# MEASUREMENT OF AORTIC INJURIES IN LOWER SEVERITY NEAR-SIDE IMPACTS

**Kennerly Digges**
George Washington University; University of Miami, William Lehman Injury Research Center
**Jeffrey Augenstein**
University of Miami Miller School of Medicine; William Lehman Injury Research Center
**Warren Hardy**
Wayne State University, Virginia Tech
**John Cavanaugh**
Wayne State University
**Jessica Steps Jermakian**
George Washington University, IIHS
**Cristina Echemendia**
George Washington University, NHTSA
**Chirag Shah**
Wayne State University, Humanetics Innovative Solutions
USA
Paper Number 11-0265

## ABSTRACT

NASS and Miami Trauma Center data were analyzed to determine the crash environments that produce aortic injuries in lower severity side impacts. Crash tests were analyzed to determine the injury producing acceleration and intrusion environments. Cadaver tests were conducted using high speed X-ray to examine aortic displacements in response to impacts. Biaxial tensile tests of aortic tissue were conducted to determine their dynamic response to loading. FEM and MADYMO models were run to determine the response of the vehicle structure, the human and the aorta when exposed to injury producing environments.

For the seriously or fatally injured population in the William Lehman Injury Research Center (WLIRC) database who were exposed to side impacts, 24% had aortic injuries. By contrast, the injury rate in NASS was about 5%. In WLIRC data, 60% of the aortic injuries occurred at crash severities below 30 mph delta-V. In NASS, 28% occurred at the lower crash severity.

Crash factors in lower severity near-side crashes that influence aortic injury risk include the extent of intrusion, the occupant age, and a D or Y vehicle damage pattern. The best predictor of aortic injury risk, based on currently available cadaver tests utilizes a combination of spinal z acceleration and chest viscous criterion. Based on this metric, the IIHS test condition produced a higher risk of aortic injury than the side NCAP or the side Y-NCAP tests.

Testing of aortic tissue found a general weakness in tension. The inner layer of aortic tissue was found weaker during tension tests of the tissue and initialized tearing under yield tensile loading to the tissue. Rupture of the inner layer may not produce physiological changes immediately but sudden death can result should all three layers rupture. Death caused by delayed rupture of all layers occurred for 60% of the WLIRC patients with side impact induced aortic injuries who survived more than one hour. This result suggests that a large fraction of those with aortic injury produced in low severity side impacts could be treated successfully if diagnosed in time.

## INTRODUCTION

This paper summarizes the results of ten years of research on aortic injury mechanisms directed by The George Washington University and the William Lehman Injury Research Center (WLIRC) and conducted with the collaboration of Wayne State University. The various funding sources are listed in the Acknowledgement Section. The project is referred to as the Cooperative Aortic Injury Research Project.

The project originated in 2001 and was based on observations at the University of Miami's Ryder Trauma Center. At this Level 1 Trauma Center, a high percentage of motor vehicle accident victims exposed to side collisions were found to have aortic injuries. In many cases, the aortic injuries were difficult to detect and the patients were not initially triaged to the Trauma Center, resulting in a high death rate. Those who were successfully treated generally suffered no subsequent impairment [Augenstein, 2003].

These results suggested two critical needs. First, better triage methods were required to permit early identification of the crash victims with incipient aortic injuries. Second, a better understanding of the injury mechanisms was needed so that countermeasures could be designed and evaluated.

The first need was addressed by assessing the characteristics of crashes that produce aortic injuries. The results were intended to be used to raise the suspicion of aortic injury based on data from the vehicle sensors or observations at the crash scene.

The second need was addressed by comprehensive studies of existing cadaver test data, testing the properties of aortic tissue, modeling the vehicle, human and aorta, and conducting additional cadaver tests to study the motion of the aorta in response to impacts using high speed X-ray.

There exists a large amount of literature, dating back over a century that documents studies of Traumatic Rupture of the Aorta (TRA). Fundamental research during the 1980's by Mohan and Melvin [1982, 1983] and Viano [1983] provided a strong basis for the study of aortic trauma in motor vehicle crashes. Some of the most applicable studies are discussed in the paper by Hardy et.al. as part of the Cooperative Aortic Injury Research Project [Hardy, 2008]. Although much is understood about the nature of the injury, little is known about the mechanisms that produce this injury. This is because although there have been many studies examining the pathology of TRA, there have been few studies that have been successful in producing aortic rupture by blunt impact using the human cadaver or an animal as an injury model. Further, cadaver and animal studies have provided little information regarding the kinematics inside the chest and the deformation of the aorta during impact.

## STUDIES OF AORTIC INJURIES IN REAL WORLD CRASHES

The NASS/CDS (National Automotive Sampling System/ Crashworthiness Data System) is a sample of tow-away crashes that occur on US roads each year. The sample is stratified by the severity of the crash. The sample rate for minor crashes is much lower than for severe crashes. In order to expand the stratified sample to the entire population it represents, an inflation factor is assigned to each case in the NASS/CDS sample. Each year approximately 6,000 cases are collected to represent about 6,000,000 occupants in tow-away crashes on the US highways. In this sample, specific injuries that occur in lower severity events are difficult to detect and to represent. For example, fifteen years ago, the severe injuries caused by airbags that deployed in low speed crashes were not observed in NASS. The phenomenon was, however, observed by the William Lehman Injury Research Center among patients transported to the Ryder Trauma Center. This Trauma Center receives a near census of all the seriously injured crash victims in the surrounding area of South Florida. Since the Trauma Center population is based on the injury severity of the occupant rather than the crash severity of the vehicle, the WLIRC database of Ryder Trauma Center patients was able to capture all serious injuries regardless of the severity of the crash in which they occurred.

The Lehman Center database used in this study contains 168 cases of near-side crashes. In these crashes, 41 sustained aortic injury resulting in 35 fatalities. Of these cases, 21 were transported to the trauma center and 15 survived for more than an hour. Six of these cases were treated successfully with no long-term impairment. For the aortic injury cases, the injury rate was 0.24 and the fatality rate was 0.85. For the group with aortic injuries, 37% survived for over an hour and had the best chance of a full recovery [Augenstein, 2003].

Occupants who survive initially but have latent aortic injuries have a high fatality risk. However, if detected and treated promptly, the outcome is generally excellent with no long-term impairment. Latent aortic injuries are often difficult to detect at the scene or in the emergency room. Twenty-three percent of latent aortic injury cases in near-side vehicle-to-vehicle crashes in the WLIRC database did not meet traditional physiologic trauma criteria at the scene, although most were transported to the trauma center under the paramedic judgment of high suspicion of injury.

Some crashes are so severe that an occupant may have sustained aortic tear but also will have sustained other life threatening injuries. For this reason, the discussion to follow will divide the data into two groups: one group contains crashes of all severities and the second contains a subset of crashes with a crash severity (delta-V) of 13.4 m/s (48.3 km/h; 30 mph) and below. Crash victims in the lower severity group are likely to have fewer numbers of serious injuries in addition to the aortic injury. Consequently, their survival is more likely.

Eighty percent of the aortic injuries in near-side crashes occurred in vehicle-to-vehicle crashes and over 60% of these were at a delta-V less than 13.4 m/s. The population of WLIRC vehicle-to-vehicle near-side crashes at delta-V less that 13.4 m/s was analyzed by Steps [Steps 2003]. The database contained 98 cases, 21 of which had an aortic injury. The injury rate generally increased with occupant age and weight.

For vehicle-to-vehicle lower severity near-side crashes, the average age of the occupants with aortic tear was 49 years old. The youngest was 15 and the oldest 89. One-hundred percent of cases had more than six inches of intrusion into the occupant compartment. Sixty-eight percent of the vehicles exhibited Y or D damage patterns. The Y and D damage patterns are depicted in Figure 1.

Steps conducted a multiple regression analysis of a database that combined NASS and WLIRC and data from other trauma centers to assess factors that might best predict aortic injury in lower severity near-side crashes. The result is shown in Table 1. The DL variable in Table 1 refers to a vehicle damage pattern that involves the front 2/3 of the vehicle or the entire side of the vehicle. Figure 1 shows this damage pattern. The damage pattern is defined by the SAE's Collision Damage Classification (CDC) [SAE 1980]

**Table 1.**
**Significant Individual Predictors of Aortic Tear in Crashes with Delta-V of 13.4 m/s (48.3 km/h) (30 mph) or Below (Steps, 2003)**

| Variable | Odds Ratio | P value |
|---|---|---|
| Age | 1.03 | <0.01 |
| Delta-v | 1.105 | <0.01 |
| DL | 2.261 | 0.03 |
| Intrusion | 1.081 | <0.01 |

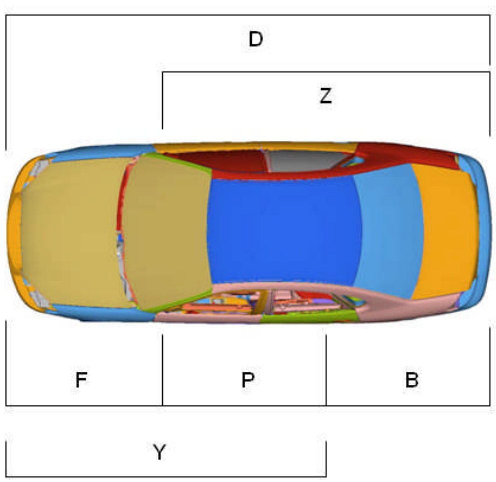


**Figure 1. CDC Definition of Damage Location (SAE 1980)** (DL, Includes Y and D Damage Patterns)

Age, delta-V and intrusion have been highlighted in the past as predictors of aortic tear.[Katyal, 1997; Horton, 2000]. However, Steps conducted the first analysis showing statistical significance of the vehicle's damage pattern. The high positive value of the DL coefficient suggests that the crash configuration may be an important factor that influences the risk of aortic injury.

Echemendia [2008] subsequently conducted a multivariate regression of NASS/CDS cases for the years 1993-2007. The condition for admission was a near-side crash with delta-V recorded. The database contained 783 cases that expanded to 59,112 using NASS weighting factors. There were 77 aortic injuries. The database was separated into two crash severity groups, as shown in Table 2. The highest speed for the low severity category was 13.4 m/sec (30 mph). The significant results of the multiple regression analysis of injuries at the lower speed are shown in Table 3.

**Table 2 –**
**Baseline NASS Data for Studying Aortic Injuries in Near Side Impacts (Echemendia, 2008)**

| | Unweighted | | | Weighted | | |
|---|---|---|---|---|---|---|
| Severity | N | Aortic Injuries | Rate | N | Aortic Injuries | Rate |
| All | 783 | 77 | 0.098 | 59,112 | 2,913 | 0.049 |
| High | 385 | 59 | 0.153 | 26,602 | 2,108 | 0.079 |
| Low | 398 | 18 | 0.045 | 32,510 | 805 | 0.025 |

**Table 3.**
**Results of Multivariate Regression Analysis of Factors that Influence Aortic Injury Risk in Lower Severity Near-side Impacts (Echemendia, 2008)**

| | Unweighted | | Weighted | |
|---|---|---|---|---|
| Parameter | Odds Ratio | P-VALUE | Odds Ratio | P-VALUE |
| Age | 1.022 | <0.0001 | 1.018 | 0.0225 |
| Weight | 1.017 | 0.005 | 1.015 | 0.0018 |
| Intrusion | 1.494 | 0.0011 | 1.828 | 0.0041 |
| Damage Location | | 0.0379 | | <0.0001 |
| Damage Location Dvs.P | 2.336 | | 4.799 | |
| Damage Location Yvs.P | 0.949 | | 0.986 | |
| Damage Location YDvs.BZFP | 1.28 | | 2.037 | |

The analysis by Echemendia indicates that occupant weight is an additional factor that influences aortic injury risk in lower severity near-side crashes. The distributed damage pattern was found to induce a much higher risk than a pattern in which damage was confined to the occupant compartment. In addition, the distributed damage pattern (D) appears to be more influential than the front 2/3 damage pattern (Y). The combination of Y and D damage patterns was more influential than the combination of other damage patterns. This result confirmed the earlier findings of Steps, who used a different database. In the WLIRC database used by Stepps, the Y damage was much more frequent and influential than D damage.

## STUDIES OF MATERIALS PROPERTIES OF THE AORTA

The aorta is a tubular structure and has two anatomical axes: the longitudinal (or axial) and the circumferential (or transverse) directions. The wall of the aorta has three layers, or tunics (Figure 2). The innermost layer is the tunica interna (the intima), which consists of a lining of endothelial cells supported by a layer of collagenous connective tissue containing a network of elastic fibers. The tunica media (the media) is the middle layer, which consists of elastic connective tissue, smooth muscle cells, and a fine network of binding collagen fibers. In the aorta, the media is the thickest layer. The outermost layer is the tunica externa (the adventitia), which is comparatively thin and consists of connective elastic and collagen fibers and bundles of smooth muscle tissue. It is in the circumferential direction that the overwhelming majority of aortic tears are observed clinically, and these tears typically involve the intima and the media (Cammack et al., 1959).

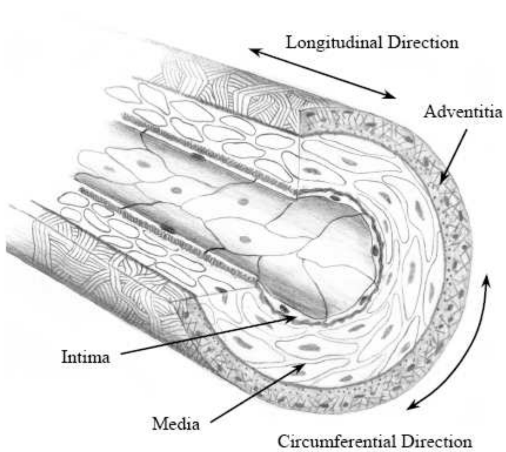


**Figure 2. Wall Structure of the Aorta (Hardy, 2008)**

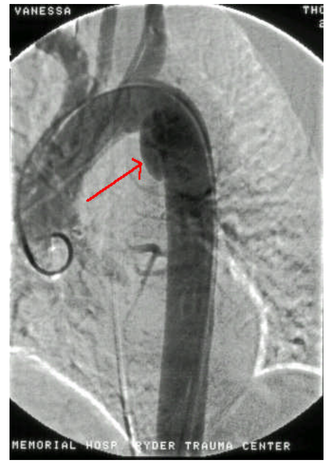


**Figure 3. Image of Aorta with Partial Rupture**

Figure 3 shows a fluoroscopic image of an aorta that has a partial rupture of the two inner layers. The difference in elasticity and ultimate strength of the three layers can explain this failure mode.

Tensile tests of specimens from each of the three layers found that the unconstrained intima and media failed at a much lower circumferential strain levels than the adventitia [Holzapfel, 2005]. For the media, the failure strain level was about 50% and for the intima the level was only 10%. Computer modeling of a three layered section of the aorta indicated that the outer layers may apply a compression stress to the intima when in situ [Zhao, 2006]. It also predicted the earlier rupture for these two layers.

The consequence of this failure mode has a profound influence on the recognition and treatment of people with aortic injuries. The greater strain tolerance of the adventitia can sustain its integrity and prevent or minimize blood loss even after partial rupture of the inner layers. Consequently, there may be no physiological indicators of the injury. However, subsequent rupture of the adventitia long time periods after the injury has occurred can lead to sudden and unexpected death. As noted earlier, 37% of the patients with aortic injuries in the WLIRC study survived for more than one hour. The difficulty of recognizing this class of aortic injuries underscores the need for a better understanding of ways to predict and prevent them.

To further the understanding of TRA and provide materials properties for computer simulation, a unique dynamic bi-axial test device was developed at Wayne State [Mason, 2005]. Shah [2006] used this device to study the mechanical properties of tissue from various regions of the aorta. The tests were performed at a nominal speed of 1m/s and 5 m/s. Aorta tissue properties and failure thresholds were obtained by conducting biaxial tissue tests on cruciate samples and longitudinal stretch tests on whole aortas. For the first time, aortic tissue was tested biaxially at an average strain rate of 85 $s^{-1}$ which is commensurate with loading rates in the automotive crash environment. Three regions of the aorta: ascending, descending, and peri-isthmus were tested to investigate differences in the regional properties of the aorta. Structural response of the aorta was obtained by longitudinal stretch test at rate of 1 m/s.

The failure strain levels determined by Shah [2007] are presented in Table 4. Of primary interest is the longitudinal tensile failure threshold for the isthmus.

**Table 4.**
**Aorta Tensile Failure Thresholds (Shah, 2007)**

| Region | Ave. Maximum Principal Strain Rate (s-1) | Longitudinal Lagrange Failure Strain |
|---|---|---|
| Ascending | 100.94 ± 31.34 | 0.277 ± 0.126 |
| Descending | 72.51 ± 49.24 | 0.244 ± 0.044 |
| Isthmus | 89.68 ± 58.18 | 0.217 ± 0.137 |
| Overall | 84.97 ± 48.07 | 0.244 ± 0.100 |

Shah's dissertation research [2007] concluded that the aorta fails with circumferential-direction tears and the intima layer fails before the media or adventitia layer. The aorta was characterized by a nonlinear stress-strain response. For the peri-isthmus and descending regions, the longitudinal failure stress increases as the strain rate increases. The aortic tissue is anisotropic with different material properties along longitudinal and circumferential directions. In the circumferential direction (Young's modulus 11.37 MPa) of the aortic tissue is stiffer than the longitudinal direction (Young's modulus 7.79 MPa). As a complete structure, the aorta fails within the peri-isthmic region and can transect completely at 92 N of axial tension or at an axial strain of 0.221. Intimal tears can accompany complete transections.

Shah's FE simulations demonstrated regions of relatively high stress and strain in the peri-isthmic region for near-side impact cases, which is indicative of those seen clinically. Shah concluded that the anterior sternum displacement may be important to TRA, as the aorta is pulled by the sternum away from the spine during side impacts.

Figure 4 shows the configuration of the aorta, its attachment to the spine and its connection to the heart. It is evident that chest compression that displaced the heart laterally could cause the aorta to stretch relative to the spine. Motion of the heart upward could also cause the aorta to stretch. Upward motion could be caused by positive displacement of the chest organs from chest compression or from vertical acceleration. Localized impacts to the chest of cadavers could be used to study the consequence of chest compression on aortic loading. However, the effects of vertical spinal acceleration cannot be easily measured by impact tests.

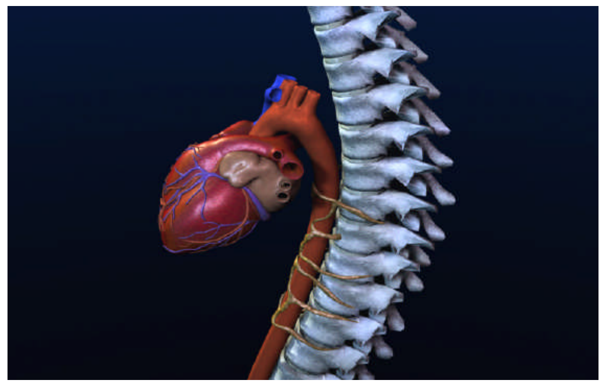

**Figure 4. The Aorta Spine Attachment**

## STUDIES OF CADAVER SIDE IMPACT TESTS THAT PRODUCED AORTIC INJURIES

As noted earlier, aortic injuries have rarely been observed in cadaver tests that simulate motor vehicle crashes. Aortic injuries were observed in only 5 of 137 side impact cadaver tests in NHTSA's database [Steps 2003]. These five injuries occurred during a project funded by the U.S. Centers for Disease Control that involved a total of seventeen tests at Wayne State University conducted by Cavanaugh [1990, 1993]. In these tests, a side crash was simulated when the test sled impacted a barrier, allowing the instrumented cadaver positioned on a low-friction seat to impact an instrumented side wall at a predetermined velocity. One purpose of the tests was to evaluate variations in side padding stiffness and geometric configurations. A configuration of particular interest, called pelvic-offset, involved 152 mm (6 inch) offset of the metal wall at the height of the pelvic region. This offset in the wall caused the material surface to load and displace the lower body before the chest loading occurred.

For the 17 tests, 3 sled speeds were used: 6.7, 9.0, and 10.5 m/s. Three wall configurations were used - rigid flat wall, rigid wall with a 152 mm offset toward the pelvis, and a flat wall with padding of varying stiffness. Multiple load and acceleration measurements were made on the wall and cadaver. Potential injury parameters were evaluated and their relative predictive abilities were examined.

Five of the seventeen tests resulted in AIS 4 or 5 TRA. Most were partial circumferential tears in the periisthmic region. All tears resulted from tests involving the rigid barrier or stiff padding. Tests involving softer padding did not result in TRA.

Cavanaugh performed a logistic regression analysis to determine if a relationship existed between TRA and independent variables in this study. Aortic injury was considered the dependent variable and was assigned a value of 0 or 1. Biomechanical responses including rib, spine and sternum accelerations, chest compression, viscous criterion and barrier forces as well as age were analyzed as independent variables. ASA, VCmax and Cmax were evaluated as injury criteria. Cavanaugh et al. [1994] suggested that average spine acceleration (ASA) was a candidate predictor of chest injury. The other two predictors of chest injuries, VCmax (Lau and Viano, 1986) and Cmax (Kroell et al., 1974) are currently used as injury criteria measured by crash test dummies. The risk prediction accuracy of these three predictors and combinations with vertical spinal acceleration (T12Z) are shown in Table 5. The addition of spinal Z acceleration in conjunction with VCmax, Cmax or ASA provided the best prediction. Upper sternum displacement (UpsX in Table 5) and ASA also produced a good prediction. These results suggest that traction on the aortic arch through anterior displacement of the sternum or vertical displacement of the spine can increase the risk of aortic injury.

**Table 5.**
**Logistic Regression Coefficients and Accuracy Measures for Aortic Injury Risk Prediction (Cavanaugh 2005)**

| Variable or Combination | k1 | k2 | k3 | Chi-square | P value |
|---|---|---|---|---|---|
| ASA 10 at T12 | | | | 5.216 | 0.0224 |
| Cmax | | | | 2.329 | 0.127 |
| VCmax | | | | 3.959 | 0.0466 |
| k1*T12Z+k2*ASA+k3 | 0.0426 | 0.2123 | -12.03 | 8.985 | 0.0027 |
| k1 *T12Z+k2*Cmax+k3 | 0.0236 | 0.3666 | -20.97 | 8.438 | 0.0037 |
| k1*T12Z+k2*VCmax+k3 | 0.0294 | 4.6622 | -10.452 | 9.76 | 0.0018 |
| k1*UpsX+k2*ASA+k3 | 0.0964 | 0.1889 | -16.168 | 8.405 | 0.0037 |

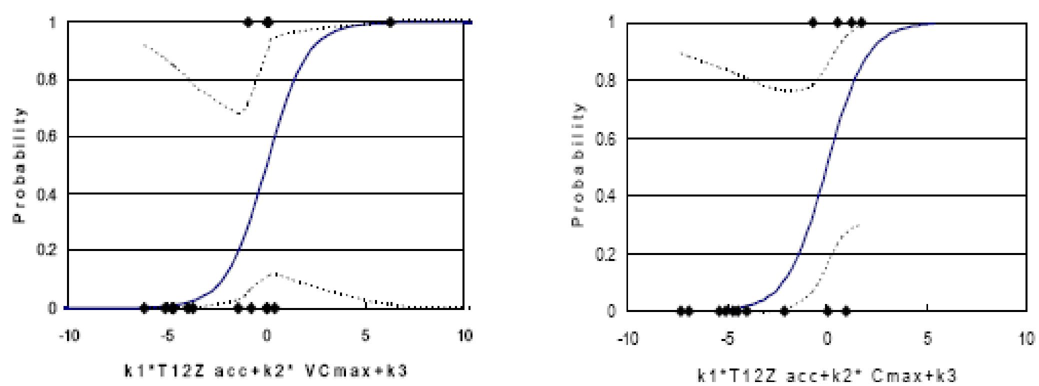


**Figure 5. Logist Plot of Probability of AIS4 or Higher to the Aorta vs. Combination of T12Z acceleration and [VC]max (left) and Cmax (right) (Cavanaugh, 2005)**

Plots of the probability of AIS 4+ aortic injuries based on T12 and VCmax or Cmax are shown in Figure 5. Theses plots are based on the population of 17 cadaver tests in the Cavanaugh et al study. The 95% confidence intervals for the probability curves of Figure 5 are fairly wide and the sample size is limited. Nevertheless, the results provide data that indicate that chest compression, vertical acceleration and sternum displacement are promising areas for further study regarding aortic injury mechanisms. Additional cadaver and simulation studies were carried to address these issues, as described in the following sections.

## CADAVER TESTS DESIGNED TO STUDY AORTIC INJURIES

Under the Cooperative Aortic Injury Research Project, Wayne State University conducted 7 cadaver tests with markers on the aorta that could be observed during a chest impact by high speed x-ray [Hardy 2008]. The author observed that the position of the heart in cadavers subjected to crash tests was lower than it would be in a living human. The position of the heart may influence the risk of producing an aortic injury. To test this hypothesis, the cadavers in this test program were inverted to reverse the effects of gravity.

A specially designed cadaver fixture, first described by Hardy et al. [2006], and linear impactor were developed for this series of tests. The high-speed biplane x-ray system of the Motion Analysis Laboratory of Henry Ford Hospital was used to image the aorta during impact. This is the same system employed by Hardy et al. [2007] for the study of head impact kinematics. Visible light video cameras were used to observe the events overall and to estimate the motion of the cadaver spine.

Three side impact tests of cadavers conducted in the program. One purpose was to investigate the mechanism associated with anterior sternum motion as discussed by Cavanaugh et al. [2005] and Melvin et al. [1998] combined with lateral heart displacement. For the three side impacts (Test XR4, XR5, and XR6), the cadavers were inverted and pitched rearward. The cadavers were rotated 30-degrees from vertical for these tests. This configuration was used to investigate lateral chest compression and anterior sternum motion as a potential TRA mechanism. Test XR4 and XR5 involved side impacts with and without engaging the arm and shoulder. In tests XR4 and XR6 the arms were placed alongside the ribcage and were engaged by the impactor and backing support plate. In Test XR5, the upper extremities were allowed to dangle below the cadaver so that the ribs were engaged directly. The impactor was aimed at the approximate location expected to be assumed by the humerus mid-diaphysis for a seated posture. The cadavers were impacted on the left side.

All three tests produced tears of aortic tissue that extended into the media. The tear in test XR4 also extended into the aventitia. All of the tears had a circumferential component, two of which were near the ligamentum arteriosum. The third was across the lesser curvature in an area involving substantial plaque.

Hardy results showed that the unique testing methods facilitated the generation of TRA in a cadaver. Circumferential tears through the intima, media, and adventitia were observed in the peri-isthmic region. High-speed biplane x-ray techniques were used to visualize the motion of the aorta and to measure longitudinal strain in the aorta. The results of this study provided a better understanding of the mechanisms associated with TRA. These results can be used for the validation of finite element models developed for the examination and prediction of TRA.

This Wayne State study found that clinically relevant TRA can be generated in the cadaver using the experimental techniques that were developed and employed. The tests showed that when atherosclerosis is present, TRA tends to occur within regions of plaque. When TRA occurs within a region of plaque, longitudinal tensile strain can be below established failure thresholds for the aorta.

The study described the motion of the aorta under side impact. The high speed X-rays showed that the isthmus of the aorta moves medially and anteriorly during impact to the left side. Dorsocranial and anteromedial motion of 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. Consequently, the anterior sternum displacement may be important to TRA, as the aorta is pulled by the sternum away from the spine during side impacts.

## CRASH TEST SIMULATIONS ADRESSING AORTIC INJURY RISK

Steps [2003] used a finite element model of a Dodge Neon to evaluate the damage and intrusion observed in crash tests that produced Y and P damage patterns as defined in Figure 1. A FE model of the NHTSA barrier was used as the bullet vehicle. Two impact locations were simulated. The first duplicated the side NCAP test and produced P-damage. The second impacted at the front wheels and produced Y-damage. The resulting door damage profile and intrusion were used as input data to a MADYMO simulation of the occupant response. Available side dummy models were used in the MADYMO simulations. The simulation results indicated that the MADYMO human facet model reported differences in injury risk in Y-damage crashes while the SID model did not. This result suggests that a more sophisticated dummy than the SID may be required to predict aortic injuries. A major feature of the MADYMO human facet model is a more human-like spine.

Alonso [2007] evaluated the kinematics of MADYMO dummies in far-side crashes. He found that the head excursion of the MADYMO human facet model closely matched that observed during a baseline cadaver test. Other MADYMO dummies including the BioSID, EuroSID and SID2s experienced less head excursion and did not react in a way similar to the cadaver in the baseline test. Alonso's research tends to confirm the observation by Steps that a more flexible spine is desirable to improve injury predictions that require head excursion or Z acceleration.

Shah [2005] reconstructed a crash from the WLIRC database that involved an aortic injury. He used a finite element model of a Ford Taurus and a whole-body human FE model [Shah 2001, 2004] developed by Wayne State University. The whole-body human FE model was not able to simulate rib fractures and rupture of other tissues. Shah concluded that significant limitations need to be addressed before reconstruction of actual crashes can be used to reliably investigate aortic injury mechanisms.

Echemendia applied computer modeling to evaluate the test conditions most likely to produce aortic injury [Echemendia, 2008]. The finite element models of the vehicle and moving deformable barriers used in this study were developed and validated by the National Crash Analysis Center at The George Washington University. The vehicle model was of a 2001 Taurus. The NHTSA and IIHS barrier models were used as bullet vehicles. The research focused on the evaluation of how the crash environment produced by different test conditions would influence the risk of aortic injury.

The models were used to reproduce three different crash environments, as shown in Figure 6. The first environment, designated NCAP, was a crash test using the NHTSA barrier at an impact speed of 61.95 k/hr (38.5 mph) and impacting the occupant compartment in the same impact location and barrier orientation as the NCAP test. The second environment, designated Y-NCAP, was the same barrier and speed configuration as the first, but changing the impact location to the front wheels in order to produce Y damage. The third configuration, designated IIHS, used the IIHS barrier and test configuration – 50 k/hr and impact at the occupant compartment. .

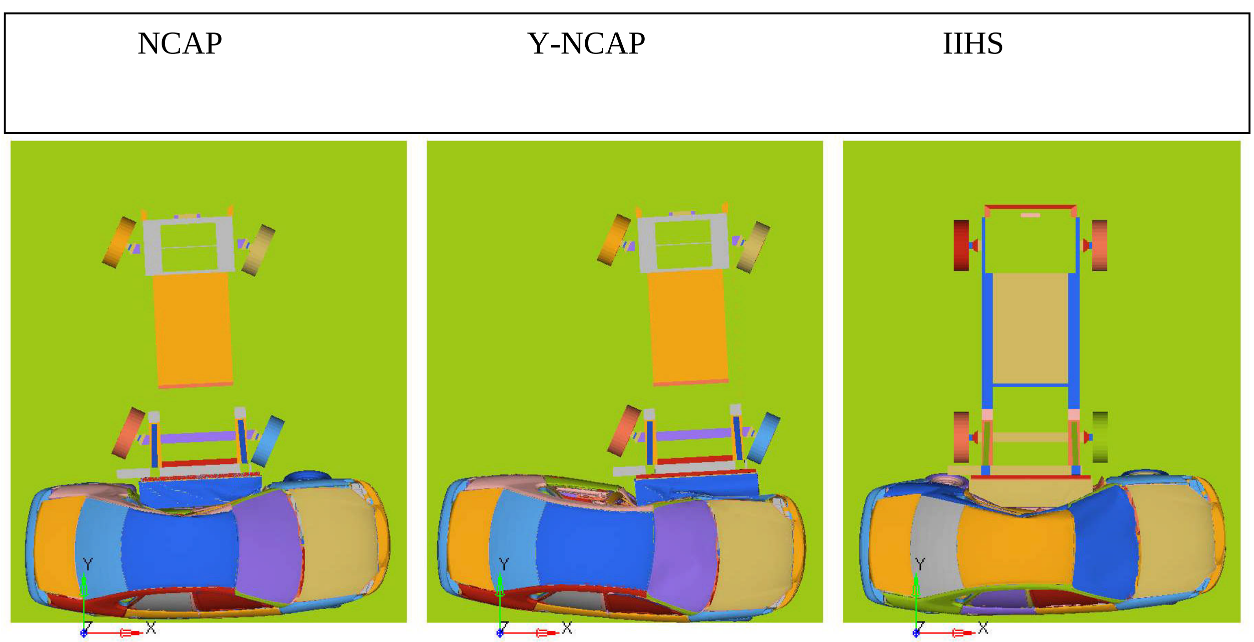


**Figure 6. Top View of FE Simulations Side NCAP, Y-Damage NCAP and IIHS Tests**

Figure 6 depicts the difference in damage patterns produced by the three test conditions. The NCAP test produced the maximum intrusion at the rear door. The Y damage test impacted the stiff front suspension inducing maximum intrusion at the center of the front door. The IIHS test produced uniform occupant compartment damage and the largest amount of door intrusion at the center of the front door.

The vehicle simulations produced the vehicle accelerations and the door intrusion profiles and velocities that were applied to an occupant model to evaluate injury response. The occupant model used was the MADYMO human facet model. This model replicates the response of the human spine more closely than the dummies currently used in side crash tests.

The human facet dummy was subjected to the three crash environments and the injury risks were calculated by applying aortic injury predictors suggested by Cavanaugh, Table 5. Cavanaugh risk functions that used T12Z in combination with VCmax and Cmax were calculated based on the maximum values produced by either rib 4 or rib 8. In both cases, the order of increasing severity was: NCAP, Y-NCAP, and IIHS. The increasing risk values for T12Z-VCmax were: 11%, 75% and 98%. The increasing values for T12Z-Cmax were: 35%, 48% and 100%. These results indicate that the IIHS barrier test produced the highest risk of aortic injury.

In order to gain insight into the role of the T12z as related to aortic injury risk, Echemendia incorporated a simple spring- mass model into the MADYMO human facet model. The mass of the heart was constrained to displace in the z-direction and was resisted by a spring with aortic properties as determined by a Wayne State University dissertation that was part of this project [Shah 2007].

Figure 7 shows the stress-strain response for the peri-isthmus region that was developed by Echemendia to represent a typical aortic response. Failure was assumed at a strain of 0.175.

Using Figure 7 as the basis for a spring model that represented the aorta, the percentage of the failure elongation for the three test conditions was: NCAP - 21%; Y-NCAP – 62% and IIHS - 76%.

In addition, Echemendia used the human facet model with the simple heart/aorta model to simulate the Cavanaugh cadaver tests with and without pelvic offset. The percentages for the aorta elongation results were - no pelvic offset: 9%; pelvic offset: 111%. The T12-VCmax predictor of injury risk gave the following results - no pelvic offset: 14%; pelvic offset: 76%.

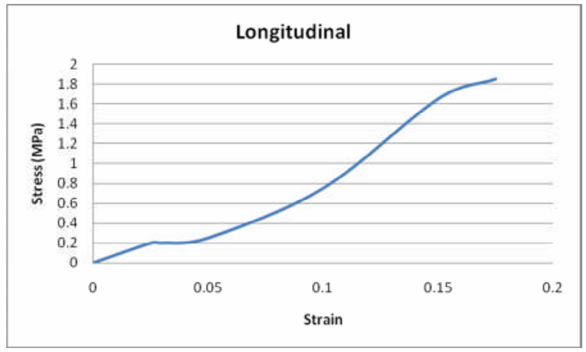


**Figure 7. Longitudinal Stress-Strain Response for the Peri-Sithmus Region of the Aorta** Adapted by Echemendia from Shah, 2007

**DISCUSSION**

The motivation for this study came from observations of patients in the William Lehman Injury Center (WLIRC) database who had been seriously or fatally injured in motor vehicle crashes. The WLIRC database is a near census of seriously or fatally injured occupants in South Florida who were involved in side crashes or in frontal crashes when protected by seat belts and/or air bags. Aortic injuries were frequently observed in both frontal and side crashes. However, those patients with aortic injury who were injured in frontal crashes generally had other injuries of equal or greater severity. In side crash population, the aortic injury was generally the most severe injury and the cause of death.

For the seriously or fatally injured population in the WLIRC database that was exposed to side impact, 24% had aortic injuries. By contrast, the aortic injury rate in NASS was about 5%. In WLIRC data, 60% of the aortic injuries occur at crash severities below 30 mph. In NASS, 28% occur at the lower crash severity.

There are several possible reasons to explain this difference in aortic injury rate. The first reason involves the difficulty in clinically recognizing many of the potentially fatal aortic injuries. Rupture of the inner two layers of the aorta may be undetected in some patients (when the adventitia remains intact) or may produce sudden death in others. A second reason may be that the NASS sample of fatalities with complete autopsies may be insufficient to accurately determine the frequency of aortic injuries. By contrast, medical personnel from WLIRC were present at the autopsies of fatally injured crash victims that were transported directly to the facilities of the medical examiner without entering the Trauma Center. Autopsies were performed on 100% of the fatalities and the results were entered into the WLIRC database.

Crash factors in lower severity near-side crashes that influence TRA risk include extent of intrusion, occupant age and vehicle damage pattern. NASS data suggest that occupant weight is also a factor. With regard to damage pattern, two different patterns appear influential. Both NASS and WLIRC data indicate that the combination of D and Y patterns are most influential. However, NASS indicates that the D pattern has more influence while WLIRC shows that the Y pattern is more influential.

TRA was not produced in the cadaver tests that formed the basis of the side impact injury measures used on side impact dummies. Based on a limited number of cadaver tests with aortic injury, Cavanaugh found that ASA or VCmax in combination with T12Z are the best candidates for aortic injury risk measures. Hardy's tests of inverted cadavers impacted in the side found that the heart and aortic arch move anteriorly with the sternum to which they are tethered. When the impact is through the arms, the ribcage and shoulder (via connection to the clavicle) can force the sternum away from the spine to a greater extent than when the impact is administered directly to the chest. Motion and subsequent stretching of the aortic arch relative to the spine was reported to be the cause of TRA in Hardy's tests. The results of Melvin et al. [1998] and Cavanaugh et al. [2005] reinforce the importance of anterior motion of the sternum, and the importance of limiting chest compression and clavicle motion. Hardy's observations in conjunction with Cavanaugh's finding that T12Z is an influencing factor suggests that anterior motion of the sternum as well as a vertical motion component might be important to TRA.

The research of Hardy [2008] highlights the reasons that TRA has been largely absent in previous cadaver tests. The historical lack of success in generating TRA in whole-body cadaver testing is most likely related to the position and orientation of the heart and aorta in the cadaver. In the seated cadaver, the heart is typically more caudal and dorsal, and tends to pitch rearward as compared to the human [Gardner et al., 1960]. Therefore, the typical seated posture used for cadaver tests would place the heart and aorta in a configuration unlikely to generate the level of longitudinal tension in the aortic isthmus that is required for TRA to occur during impact. Further, loading modes designed to maximize longitudinal strain in the peri-isthmic region have not been investigated in all cases. Finally, appropriate perfusion techniques, which have not always been employed as a rule, can aid in the ability to generate TRA in the laboratory.

The research of Shah [2005, 2006 and 2007] provides materials data and models to assist in modeling aortic injury. Hardy's tests [2008] provide strain and motion data for the peri-isthmic region during impact. These data can be used for model development and validation.

Using criteria suggested by Cavanaugh, the computer simulations by Echemendia [2008] indicate that the IIHS side impact test produces a higher risk of aortic injury compared to the NCAP and Y-NCAP tests. The simulations further suggest that the pelvic offset configuration increased the aortic risk for the crash environments used by Cavanaugh.

**CONCLUSIONS**

Studies of the William Injury Research Center database of vehicle occupants with serious or fatal injuries from near-side crashes found that about half died at the scene. The other half was transported to a medical center. Of those transported to the medical centers, 60% survived for over one hour, but more than half of this group died. Survivors who were discharged suffered no long term impairment. Normal physiological indicators frequently give no indication of potentially fatal aortic injuries when rupture is limited to the inner layers, but when recognized and treated the outcome is good.

Aortic injuries represented 24% of the serious or fatal injuries in near side impacts in the WLIRC data compared to 5% in NASS. The death rate for WLIRC cases with aortic injury was 85%. About 60% of the WLIRC aortic injuries were in crashes with a delta-V less severe than 13.3 m/s (30 mph) compared to 28% in NASS.

Studies of aortic tissue subjected to dynamic bi-axial loading produced the following results:

- The aorta fails with circumferential-direction tears,
- The intima layer fails before the media or adventitia layer of the aorta,
- Material properties of aortic tissue subjected to dynamic bi-axial loading are now available.

Studies of cadavers subjected to lateral impacts provided the following results:

- The isthmus of the aorta moves medially and anteriorly during impact to the left side,

- Dorsocranial and anteromedial motion of 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,
- The anterior sternum displacement may be important to TRA, as the aorta is pulled by the sternum away from the spine during side impacts.

Crash factors in lower severity near-side crashes that influence TRA risk include:

- Extent of intrusion,
- Occupant age,
- D or Y vehicle damage pattern as defined in Figure 1.

Studies of the Cavanaugh cadaver tests and modeling of crash and dummy tests produced the following results:

- The best predictor of aortic injury risk, based on Cavanaugh's tests was a combination of spinal Z acceleration and chest viscous criteria,
- Based on the spinal Z acceleration and chest viscous criterion, the IIHS test condition produced a higher risk of aortic injury than the side NCAP or the side Y-NCAP tests.

**ACKNOWLEDGEMENT**

The initial studies of aortic injuries at the WLIRC were sponsored by the Takata Corporation under the direction of Mr. K. Higuchi. The WLIRC database was developed with the support of the National Highway Traffic Administration. The subsequent funding for this research has been provided [in part] by private parties, who have selected Dr. Kennerly Digges [and FHWA/NHTSA National Crash Analysis Center at The George Washington University] to be an independent solicitor of and funder for research in motor vehicle safety, and to be one of the peer reviewers for the research projects and reports. Neither of the private parties have determined the allocation of funds or had any influence on the content of this report.

**REFERENCES**

Alonso, B., Digges, K., and Morgan, R. (2007) Far-side vehicle simulations with MADYMO. SAE 2007-01-0378, April 2007.

Augenstein, J, Digges, K., Steps, J., Higuchi, K., and Ato., T. (2003) Crash attributes that influence aortic injuries in near-side crashes. Paper 232, Proceedings of the ESV Conference, May, 2003.

Cammack, K., Rapport, R.L., Paul, J., and Baird, W.C. (1959) Deceleration injuries of the thoracic aorta. AMA Archives of Surgery, 79(2):244-251.

Cavanaugh, J.M., Koh, S.W., Kaledhonkar, S.L., and Hardy, W.N. (2005) An analysis of traumatic rupture of the aorta in side impact sled tests. SAE Technical Paper No. 2005-01-0304. Society of Automotive Engineers, Warrendale, PA.

Cavanaugh, J.M., Zhu, Y., Huang Y., and King, A.I. (1993) Injury Response of the thorax in side impact cadaveric tests. Proc. 37th Stapp Car Crash Conference, pp. 199-222.

Cavanaugh, J.M., Walilko, T.J., Malhotra, A., Zhu, Y., and King, A.I. (1990) Biomechanical response and injury tolerance of the thorax in twelve sled side impacts. Stapp Car Crash Journal, 34:28-38.

Echemendia, C., (2008) Inertia effects of the heart as a factor in aortic injuries in near-side impacts, Master's Thesis, The George Washington University, December, 2008.

Gardner, E., Gray, D.J., and O'Rahilly, R. (1960) Anatomy. W.B. Saunders Co., Philadephia, PA.

Hardy, WN; Shah, CS; Mason, MJ; Kopacz, JM; Yang, KH; King, AI; Van Ee, CA; Bishop, JL; Banglmaier, RF; Bey, MJ; Morgan, RM; Digges, KH (2008) Mechanisms of Traumatic Rupture of the Aorta and Associated Peri-isthmic Motion and Deformation. Stapp Car Crash Journal, 52:233-265.

Hardy, W.N., Mason, M.J., Foster, C.D., Shah, C.S., Kopacz, J.M., Yang, K.H., King, A.,I., Bishop, J., Bey, M., Anderst, W., and Tashman, S. (2007) A study of the response of the human cadaver head to impact. Stapp Car Crash Journal, 51:17-80.

Hardy, W.N., Shah, C.S., Kopacz, J.M., Yang, K.H., Van Ee, C.A., Morgan, R., and Digges, K. (2006) Study of potential mechanisms of traumatic rupture of the aorta using in situ experiments. Stapp Car Crash Journal, 50:247-265.

Hardy, W.N., Schneider, L.W., and Rouhana, S.W. (2001) Abdominal impact response to rigid-bar, seatbelt, and airbag loading. Stapp Car Crash Journal, 45:1-31.

Holzapfel, A, Sommer G, Gasser TC, and Regitnig R. (2005) Determination of the layer-specific mechanical properties of human coronary arteries with non-atherosclerotic intimal thickening, and related constitutive modeling. American J. Physiology Heart Circulation Physiology 2005; 289: H2048-2058.

Horton, T, Cohn, S., Heid, M., Augenstein, J., Bowen, J., McKenney, M., Duncan. R. (2000) Identification of trauma patients at risk of thoracic aortic tear by mechanism of injury. Journal of Trauma-Injury Infection & Critical Care 48(6): 1008-13; June, 2000.

Katyal, D., McLellan, B.A., Brenneman, F.D., Boulanger, B.R., Sharkey, P.W., and Waddell, J.P. (1997) Lateral impact motor vehicle collisions: Significant cause of blunt traumatic rupture of the thoracic aorta. The Journal of Trauma, 42(5):769-772.

Kroell, C., Schneider D., and Nahum, A. (1974) Impact tolerance and response of the human thorax II. Proc. 18th Stapp Car Crash Conference, pp. 383-457. Society of Automotive Engineers, Warrendale, PA.

Lau, I.V., and Viano, D.C. (1986) The viscous criterion - basis and applications of an injury severity index for soft tissues. Proc. 30th Stapp Car Crash Conference, pp. 123-142. Society of Automotive Engineers, Warrendale, PA.

Mason, M.J., Shah, C.S., Maddali, M., Yang, K.H., Hardy, W.N., Van Ee, C.A., Digges, K. (2005) A new device for high-speed biaxial tissue testing: application to traumatic rupture of the aorta. Transactions of the Society of Automotive Engineers, Paper No. 2005-01-0741.

Melvin, J.W., Baron, K.J., Little, W.C., and Gideon, T.W. (1998) Biomechanical analysis of Indy race car crashes. Proc. 42nd Stapp Car Crash Conference, pp. 247-266. Society of Automotive Engineers, Warrendale, PA.

Mohan, D. and Melvin, J. (1982) Failure properties of passive human aortic tissue. I-uniaxial tension tests. Journal of Biomechanics, 15(11):887-902.

Mohan, D. and Melvin, J. (1983) Failure properties of passive human aortic tissue. II-Biaxial Tension Tests. Journal of Biomechanics, 16(1):31-44.

SAE J 224 (1980) Collision deformation classification, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, USA, 1980.

Shah, C.S. (2007) Investigation of traumatic rupture of the aorta (TRA) by obtaining aorta material and failure properties and simulating real-world aortic injury crashes using the whole-body finite element (FE) human model. PhD Dissertation, Mechanical Engineering, Wayne State University, Detroit, Michigan.

Shah, C.S., Hardy, W.N., Mason, M.J., Yang, K.H., Van Ee, C.A., Morgan, R., and Digges, K. (2006) Dynamic biaxial tissue properties of the human cadaver aorta. Stapp Car Crash Journal, 50:217-245.

Shah, C.S., Hardy, W.N., Yang, K.H., Van Ee, C.A., Morgan, R.M., and Digges, K.H. (2007) Investigation of traumatic rupture of the aorta (TRA) by simulating real-world accidents. 2007 Conference of the International Research Council on Biomechanics of Injury, pp. 349-359.

Shah, C.S., Lee, J.B., Hardy, W.N., and King, K.H. (2004) A partially validated finite element whole-body human model for organ level injury prediction. Proc. 2004 ASME International Mechanical Engineering Congress and Exposition, IMECE2004-61844. American Society of Mechanical Engineers, New Yrok, NY.

Shah, C.S., Maddali, M., Mungikar, S.A., Beillas, P., Hardy, W.N., Yang, K.H., Bedewi, P.G., Digges, K., and Augenstein, J. (2005) Analysis of a real-world crash using finite element modeling to examine traumatic rupture of the aorta. SAE Technical Paper No. 2005-01-1293. Society of Automotive Engineers, Warrendale, PA.

Shah, C.S., Yang, K.H., Hardy, W.N., Wang, K.H., and King, A.I. (2001) Development of a computer model to predict aortic rupture due to impact loading. Stapp Car Crash Journal, 45:161-182.

Steps, J.A., (2003), Crash characteristics indicative of aortic injury in near side vehicle-to- vehicle crashes. Doctoral Dissertation, The George Washington University, April, 2003.

Viano, D.C. (1983) Biomechanics of non-penetrating aortic trauma: A review. Proc. 27th Stapp Car Crash Conference, pp. 109-114. Society of Automotive Engineers, Warrendale, PA.

Zhao A. Pericevic IO, Digges KH., Kan C., Moatamedi M., Augenstein J., (2006) FE modeling of the orthotropic and three-layer human thoracic aorta. The 2006 ASME Pressure Vessels and Piping/ICPVT-11 Conference, Vancouver, British Columbia, Canada, July 23-27, 2006