previous study at the Medical School Hannover [6,7] analyzed cases of 107 traffic accident victims in which 26 aortic ruptures were found. The Aortic ruptures could be correlated to a severe ventral or ventro-lateral thoracic compression trauma. The new data of this study shows that a high percentage of the aortic ruptures are correlated to a force from caudal ventral or caudal ventral-lateral to dorsal. Also the same mechanisms found by Gotzen et al. [6,7] can be found within this study. This applies within the current traffic accident scene especially for unbelted car and truck occupants in frontal collisions with direct impact of the thorax against the steering wheel or dashboard. Also for belted car occupants with or without airbag deployment, such kind of injury is happening in cases where high deformation patterns are registered. Another high percentage of aortic ruptures is found in a force to the side of the thorax, especially in lateral car collisions and in pedestrians after a collision with a vehicle.

In most of the analyzed cases the injured persons with aortic ruptures suffered a polytrauma and the cause of death was a combination of severe injuries at the head, thorax, spine, abdomen and/or pelvic. Many companion injuries at the thorax were found in these cases (serial rib fractures and/or organ injuries). The analysis showed that only 7.5% of the injured persons with aortic ruptures survived in 1973-1994 whereas 14.5% survived in 1995-2014. This is probably a result of the better medical treatment nowadays. Additionally the diagnosis of an aortic rupture after a traffic accident was often delayed or missed many years ago [18].

A study of Arajarvi et al. [9] showed that the location of the aortic rupture in unbelted victims was more often in the ascending aorta, especially in drivers, whereas in seat belt wearers the distal descending aorta was statistically more often ruptured, especially in co-drivers. These results could not be confirmed with our data. Regarding only the unbelted car occupants (n=43) a rupture of the ascending aorta occurred only in 9.3% (n=4), much more often in the descending aorta with 39.5% (n=17) and at the arch of the aorta with 23.3% (n=10). The exact location was unknown in 27.9% (n=12). For seatbelt users with aortic ruptures (n=29) the location of the rupture was registered at the ascending aorta with 6.9% (n=2), in the descending aorta with 31.0% (n=9), in the arch of the aorta with 17.3% (n=5) and in 44.8% (n=13) the exact location was unknown.

Conclusions

This study showed that the aortic rupture is caused by direct and massive compression force to the thorax, in most cases and especially for car and truck occupants as well as for motorcyclists from caudal-ventral and ventral-lateral as so called “shovel mechanism”. Compared to the accident situation in the 60ies and 70ies where mostly frontal impact were linked with an aortic rupture, in today´s accidents a high percentage could be found in load to the thorax from the right or left side, especially in belted car occupants and in pedestrians which were impacted at the side of the body by a vehicle and were wrapped around over the bonnet to the windscreen and roof structures at high velocity.

The study showed that the occurrence of aortic ruptures has decreased enormously over the last 40 years for car occupants, cyclists and pedestrians. A little increase could be registered for truck occupants and riders of motorized two wheelers. While some of the reasons for the reduction in AR in Germany over time are likely to be found in better car design and medical practices, statements to this effect are speculative, and cannot supported by specific data presented in the paper. It could be analyzed on the whole dataset of GIDAS that the parameter for accident severity delta-v is reduced from 1999 (mean-value 20.5) until 2014 (mean-value 8.5) on one hand and the belt using rate in Germany increased from 60% to 100% in the same period. On the other hand, there is a significant lower number of fatalities and severely injured causalities in nearly all kinds of traffic victims during the last decades based on better safety standards implemented in vehicles. The correlation to the causes of death seems to be logical, i.e., the causes of the aortic rupture itself after a traffic accident is nowadays not that much of a problem as is was in the past years, especially some decades ago. Nowadays persons with aortic ruptures are more likely to survive which is most likely a result of a better medical treatment and a faster diagnosis of the concerning injury. Nevertheless, a high mortality rate can be registered with AR-resulting from a major aortic dissection where blood loss is very significant. The study showed that the aortic ruptures or serious thorax injuries by itself lead to the death in approximately 23.8% of cases in 1973-1994 and only in approximately 15.2% of the cases in 1995-2014. In most of the cases the injured persons suffered a polytrauma and the cause of death was a combination of severe injuries at the head, thorax, spine and/or abdomen.

Presently, the focus of aortic ruptures has changed and is still existing for unbelted car occupants, belted and airbag protected occupants in cases with high speed and large deformation pattern (especially in side impacts) and also in impacts with vulnerable road users in pedestrians, bicyclists and riders of motorized two-wheelers if the impact speed leads to enormous load transmission to the thorax from caudal ventral to dorsal direction. Therefore countermeasures can be seen in speed reduction, seatbelt use and avoiding edgy parts in the areas of impacts (i.e., focal point loading) of vulnerable road users or the implementation of airbags on motorcycles.

Acknowledgement

For the present study accident data from GIDAS (German In-Depth Accident Study) was used. Due to a well-defined sampling plan, representativeness compared to the federal statistics is also guaranteed. Since the middle of 1999, the GIDAS project has collected about 2,000 cases on-scene of the accident per year in the areas of Hannover (Medical University Hannover) and Dresden (Technical University Dresden). GIDAS collects data from accidents of all kinds and, due to the on-scene investigation and the full reconstruction of each accident, gives a comprehensive view on the individual accident sequences and its causation. The project is funded by the Federal Highway Research Institute (BASt) and the German Association for Research in Automobile Technology (FAT), a department of the VDA (German Association of the Automotive Industry). Use of the data is restricted to the participants of the project.

Further information can be found at http://www.gidas.org.

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