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

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MATERIALS & METHODS I

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 340º - 0 - 20º).
334 LATERAL MVCs (PDOF <340º-190º OR >20º-170º). INCLUDES **46 FRONTAL MVC AORTIC INJURY (AI)** AND **34 LATERAL MVC AI** CASES.

MATERIALS & METHODS II

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:

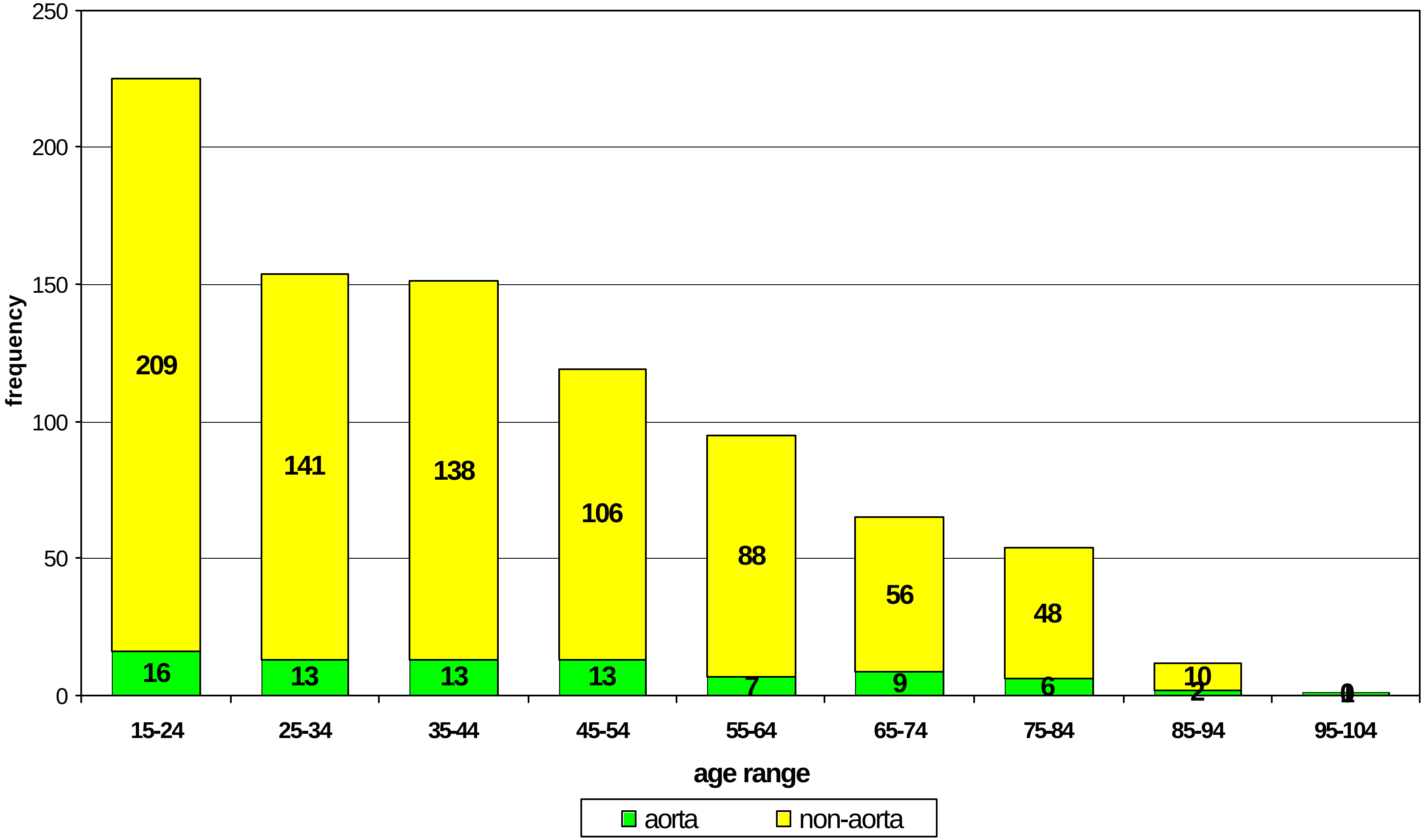
CRASH RECONSTRUCTION DATA FOR MECHANISM OF CRASH WITH SCENE DIAGRAM AND DETERMINATION OF PRINCIPAL DIRECTION OF FORCE (**PDOF**) ON SUBJECT VEHICLE (**V1**)

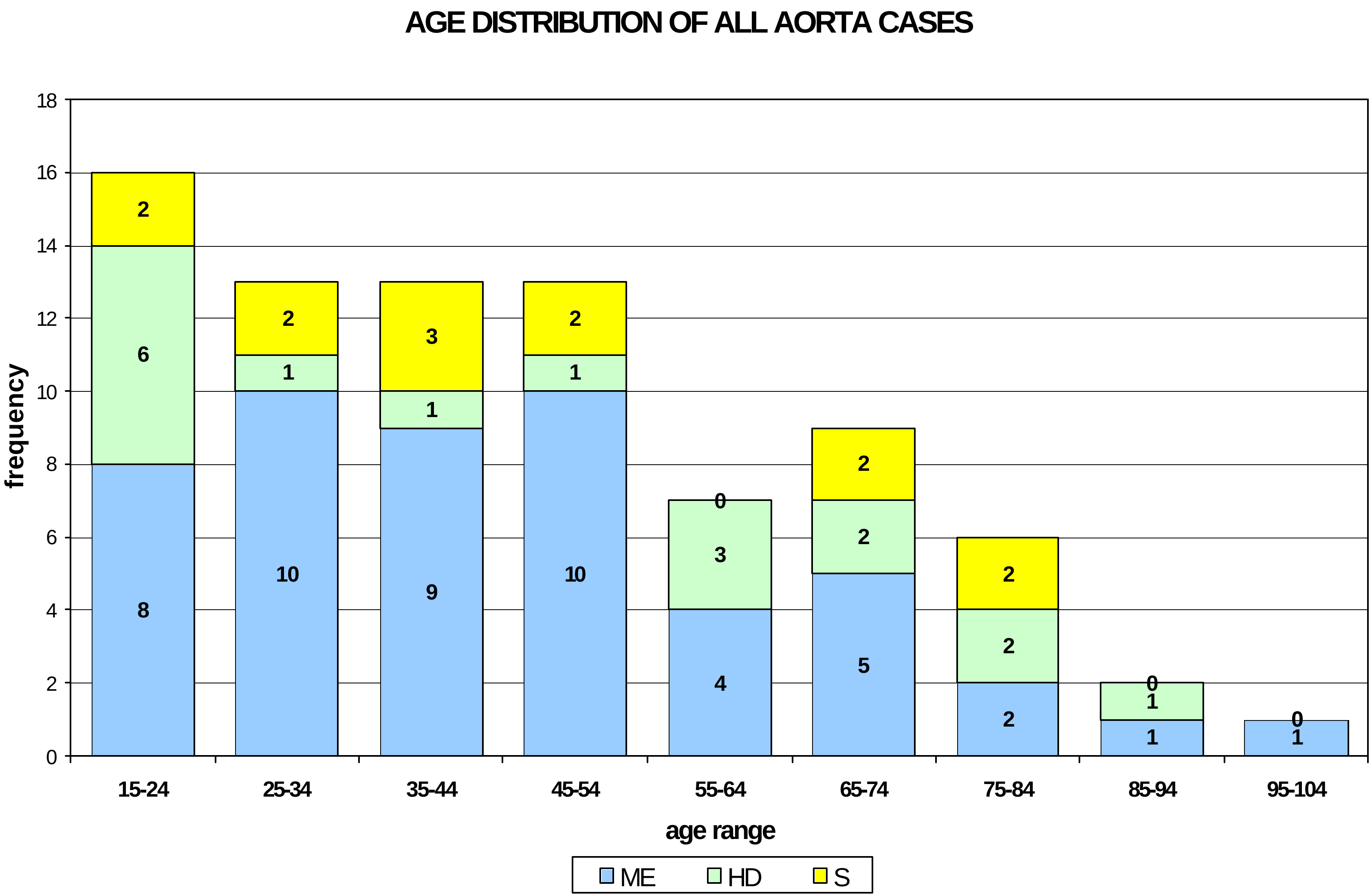
DELINEATION OF SITES OF DRIVER AND/OR FRONT-SEAT PATIENT'S INJURY PRODUCING CONTACT WITH PASSENGER COMPARTMENT STRUCTURES

COMPUTATION OF DECELERATION ON IMPACT (**DELTA V**) ON V1 VEHICLE

COMPUTATION OF IMPACT ENERGY DISSIPATION (**IE**) ON V1 VEHICLE

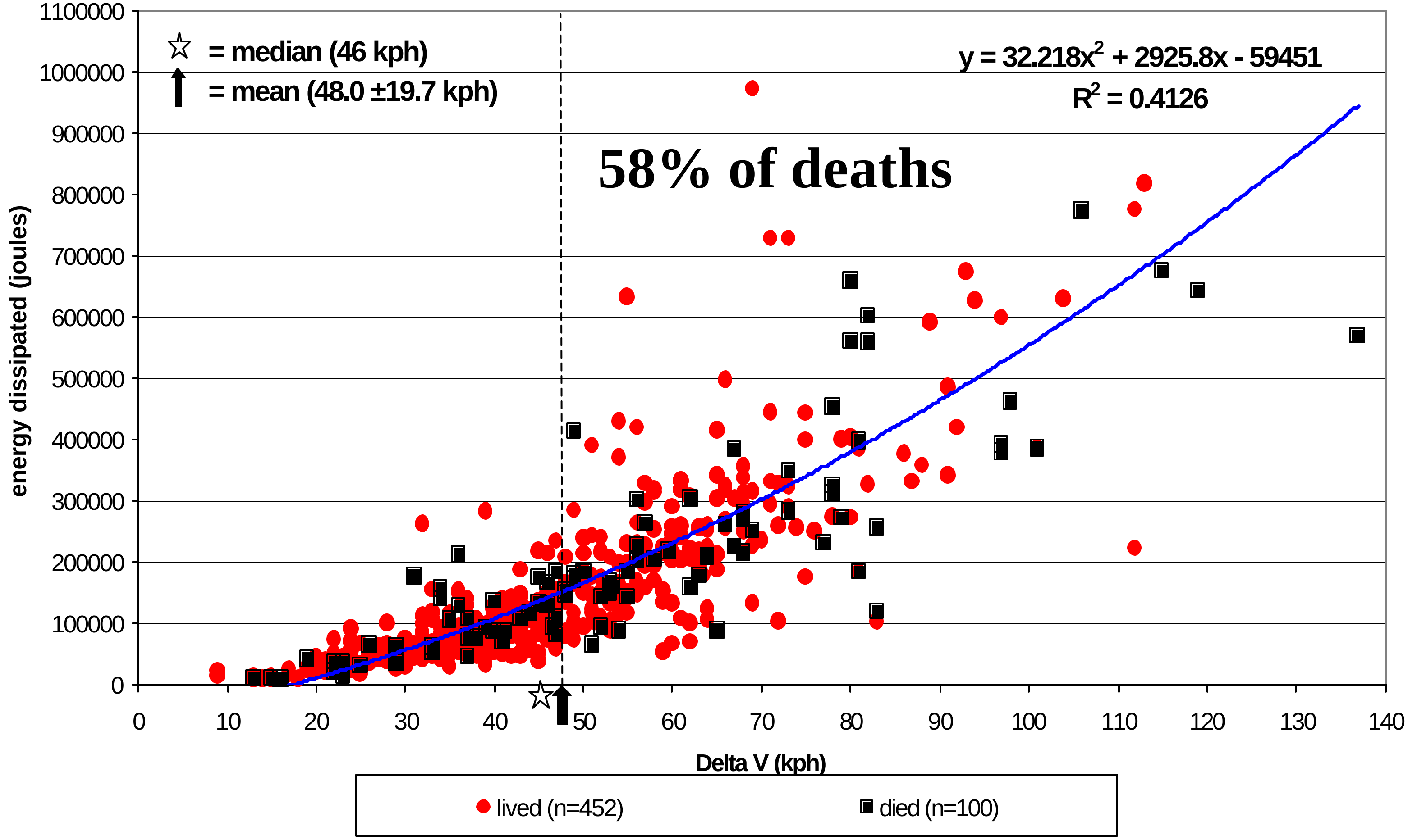
AGE DISTRIBUTION OF ALL CASES

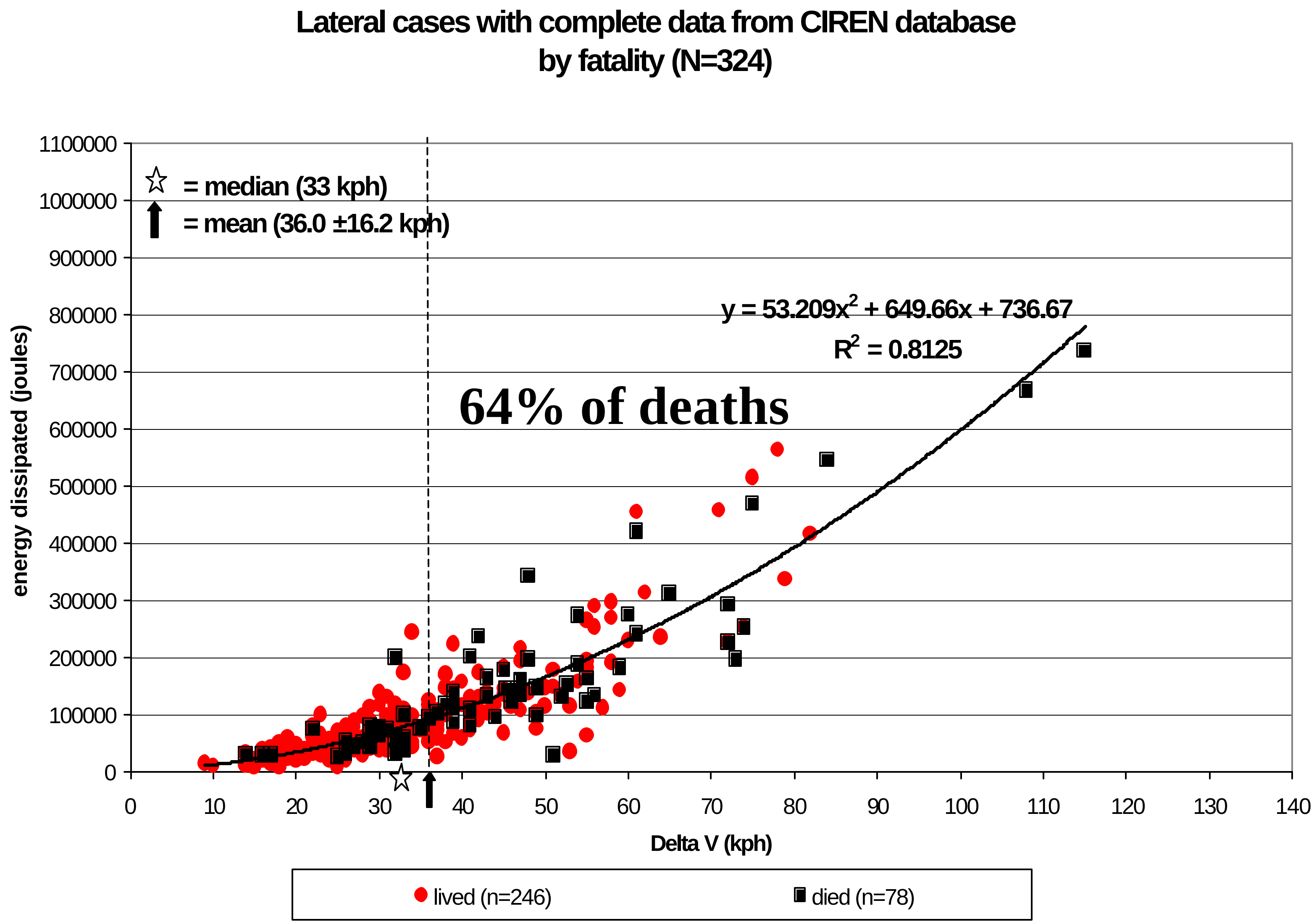




AGE DISTRIBUTION OF ALL AORTA CASES
frequency
0
2
4
6
8
10
12
14
16
18
15-24
25-34
35-44
45-54
55-64
65-74
75-84
85-94
95-104
age range
ME
HD
S
8
6
2
10
1
2
9
1
3
10
1
2
4
3
0
5
2
2
2
2
2
1
1
0
1
0

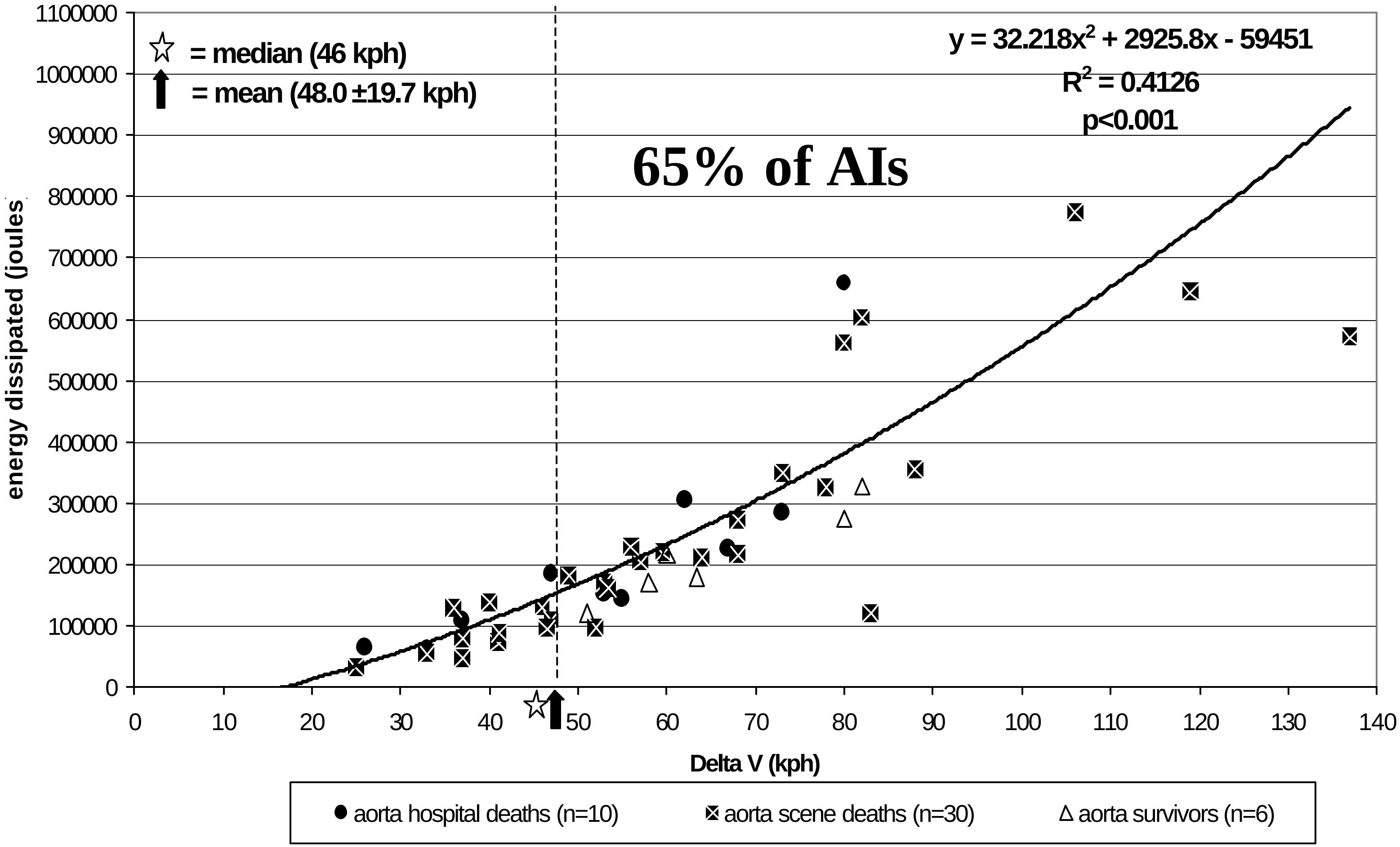
Frontal cases with complete data from CIREN database by fatality (N=552)

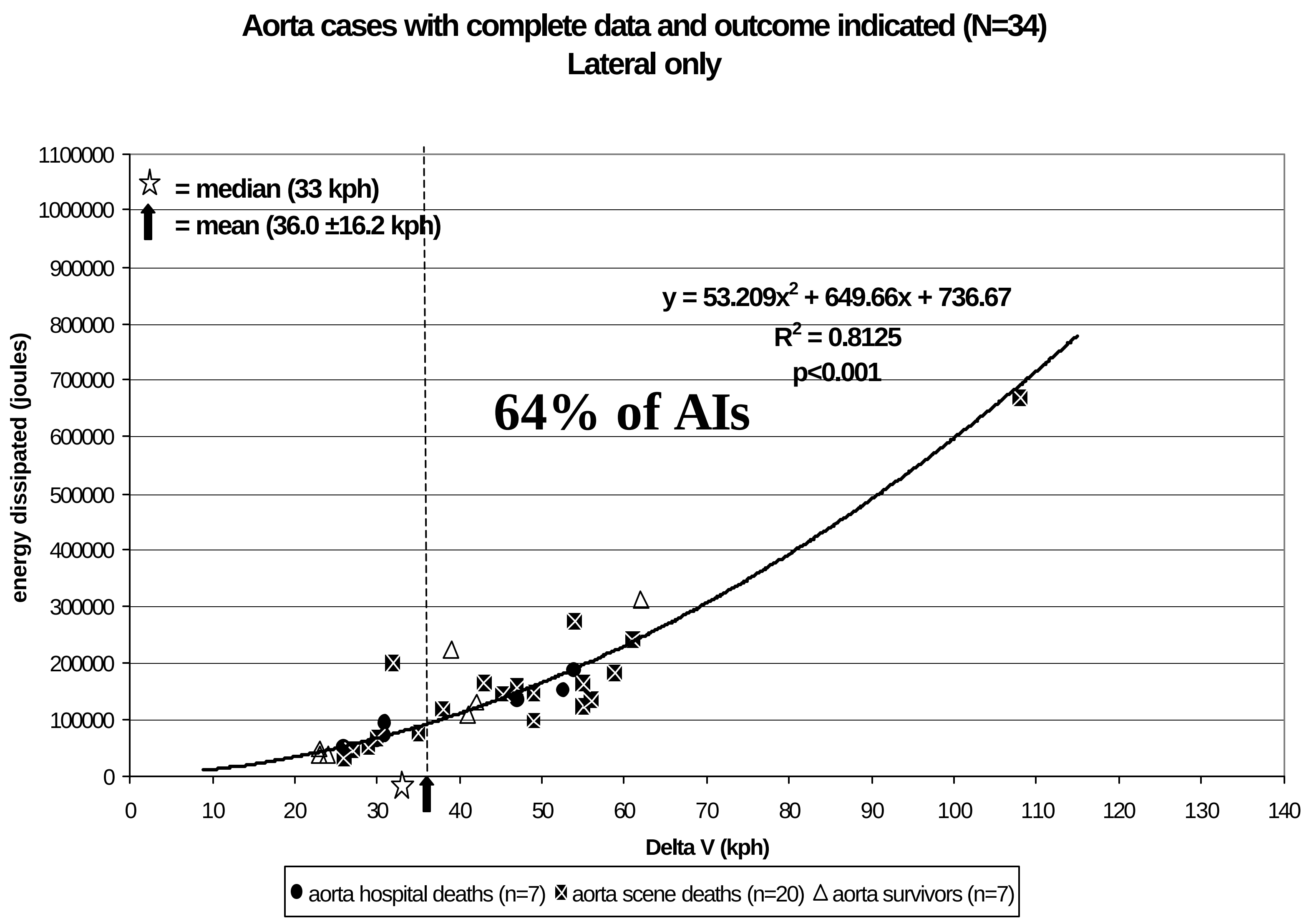


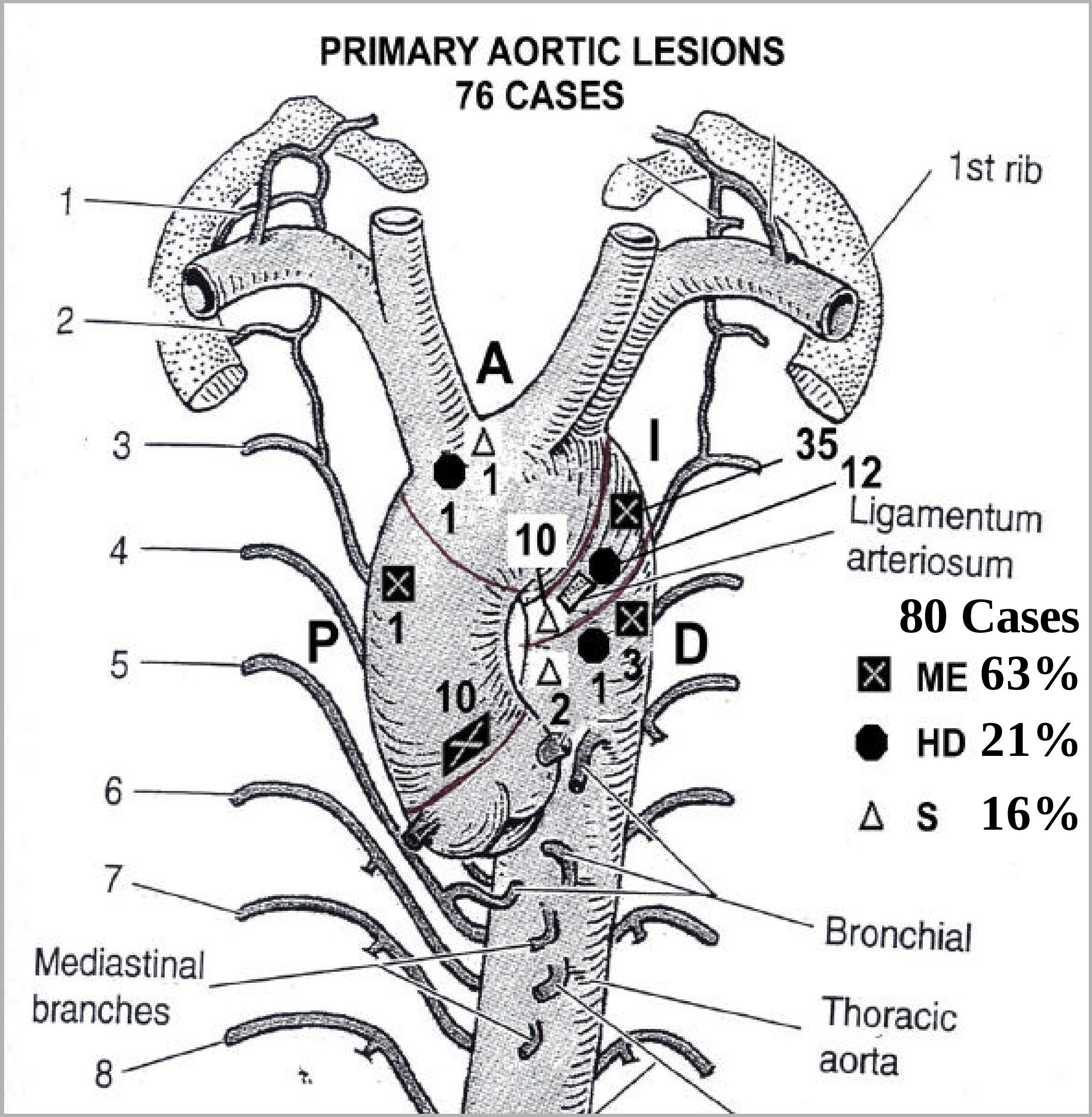


Lateral cases with complete data from CIREN database
by fatality (N=324)
= median (33 kph)
= mean (36.0 ±16.2 kph)
y = 53.209x2 + 649.66x + 736.67
R2 = 0.8125
64% of deaths
energy dissipated (joules)
1100000
1000000
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Delta V (kph)
lived (n=246)
died (n=78)

Aorta cases with complete data and outcome indicated (N=46)
Frontal only



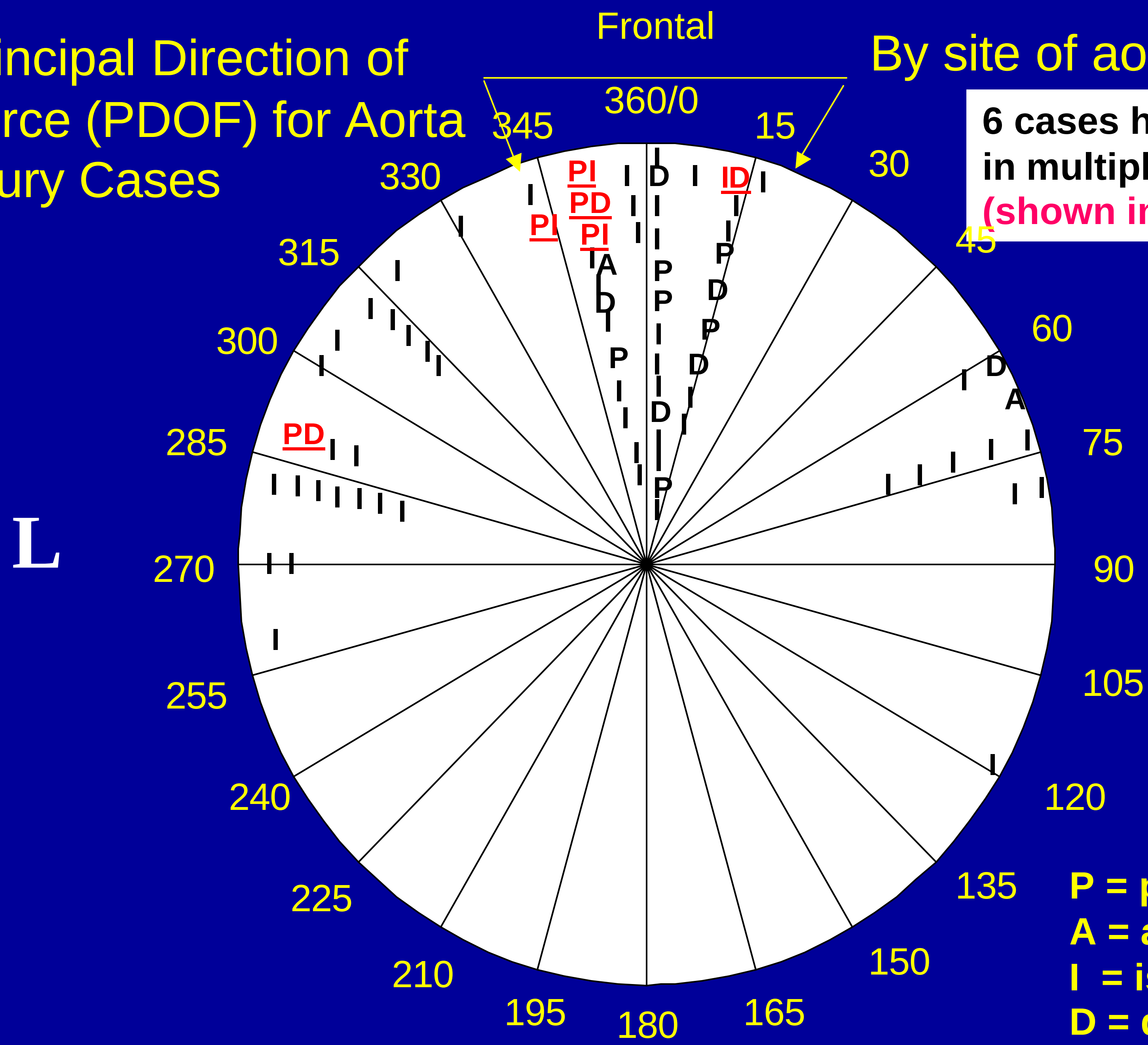

Aorta cases with complete data and outcome indicated (N=34)
Lateral only
= median (33 kph)
= mean (36.0 ±16.2 kph)
y = 53.209x2 + 649.66x + 736.67
R2 = 0.8125
p<0.001
64% of AIs
energy dissipated (joules)
1100000
1000000
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Delta V (kph)
aorta hospital deaths (n=7)
aorta scene deaths (n=20)
aorta survivors (n=7)



PRIMARY AORTIC LESIONS
76 CASES
1st rib
1
2
3
4
5
6
7
8
A
I
P
D
35
12
10
10
1
1
1
1
3
1
2
Ligamentum arteriosum
80 Cases
ME 63%
HD 21%
S 16%
Bronchial
Mediastinal branches
Thoracic aorta

Principal Direction of Force (PDOF) for Aorta Injury Cases

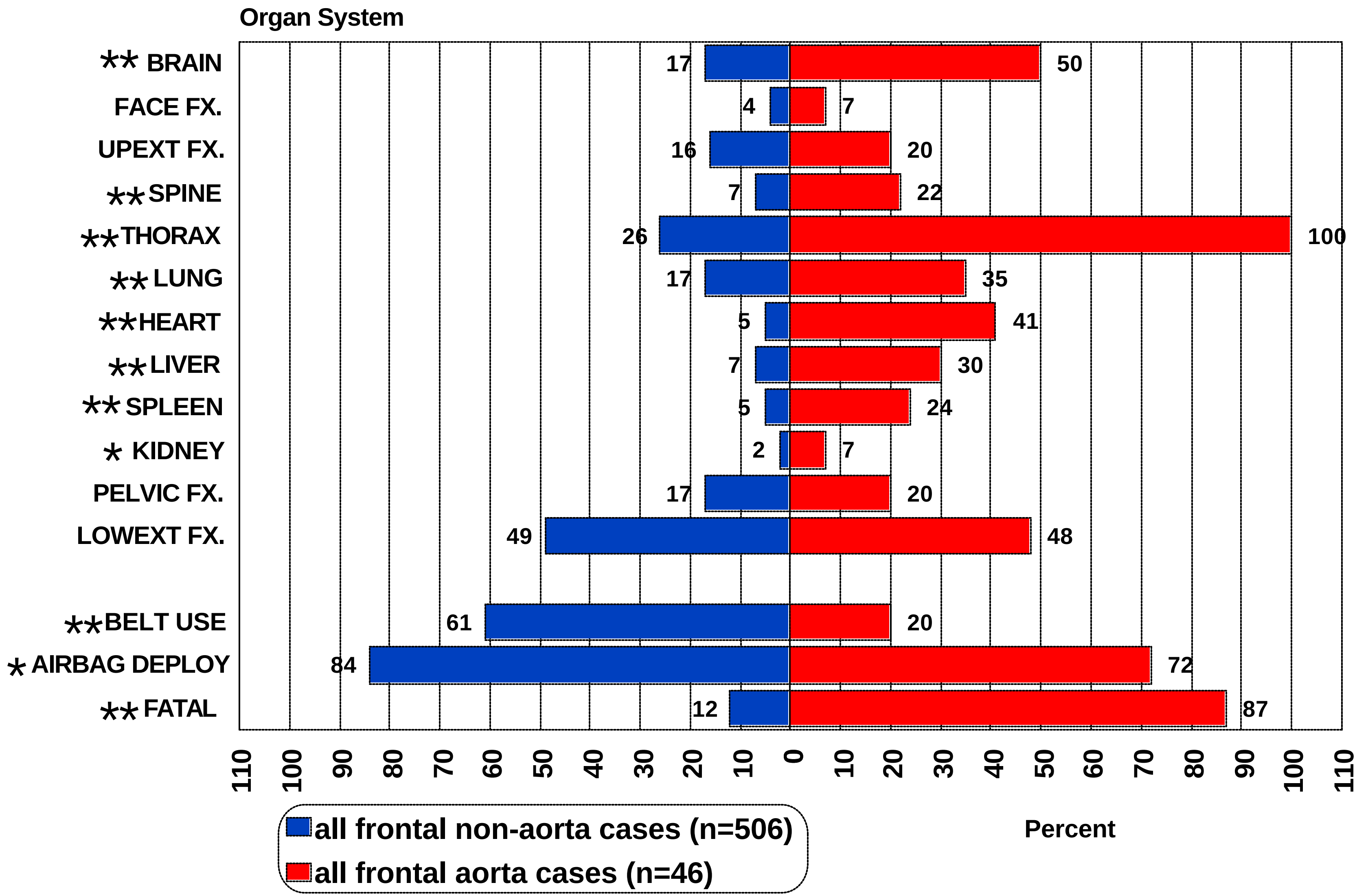
By site of aortic lesion



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

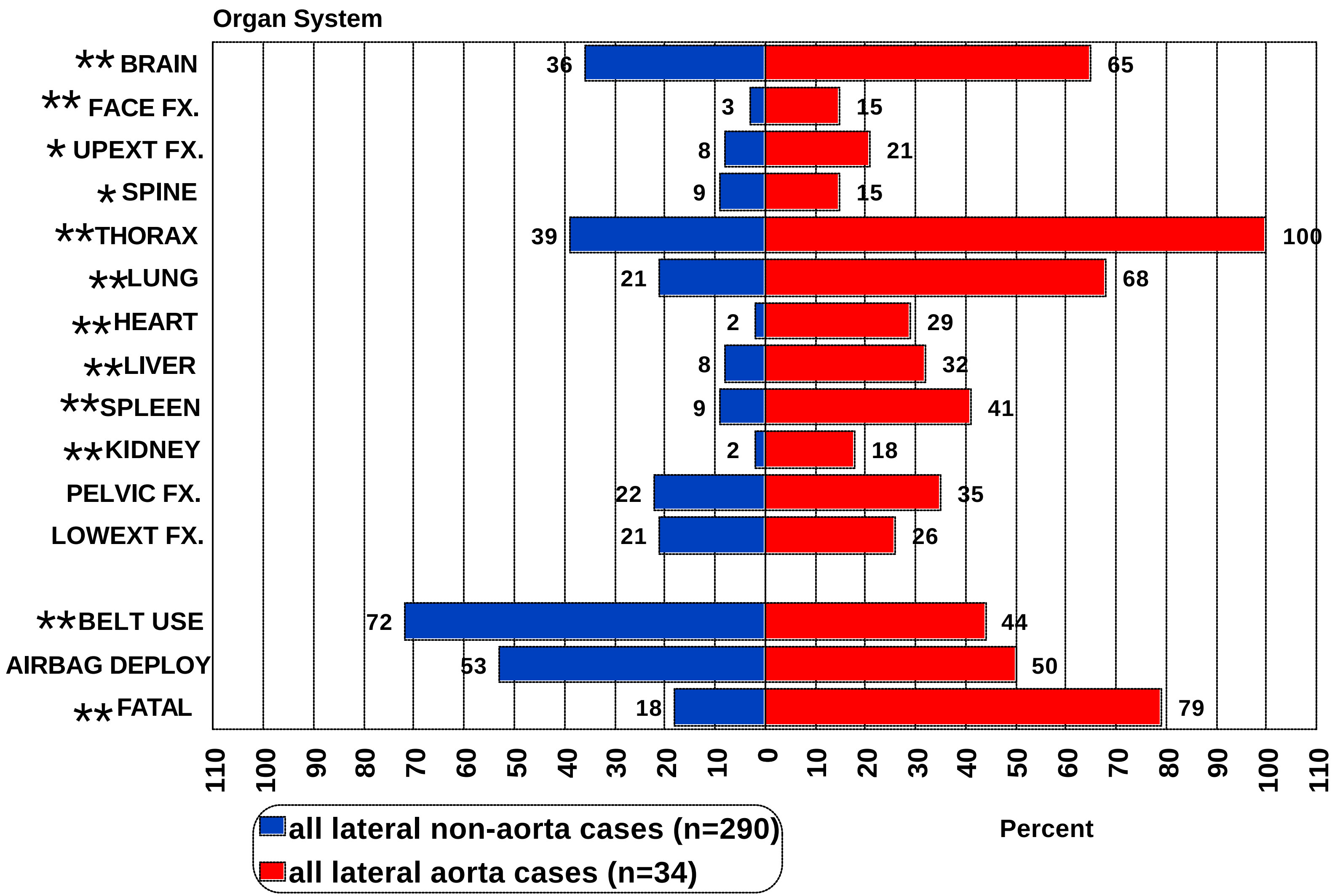
P = proximal
A = arch
I = isthmus
D = desc. thor.

Frontal Non-Aorta vs Aorta Injury Cases



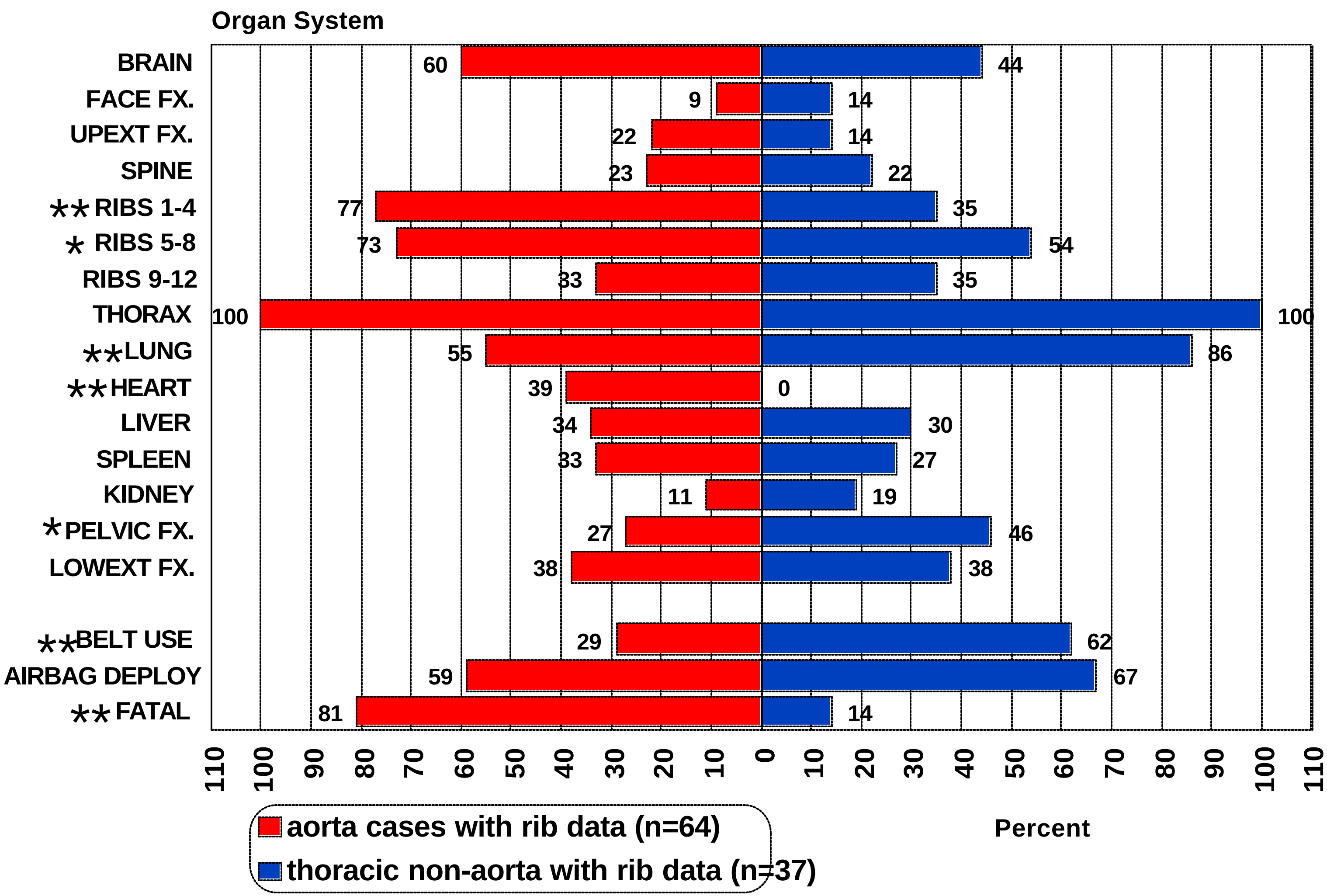
* = p<0.05
** = p<0.01

Lateral Non-Aorta vs Aorta Injury Cases



* = p<0.05
** = p<0.01

Aorta Injury vs Thoracic Non-Aorta Cases



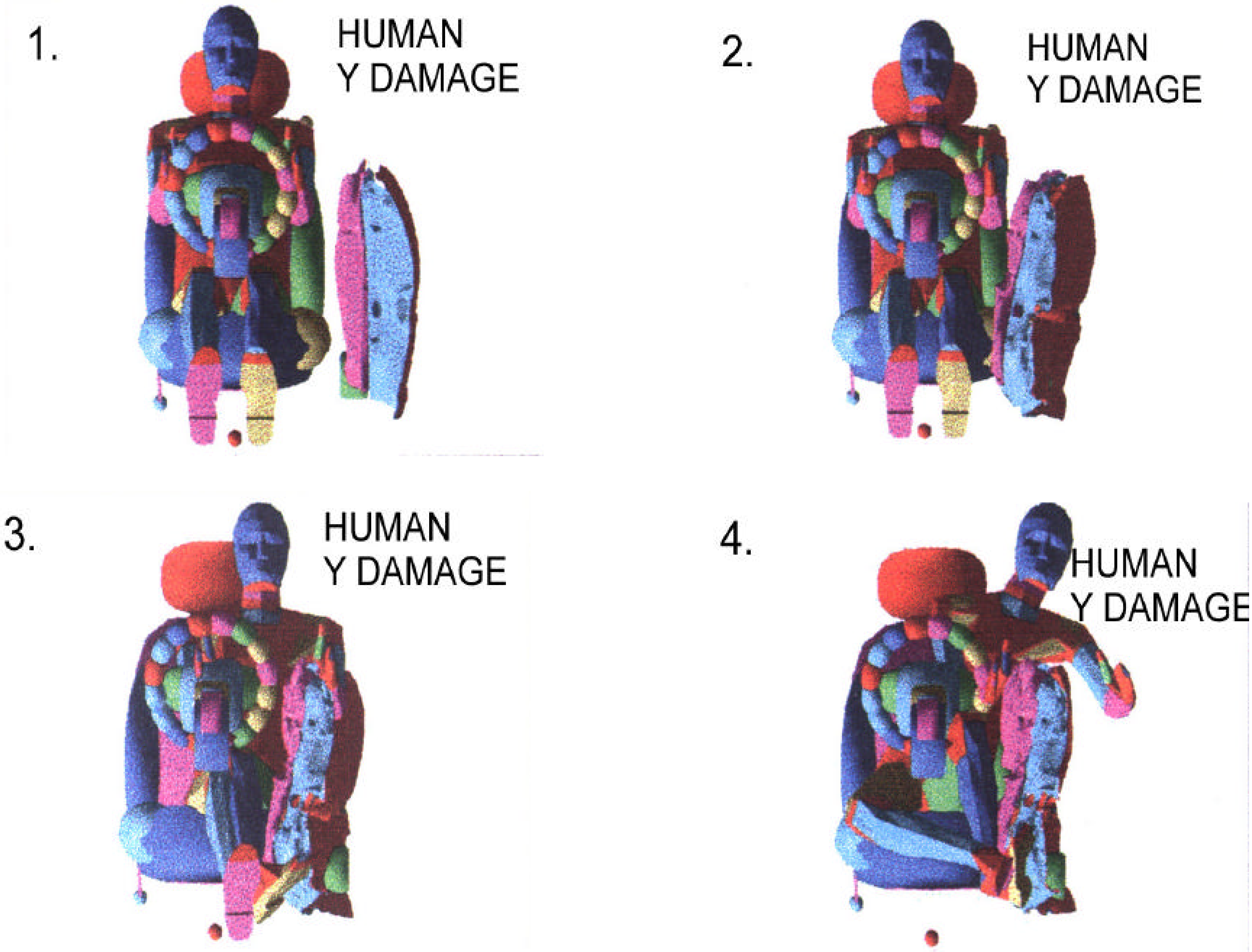
* = $p<0.05$
** = $p<0.01$

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 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 INURY PATIENTS. HOWEVER, THE AI SURVIVORS HAD A SIGNIFICANTLY LOWER AIRBAG DEPLOYMENT THAN THE NON-AORTIC THORACIC INJURY SURVIVORS.


1.
HUMAN
Y DAMAGE
2.
HUMAN
Y DAMAGE
3.
HUMAN
Y DAMAGE
4.
HUMAN
Y DAMAGE

THE ARCHIMEDES LEVER HYPOTHESIS OF THE MECHANISM OF AORTIC INJURY

CIREN Case

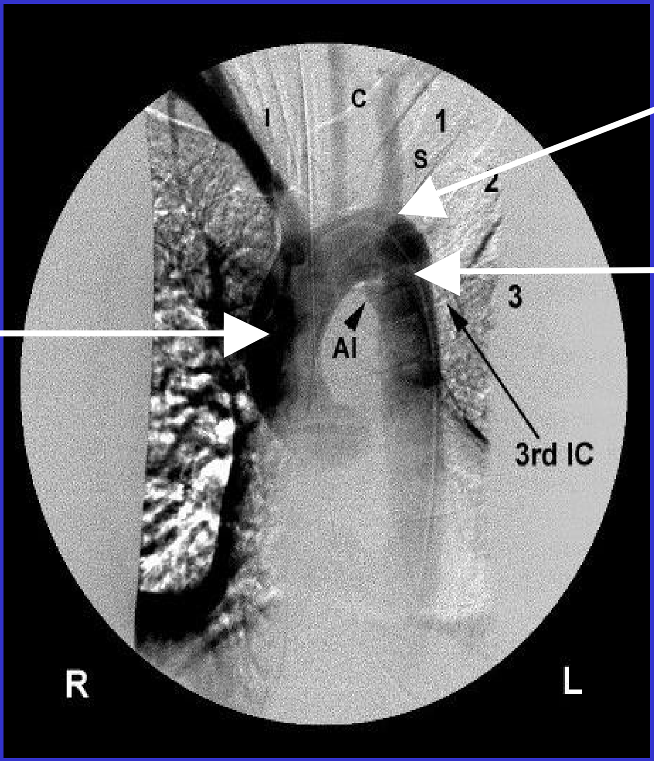
- Case Vehicle was a 2002 Dodge Stratus with a Left Side Impact, PDOF = 260
- CDC was 09LYAW3
- Max Crush was 45 cm (17.7 inches)
- Delta V was 41 KM/hr (25.5 MPH)
- Energy 110087 joules
- Weight = 1332 kg case vehicle
- Weight = 2533 kg non-case vehicle


Crush Measurement
2002 Dodge Stratus

Documenting Contact Points

Documenting
Contact Points

A. **ANATOMIC:** AS THE THORACIC AORTA ARISES FROM THE HEART, IT IS SUSPENDED FROM THE GREAT VESSELS, INNOMINATE, LEFT CAROTID AND LEFT SUBCLAVIAN ARTERIES, THE LATTER BEING MOST FIXED AS IT EXITS THE THORAX OVER THE FIRST RIB. THE DESCENDING AORTA IS FIXED TO THE SPINE AND RIBS BEGINNING AT THE ORIGINS OF THE 3rd INTERCOSTAL ARTERIES. THE ISTHMUS LYING BETWEEN THE SUBCLAVIAN AND THE ORIFICES OF THE 3rd INTERCOSTALS IS UNTETHERED EXCEPT FOR A POTENTIAL TEAR-TAB AT THE LIGAMENTUM ARTERIOSUM.



Fulcrum

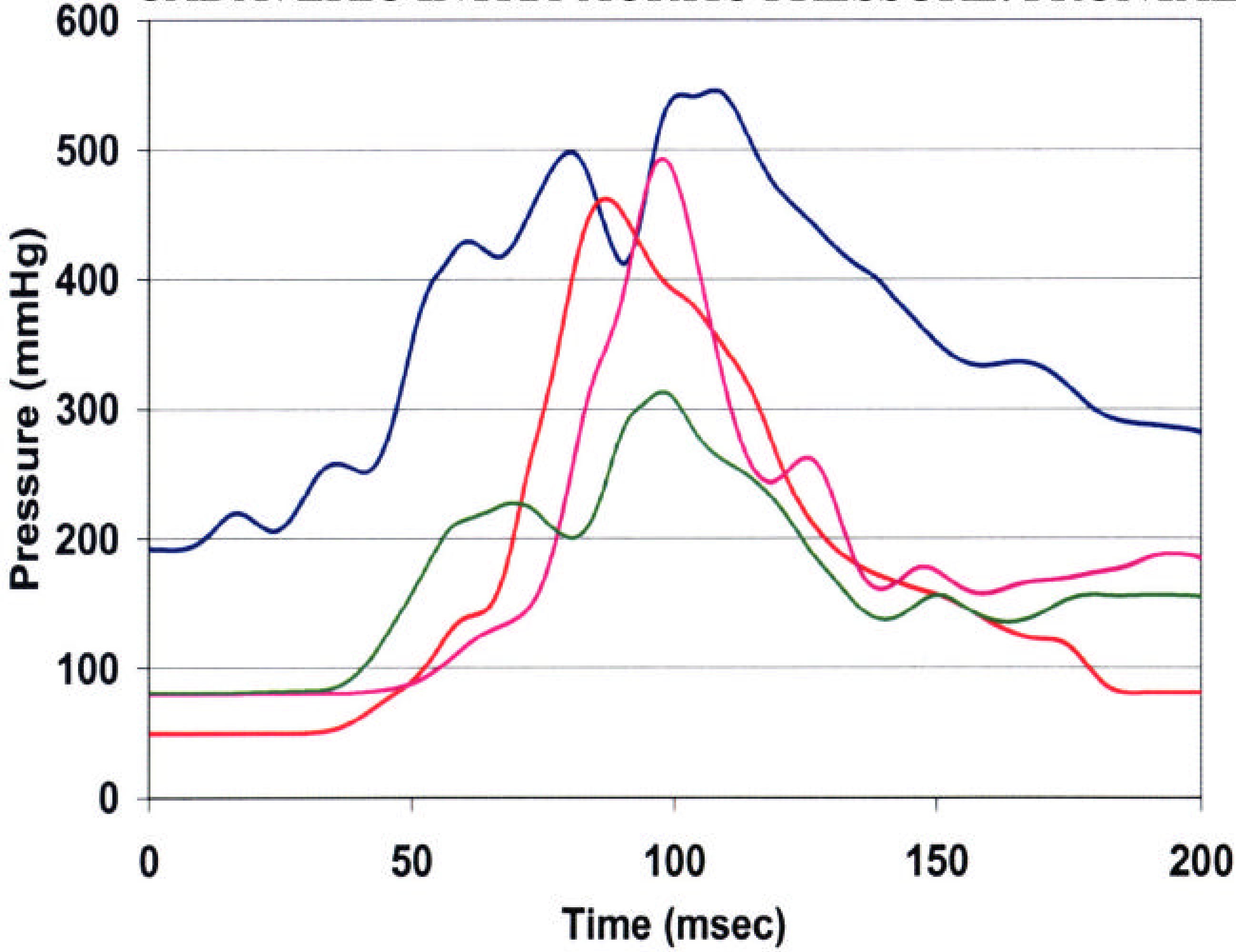
Long lever arm

Short lever arm

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.**

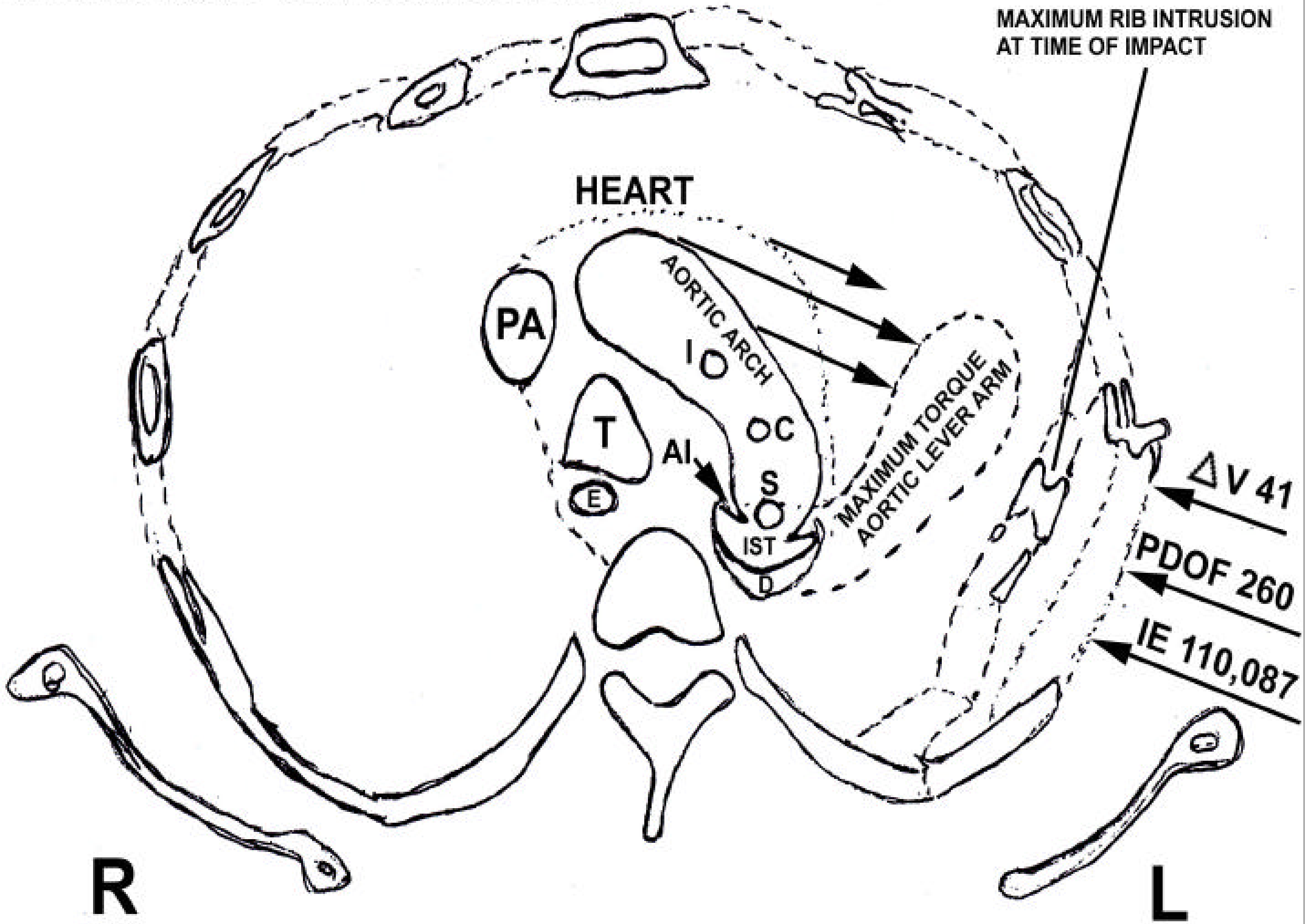
CADAVERIC INTRA-AORTIC PRESSURE: FRONTAL CRASH

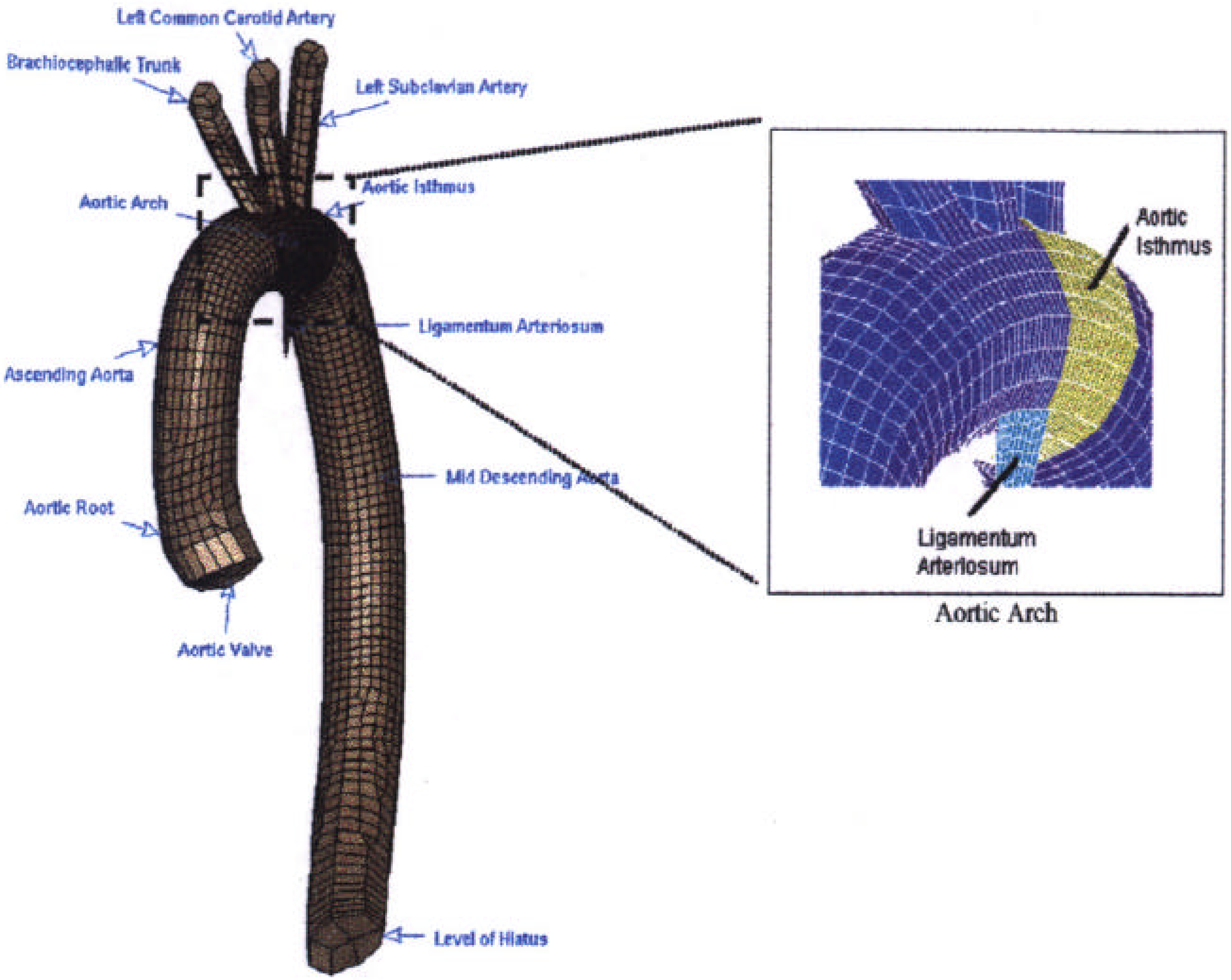


UVA: Internal aortic pressure time histories from frontal sled tests.

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





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

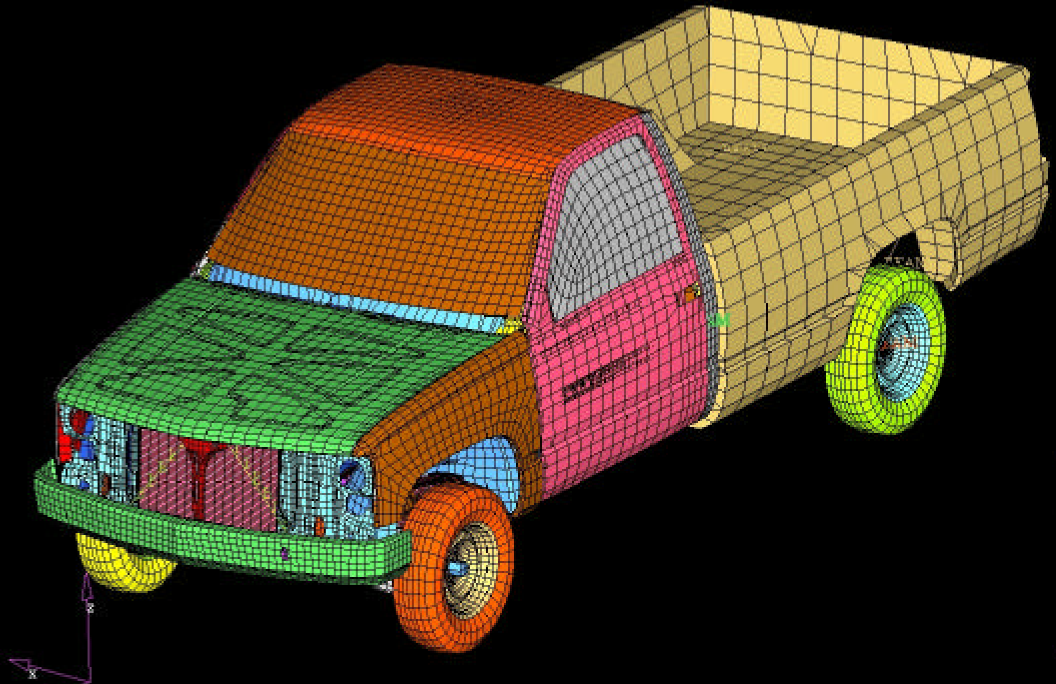
- **Introduction**

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

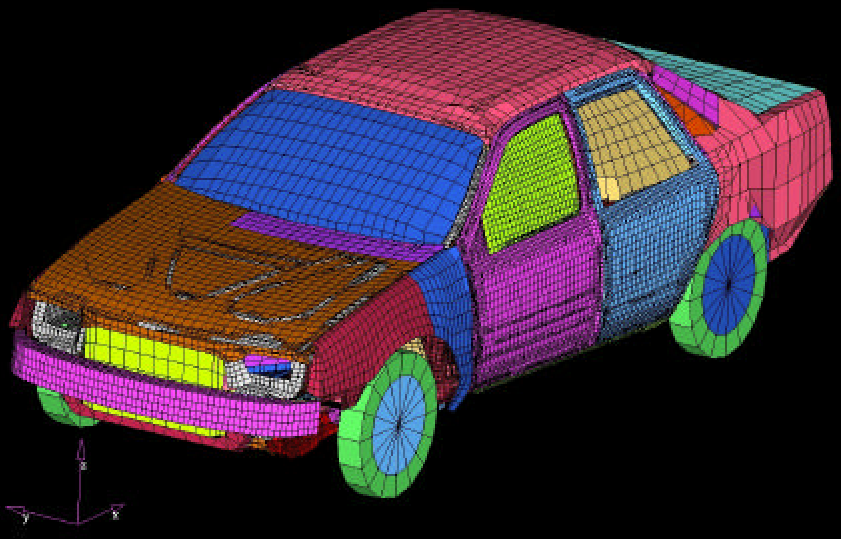
Car to Car Crash Numerical Reconstruction

	Target vehicle	Bullet Vehicle
Actual Crash	2002 Four door Dodge Stratus	1995 Van Ford E350
FE reconstruction	Ford Taurus	Chevrolet C1500 Pickup
Gross Weight kg (lbs)	1432 (2937)	2547 (5584)

FE Models of Vehicle



Non case vehicle -Chevrolet C1500 Pickup



Case vehicle - Ford Taurus

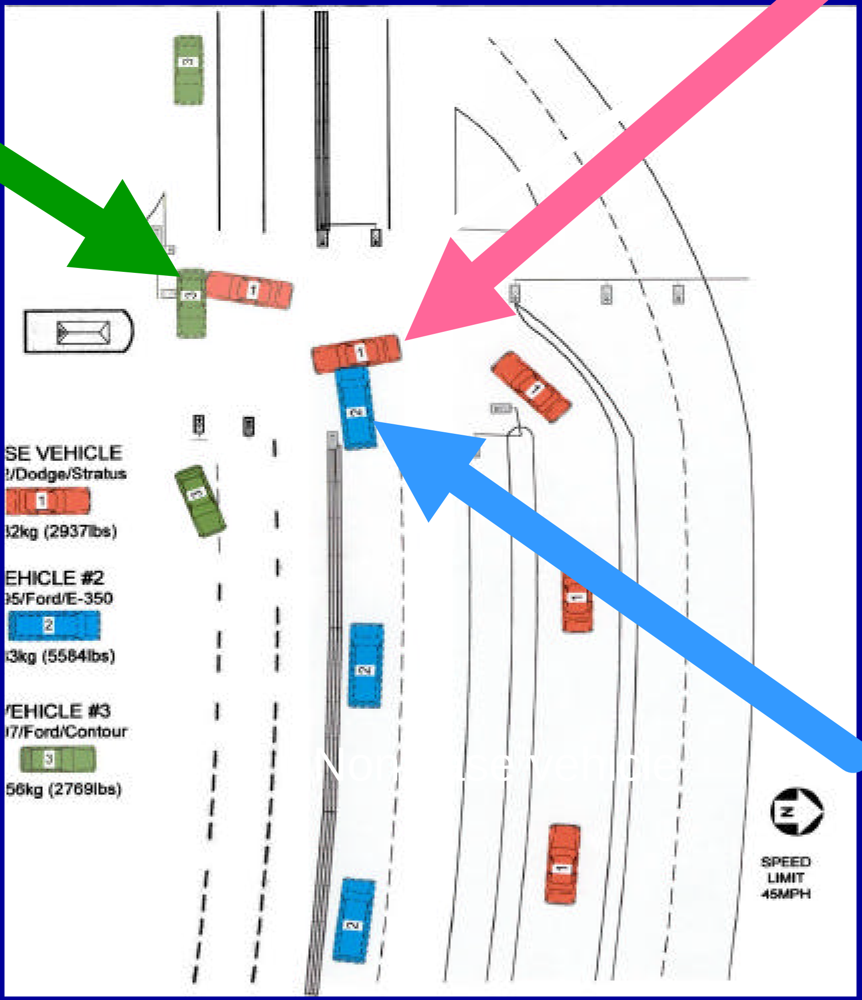
Reference : http://www.ncac.gwu.edu/vml/models.html

Crash Scene

Secondary impact

Case Vehicle

(Dodge Stratus)



Non Case Vehicle

(Ford Van)

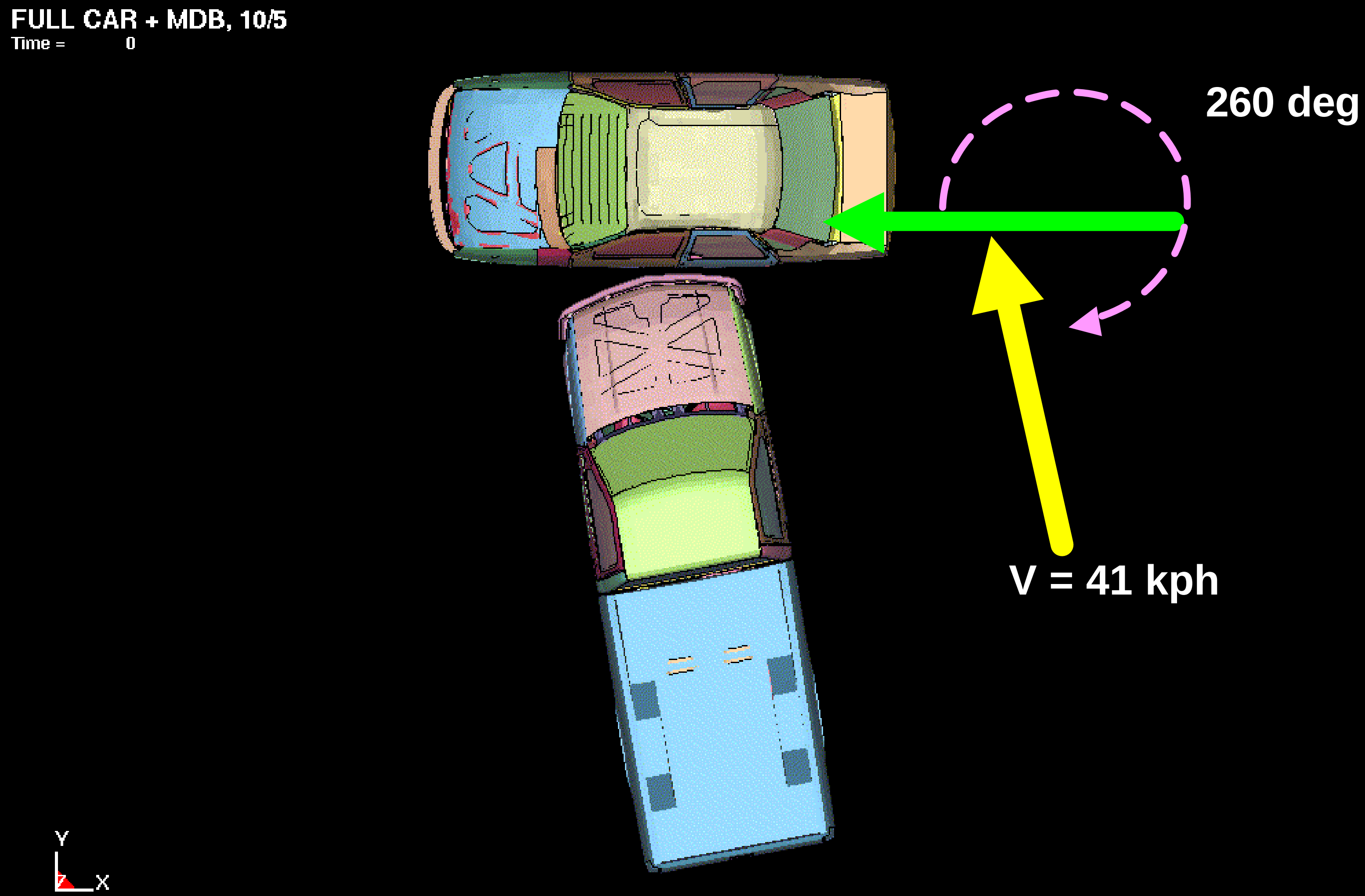
Numerical Reconstruction

- 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

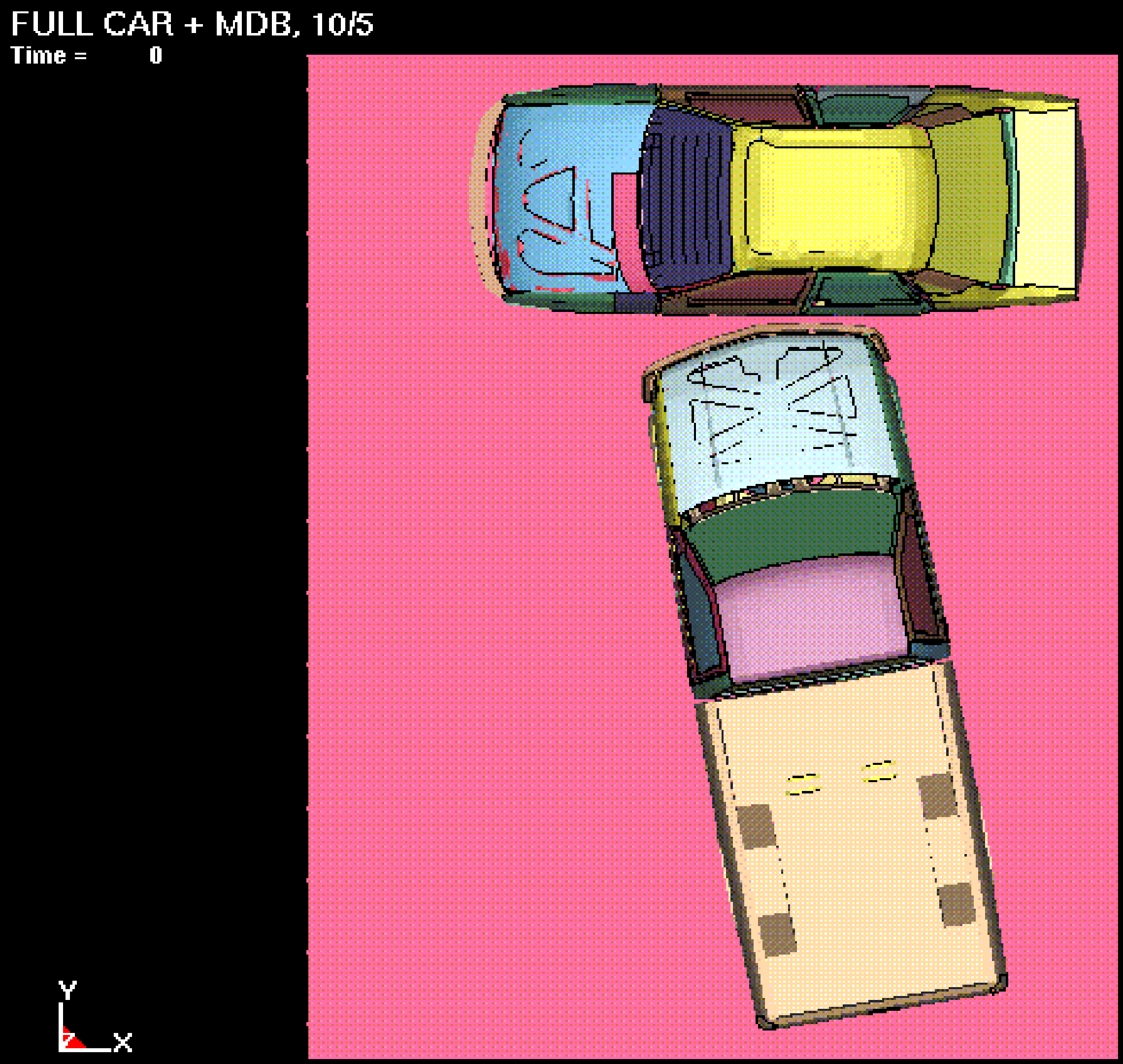
Numerical Reconstruction

- 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

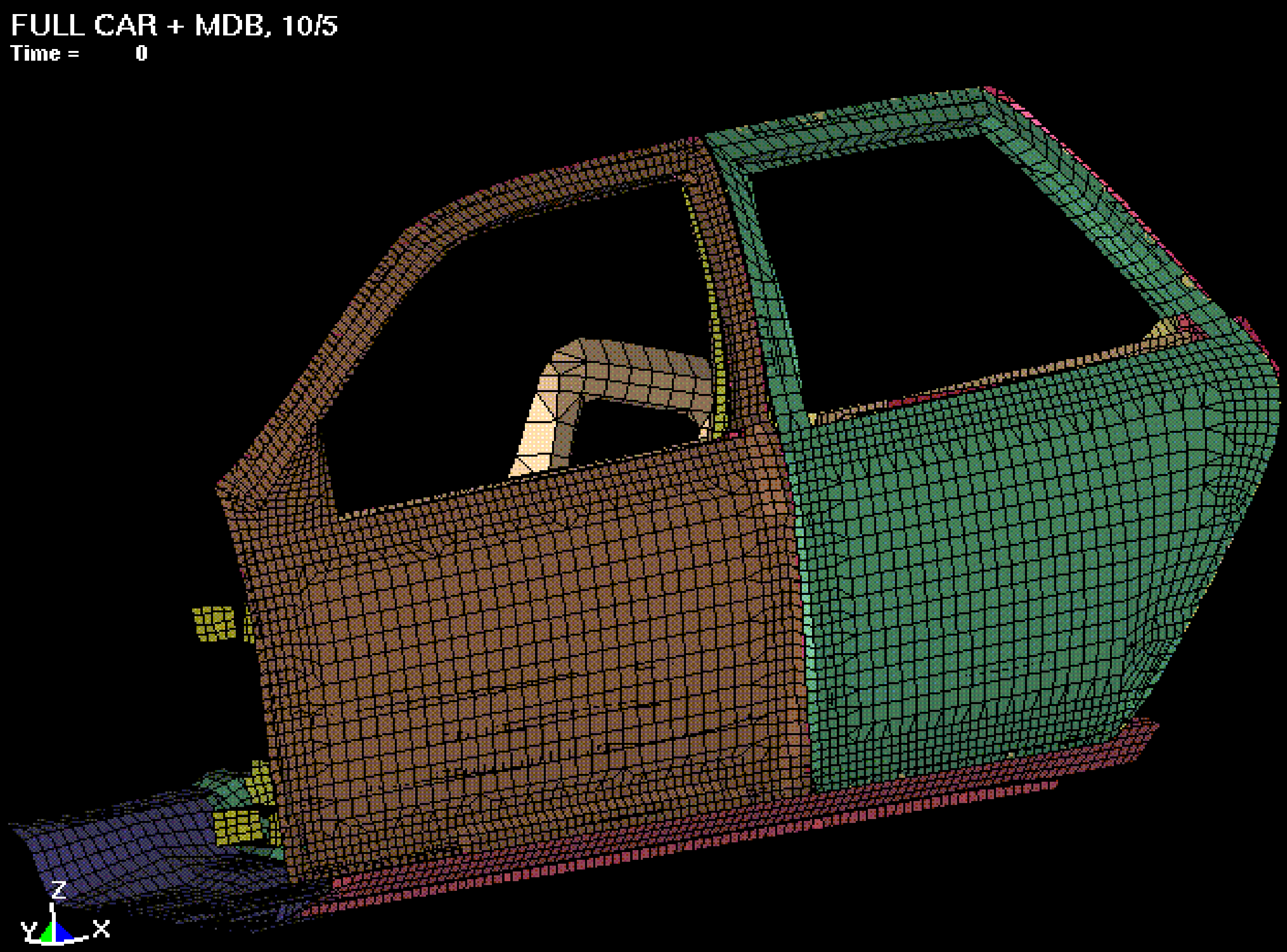
Direction and location of impact



Kinematics

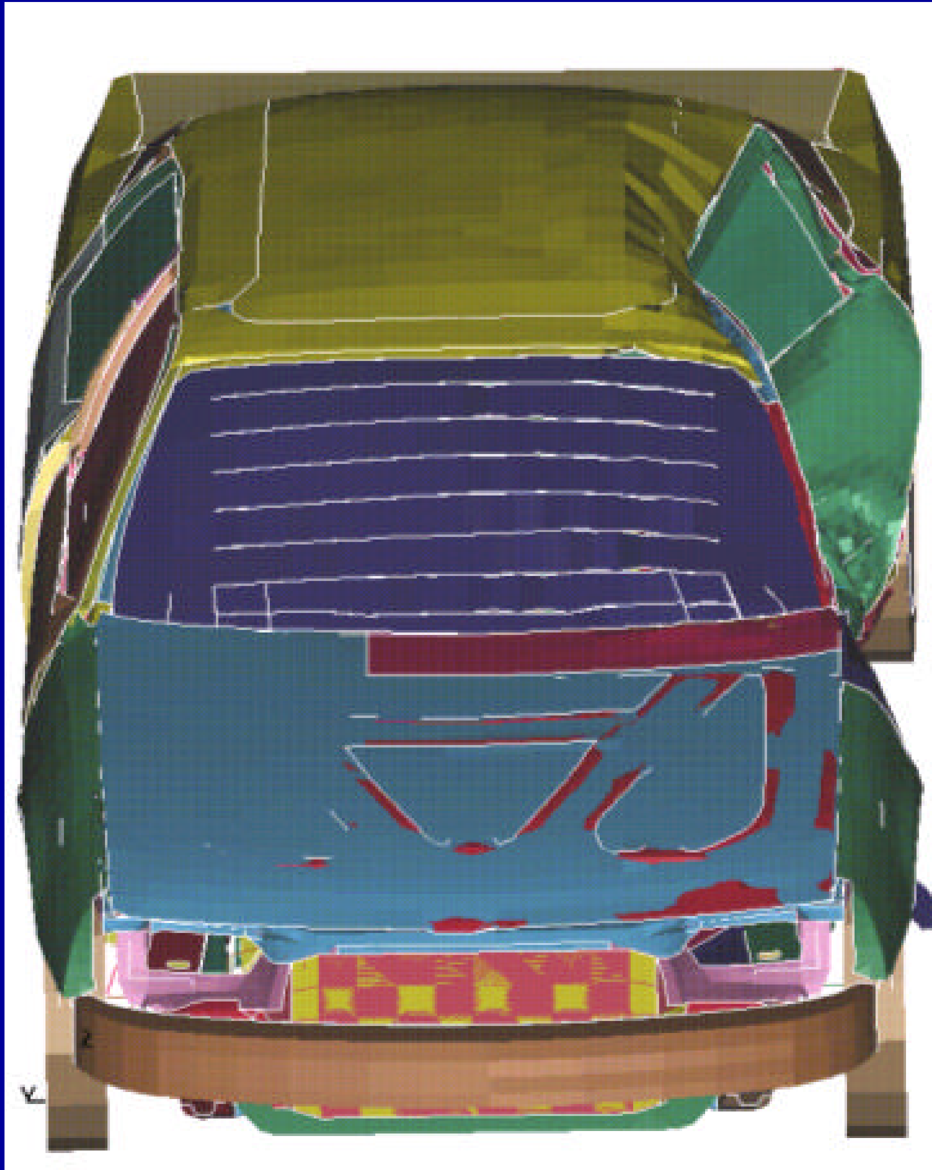


External Door Deformation



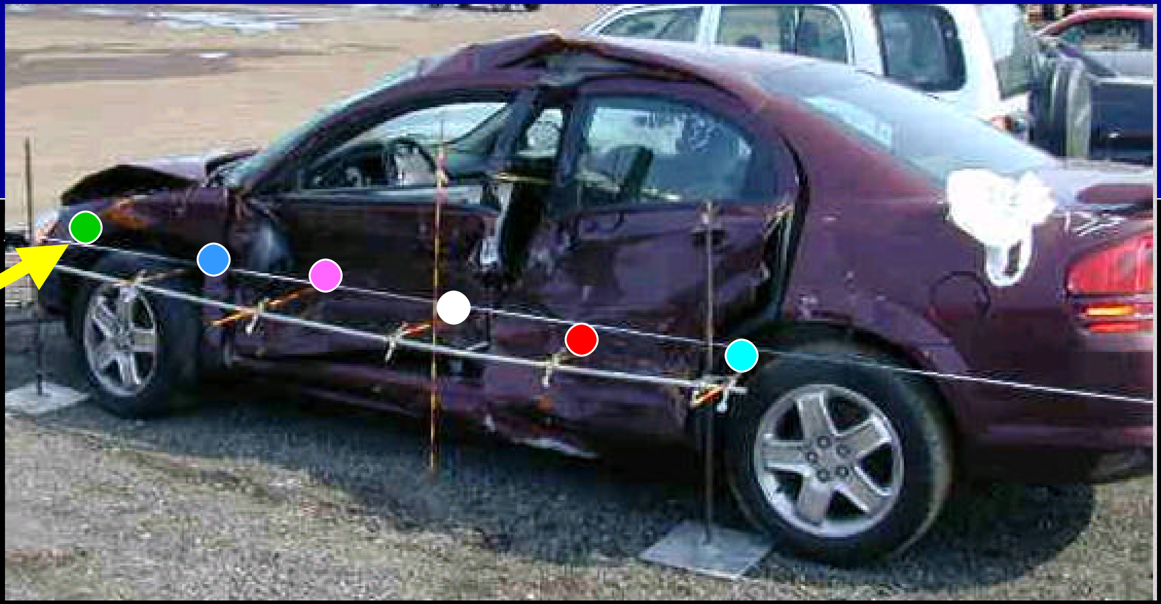
Internal Door Deformation

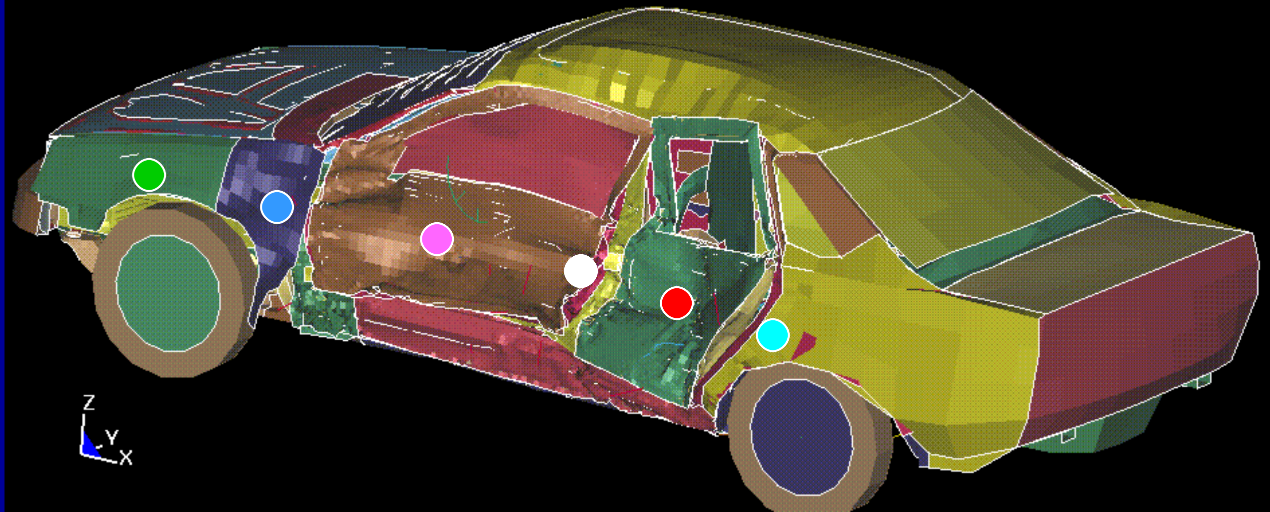
Vehicle Deformation



Deformation Measurement

Points of deformation measurement



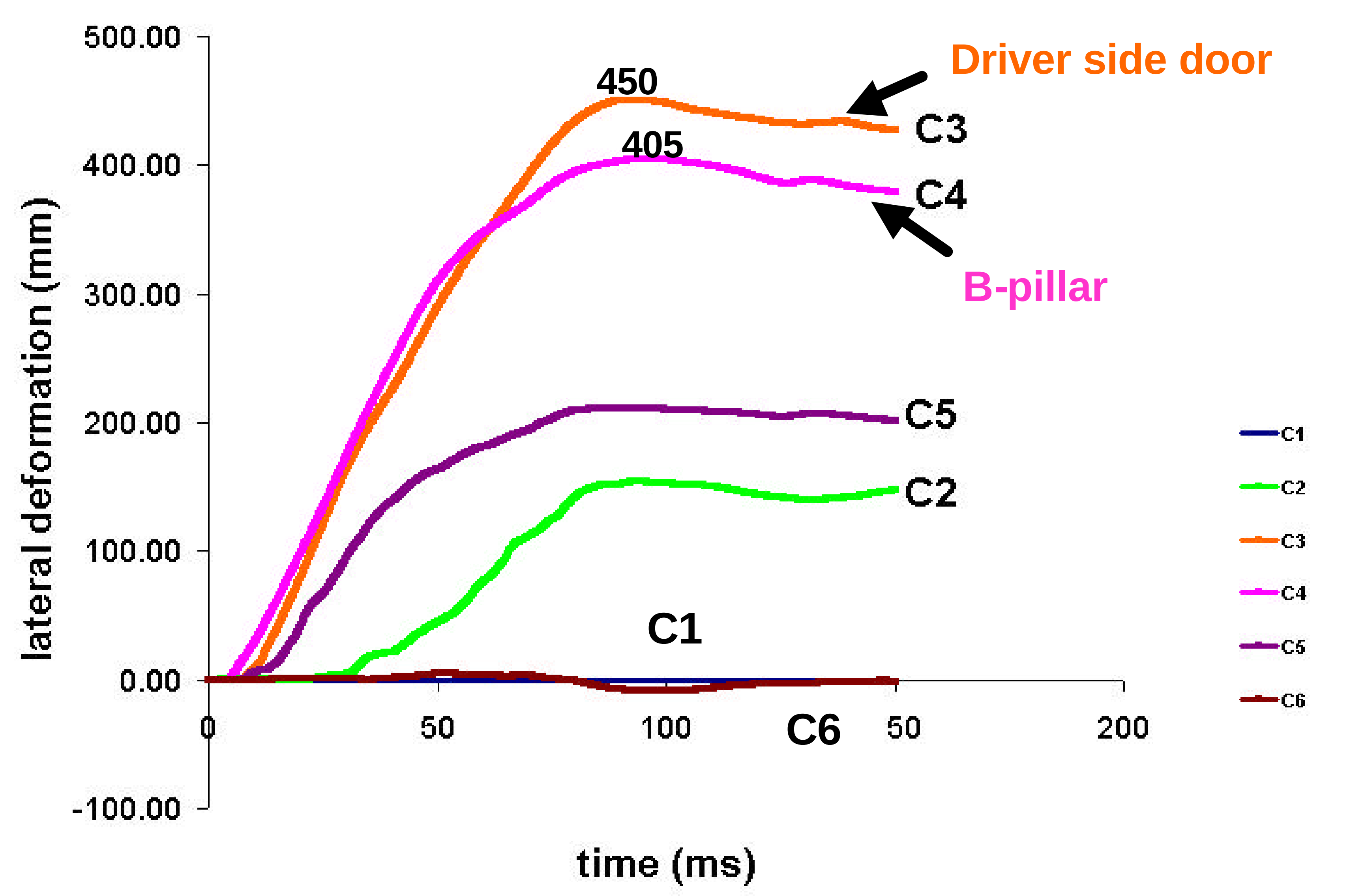


- C1
- C2
- C3
- C4
- C5
- C6

Deformation Pattern

Deformation points	Real case Deformation (mm)	FE Deformation (mm)
C1	30	0 (b/c rigid Front)
C2	270	155 (b/c rigid Front)
C3 (driver front door)	450	450
C4 (b-pillar)	340	405
C5	240	206
C6	80	8 (b/c rigid Rear)

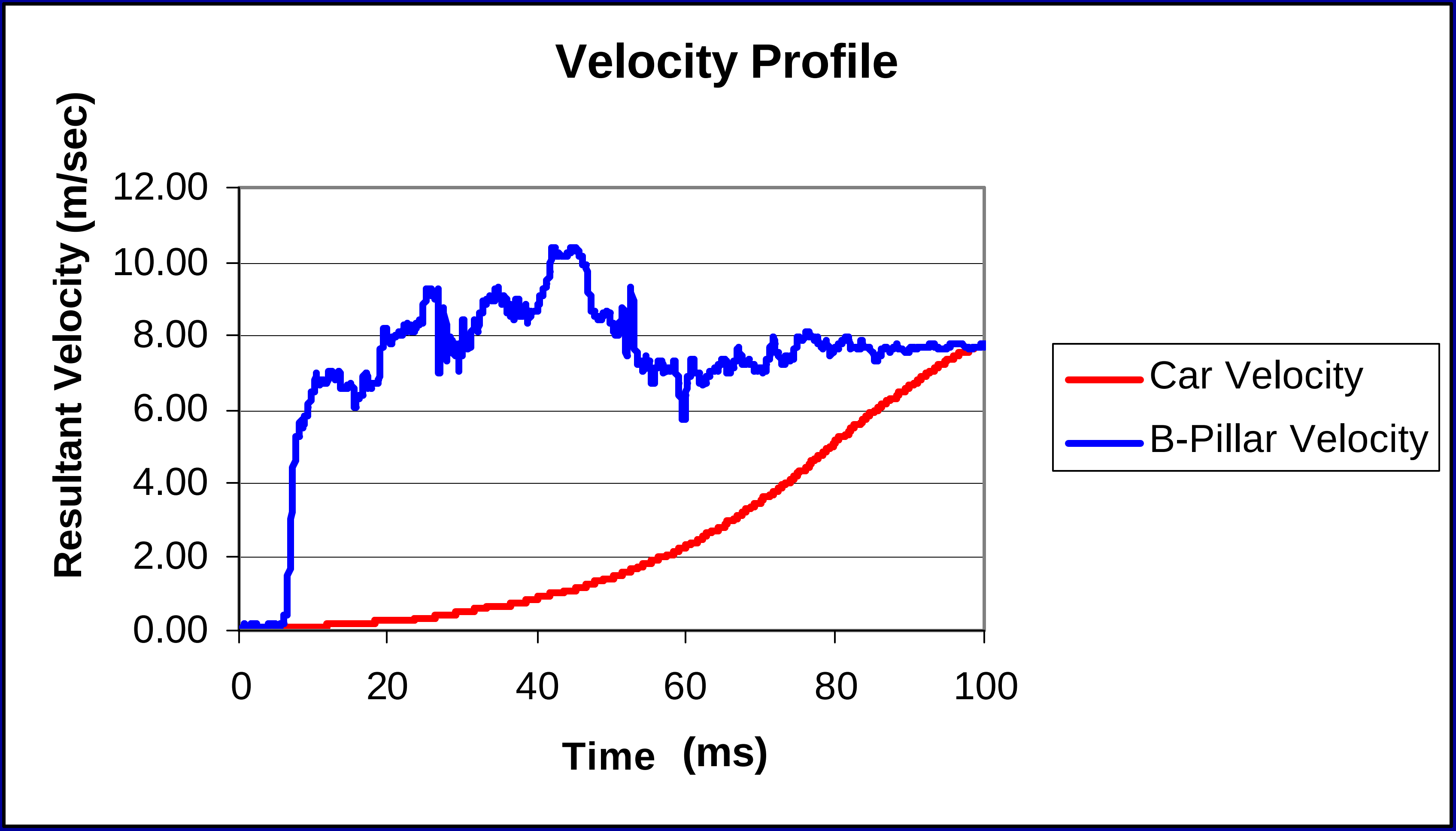
Deformation Time History



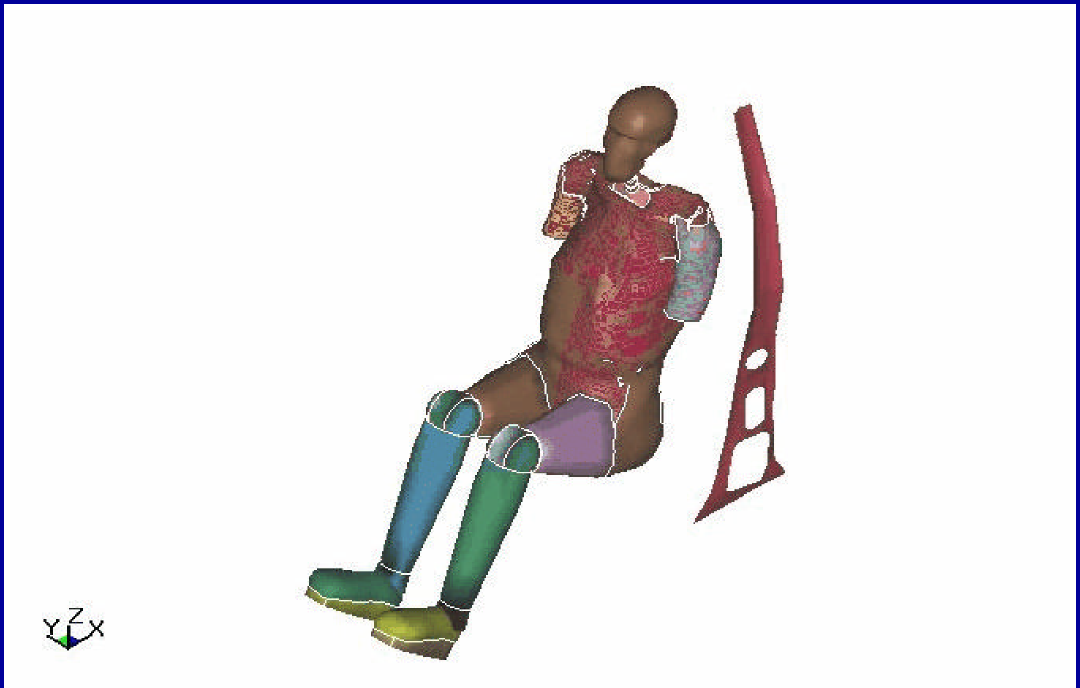
Sub-Structured B-Pillar Simulation

- 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)

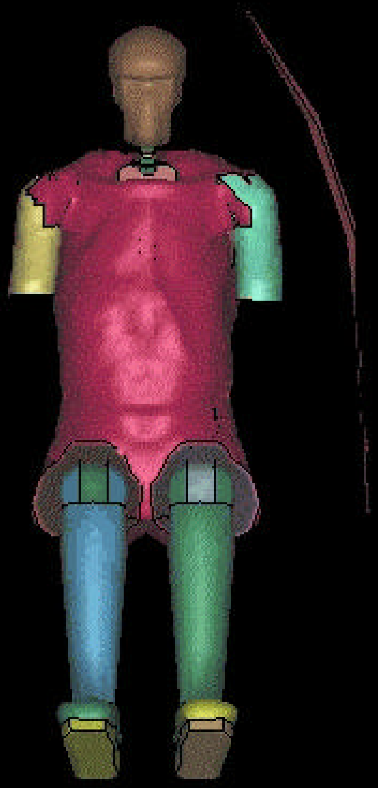
Velocity Time History



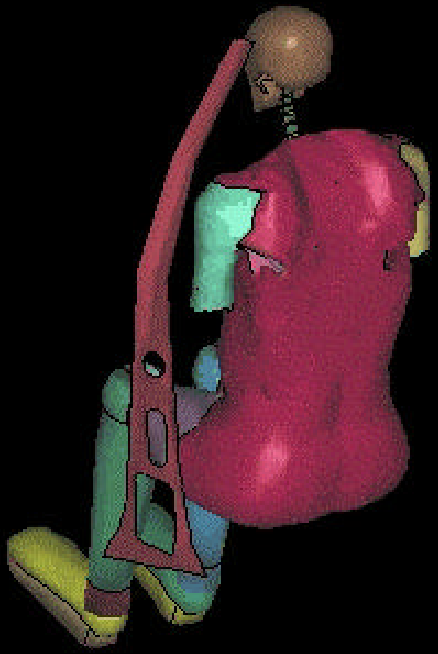
B-Pillar vs. Human Model Simulation



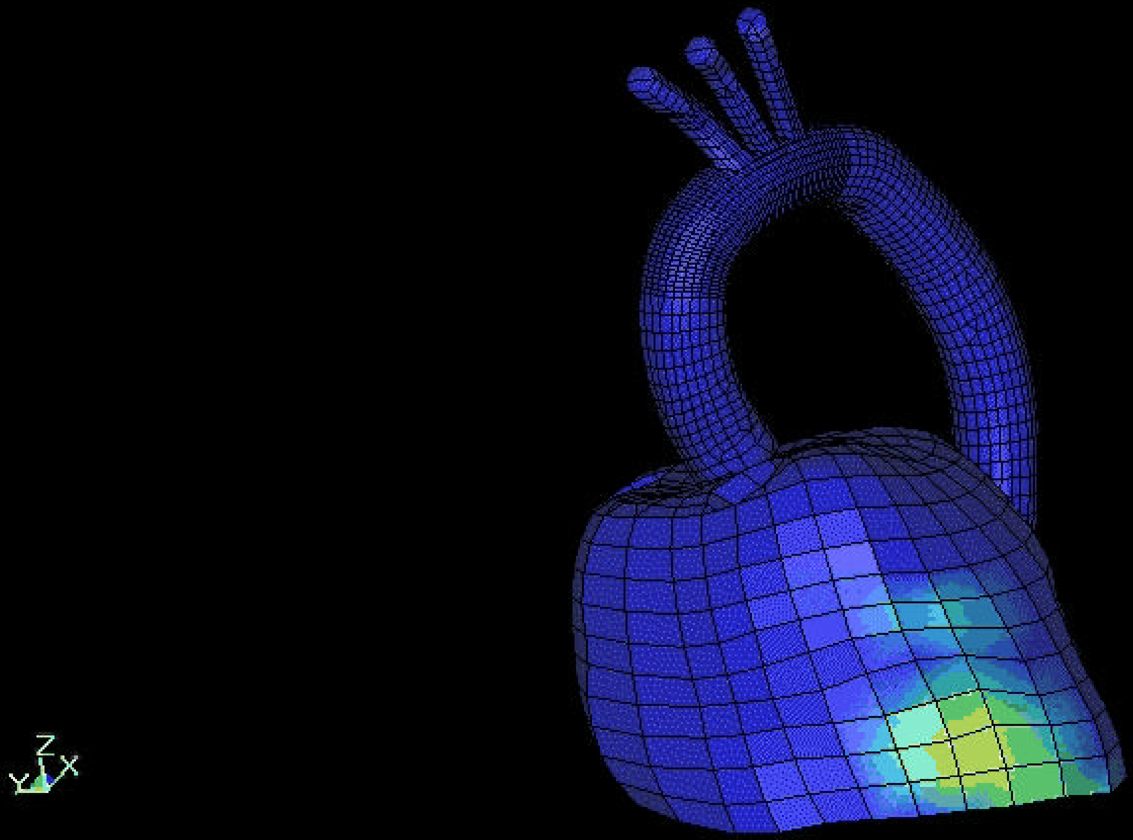
B-Pillar vs. Human Model Simulation



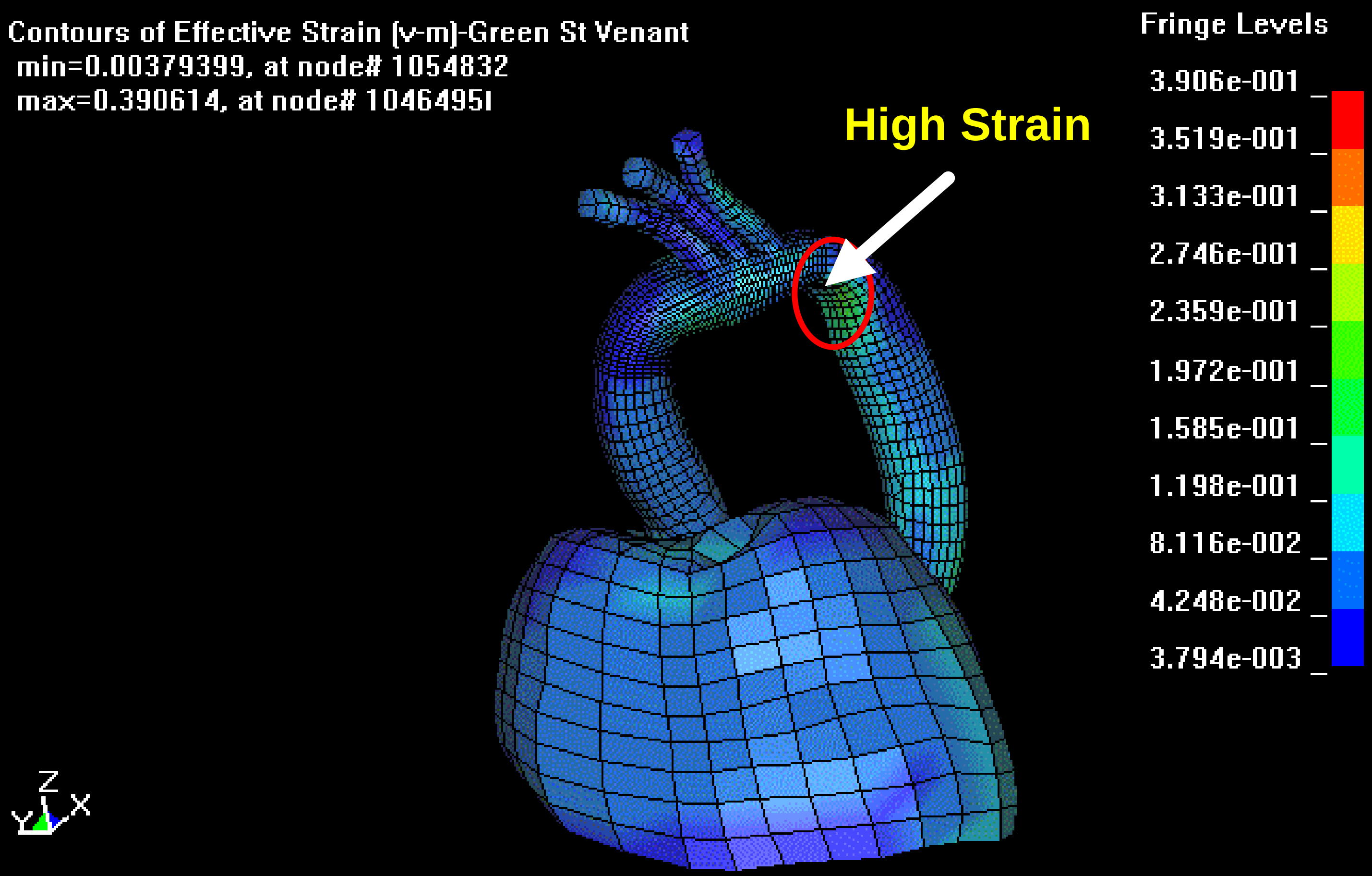
B-Pillar vs. Human Model Simulation



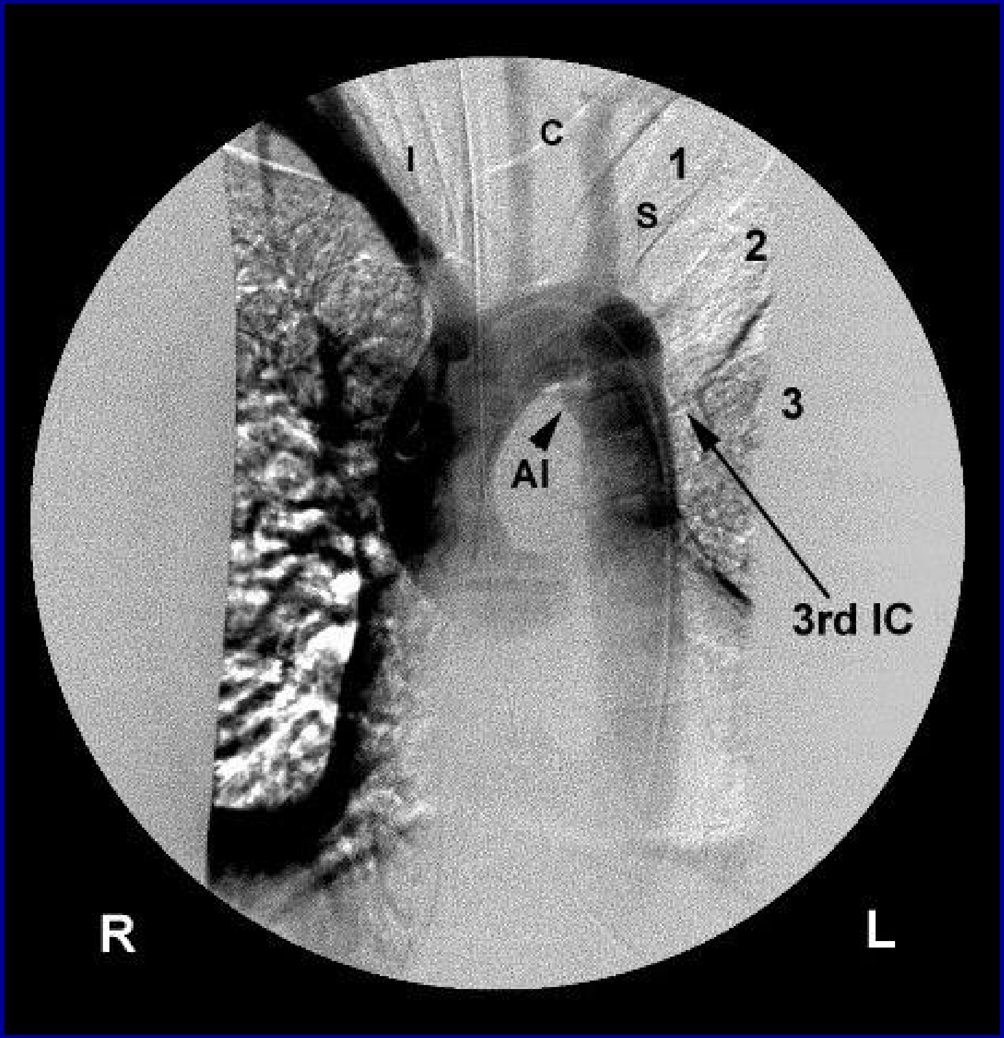
Aorta Kinematics:
B-Pillar vs. Human Whole Body Simulation



Maximum Strain in Aorta
Whole Body Simulation



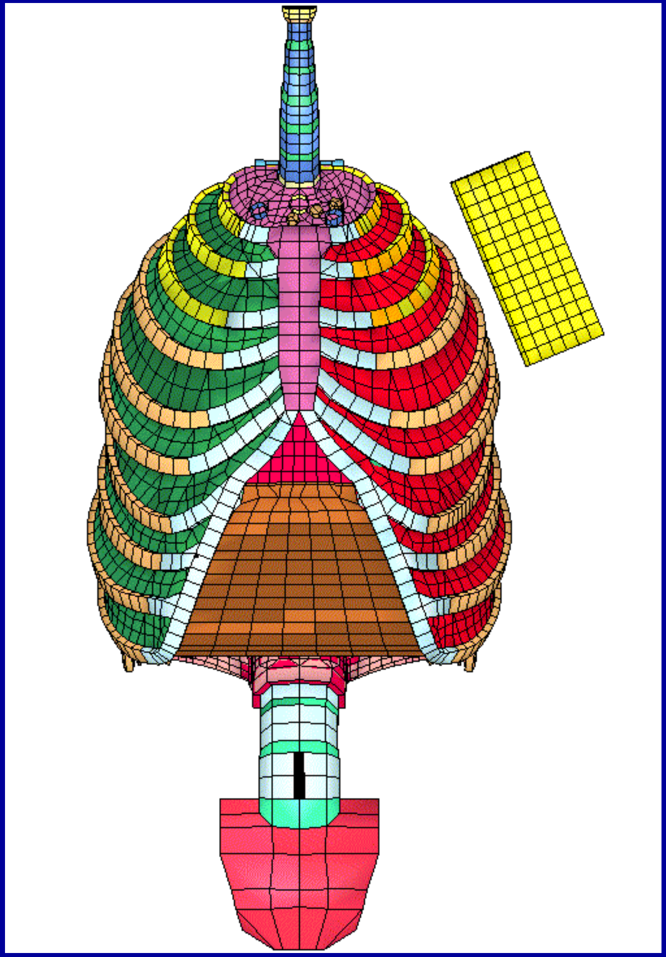
Injury Comparison

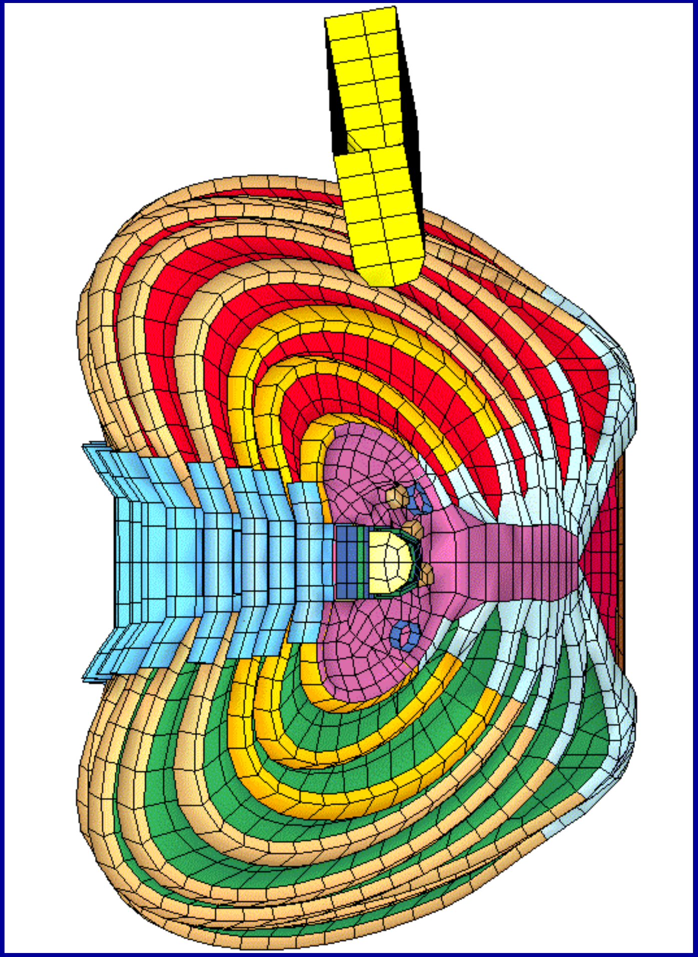


Parametric Study

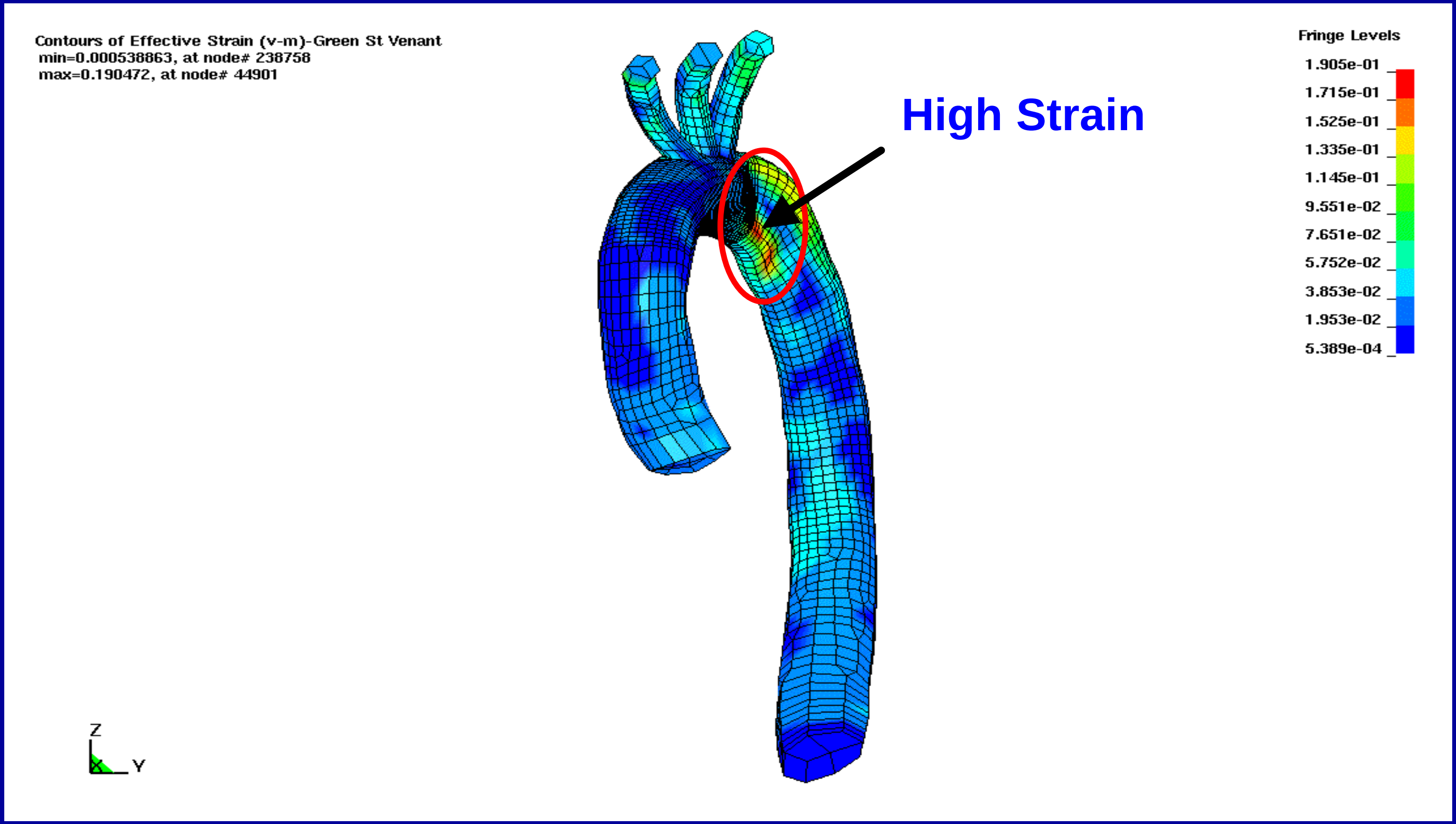
- Two variables
  - Pressure (200,400,500 mm of Hg)
  - Impact location (Upper, mid, and lower torso)
- Impactor (a narrow piece of the B-Pillar)
- Impactor mass 19.64 kg
- Impactor velocity 6.5 m/s (14.5 mph)
- Direction: 260º PDOF
- Total 9 simulations

Upper Thorax Impact

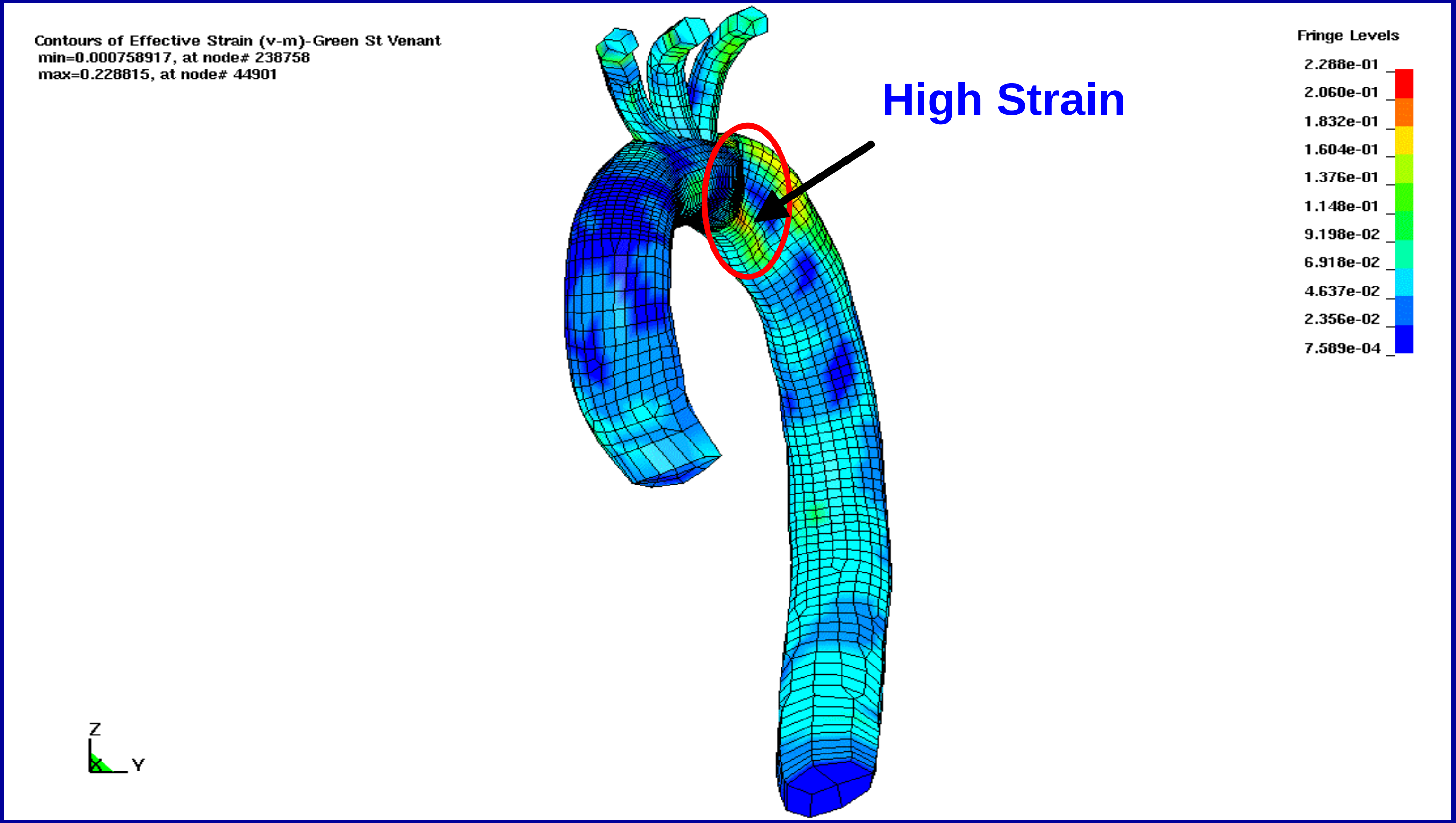




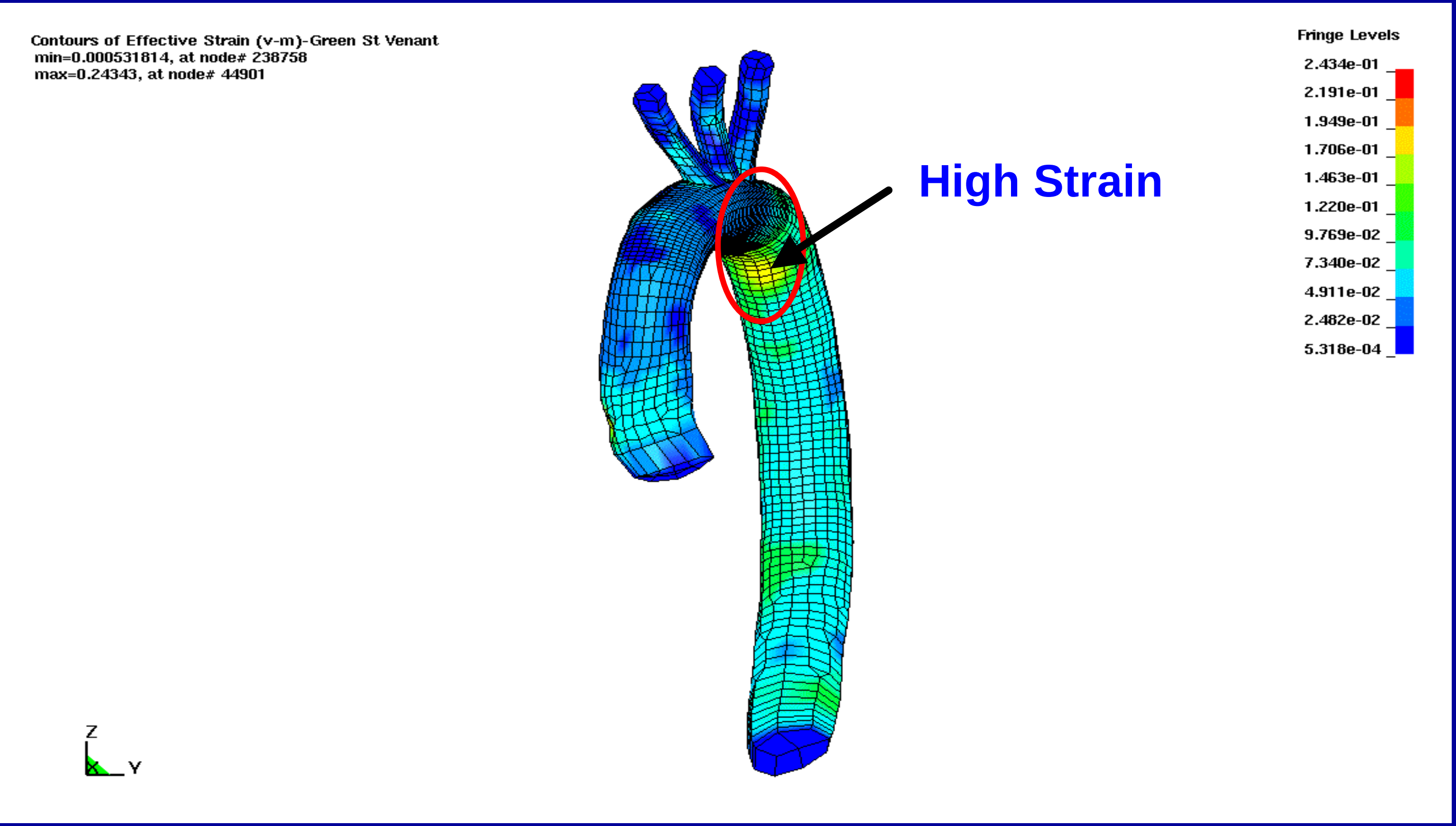
Upper Thorax Impact
(Aorta Pressure 200 mm Hg)



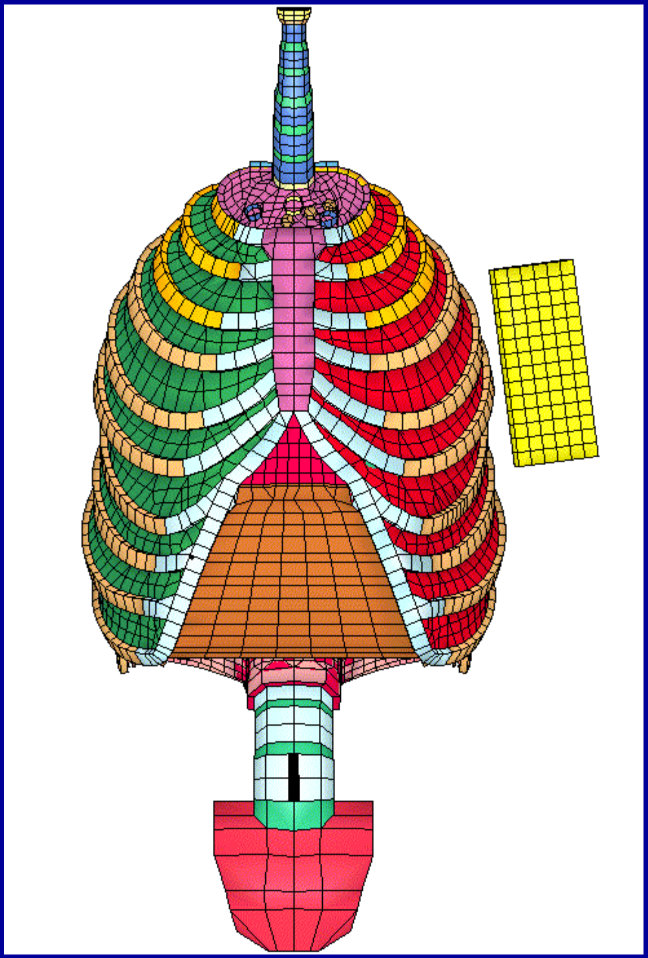
Upper Thorax Impact (Aorta Pressure 400 mm Hg)

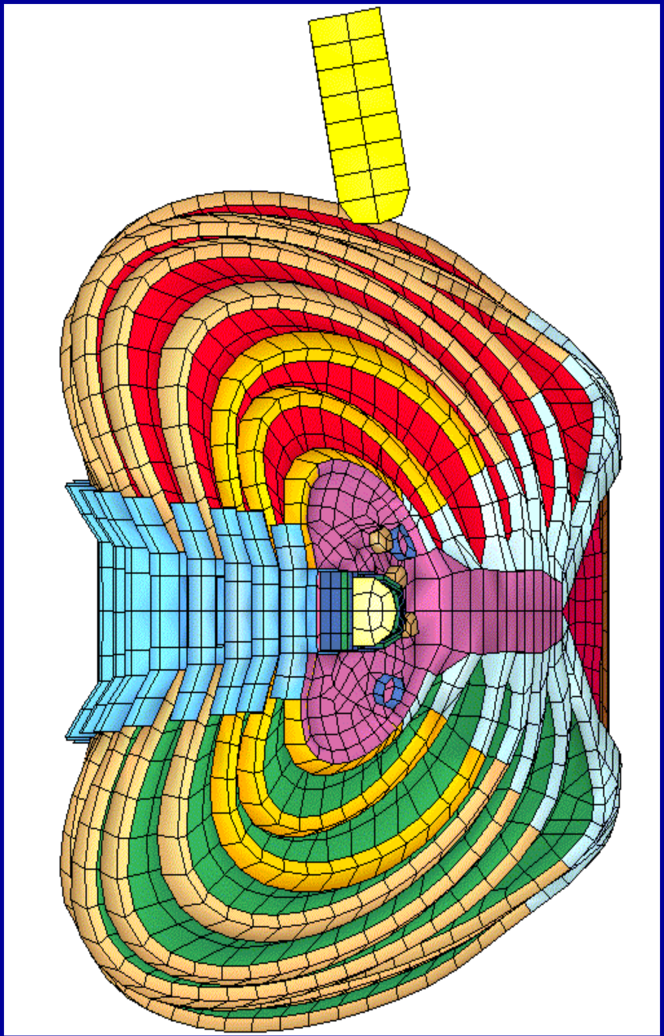


Upper Thorax Impact
(Aorta Pressure 500 mm Hg)

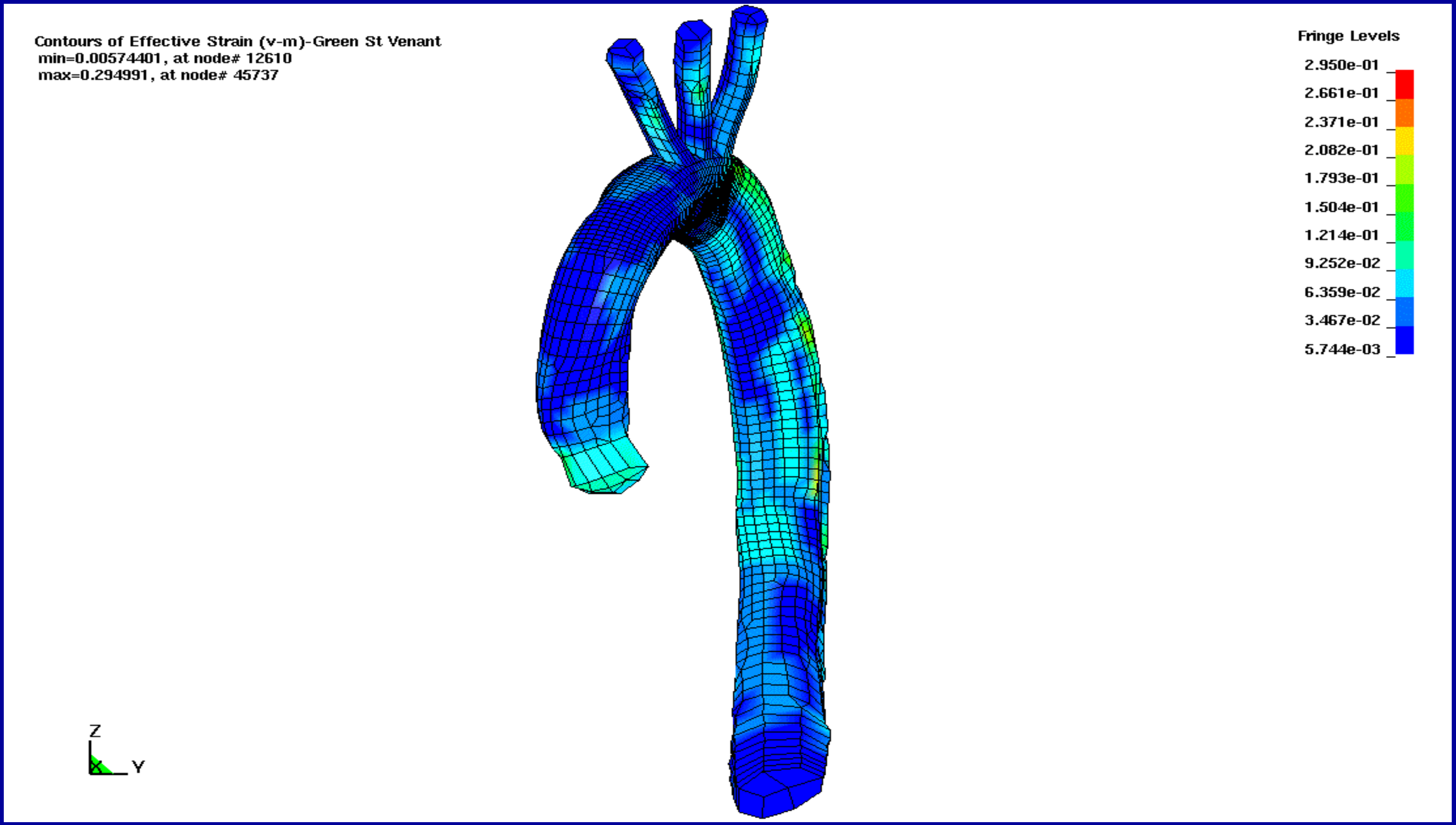


Mid Thorax Impact

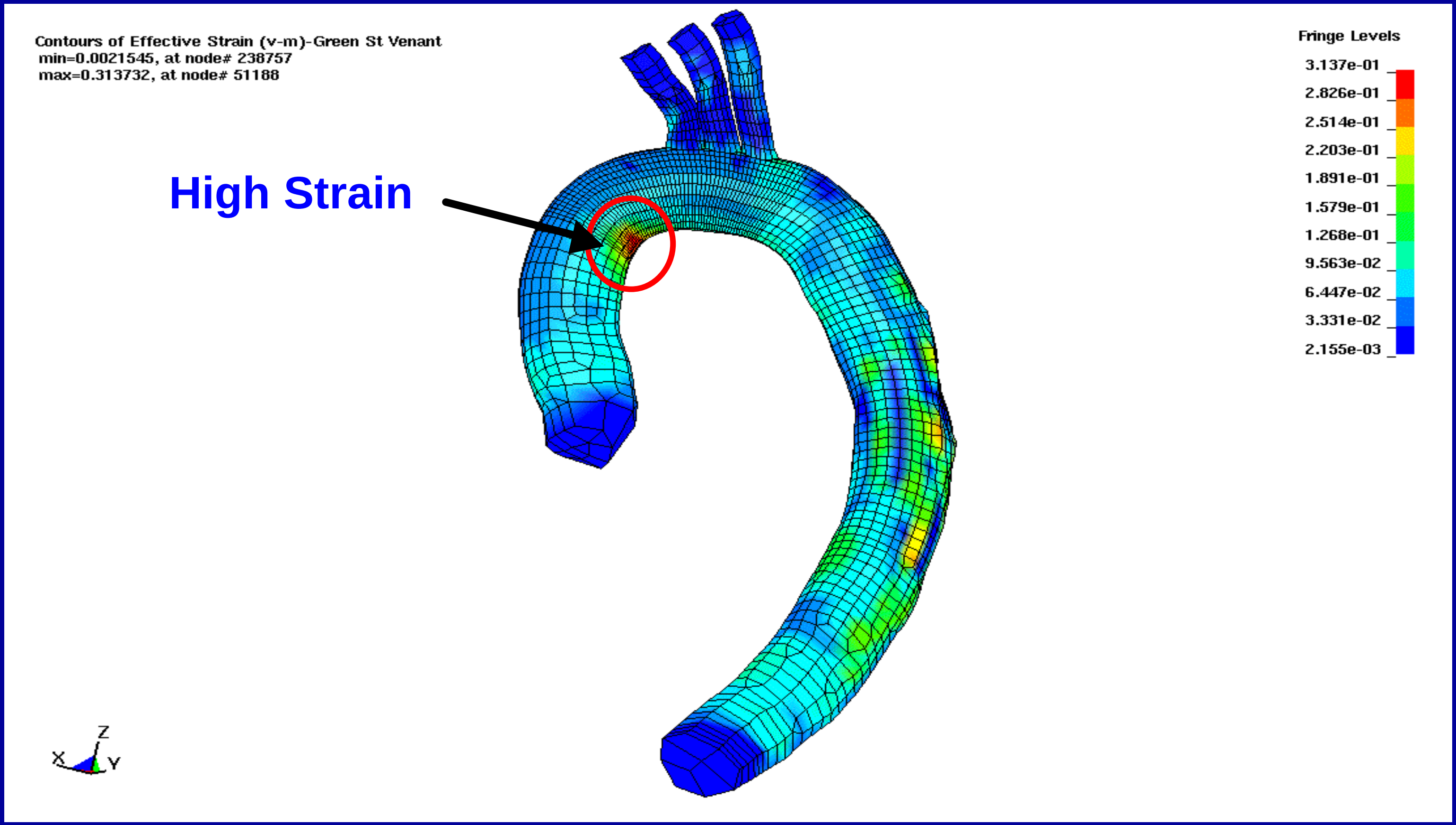




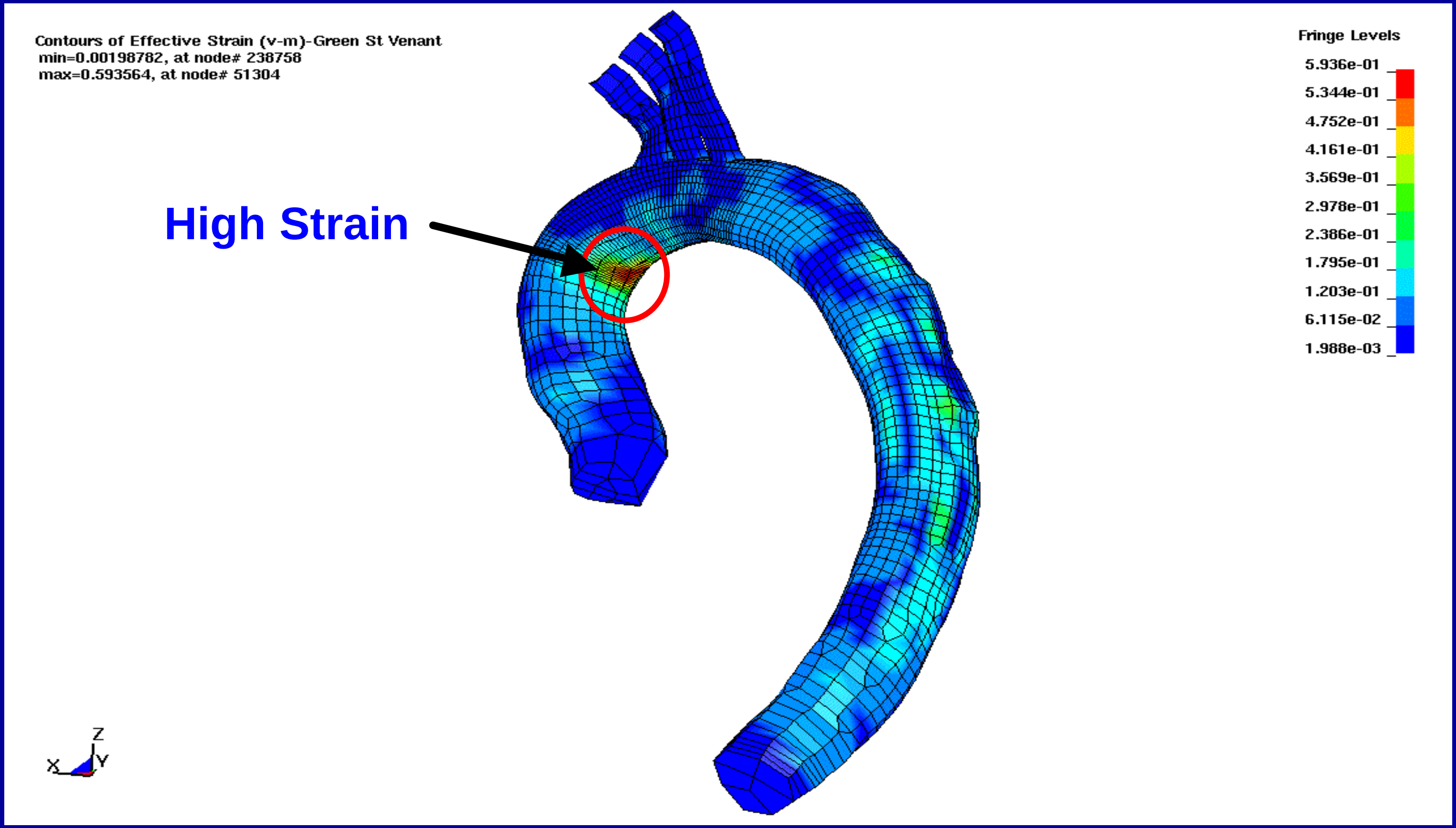
Mid Thorax Impact
(Aorta Pressure 200 mm Hg)



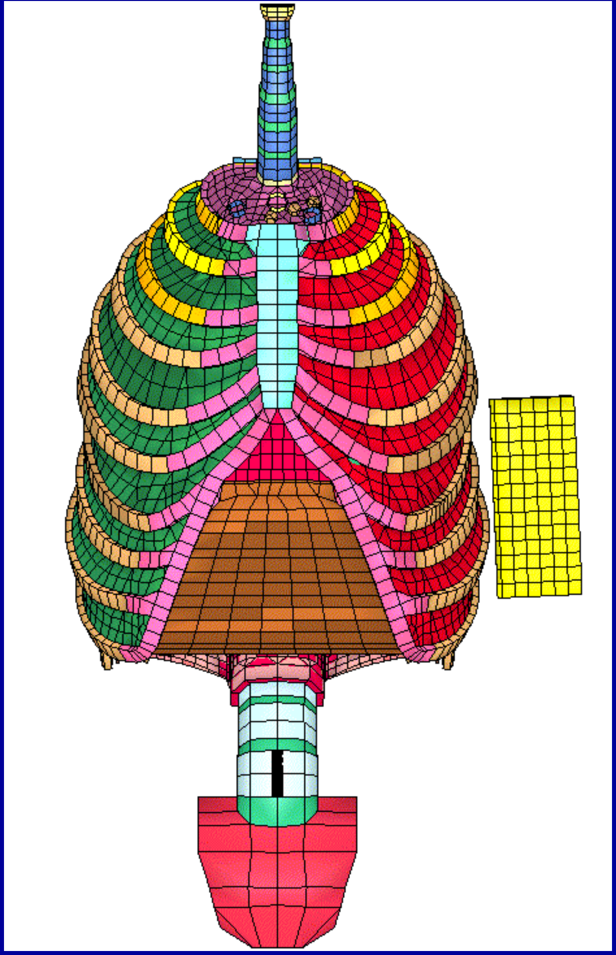
Mid Thorax Impact
(Aorta Pressure 400 mm Hg)

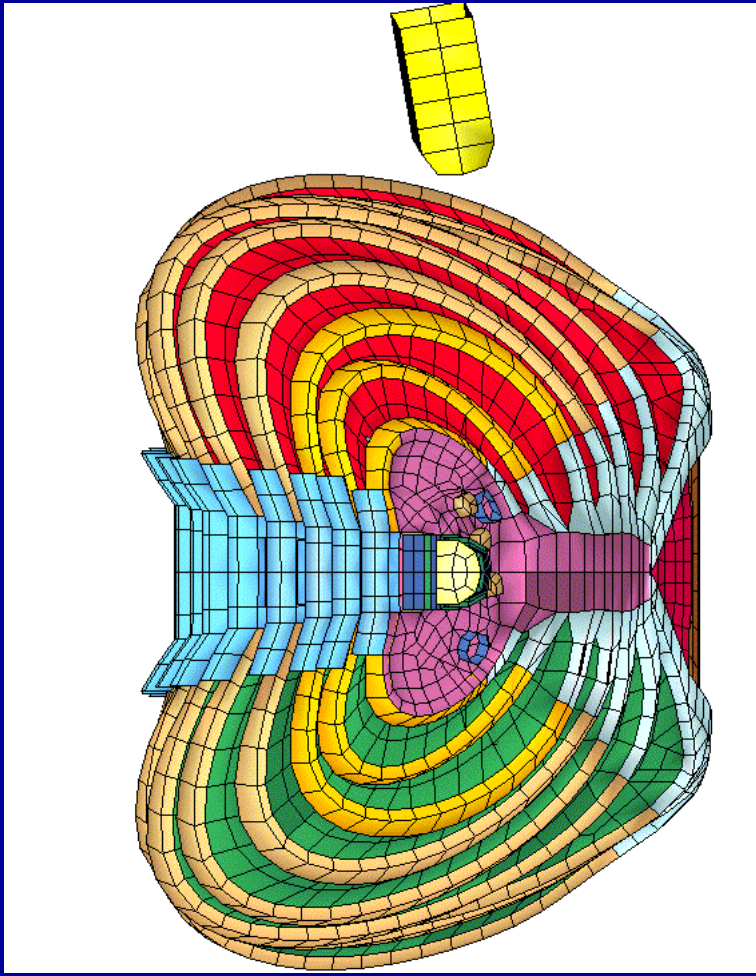


Mid Thorax Impact (Aorta Pressure 500 mm Hg)

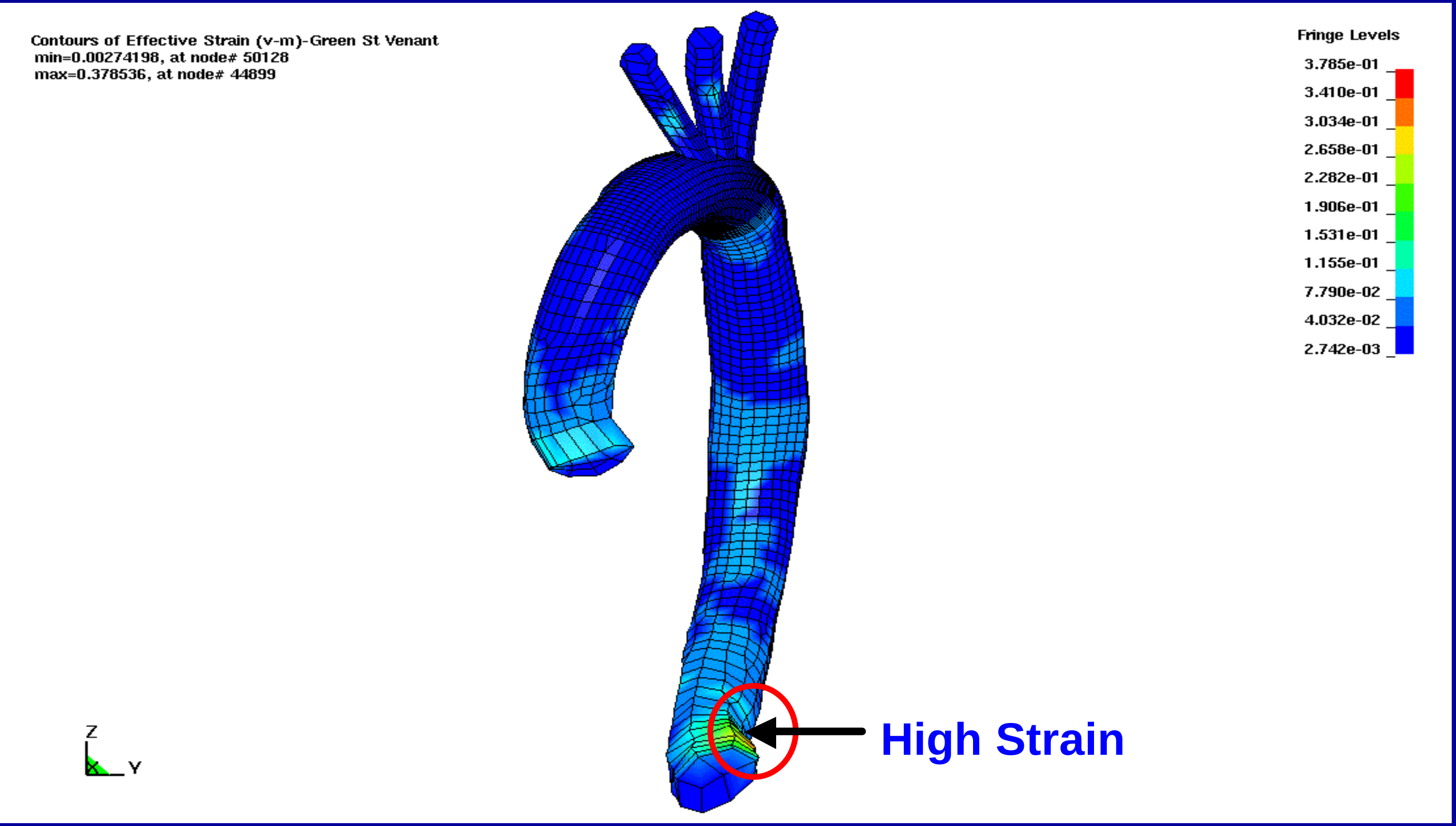


Lower Thorax Impact

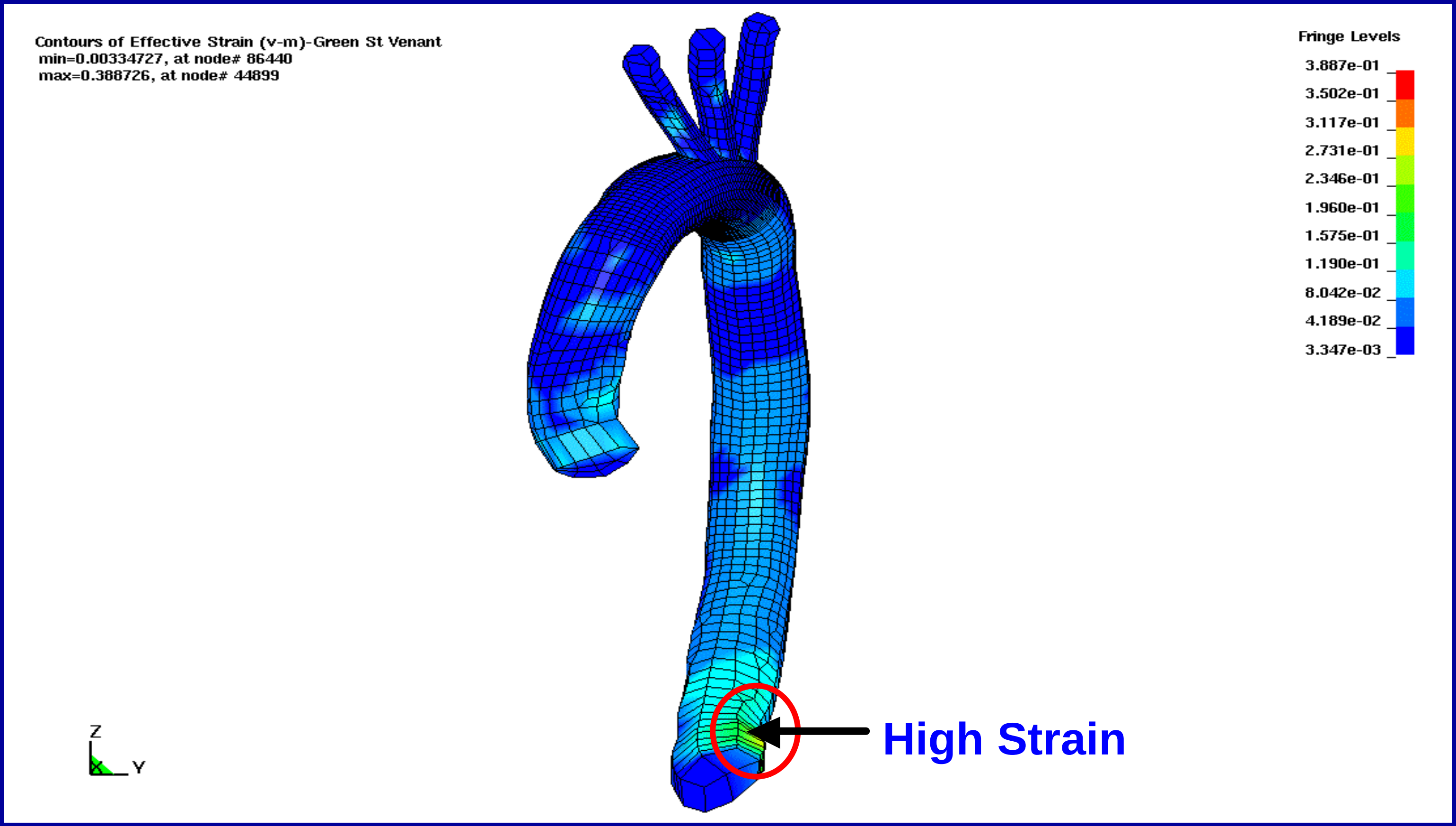




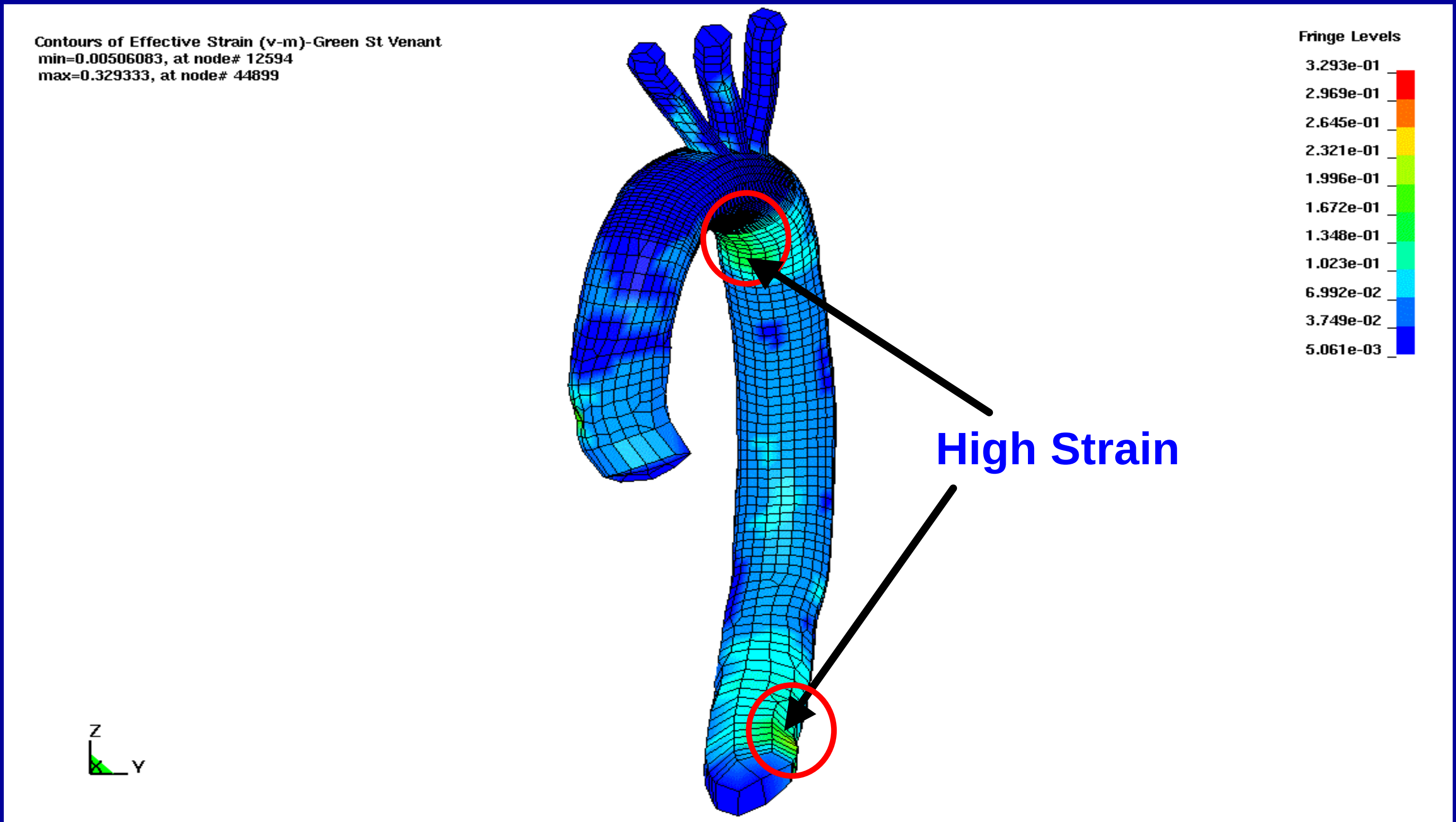
Lower Thorax Impact
(Aorta Pressure 200 mm Hg)



Lower Thorax Impact (Aorta Pressure 400 mm Hg)



Lower Thorax Impact (Aorta Pressure 500 mm Hg)



Maximum Strain in Aorta

	200 mm Hg	400mm Hg	500 mm Hg
Upper torso impact	0.1887	0.1910	0.2042
Mid torso impact	0.1826	0.2954	0.6809
Lower torso impact	0.2587	0.2645	0.2545

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

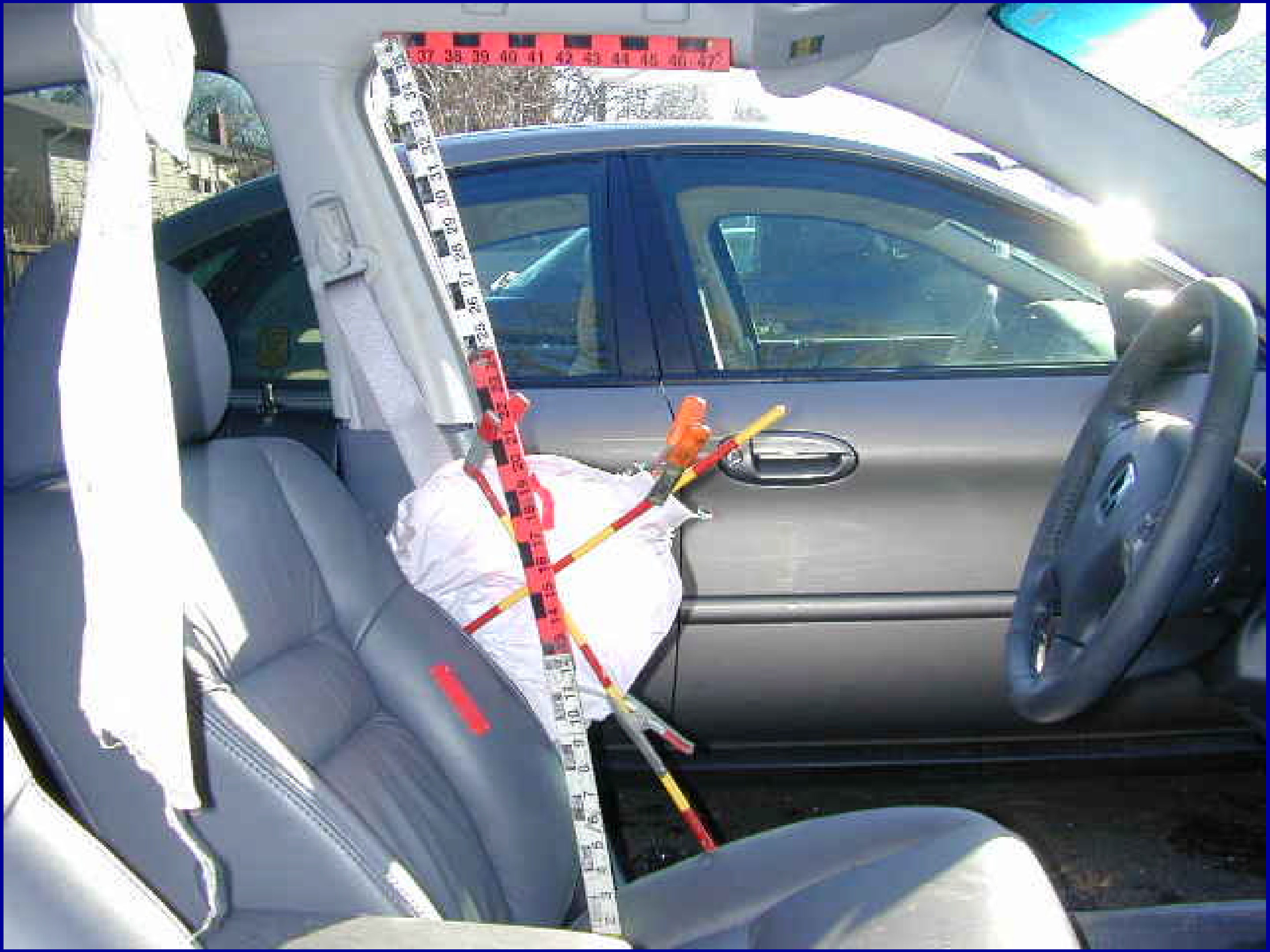
- **Both the human data and the simulations are compatible with the idea of a superpressurized proximal aorta and aortic arch acting as a lever system about the subclavian artery fulcrum to exert maximum strain on the aortic isthmus when the site of impact is at the level of the upper thorax (ribs 1-4)**

Future Research Goals

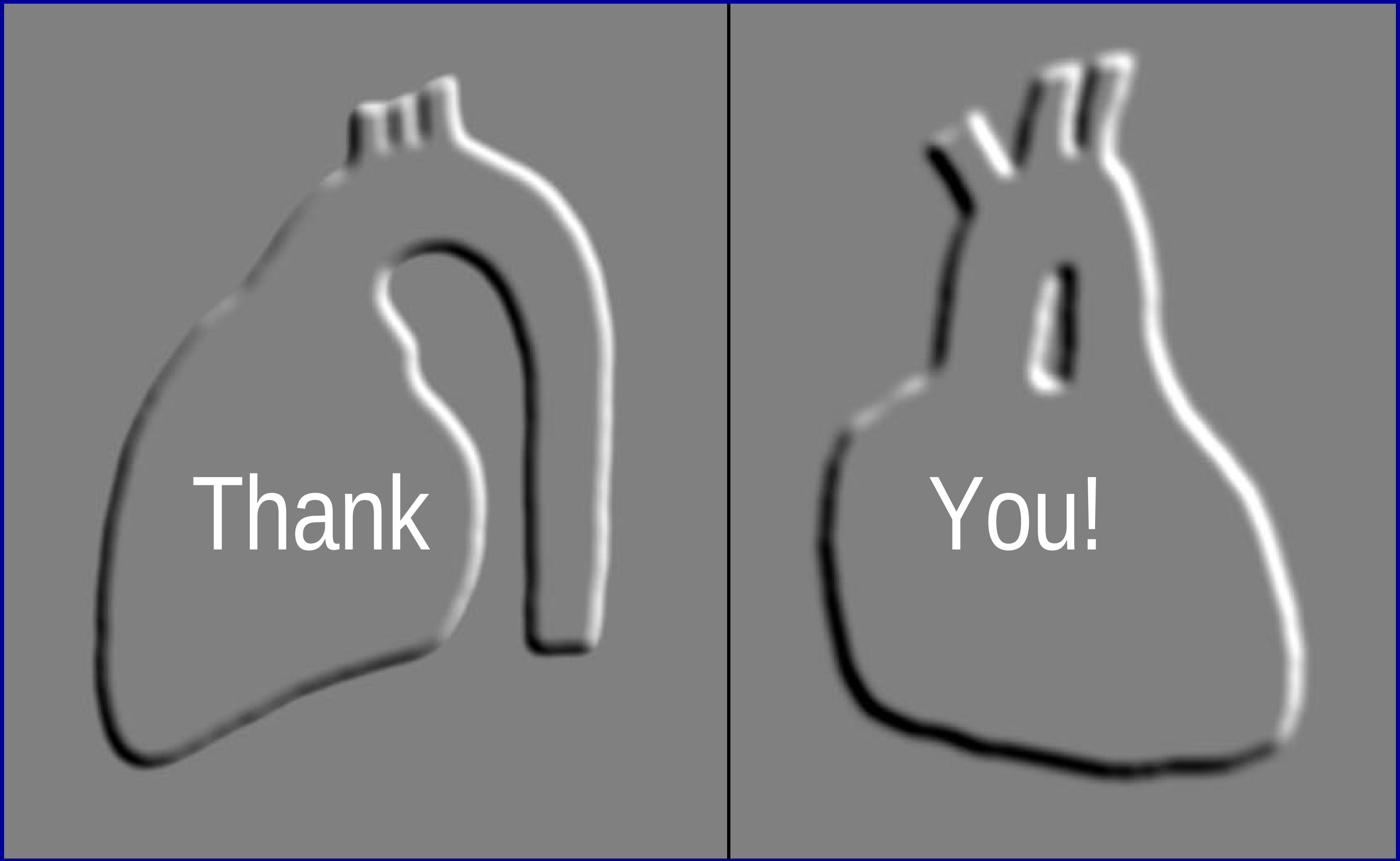
- Refine the simulations to include all chest structures and organs between the thoracic rib cage and the aorta and heart
- Evaluate whether aortic strain compatible with sites of clinical aortic rupture can occur within the range of PDOF from >20°-100° (right lateral), 340°-20° (frontal) and <340°-260°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



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