Investigations and Injury Mechanisms of Aortic Ruptures among Vehicle Occupants and Vulnerable Road Users over Time

Dietmar Otte, Thorsten Facius, Michael Klintschar, Stephan Brand

Abstract A rupture of the aorta was a common injury observed in the 1960s and 1970s among unprotected car occupants, being reported in 10–15% of traffic accident fatalities. Based on in-depth accident cases from the German-In-Depth-Accident-Study (GIDAS), a representative sample of all traffic accidents over a 40-year period (1973–2014) was available with more than 100.000 involved persons and those cases with aortic ruptures AR (n=142) were analyzed in detail to identify changes over time with regard to different kinds of traffic participation and injury mechanisms. Aortic rupture is often observed in high-speed accidents with high body deceleration and direct load to the thorax. In nearly all cases a high compression of the thorax is responsible for the load to the heart vessel. The study found load resulting in most cases from caudal-ventral (26.1%), but also from ventral (21.1%), followed by load from the left and the right side (19.7% each) and 7.5% from run-over events of vehicles with high thorax compression. The classical rupture site was on the area of the aortic arch into pars descendens. In today's accident statistics (1995-2014), aortic rupture is very seldom reported for car occupants (0.08%) or cyclists (0.04%), and is just slightly more frequent for pedestrians (0.21%) and motorcyclists (0.24%).

Keywords Injury Mechanism, Biomechanics, Injury Severity, Time History of Aortic Ruptures, Traffic Accidents

I. INTRODUCTION

Some decades ago, aortic rupture was a common injury in road traffic accidents in Germany and in other countries. Former studies [1] [2] [3] [4] showed that it was detected in 10–15% of vehicle mortalities and that it was the primary cause of death in a high percentage of cases. Richens *et al.* [5] mentioned an occurrence of blunt traumatic aortic rupture in 20% of all vehicle fatalities and a scene survival of the victim of 2–5%. Following Pongratz *et al.* [6], a rupture of the descending thoracic aorta is the second most common cause of death after the traumatic brain injury (TBI). Most of the patients die at the accident location, before arrival of the rescue services, while only 5–15% survive until arrival at the hospital. Of those who do survive to reach the hospital, another 50% die within the next 24 hours.

In the 1960s, Voigt *et al.* [7] investigated the injury mechanisms of unrestrained drivers in head-on collisions. Their evaluation of autopsies led to an explanation of fatal aortic rupture at the classical location, closely below the insertion of the ligature arteriosum Botalli. In the majority of cases (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 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 with the result of an aortic rupture at the classical site.

Gotzen *et al.* [8] [9] analyzed 26 aortic ruptures, which were found in 107 autopsies of vehicular trauma victims: 14 car passengers, four pedestrians and two cyclists. The aortic ruptures observed could be correlated to a severe ventral or ventro-lateral thoracic compression trauma. The impressed anterior chest wall produces the above-mentioned shoveling effect on the intrathoracic 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 will then be pushed upwards, deflected and twisted, and in this manner severe shearing and stretching

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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.* [10], traffic accidents in Oxfordshire were analyzed by a combined team of surgeons and engineers over a three-year period, with the study parameters limited to car occupants. All persons with a thoracic aortic rupture were front passengers and most of them (nine out of 12) were not wearing a seatbelt. The most frequent cause of the rupture was the steering assembly.

In the study conducted by Arajärvi *et al.* [11], 4,169 fatally injured victims investigated by the Boards of Traffic Accident Investigation of Insurance Companies in Finland during the period of 1972–1985 were analyzed. Chest injuries (26.9%) were recorded as the main cause of death. Only 5% of the victims were wearing a seatbelt, and autopsies showed aortic ruptures 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 [12], violent lateral blunt impacts to the chest, such as are 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 wounding 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 of that study points out that seatbelts and (frontal) airbags do not protect car occupants in lateral collisions.

Shkrum *et al.* [13] examined 35 collisions occurring in the years 1984–1991 in which 39 fatally injured victims sustained aortic traumata. An occupant's 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 with induced shearing forces that result in transverse laceration and rupture of the aorta.

Bass *et al*. [14] designed in vitro and in situ tests to provide aortic failure data under pressure forcing to compare with finite element (FE) models and to investigate the pressure mechanism itself as a potential cause of traumatic aortic rupture. In 70% of the tests the rupture location was the aortic isthmus. 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*. [15] 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. This model predicted that, in frontal impact, the isthmus and the root of the aorta are the two most likely 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 suffer high stress, whereas in a right-sided lateral impact the isthmus, root of the aorta and the mid descending aorta are vulnerable.

Forman *et al*. [16] 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/98 g; chest c.g. accelerations as high as 131 g (3 ms clip); mid-spine accelerations up to 102 g (3 ms clip); and thoracic deflections less than 6%/10 % of the undeformed chest depth. These tests resulted in no significant injuries to the thorax and did not generate any thoracic vascular trauma in human cadavers exposed to chest acceleration magnitudes as high as 117 g (CFC 180).

Cavanaugh *et al*. [17] analyzed the traumatic rupture of the aorta in 17 Heidelberg-style side-impact sled tests using human cadavers and 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 but a positive correlation between peak aortic pressure and aortic injury did not exist here.

Shah *et al*. [18] 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. The aorta tissue exhibits non-linear behavior. The aorta as complete structure can transect completely from 92 N axial load and 0.221 axial strain.

Lee *et al*. [19] 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 modelled as a single-layered thick wall composed of two families of collagen fibers using an 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, i.e. 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*. [20] [21] studied TRA using human cadavers 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. Axial elongation (longitudinal stretch) 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*. [22] 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, using 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 was 0.1551±0.0172, while the average maximum pressure was 110.50±4.25 kPa. The 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 the literature, past studies showed a shoveling effect on the thorax [7] [9]. The load was often transferred to the thorax of the car occupant by the steering wheel assembly [7] [9] [19] [11]. Most loads to the thorax were reported from the front, but a few studies also showed risks for aortic ruptures in side impact conditions [12] [17]. In the previous studies, most of the casualties with aortic ruptures were found in not-belted situations. The former studies [5] [13] pointed out a rapid chest deceleration as an important factor for the occurrence of aortic ruptures, whereas in more recent studies [19] [20] [21] the chest deceleration is mostly mentioned as a side-effect, along with chest compression, and is not regarded as the main influencing factor for this type of severe injury.

II. METHODS

Approach of this study

While in recent years the number of fatally and severely injured traffic accident victims was reduced worldwide and safety standards of vehicles were improved dramatically, it is interesting to analyze the changes in the occurrence of aortic ruptures in traffic accidents. As 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. In this study, the occurrence, frequency, mechanisms and causes of aortic rupture are analyzed over a period of 40 years. Traffic accidents from 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.

Accident Sample and Data Structure of GIDAS

GIDAS 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 Hannover area, GIDAS sampling began in 1999 in two research areas, Dresden and Hannover, based on the established research activities of the Medical University Hannover [23]. About 2,000 accidents of all kinds of traffic participants are recorded each year in a statistically random procedure, resulting in a representative sample of the national German accident statistics [24]. The investigating teams, consisting of technical and medical students, examine 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, 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 (AIS) of 1998 [25] was used, because the past cases were coded in that format. The injuries are coded with medical knowledge of the comprehensive anamneses 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, along with the detailed photos of the vehicles involved and the accident scene, every accident can be fully reconstructed [26] [27] with regard to the pre- and post-crash motion of the traffic participants, as well as collision speeds, delta-v and angle of impulse.

For this study, accidents from the years 1973 to 2014 were analyzed. In order to avoid any bias in the database, the data collected in the study is compared to the official accident statistics in Germany for every single year for estimation of weighting factors. This process explains why the data captured by the research teams can be seen as representative for their areas [28]. As reference data, the official accident data of the respective year from the German Federal Statistics Office (Destatis) [29] was used. As weighting factors, the accident site (rural, urban), main accident type (1 to 7) and injury severity (slightly injured, severely injured, fatal) were used. This resulted in 2 × 7 × 3 = 42 weighting factors for the analysis. This implies that the used absolute n-numbers in this study and the percentage numbers cannot be directly converted into each other if weighting was carried out. In total, there were 41,670 traffic accidents with personal injuries with 104,507 involved persons and 53,851 injured persons. An aortic rupture was registered in 142 (0.42%) of the injured persons.

III. RESULTS

Injury Frequency of Aortic ruptures

Figure 1 shows a pie chart of the distribution of aortic ruptures for the different kinds of traffic participation. The majority of those with aortic ruptures (n=142) were car occupants (53.5%), followed by pedestrians (19.0%), motorcyclists (16.9%), bicyclists (7.8%) and truck occupants (2.8%).

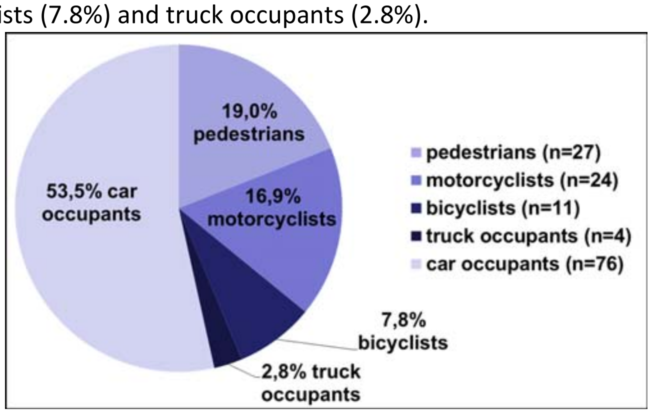

Fig. 1. Pie chart of the distribution of AR for the different kinds of traffic participation.

Fig. 2 shows the distribution of aortic ruptures from 1973 to 2014, grouped in three-year intervals. The occurrence of aortic ruptures in traffic accidents was higher in the 1970s and 1980s, at 0.44–2.46% of all injured casualties. In the last 20 years, the occurrence of aortic ruptures could be registered at 0.04–0.16%. A statistical test (Pearson Chi-Square) was performed to analyze the statistical significance of the occurrence of aortic ruptures over the 40 year period. The results show that the occurrence of aortic ruptures was significant lower in more recent accident years 1995-2014 compared to the past accident years 1973-1994 (Value 253.483; df 1; asymptotic significance < 0.001). There is also a statistical significance when comparing all accident years (Value 1047.042; df 41; asymptotic significance < 0.001). Table I shows a breakdown of the aortic ruptures by kind of traffic participation and calendar year grouping.

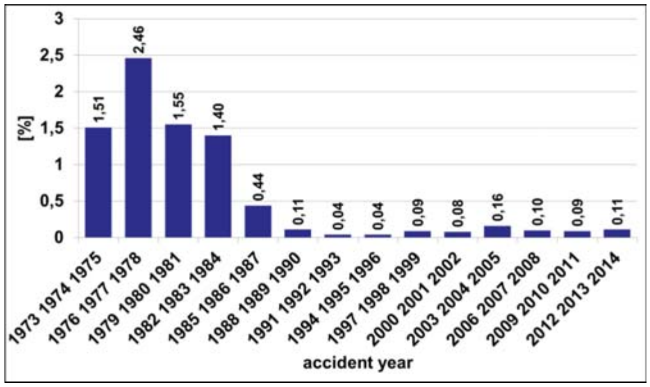

Fig. 2. Percentage of AR after traffic accidents over the past 40 years (a statistically weighted result of in-depth-investigated cases of the Accident Research Unit at Medical University Hannover).

TABLE I

CASES OF AR BY KIND OF TRAFFIC PARTICIPATION AND CALENDAR YEAR GROUPING

Accident years	Kind of traffic participation				
	Car occup. n=76	Pedestrians n=27	Motorcyclists n=24	Bicyclists n=11	Truck occup. n=4
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	-
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 II shows the age distribution for persons with aortic rupture after traffic accidents for the different kinds of traffic participation and also a comparison to the injured persons in GIDAS without aortic rupture. The distribution shows that, particularly among motorcyclists, those with aortic ruptures are very young (67% under 30 years of age). This could be explained by the number of accidents occurring in this age group, largely due to limited driving experience, overestimation of one's own driving skills and higher driving speeds of young motorcyclists. In this context, the most frequent motorcycle accidents with severe injuries (MAIS 3+) are object collisions (guardrails, trees, poles, etc.), including falls [30]. Falls of motorcyclists prior to an impact of the motorcyclist against a vehicle are also relevant in this category. 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 [31]. This is remarkable when compared with casualties without an aortic rupture. The distribution of truck occupants is not relevant because the n-number is very low (n=4).

For all cases, detailed injury documents of the traffic participants were available. In most cases the position of the aortic rupture was known but in n=41 (28.9%) cases, the exact location was unknown. In the autopsy report or medical documents of these cases, it was simply stated that aortic rupture had occurred, without declaration of the location. Fig. 3 shows the structure of the aorta and the distribution of the aortic ruptures for all kinds of traffic participation. The most commonly ruptured part of the aorta was the descending part (42.9%), followed by the arch of the aorta (16.9%) and the ascending part of the aorta (11.3%).

TABLE II
AGE DISTRIBUTION AND KIND OF TRAFFIC PARTICIPATION FOR INJURED TRAFFIC PARTICIPANTS WITH AND WITHOUT AR

		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	48.9%	23.2%	**27.9%**	42.4%	45.1%	12.5%
	Pedestrians n=27 with AR	7.3%	**62.5%**	30.2%	44.5%	28.1%	27.4%
	Motorcyclists n=24 with AR	**66.7%**	33.3%	-	46.8%	46.4%	6.8%
	Bicyclists n=11 with AR	17.0%	-	**83.0%**	38.8%	41.8%	19.4%
	Truck occupants n=4 with AR	-	46.2%	53.8	26.9%	53.6%	19.5%
	Overall n=142 with AR	**43.2%**	**33.4%**	**23.4%**	**41.7%**	**43.7%**	**14.6%**

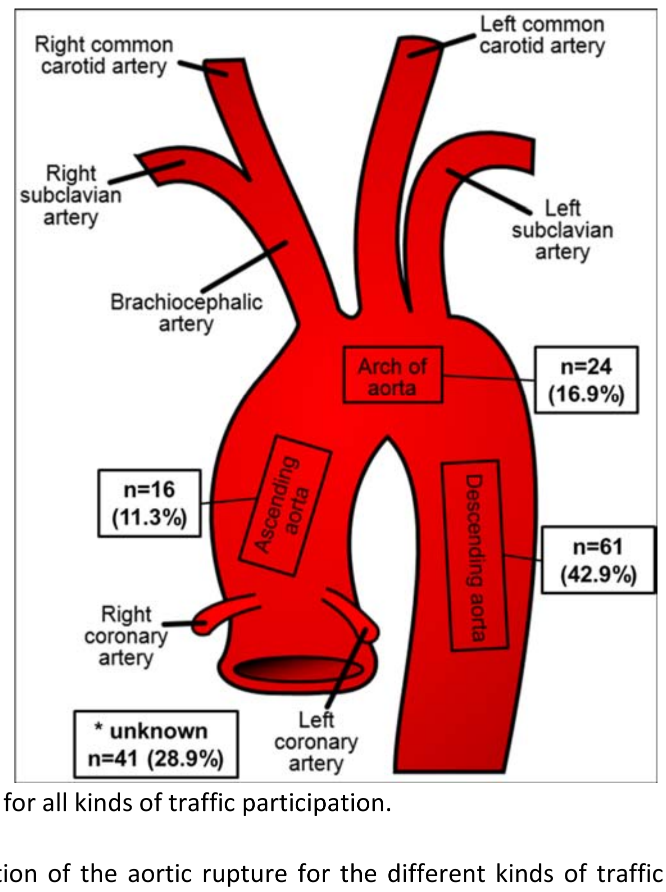

Fig. 3. Location of the AR for all kinds of traffic participation.

Table III shows the location of the aortic rupture for the different kinds of traffic participation. For all the analyzed kinds of traffic participation (except for truck occupants because of the low n-number), the descending aorta was ruptured most often. For car occupants, the arch of the aorta was 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 III
LOCATION OF THE AR FOR THE DIFFERENT KINDS OF TRAFFIC PARTICIPATION

		Location of aortic rupture			
		ascending	arch	descending	unknown
Kind of traffic participation	**Car occupants** n=76	6 7.9%	17 22.4%	28 36.8%	25 32.9%
	Pedestrians n=27	3 11.1%	2 7.4%	15 55.6%	7 25.9%
	Motorcyclists n=24	3 12.5%	2 8.3%	14 58.4%	5 20.8%
	Bicyclists n=11	3 27.3%	2 18.2%	4 36.3%	2 18.2%
	Truck occupants n=4	1 25.0%	1 25.0%	-	2 50%
	Overall n=142	**16** **11.3%**	**24** **16.9%**	**61** **42.9%**	**41** **28.9%**

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. Fig. 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 mechanisms are detected in frontal collisions with severe deformation of the car and were often the 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 had occurred, were not belted. Another high percentage of aortic ruptures was 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 AR were found without belt (n=43), followed by with belt (n=29) and then with airbag deployment (n=10).

For pedestrians, commonly 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 at high speed and 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 run-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 the dominant cause of aortic ruptures in such scenarios. Some motorcyclists were run over by a vehicle (12.5%) after a fall and before the vehicle crash, or impacted to the roof of the vehicle compartment. The direction of force was mainly from frontal (37.5%), with the right responsible for 12.5% of the aortic ruptures and the left side responsible 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 run-over (18.2% each). A direction of force from ventral and from the right side accounts for 9.1% each. It is notable 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 caused by a caudal-ventral or caudal force (50% each) resulting from a direct impact of the thorax against the steering wheel or the dashboard. Only one of the four truck occupants was belted. In many cases, a large intrusion of the frontal interior can also be observed.

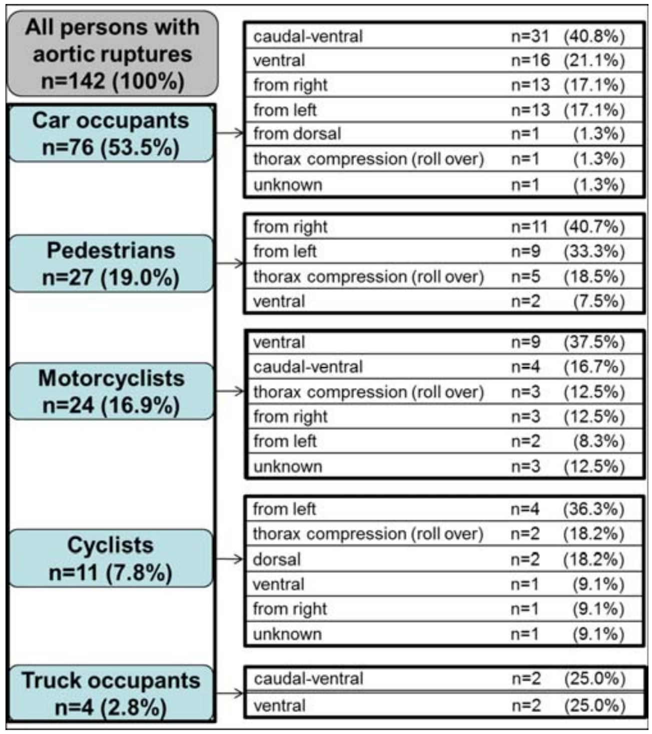

Fig. 4. Direction of force to the aorta in case of an AR for the different kinds of traffic participation.

Characteristics of typical mechanisms of aortic ruptures

A characteristic mechanism for aortic rupture can be found for each type of traffic participation. While for car/truck occupants (Fig. 5) and motorcyclists (Fig. 7) the load was mainly from ventral or caudal-ventral, for the other vulnerable road users, pedestrians (Fig. 8) and cyclists, a more lateral load could be detected in the analyzed cases.

In the 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 Fig. 6.

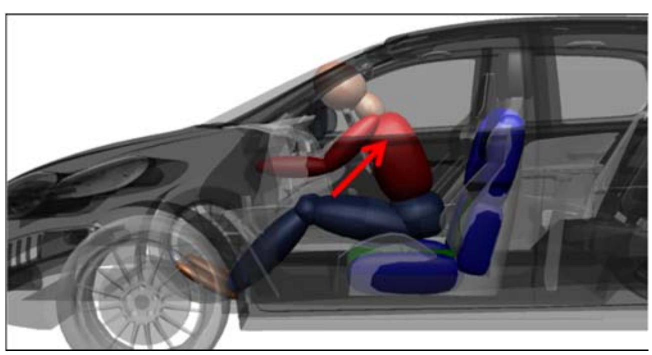
Fig. 5. Typical injury mechanism of AR for car/truck occupants: caudal / caudal-ventral thoracic load (*red arrow*).

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 shear forces because of the simultaneous motions of the organs in the mediastinum. This leads to transection of the aortic wall. As a further mechanism, a sudden compression of the thorax with intrathoracic or intra-abdominal pressure boosting is possible. Blunt thoracic traumata, i.e. impact against a steering wheel, explosions or incarceration of the thorax, are also possible [6].

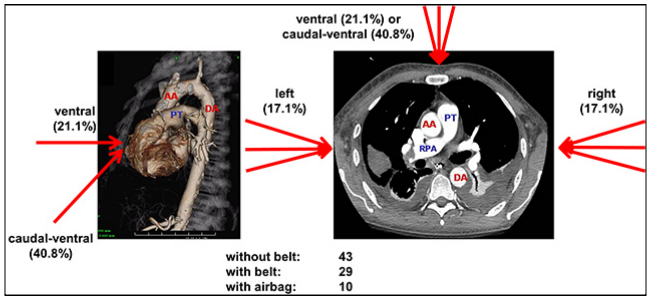

Fig. 6. Direction of load to the thorax and corresponding injury mechanism for car occupants (AA: ascending aorta; DA: descending aorta; PT: pulmonary trunk; RPA: right pulmonary artery).

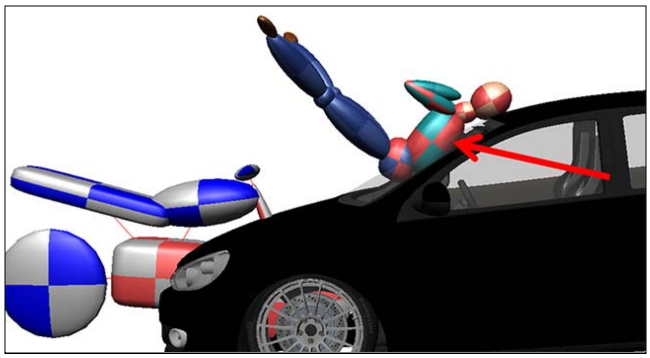

Fig. 7. Typical injury mechanism of AR for motorcyclists: caudal or caudal-ventral thoracic load (*red arrow*), respectively, a frontal or lateral impact of the thorax to the roof, A-pillar or side compartment of the car/truck.

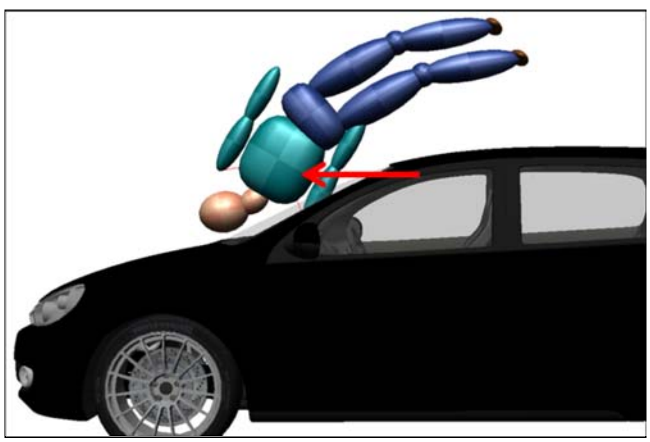

Fig. 8. Typical injury mechanism of AR for pedestrians: lateral thoracic load (*red arrow*). The thorax impacted the roof structure during the wrap-around movement within a rotation of the full body as a result of the high speed of the car (>80 km/h).

The current study can identify the typical mechanism for aortic ruptures, as shown in Fig. 9. The compression of the thorax leads to a movement of the heart, leading to torsion of the upper part of the aorta. This relative motion leads to a laceration of the aorta descendens at the fixation through the ligamentum ductus botalli, just after the outgoing circuit of the aorta subclavian. Thus the mechanisms shown by [6] and [32] can be confirmed by the findings of this study.

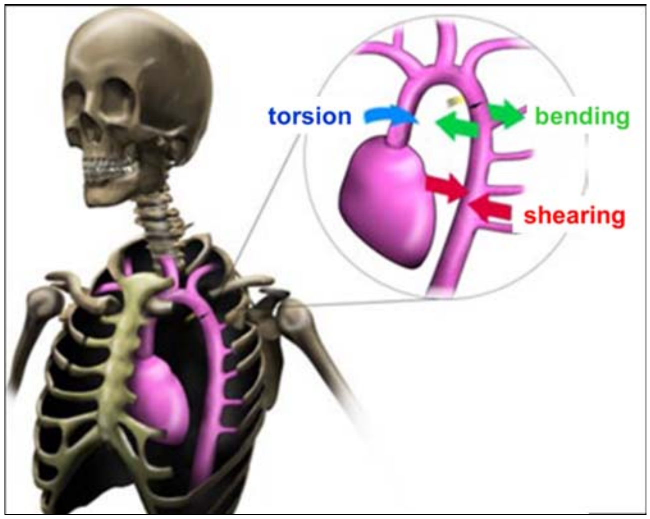

Fig. 9. Typical injury mechanism of AR: torsion (*blue*), bending (*green*) and shearing forces (*red*) at the thoracic aorta (picture from [32], slightly modified).

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

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

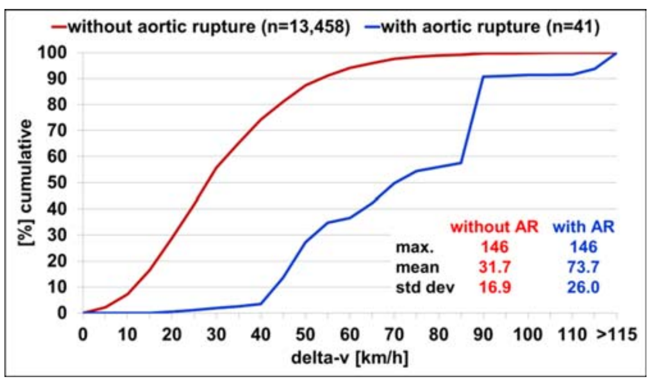

Fig. 10. Cumulative distribution of delta-v in frontal impacts for car occupants with and without AR.

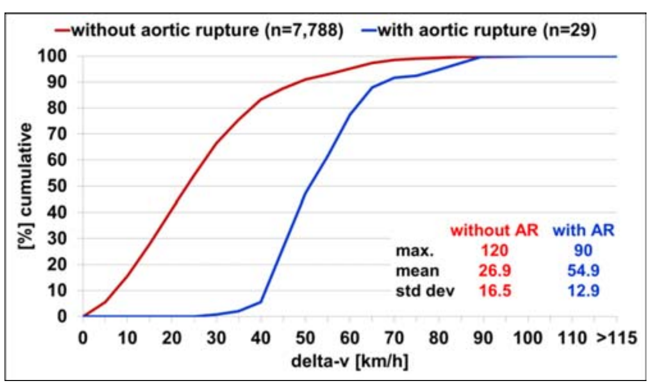

Fig. 11. Cumulative distribution of delta-v in side impacts for car occupants with and without AR.

The collision velocities of the opposing vehicles in pedestrian and bicycle accidents (Fig. 12 and Fig. 13) with an aortic rupture of the vulnerable road user were much higher in comparison with accidents without aortic rupture. Of the total number of pedestrians and cyclists, 70% 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 pedestrians and 50% higher than 80 km/h for cyclists.

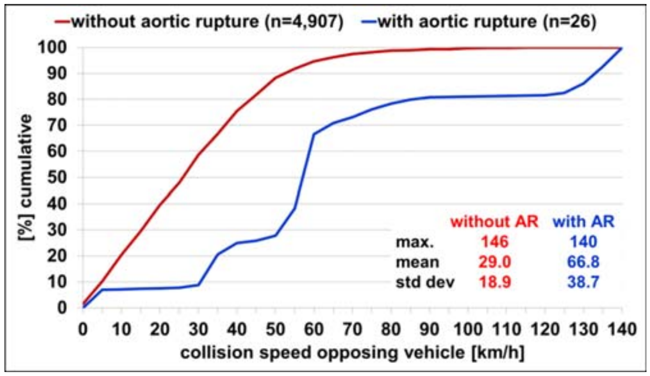

Fig. 12. Cumulative distribution of collision speed of the opposing vehicle for pedestrians with and without AR.

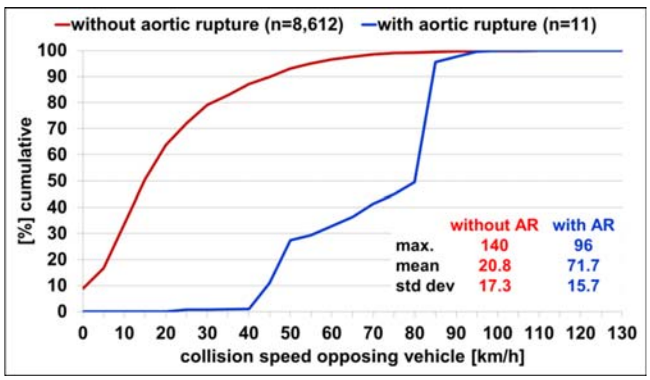

Fig. 13. Cumulative distribution of collision speed of the opposing vehicle for cyclists with and without AR.

For motorcyclists, the relative speed between motorcycle and opposing vehicle can be seen as an indicator for injury severity [30] [33]. For aortic ruptures in motorcycle crashes, the relative speed at the point of collision is mainly high, with 90% above 50 km/h. Compared to these cases, 70% of motorcyclists without aortic rupture had a relative speed of up to 50 km/h (Fig. 14).

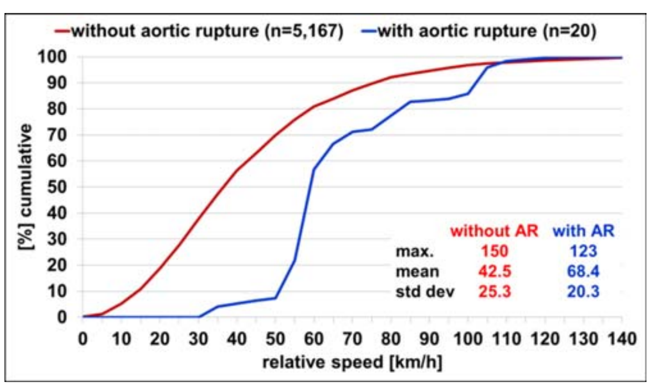

Fig. 14. Cumulative distribution of relative speed for motorcyclists with and without AR.

For truck occupants, the cumulative frequency is limited based on the very low number of truck occupants with aortic ruptures (n=4), but the trend also shows a high accident severity, with high deformation pattern of the truck interior related to aortic ruptures.

Comparison across accident years 1973–1994 / 1995–2014

The analyzed cases were split into two groups: accidents from 1973 to 1994 (called "**past**" cases) and accidents from 1995 to 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 0.94% in the years 1973–1994 and at only 0.10% in the years 1995–2014. A year-related reduction of 89% from 1973–1994 to 1995–2014 of the occurrence of aortic rupture can be calculated from the accident sample. A statistical test (Pearson Chi-Square) was performed to analyze the statistical significance of the occurrence of aortic ruptures over the 40 year period. The results show that the occurrence of aortic ruptures was significant lower in more recent accident years 1995-2014 compared to the past accident years 1973-1994 (Value 253.483; df 1; asymptotic significance < 0.001). There is also a statistical significance when comparing all accident years (Value 1047.042; df 41; asymptotic significance < 0.001). A high reduction of the occurrence of aortic rupture can be registered in Fig. 15, especially for bicyclists (97%), car occupants (92%) and truck occupants (88%, but very low n-number). The decrease of aortic rupture in riders of motorized two-wheelers (65%) and pedestrians (60%) was lower.

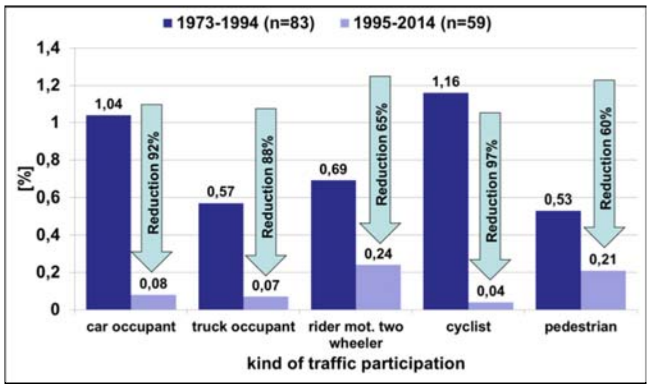

Fig. 15. Distribution of AR for the years 1973–1994 and 1995–2014 for the different kinds of traffic participation.

Fig. 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 died. Additionally, for every person the localization of fatal injuries is coded (head, spine, thorax, abdomen, pelvis, extremities, cumulative causes, not due to injuries, unknown). Analysis of these variables showed that the injuries at the thorax alone were responsible for 18.2% of fatalities in the years 1973–1994, and for 15.5% 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 mentioned. In the past, only 2.6% of the persons with aortic rupture survived, whereas 14.4% survive in present years. Nowadays the cause of death is often a result of severe spine injuries.

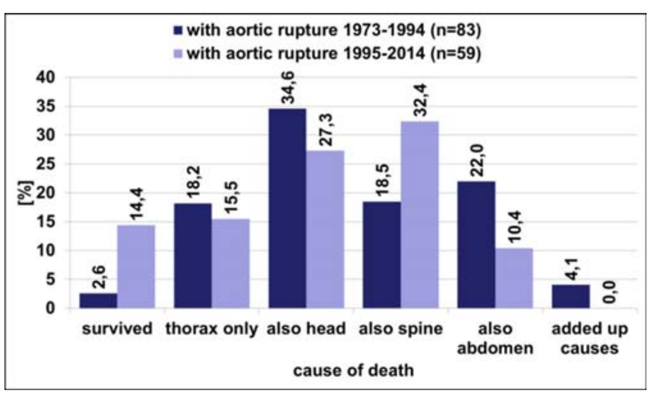

Fig. 16. Causes of death for the persons with AR for the years 1973–1994 and 1995–2014.

The analysis of companion injuries shows that a high number of companion injuries at the thorax are registered in patients with aortic rupture after traffic accidents. That is a reasonable finding because the accidents are characterized by high impact speeds and high accident severity. Serial rib fractures could be found in many of the analyzed cases, especially in vulnerable road users. Injuries at the spine are also often registered among the vulnerable road users. Companion injuries at the chest organs are also often registered in all kinds of traffic participation, especially at the liver, but also at the kidney and the spleen.

A Chi-Square test (Pearson) was performed to analyze the influence of the specific car structures of "old" cars (date of manufacturing before 2005) compared to "new" cars (date of manufacturing after 2004). The thorax injuries of the vulnerable road users (pedestrians, cyclists, motorcyclists) were grouped in three categories (AIS 0-1: uninjured/slightly injured; AIS 2-3: moderate/heavily injured; AIS 4-6: most heavily injured). The test shows a statistical significance (Value 120.66; df 2; asymptotic significance < 0.001) regarding the injury severity of the thorax of vulnerable road users when comparing the collision partners (old/new cars).

IV. Discussion

In this study traffic accidents of the past 40 years were analyzed based on an in-depth investigation via GIDAS data. All cases contain detailed information about the environment, vehicles, injured persons and injuries; every accident was fully reconstructed with regard to 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 and 53,851 injured traffic participants, 142 persons with aortic rupture 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 rupture are characterized by high-speed collisions with multiple body injuries and comprehensive thorax compression of the involved traffic participants. This criterion applies for all kinds of analyzed traffic participation (car/truck occupants, motorcyclists, pedestrians and cyclists). The descriptive statistics show that a large reduction in the occurrence of aortic rupture can be registered over time during the last 40 years (approximately 89% from 1973–1994 to 1995–2014, all kind of road users included).

In the past, aortic rupture was mentioned mainly for non-belted car occupants, while today belted and airbag-protected occupants also suffer from this kind of severe thorax injury and aortic rupture can be observed for motorcyclists, bicyclists and pedestrians, albeit in a very low frequency. The detailed analysis of the 142 cases of this study showed that the force vector to the thorax and the aorta comes 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 was reported in many accidents. As a result, the steering wheel was shifted up and towards the driver of the car (Fig. 17).

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

A direct impact of the thorax against the steering wheel was the main cause of aortic rupture for the driver and impact against the dashboard for the front-seat passenger. Nowadays, in frontal car collisions involving modern cars, an aortic rupture is very rarely reported. This is a result of the improvement of the safety of cars, in particular improvement of the crumple zone, the implementation of front airbags and an improved construction of the steering column. Additionally, the rate of seatbelt use is much higher in present cases compared to past cases. The seatbelt-wearing rate of all car occupants was at 53.8% in the years 1973–1994, whereas it was at 93.0% for 1995–2014.

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 typical for a pedestrian crossing a street and being impacted by a vehicle, resulting in a lateral impact of the thorax against stiff structures of the vehicle, i.e. roof edge (Fig. 18), bonnet, A-pillar or vehicle front (bus, tram, etc.).

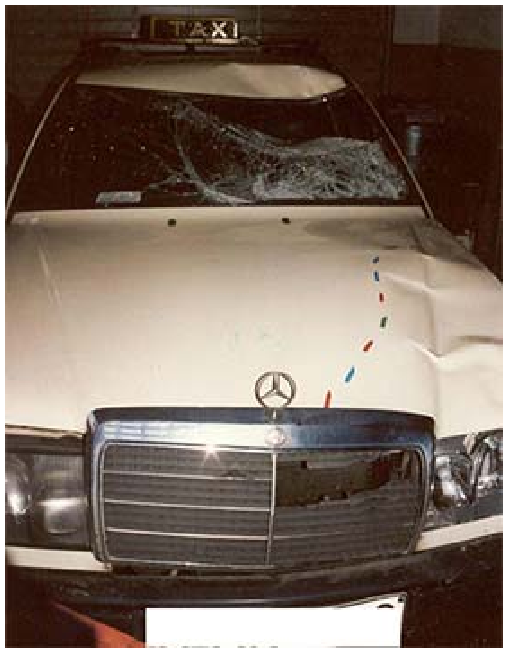

Fig. 18. Example of car–pedestrian accident 1989: thorax impact of the pedestrian at the roof edge of the car.

The aortic rupture in pedestrian accidents has also decreased over the past 40 years but not as much as in car occupants and cyclists. This is among others a result of the improved pedestrian safety of new cars and pedestrian friendly front structures of cars. Today's crash tests also integrated tests to rate the pedestrian protection of cars, i.e. Euro NCAP [34]. Modern cars are equipped with automatic braking systems, which are designed 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 in order to absorb the head-impact energy and reduce the injury severity. Additionally, modern car manufacturers are developing pedestrian airbags, which could also mitigate the injury severity in a car–pedestrian accident.

Related to the motorcyclists, the direction of force from ventral (37.5%) and caudal-ventral (16.7%) to the thorax/aorta of the motorcyclist was the dominant cause of aortic rupture. The occurrence of aortic rupture in motorcyclists has also decreased over the years but not as much as in car occupants and cyclists. This can be explained by an increase of special collision types for motorcyclists over the last 40 years, i.e. accidents with motorcyclist impacts against objects (tree, guardrail) or falls on the road prior to vehicle impact [30] with a high incidence of a run-over of the motorcyclist (15% in 1973–1994 vs. 36% in 1995–2014). Additionally, and in contrast to the improved safety of cars, there have been very few 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 not a given, as it is for cars. For motorcycles there is no crush-collapse zone nor a solid passenger compartment for the protection of the driver. An airbag mounted on the steering column is one possibility to reduce such partly introduced load compression to the thorax by larger load distribution.

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

For truck occupants, the dominant cause of aortic rupture is a force to the thorax from caudal-ventral or caudal. Similar to car occupants, it is caused by direct impact against the steering wheel for the driver or against the dashboard for the front-seat passenger. Furthermore, the deformation of the interior also often influences the thorax deformation.

A previous study at the Medical School Hannover [8] [9] 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 provided by this study shows that a high percentage of aortic ruptures is correlated to a force from caudal-ventral or caudal ventral-lateral to dorsal. Also, the same mechanisms found by Gotzen *et al.* [8] [9] 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 type 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 rupture suffered a polytrauma and in most cases the cause of death was a combination of severe injuries at the head, thorax and spine. Many companion injuries at the thorax were found in these cases (serial rib fractures and/or organ injuries). The analysis showed that only 2.6% of the injured persons with aortic rupture survived in 1973–1994, whereas 14.4% survived in 1995–2014. This is probably a result of better medical treatment in modern hospitals. Additionally, the diagnosis of an aortic rupture after a traffic accident was often delayed or missed in past cases [12].

A study of Arajärvi *et al*. [11] showed that the location of the aortic rupture in unbelted victims was more often in the ascending aorta, especially in drivers, whereas in seatbelt wearers the distal descending aorta was statistically more often ruptured, especially in right-front passengers. These results could not be confirmed by 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 41.8% (n=18), and at the arch of the aorta with 23.3% (n=10). The exact location was unknown in 25.6% (n=11). For seatbelt users with aortic rupture (n=29), the location of the rupture was registered at the ascending aorta in 6.9% (n=2), in the descending aorta in 31.0% (n=9), in the arch of the aorta in 24.1% (n=7); in 38.0% (n=11) the exact location was unknown.

V. CONCLUSIONS

This study showed that aortic rupture is caused by direct and massive compression force to the thorax, in most cases, and especially for car and truck occupants and motorcyclists, from caudal-ventral and ventral-lateral as so-called “shovel mechanism”. Compared to the accident situation in the 1960s and 1970s, where mostly frontal impacts 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 with side impact and in pedestrians who were impacted at the side of the body by a vehicle and then wrapped around over the bonnet to the windscreen and roof structures at high velocity.

The study showed that the occurrence of aortic rupture has decreased enormously over the last 40 years for all kinds of traffic participation. While some of the reasons for the reduction in aortic rupture in Germany over time are likely to be found in better car design and medical practices, statements to this effect are speculative and cannot be supported by specific data presented in the paper. It could be analyzed, based on the whole dataset of GIDAS, that, on the one hand, the parameter for accident severity delta-v reduced from 1999 (mean-value 20.5) to 2014 (mean-value 8.5) and the seatbelt-using rate of all car occupants in Germany increased enormously in same period. On the other hand, there is a significantly lower number of fatalities and severely injured casualties among all kinds of traffic participants over the last 40 years due to better safety standards being implemented in vehicles. Nowadays, persons with aortic rupture are more likely to survive, which is most likely a result of a better medical treatment and faster diagnosis of the concerning injury.

Today, the focus of aortic rupture has changed, although it still exists 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, such as 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 would include speed reduction, seatbelt use, avoiding edgy parts at the vehicles in the areas of impact of vulnerable road users, and the implementation of airbags on motorcycles.

VI. Acknowledgements

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. As of mid-1999, the GIDAS project has collected about 2,000 cases on-scene per year in the areas of Hannover (Medical University Hannover) and Dresden (Technical University Dresden). GIDAS collects data from accidents of all kinds of traffic participation and because of the on-scene investigation and the full reconstruction of each accident, it provides a comprehensive view of individual accident sequences and their causation. The project was 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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