CRASH INVESTIGATION AND NUMERICAL SIMULATION OF A CASE OF LATERAL IMPACT MOTOR VEHICLE CRASH-RELATED THORACIC AORTIC INJURY

A CRASH INJURY RESEARCH ENGINEERING NETWORK (CIREN) STUDY

JOHN H. SIEGEL, MD\textsuperscript{1} AND KING H. YANG, PH.D. \textsuperscript{2}

JOYCE A. SMITH, MS\textsuperscript{1}; SHABANA Q. SIDDIQI, MD\textsuperscript{1}; CHIRAG SHAH, MS \textsuperscript{2}; MURALIKRISHNA MADDALI, BS \textsuperscript{2}; WARREN HARDY

\textsuperscript{1}NEW JERSEY MEDICAL SCHOOL: UMDNJ CIREN CENTER, NEWARK, NEW JERSEY
\textsuperscript{2} BIOENGINEERING CENTER, WAYNE STATE UNIVERSITY, DETROIT, MICHIGAN
IN ADDITION TO THE NJ CIREN CENTER, DATA INCLUDED WAS COLLECTED BY 9 OTHER CIREN CENTER PRINCIPAL INVESTIGATORS:

1) J.S. Augenstein, MD & K.E. Digges, PhD: Lehman Injury Research Center, University of Miami, Miami, FL
2) P.C. Dischinger, PhD, A.R. Burgess, M.D., & J.O’Connor, M.D. National Study Center for Trauma & EMS, University of Maryland, Baltimore, Md.
3) A.B. Eastman, M.D., D.B. Hoyt, M.D., & G. Cooper, Scripps Memorial Hospital & University of California San Diego & San Diego County Trauma System, San Diego, CA
4) M. Eichelberger, M.D., Children’s Medical Center, Washington, DC
5) S.M. Fakhry, M.D., & D.D. Watts, PhD., Fairfax Hospital – Honda Inova Center, Falls Church, VA
6) T.A. Gennarelli, M.D., Froedtert Hospital & Medical College of Wisconsin, Milwaukee, WI
7) D. Grossman, M.D., C. Mock, M.D., F. Rivara, M.D., Harborview Injury Prevention & Research Center, University of Washington, Seattle, WA
8) L.W. Rue III, M. D., Mercedes-Benz Center: University of Alabama Health System, Birmingham. AL
9) S.C. Wang, M.D., & L. Schneider, PhD., University of Michigan Health System & University of Michigan Transportation Research Institute, Ann Arbor, MI
CIREN DATA FROM 876 ADULT DRIVERS OR FRONT-SEAT OCCUPANTS OF MOTOR VEHICLE CRASHES (MVCs) INVOLVING CARS; OR SPORT UTILITY, VANS, OR LIGHT PICK-UP TRUCKS (SUVT). CRASHES WITH FULL ROLLOVERS, REAR-END COLLISIONS, OR EJECTED PATIENTS EXCLUDED. NO SIDE AIRBAGS IN SERIES. DATA SPAN PERIOD 1996-2002 FROM 10 CIREN CENTERS.

552 FRONTAL MVCs (PDOF 340° - 0 - 20°).
334 LATERAL MVCs (PDOF <340°-190° OR >20°-170°). INCLUDES 46 FRONTAL MVC AORTIC INJURY (AI) AND 34 LATERAL MVC AI CASES.
PATIENT:
1) AGE, SEX, HEIGHT & WEIGHT
2) DIRECTION OF CRASH FMVC OR LMVC
3) OCCUPANT VEHICLE (V1) VS OTHER VEHICLE (V2) OR NON VEHICLE (FO)
4) SEAT-BELT AND AIRBAG DEPLOYMENT
5) SURVIVAL OR DEATH STATUS
6) PATIENT OR NEXT OF KIN INFORMED CONSENT OR
7) MEDICAL EXAMINERS AUTHORITY FOR SCENE FATAL CRASHES
8) POLICE, EMS & HOSPITAL RECORDS
9) MEDICAL EXAMINER AUTOPSY REPORTS
10) PSYCHOSOCIAL EVALUATION IN HOSPITAL & FOLLOW-UP AT 6, 12 & 18 MONTHS
MATERIALS & METHODS III

VEHICLE:
CRASH RECONSTRUCTION DATA FOR MECHANISM OF CRASH WITH SCENE DIAGRAM AND DETERMINATION OF PRINCIPAL DIRECTION OF FORCE (PDOF) ON SUBJECT VEHICLE (V1)
DELINEATION OF SITES OF DRIVER AND/OR FRONT-SEAT PATIENT’S INJURY PRODUCING CONTACT WITH PASSENGER COMPARTMENT STRUCTURES
COMPUTATION OF DECELERATION ON IMPACT (ΔV) ON V1 VEHICLE
COMPUTATION OF IMPACT ENERGY DISSIPATION (IE) ON V1 VEHICLE
### Age Distribution of All Cases

<table>
<thead>
<tr>
<th>Age Range</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-24</td>
<td>209</td>
</tr>
<tr>
<td>25-34</td>
<td>141</td>
</tr>
<tr>
<td>35-44</td>
<td>138</td>
</tr>
<tr>
<td>45-54</td>
<td>106</td>
</tr>
<tr>
<td>55-64</td>
<td>88</td>
</tr>
<tr>
<td>65-74</td>
<td>56</td>
</tr>
<tr>
<td>75-84</td>
<td>48</td>
</tr>
<tr>
<td>85-94</td>
<td>10</td>
</tr>
<tr>
<td>95-104</td>
<td>2</td>
</tr>
</tbody>
</table>

The chart above illustrates the age distribution of all cases, with frequency counts for each age range. The bars represent cases overall, with separate sections for aorta-related cases (green) and non-aorta-related cases (yellow).
Frontal cases with complete data from CIREN database by fatality (N=552)

\[ y = 32.218x^2 + 2925.8x - 59451 \]

\[ R^2 = 0.4126 \]

58% of deaths
Lateral cases with complete data from CIREN database by fatality (N=324)

\[ y = 53.209x^2 + 649.66x + 736.67 \]

\[ R^2 = 0.8125 \]

64% of deaths
Aorta cases with complete data and outcome indicated (N=46)
Frontal only

\[ y = 32.218x^2 + 2925.8x - 59451 \]
\[ R^2 = 0.4126 \]
p<0.001

65% of AIs

- Median (46 kph)
- Mean (48.0 ±19.7 kph)

- ▲ aorta hospital deaths (n=10)
- □ aorta scene deaths (n=30)
- Δ aorta survivors (n=6)
Aorta cases with complete data and outcome indicated (N=34)

Lateral only

\[ y = 53.209x^2 + 649.66x + 736.67 \]

\[ R^2 = 0.8125 \]

\[ p<0.001 \]

\( 64\% \) of AIs
Principal Direction of Force (PDOF) for Aorta Injury Cases

By site of aortic lesion

6 cases had lesions in multiple locations (shown in red)

P = proximal
A = arch
I = isthmus
D = desc. thor.
Frontal Non-Aorta vs Aorta Injury Cases

**BRAIN**
- All frontal non-aorta cases: 50
- All frontal aorta cases: 100

**FACE FX.**
- All frontal non-aorta cases: 17
- All frontal aorta cases: 16

**UPEXT FX.**
- All frontal non-aorta cases: 4
- All frontal aorta cases: 7

**SPINE**
- All frontal non-aorta cases: 20
- All frontal aorta cases: 22

**THORAX**
- All frontal non-aorta cases: 17
- All frontal aorta cases: 26

**LUNG**
- All frontal non-aorta cases: 17
- All frontal aorta cases: 17

**HEART**
- All frontal non-aorta cases: 4
- All frontal aorta cases: 5

**LIVER**
- All frontal non-aorta cases: 10
- All frontal aorta cases: 7

**SPLEEN**
- All frontal non-aorta cases: 7
- All frontal aorta cases: 5

**KIDNEY**
- All frontal non-aorta cases: 2
- All frontal aorta cases: 7

**PELVIC FX.**
- All frontal non-aorta cases: 17
- All frontal aorta cases: 17

**LOWEXT FX.**
- All frontal non-aorta cases: 49
- All frontal aorta cases: 48

**BELT USE**
- All frontal non-aorta cases: 61
- All frontal aorta cases: 72

**AIRBAG DEPLOY**
- All frontal non-aorta cases: 84
- All frontal aorta cases: 87

**FATAL**
- All frontal non-aorta cases: 12
- All frontal aorta cases: 20

* = p<0.05
** = p<0.01
Lateral Non-Aorta vs Aorta Injury Cases

Organ System

** BRAIN
** FACE FX.
* UPEXT FX.
* SPINE
** THORAX
** LUNG
** HEART
** LIVER
** SPLEEN
** KIDNEY
PELVIC FX.
LOWEXT FX.
** BELT USE
AIRBAG DEPLOY
** FATAL

** = p<0.01
* = p<0.05

all lateral non-aorta cases (n=290)
all lateral aorta cases (n=34)
Aorta Injury vs Thoracic Non-Aorta Cases

Organ System

BRAIN
FACE FX.
UPEXT FX.
SPINE
** RIBS 1-4
* RIBS 5-8
RIBS 9-12
THORAX
** LUNG
** HEART
LIVER
SPLEEN
KIDNEY
* PELVIC FX.
LOWEXT FX.
** BELT USE
AIRBAG DEPLOY
** FATAL

- Aorta cases with rib data (n=64)
- Thoracic non-aorta with rib data (n=37)

* = p<0.05
** = p<0.01
SUMMARY & CONCLUSIONS I

WHEN AORTIC INJURY PATIENTS WERE COMPARED TO PATIENTS WHO SUSTAINED SEVERE GRADE III OR GREATER THORACIC INJURIES WITHOUT AORTIC DISRUPTIONS, IT WAS FOUND THAT THE AORTIC INJURY PATIENTS HAD A SIGNIFICANTLY GREATER INCIDENCE OF FRACTURES OF RIBS 1-4 & 5-8. THEY ALSO HAD SIGNIFICANTLY MORE CARDIAC INJURIES AND PELVIC FRACTURES, BUT A MUCH LOWER INCIDENCE OF SEAT-BELT USE AND A HIGHER FATALITY RATE. IN CONTRAST, THE NON-AORTIC THORACIC INJURY PATIENTS HAD A SIGNIFICANTLY GREATER INCIDENCE OF LUNG INJURY.
SUMMARY & CONCLUSIONS II

THE SIGNIFICANT INCREASE IN FRACTURES OF RIBS 1-4 CONTINUED TO BE SEEN EVEN EVEN WHEN THE AORTIC INJURY SURVIVORS WERE COMPARED TO THE NON-AORTIC INJURY THORACIC TRAUMA SURVIVORS, WHO IN CONTRAST CONTINUED TO MANIFEST A SIGNIFICANTLY HIGHER INCIDENCE OF LUNG INJURY THAN THE AORTIC INJURY PATIENTS. HOWEVER, THE AI SURVIVORS HAD A SIGNIFICANTLY LOWER AIRBAG DEPLOYMENT THAN THE NON-AORTIC THORACIC INJURY SURVIVORS.
THE ARCHIMEDES LEVER HYPOTHESIS OF THE MECHANISM OF AORTIC INJURY

“GIVE ME A LEVER LONG ENOUGH, A FULCRUM AND A PLACE TO STAND, AND I WILL MOVE THE WORLD”.
CIREN Case

- Case Vehicle was a 2002 Dodge Stratus with a Left Side Impact, PDOF = 260
- CDC was 09LYAW3
- Max Crush was 45 cm (17.7 inches)
- Delta V was 41 KM/hr (25.5 MPH)
- Energy 110087 joules
- Weight = 1332 kg case vehicle
- Weight = 2533 kg non-case vehicle
Crush Measurement
2002 Dodge Stratus
Documenting Contact Points
B. FUNCTIONAL: THE ASCENDING AORTA AND THE ARCH AS FAR AS THE LEFT SUBCLAVIAN ARTERY, IF MADE RIGID, CAN FUNCTION AS A LONG LEVER ARM WITH THE SUBCLAVIAN TAKE-OFF AS THE FULCRUM TO EXERT A LARGE TORSIONAL FORCE ON THE RELATIVELY SHORT ARM OF THE UNTETHERED ISTHMUS WHICH IS ATTACHED AT ITS LOWER END TO THE FIXED PROXIMAL DESCENDING AORTA
C. MECHANISTIC I: WITHIN 50-100 MSEC OF A CRASH MEDIATED IMPACT FORCE WHICH IS NARROWLY FOCUSED ACROSS THE REGION OF THE 2nd TO 5th RIBS (WHICH DELINEATES THE LOCUS OF THE AORTIC ARCH – ISTHMUS SYSTEM), THE INTRA-AORTIC PRESSURE RISES TO LEVELS WHICH MAY APPROXIMATE OR EXCEED 500 MM HG. THIS INTRA-AORTIC PRESSURE SELDOM RUPTURES THE AORTA IN ITSELF, BUT RATHER FUNCTIONS TO CAUSE THE ENTIRE ASCENDING AORTA – AORTIC ARCH SYSTEM TO FUNCTION AS A SINGLE TURGID, RIGID LEVER WHOSE FULCRUM IS THE SUBCLAVIAN ARTERY.
CADAVERIC INTRA-AORTIC PRESSURE: FRONTAL CRASH

UVA: Internal aortic pressure time histories from frontal sled tests.
D. MECHANISTIC II: AT THE SAME TIME, THE ENTIRE SYSTEM OF HEART, ASCENDING AORTA AND AORTIC ARCH MOVES TOWARD THE IMPACTING FORCE, THUS CAUSING THE AORTIC LEVER ARM TO PRODUCE A FORCEFUL TORSIONAL ROTATION OF THE ISTHMUS ON THE PROXIMAL DESCENDING AORTA, WITH ITS TEAR POINT IN THE REGION OF THE LIGAMENTUM ARTERIOSUM, WHICH IS FIXED TO THE LEFT PULMONARY ARTERY. THIS TORSIONAL FORCE, WHICH IS MAGNIFIED BY THE DIFFERENCE IN LENGTH BETWEEN THE AORTIC ARCH SYSTEM AND THE ISTHMUS, PRODUCES A SUFFICIENT AMPLIFICATION OF THE IMPACT ENERGY TRANSMITTED TO THE PATIENT’S THORAX DURING IMPACT DECELERATION TO TEAR THE AORTA AT THE ISTHMUS OR PROXIMAL DESCENDING AORTA.
MECHANISM FOR AORTIC INJURY

MAXIMUM RIB INTRUSION AT TIME OF IMPACT

AORTIC ARCH

MAXIMUM TORQUE
AORTIC LEVER ARM

PA

S

OC

T

E

IST

D

R L

ΔV 41

PDOF 260

IE 110,087
WSU model of the thoracic aorta
Part II: Numerical Simulation of A CIREN Case with Aorta Injury

Chirag Shah, Muralikrishna Maddali, Warren Hardy, and King H. Yang

Bioengineering Center
Wayne State University

May 11, 2004, Washington, DC
Aortic Injury Case Reconstruction

● **Introduction**

1. Car to car crash numerical reconstruction
2. Sub-structured B-Pillar to whole body human FE model simulation
3. Parametric study using a FE human thorax model
# Car to Car Crash Numerical Reconstruction

<table>
<thead>
<tr>
<th>Actual Crash</th>
<th>Target vehicle</th>
<th>Bullet Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2002 Four door Dodge Stratus</td>
<td>1995 Van Ford E350</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FE reconstruction</th>
<th>Target vehicle</th>
<th>Bullet Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ford Taurus</td>
<td>Chevrolet C1500 Pickup</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gross Weight kg (lbs)</th>
<th>Target vehicle</th>
<th>Bullet Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1432 (2937)</td>
<td>2547 (5584)</td>
</tr>
</tbody>
</table>
FE Models of Vehicle

Non case vehicle - Chevrolet C1500 Pickup

Case vehicle - Ford Taurus

Reference: http://www.ncac.gwu.edu/vml/models.html
Crash Scene

Secondary impact

Case Vehicle
(Dodge Stratus)

Non Case Vehicle
(Ford Van)
Numerical Reconstruction

- Masses of target and bullet vehicle models adjusted
- Width of bullet vehicle
  - case vehicle (Ford E350 Van) - 202 cm
  - Numerical vehicle (C1500 pick-up) - 197 cm
- Direction of impact and velocity assumed to be the same as those estimated from inspection
Numerical Reconstruction

- Delta V = 41 KPH (25.5 MPH)
- PDOF = 260 degrees (approx)
- Total time of impact = 120 ms
- Initial time step = 5.35 µs
- Local coordinate system defined for case vehicle for collecting deformation data
Direction and location of impact

V = 41 kph

260 deg
Kinematics
External Door Deformation
Internal Door Deformation

FULL CAR + MDB. 10/5
Time = 0
Vehicle Deformation
Deformation Measurement

Points of deformation measurement

C1
C2
C3
C4
C5
C6
## Deformation Pattern

<table>
<thead>
<tr>
<th>Deformation points</th>
<th>Real case Deformation (mm)</th>
<th>FE Deformation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>30</td>
<td>0 (b/c rigid Front)</td>
</tr>
<tr>
<td>C2</td>
<td>270</td>
<td>155 (b/c rigid Front)</td>
</tr>
<tr>
<td>C3 (driver front door)</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>C4 (b-pillar)</td>
<td>340</td>
<td>405</td>
</tr>
<tr>
<td>C5</td>
<td>240</td>
<td>206</td>
</tr>
<tr>
<td>C6</td>
<td>80</td>
<td>8 (b/c rigid Rear)</td>
</tr>
</tbody>
</table>
Deformation Time History

Driver side door

B-pillar
Sub-Structured B-Pillar Simulation

- Kinematics of the B-pillar recorded from car to car simulation
- B-Pillar sub-structure was used for interaction with a whole body FE human model consists of:
  - thorax (Shah et al 2001)
  - abdomen (Lee and Yang 2001)
  - shoulder (Iwamoto et al 2000)
Velocity Time History

Velocity Profile

Resultant Velocity (m/sec)

Time (ms)

Car Velocity
B-Pillar Velocity
B-Pillar vs. Human Model Simulation
B-Pillar vs. Human Model Simulation
B-Pillar vs. Human Model Simulation
Aorta Kinematics: B-Pillar vs. Human Whole Body Simulation
Maximum Strain in Aorta
Whole Body Simulation

Contours of Effective Strain [v-m]-Green St Venant
min=0.00379399, at node# 1054032
max=0.390614, at node# 10464951

High Strain
Injury Comparison
Parametric Study

- Two variables
  - Pressure (200, 400, 500 mm of Hg)
  - Impact location (Upper, mid, and lower torso)
- Impactor (a narrow piece of the B-Pillar)
- Impactor mass 19.64 kg
- Impactor velocity 6.5 m/s (14.5 mph)
- Direction: 260° PDOP
- Total 9 simulations
Upper Thorax Impact
Upper Thorax Impact
(Aorta Pressure 200 mm Hg)
Upper Thorax Impact (Aorta Pressure 400 mm Hg)

High Strain
Upper Thorax Impact
(Aorta Pressure 500 mm Hg)

Contours of Effective Strain (ε-strain) Green Str Vessel
min=-0.8095331814, at node 238760
max=0.243433, at node 41961

High Strain
Mid Thorax Impact
Mid Thorax Impact
(Aorta Pressure 200 mm Hg)
Mid Thorax Impact
(Aorta Pressure 400 mm Hg)
Mid Thorax Impact
(Aorta Pressure 500 mm Hg)

High Strain
Lower Thorax Impact
Lower Thorax Impact
(Aorta Pressure 200 mm Hg)
Lower Thorax Impact
(Aorta Pressure 400 mm Hg)
Lower Thorax Impact
(Aorta Pressure 500 mm Hg)
## Maximum Strain in Aorta

<table>
<thead>
<tr>
<th></th>
<th>200 mm Hg</th>
<th>400 mm Hg</th>
<th>500 mm Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upper torso impact</strong></td>
<td>0.1887</td>
<td>0.1910</td>
<td>0.2042</td>
</tr>
<tr>
<td><strong>Mid torso impact</strong></td>
<td>0.1826</td>
<td>0.2954</td>
<td>0.6809</td>
</tr>
<tr>
<td><strong>Lower torso impact</strong></td>
<td>0.2587</td>
<td>0.2645</td>
<td>0.2545</td>
</tr>
</tbody>
</table>

- Isthmus
- Ascending
- Descending
Discussion

- Limitations:
  - The vehicle models used in the simulation are not the same as those in real world cases
  - Vehicle velocity and seat deformation are not simulated
  - The anthropometry of the human model is not the same as that of the actual victim
Conclusions

- Simulation of real world crash cases with aortic rupture is feasible but requires proper vehicle models and more refinements in human model
- Based on clinical observation and the parametric study, aorta rupture in the isthmus region is more likely to occur when the impact location is in the upper thoracic region
Conclusions

- Both the human data and the simulations are compatible with the idea of a superpressurized proximal aorta and aortic arch acting as a lever system about the subclavian artery fulcrum to exert maximum strain on the aortic isthmus when the site of impact is at the level of the upper thorax (ribs 1-4)
Future Research Goals

- Refine the simulations to include all chest structures and organs between the thoracic rib cage and the aorta and heart.
- Evaluate whether aortic strain compatible with sites of clinical aortic rupture can occur within the range of PDOF from >20°-100° (right lateral), 340°-20° (frontal) and <340°-260° (left lateral) thoracic impacts.
Future Research Goals (continued)

- Determine the thoracic level and rate of impact energy delivered to the aorta and the resulting magnitude of strain at these potential aortic rupture sites.
- Determine characteristics of buffering materials (airbags or padding) necessary to reduce these forces to safe levels over the range of delta V and IE which can produce aortic rupture.
Is this side airbag adequate to prevent aortic rupture?
Thank You!

UMDNJ: New Jersey CIREN Center
Bioengineering Center, Wayne State University