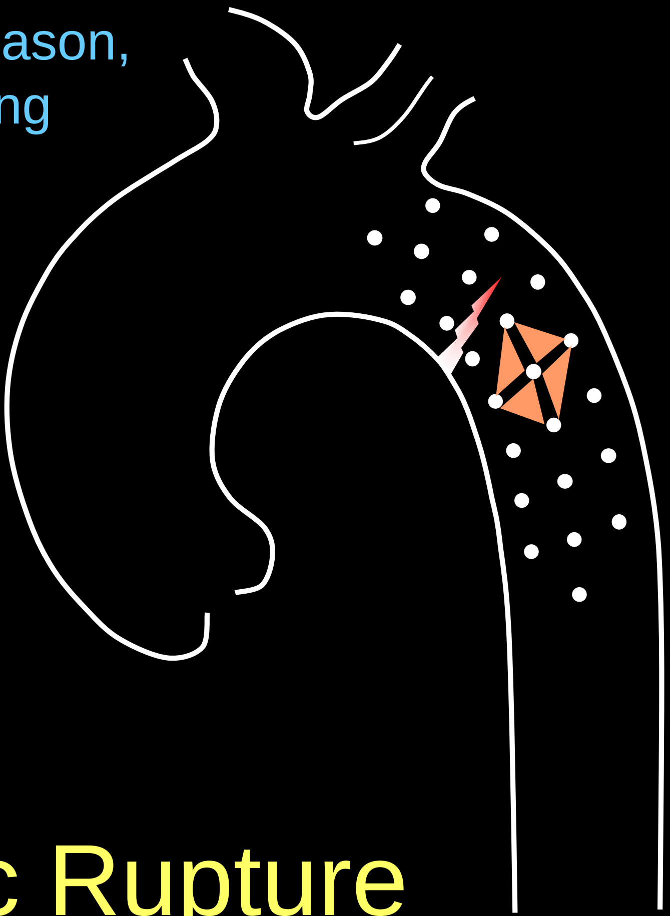
Warren N. Hardy, Chirag S. Shah, Matthew J. Mason,
James M. Kopacz, King H. Yang and Albert I. King
Wayne State University

Jennifer L. Bishop, Richard F. Banglmaier and
Michael J. Bey
Henry Ford Health System

Chris A. Van Ee
Design Research Engineering

Richard M. Morgan and Kennerly H. Digges
The George Washington University



Mechanisms of Traumatic Rupture of the Aorta and Associated Peri-isthmic Motion and Deformation

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4 November 2008, San Antonio, Texas

52nd STAPP Car Crash Conference®

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Epidemiology

Parmley (1958)
Bertrand et al. (2008)

- **Automobile crash accounts for the majority of TRA.**
- **TRA from 1998 - 2006 (United Kingdom):**
  - **1.2% of all occupants,**
  - **21.4% of all fatalities,**
  - **Side impact: 2.4%,**
  - **Frontal impact: 1.1%.**
- **Most prevalent concomitant injuries:**
  - **Multiple bilateral rib Fx.**

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Etiology

Bertrand et al. (2008)

- **The risk of TRA increases with:**
  - **Greater speed,**
  - **Passenger compartment intrusion,**
  - **Subject age.**

- **The risk of TRA decreases with:**
  - **Seatbelt use in frontal crashes.**

- **TRA is related to:**
  - **"Severe direct chest impact or compression".**

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Pathogenesis

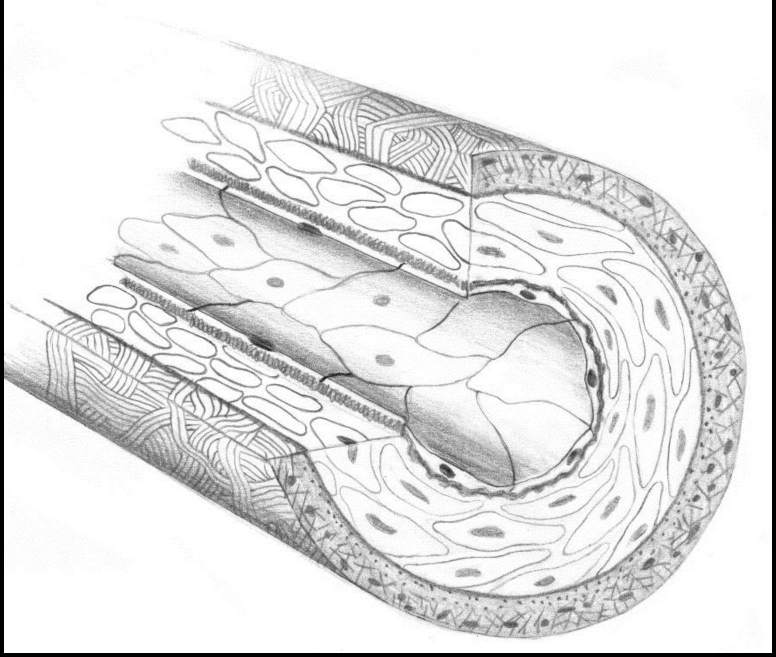
Katyal et al. (1997)
Viano (1983)

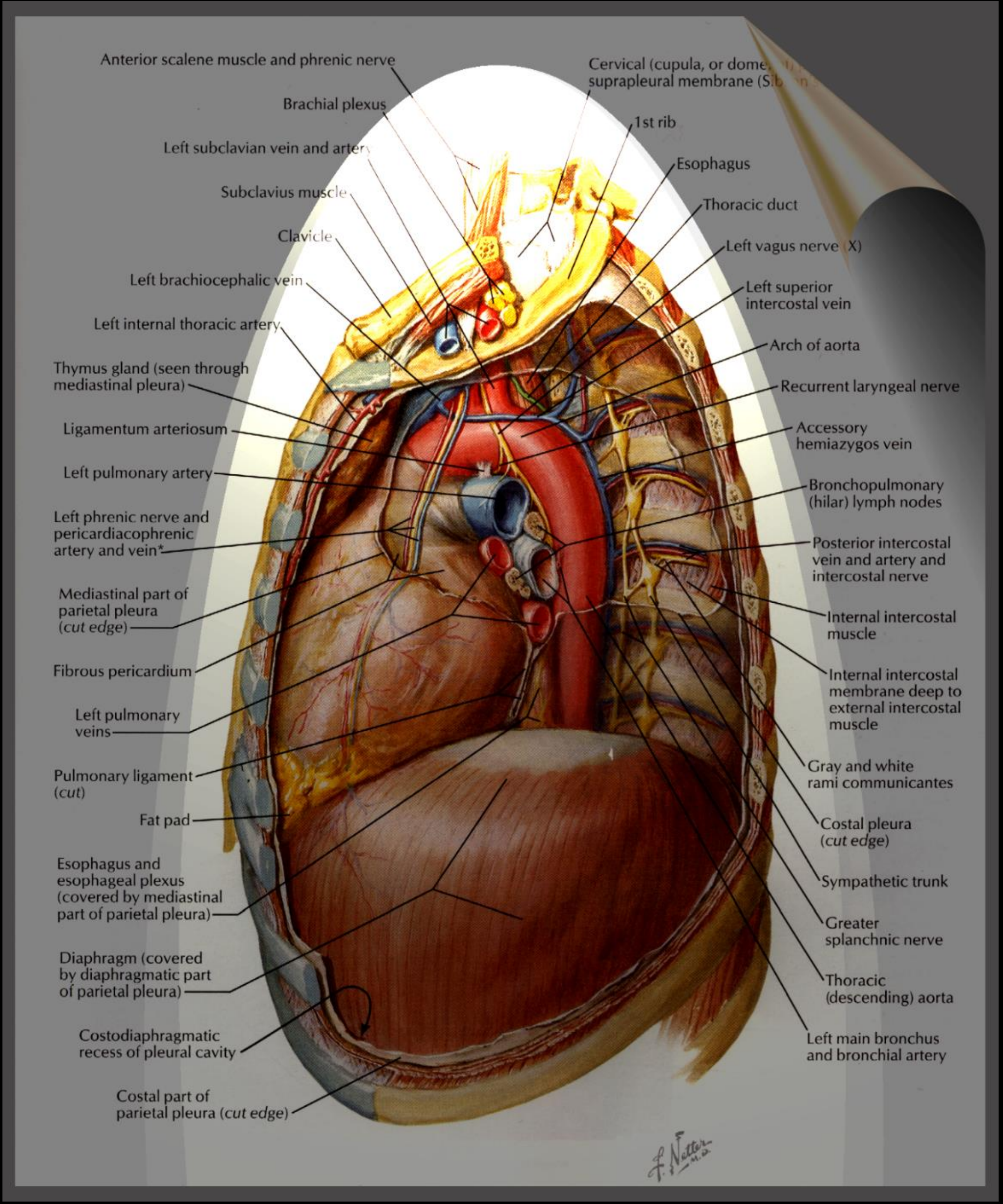
Strassmann (1947)

- **The pathology of TRA is well defined and consistent.**
- **94% of automotive TRA involves the isthmus.**
- **Aortic tears are nearly always circumferential.**
- **Aortic tears usually involve the intima and the media.**

Anatomy

Gietzen
Netter





Intima

Media

Adventitia

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Postulated Mechanisms

- **Rindfleisch (1893): Stretch deformation.**
- **Oppenheim (1918): Overpressure.**
- **Hass (1944): Differing acceleration rates.**
- **Zehnder (1960): Hilum fulcrum.**
- **Voigt (1969): Shoveling, traction of the head.**
- **Viano (1983): Atherosclerosis.**
- **Melvin (1998): Anterior sternum displacement.**

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Cadaver Testing

- **Coermann et al. (1972) frontal sled tests:**
  - **6 tests, 1 of 2 tears clinically relevant.**
- **Kroell et al. (1974) pendulum impacts:**
  - **23 tests, 2 aortic tears, 210 intraluminal kPa.**
- **Cavanaugh et al. (1990) side impact sled tests:**
  - **17 tests, 5 aortic tears, concomitant injuries.**

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Objectives

- **Develop a reliable method for producing clinically relevant TRA in the cadaver model.**
- **Investigate potential mechanisms of TRA.**
- **Determine how the aorta moves within the mediastinum during impact.**
- **Observe aortic deformation patterns and measure strain generated within isthmus.**

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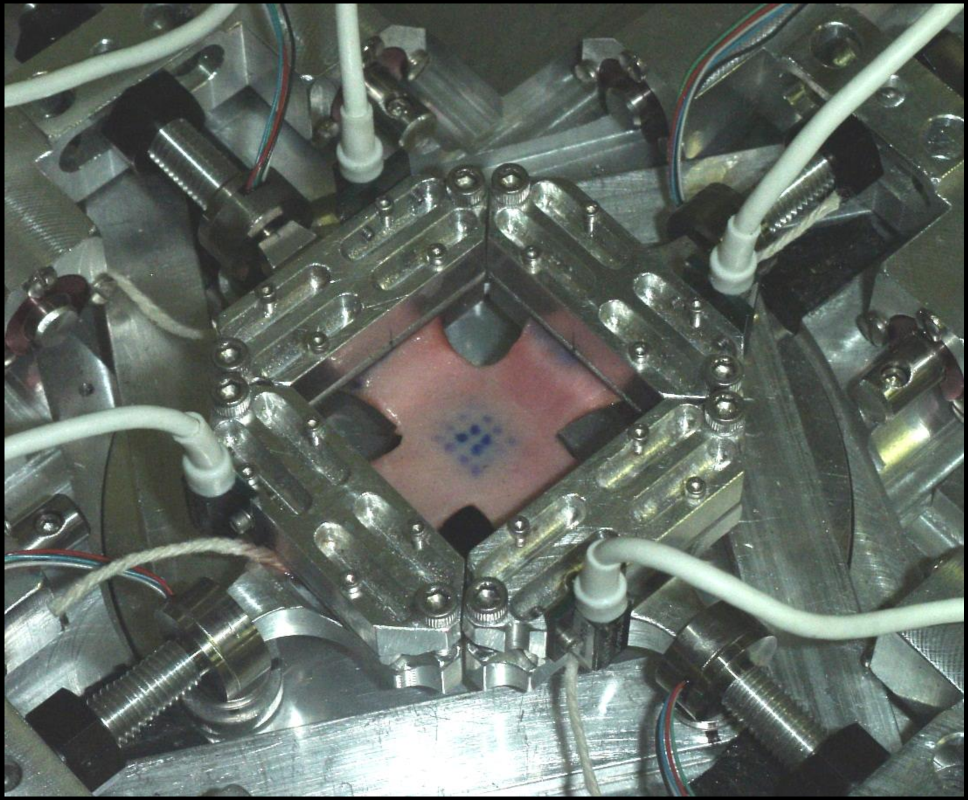
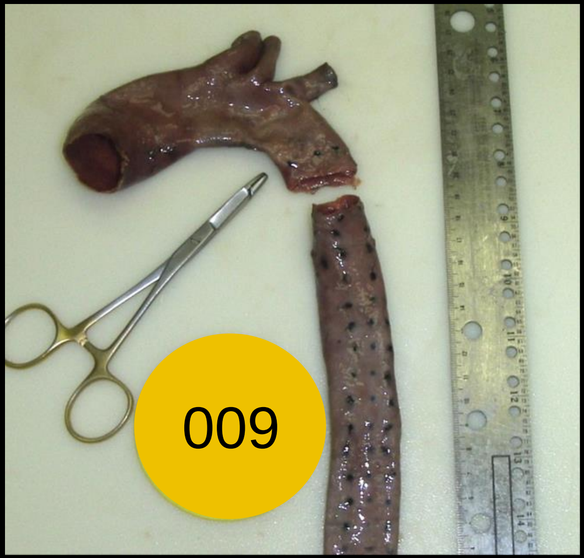
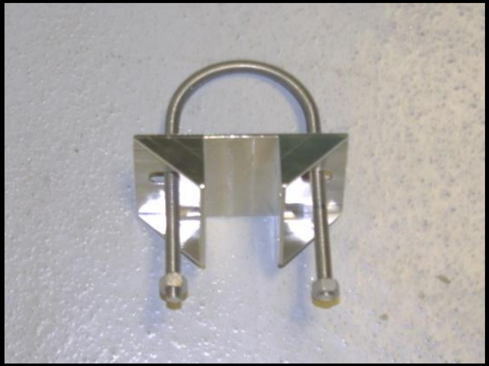
Multi-Scale Testing

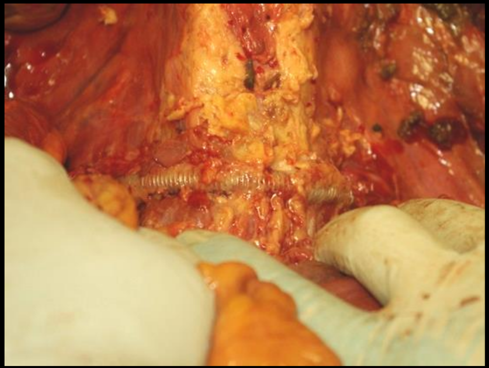




Mason et al. (2005)
Shah et al. (2005, 2006, 2007)
Hardy et al. (2006)

Whole Body Testing





High-Speed Biplane X-Ray

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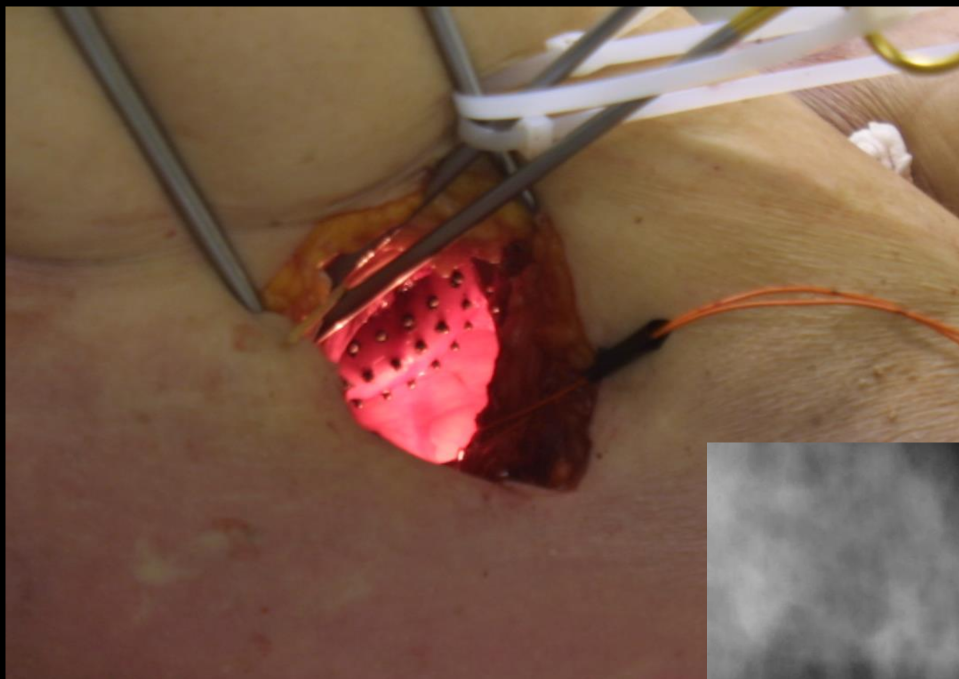
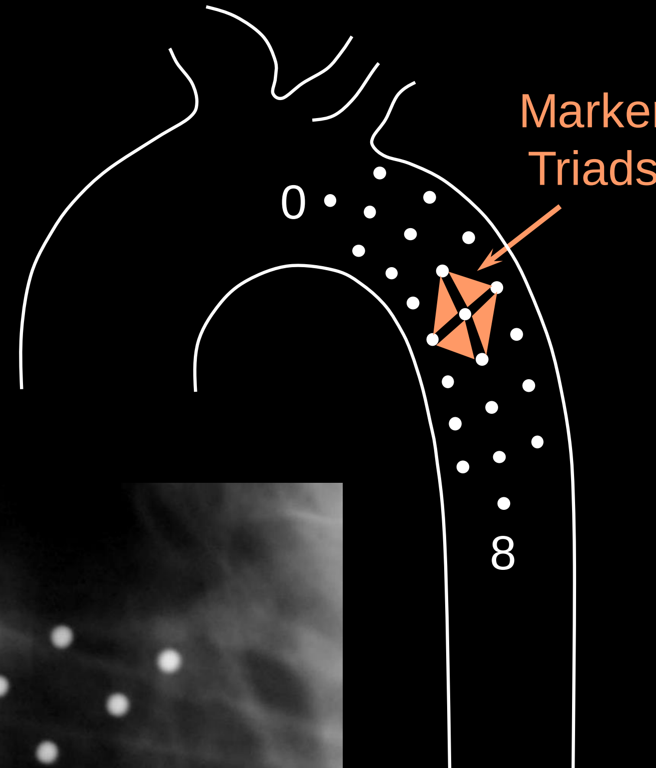
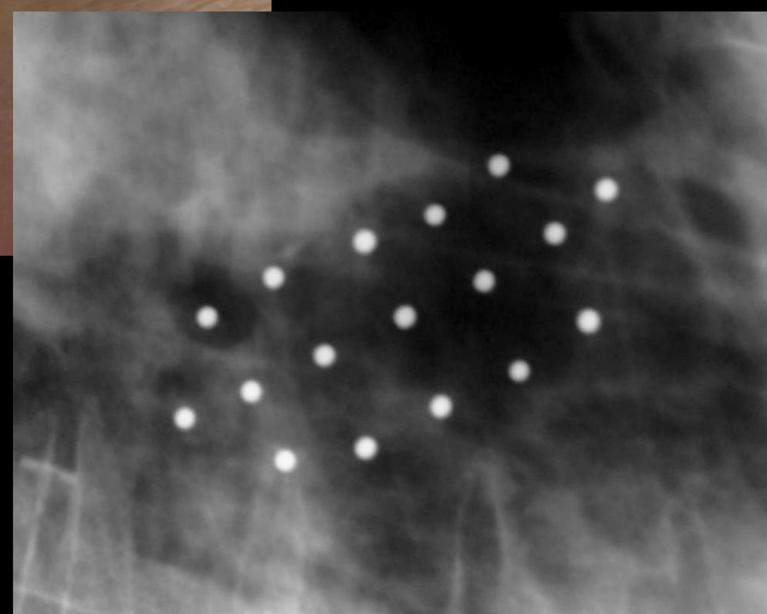
Specimen Preparation

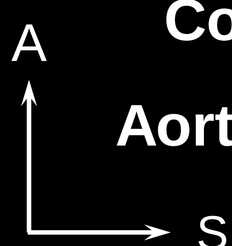






Collagen Gel

Aortic Perfusion



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Specimen Characteristics

Test	Gender	Age	Stature (cm)	Mass (kg)	Cadaver
XR1	M	72	184	63	861
XR2	M	69	184	74	536
XR3	M	69	189	87	749
XR4	F	85	163	55	666
XR5	F	63	187	47	679
XR6	M	73	182	79	710
XR7	F	62	166	78	682
XR8	F	64	153	38	792
Avg.		70	175	65	

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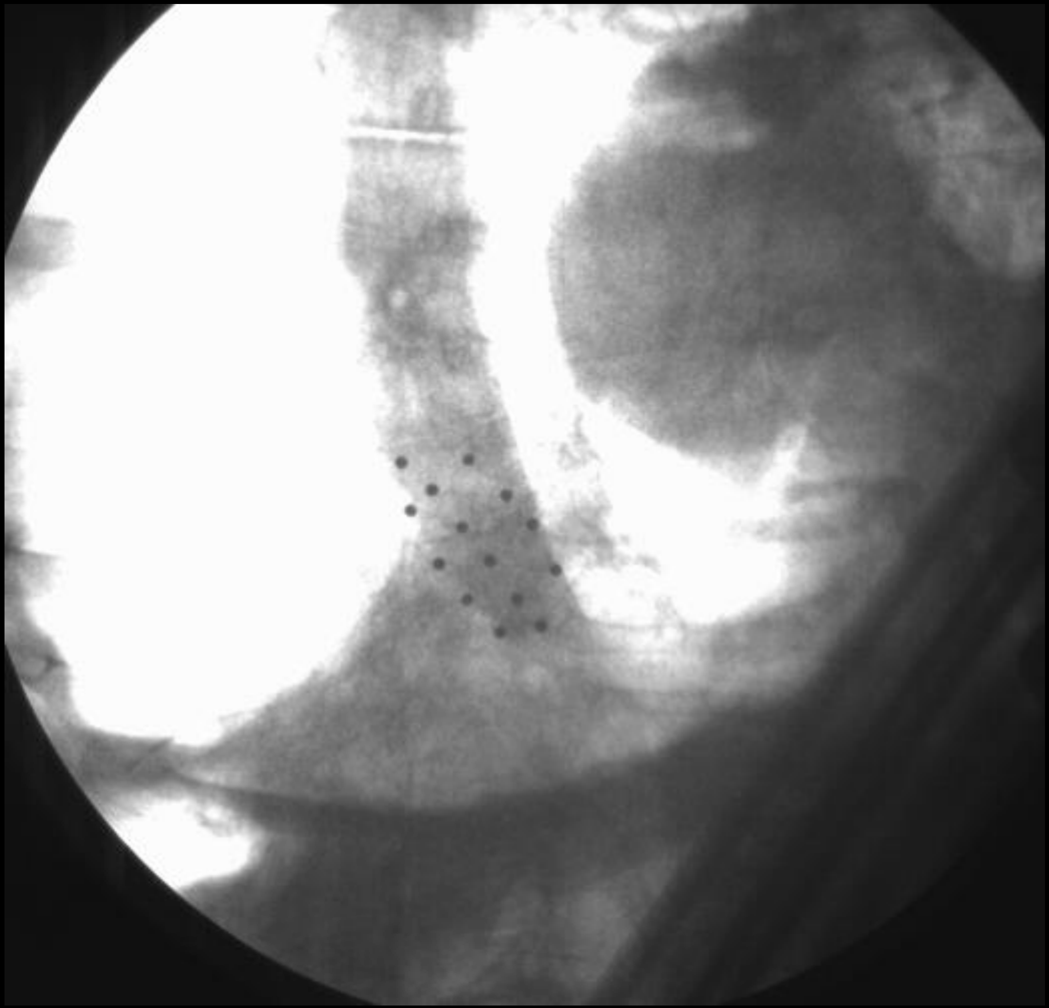
Impact Conditions

Test	External Mechanism	Direction	Location	Spine Angle (deg)
XR1	shoveling	frontal	xiphoid	40v
XR2				40v
XR3				40v
XR4	side impact	medial	left arm	30v
XR5			left ribs	30v
XR6			left arm	30v
XR7	submarining	pretensioner	umbilicus	40v
XR8	combined	oblique	left ribs	40v, 30h

Impact Conditions

Shoveling Impact

High-Speed X-Ray



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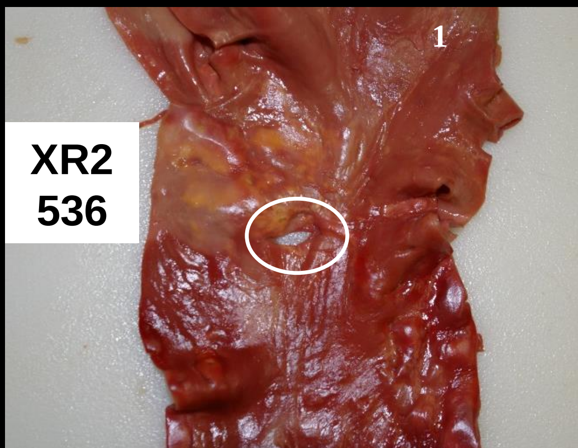
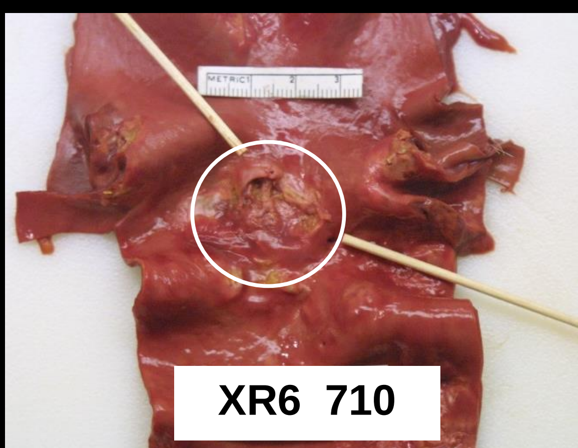
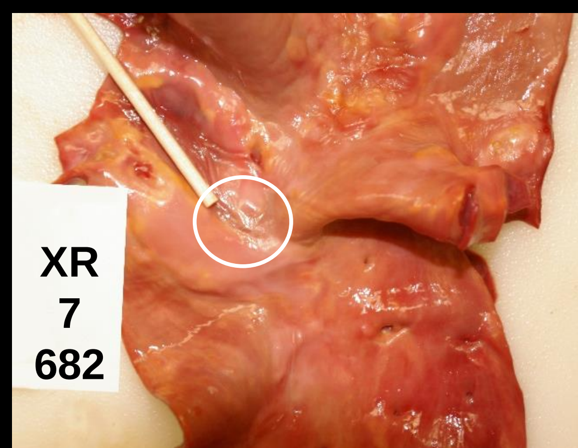
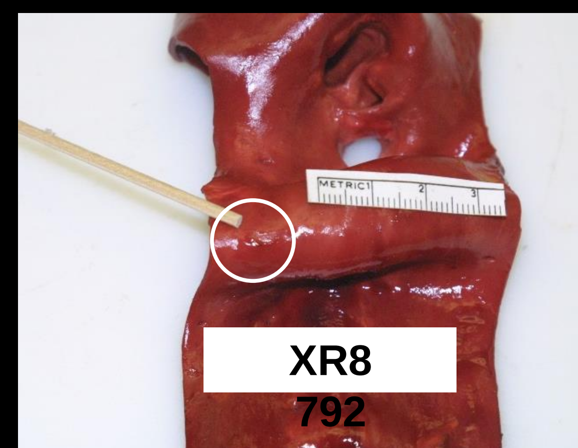
TRA Findings







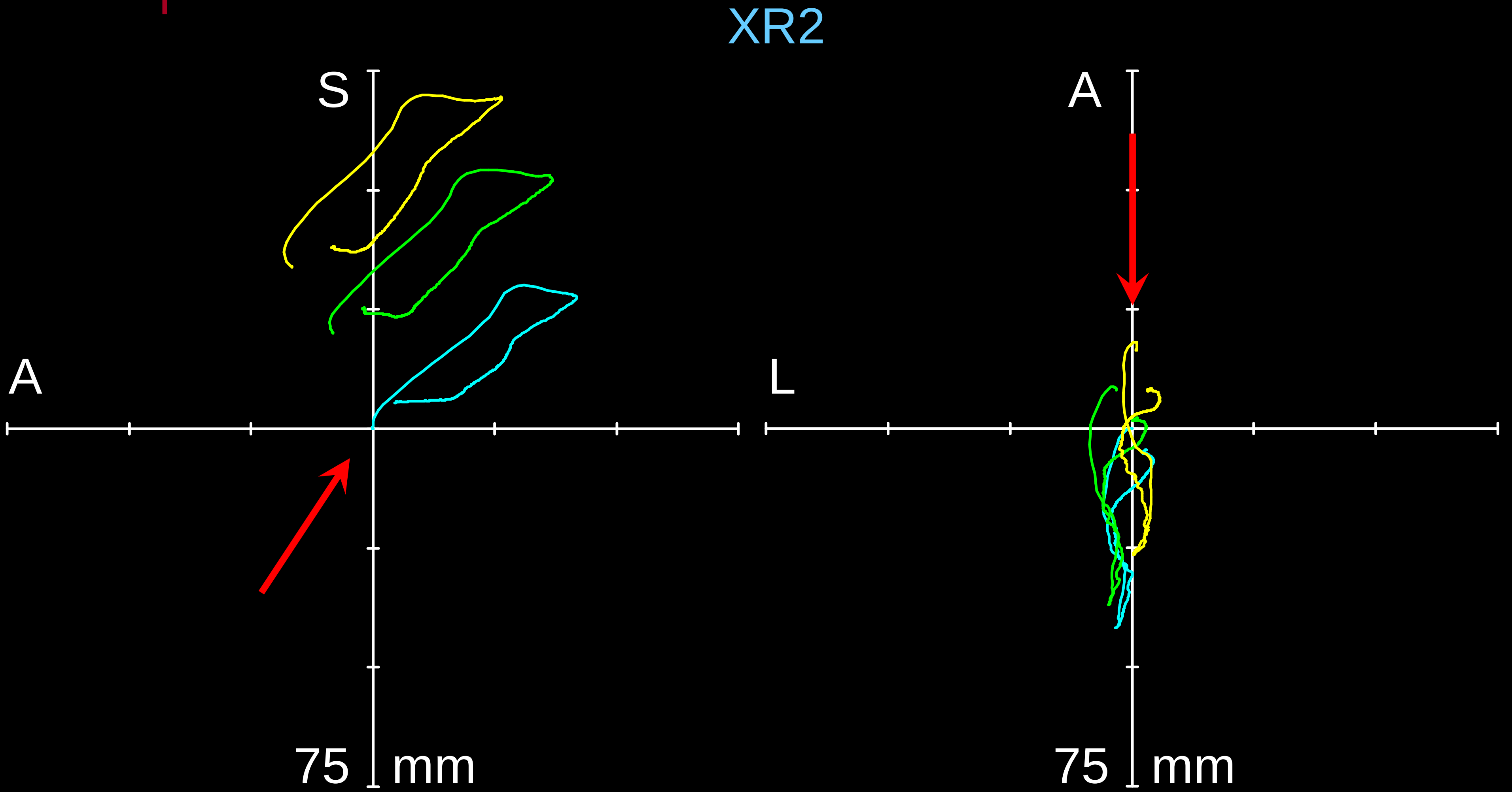


Peak Impact Responses

Mechanism	Test	Load (N)	Speed (m/s)	Pressure (kPa)	Ram Travel (mm)
Shoveling	XR 1	4953	9.3	33.5	134
	XR 2	4815	6.8	165.0	205
	XR 3	4460	7.2	85.4	255
Side impact	XR 4	3880	7.0	51.5	229
	XR 5	3166	6.9	40.0	104

CFC 180 Hz

Kinematics: Shoveling



osterior and superior along line of impact; slightly left away from spir

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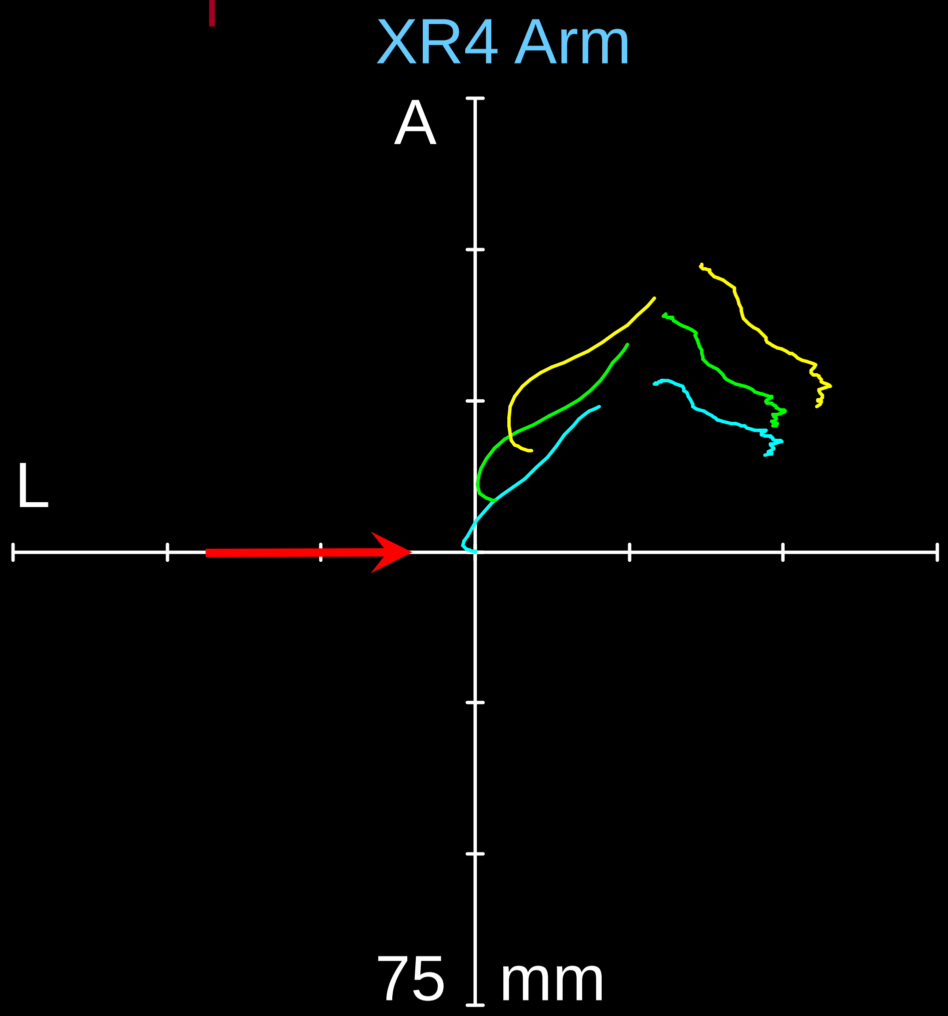
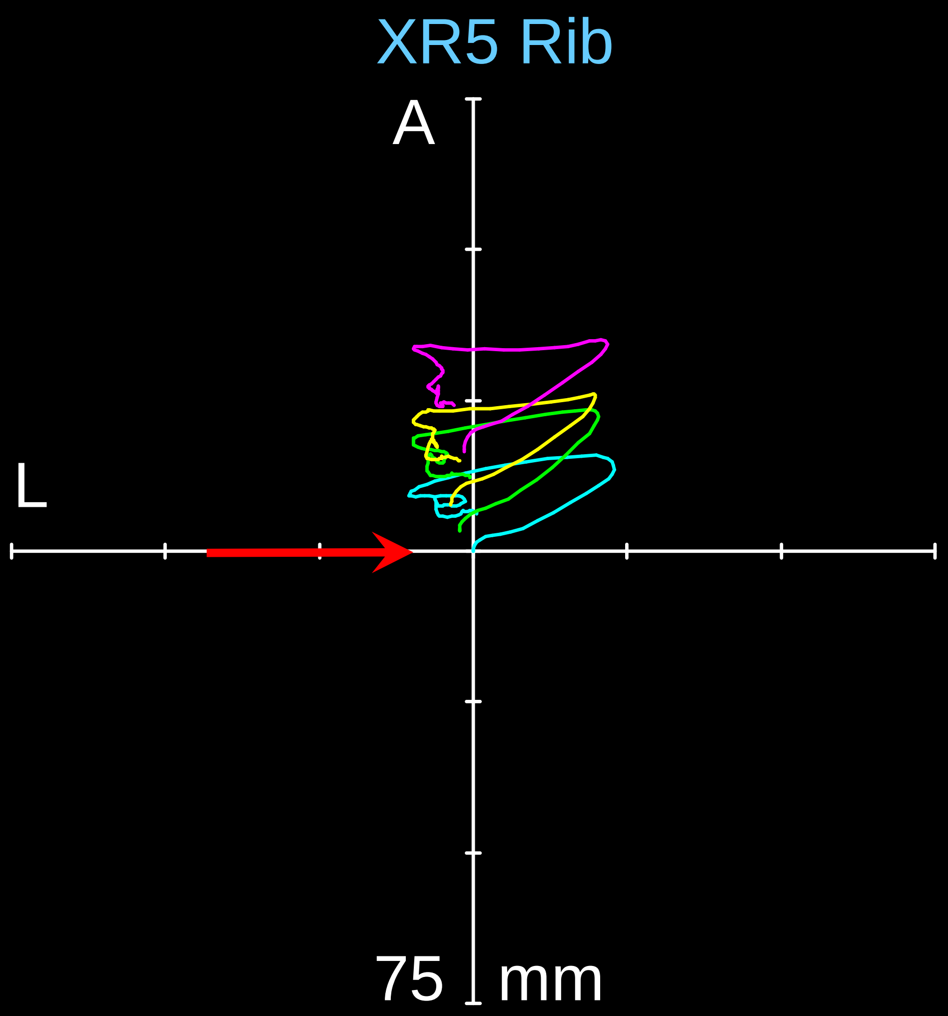
Kinematics: Side Impact

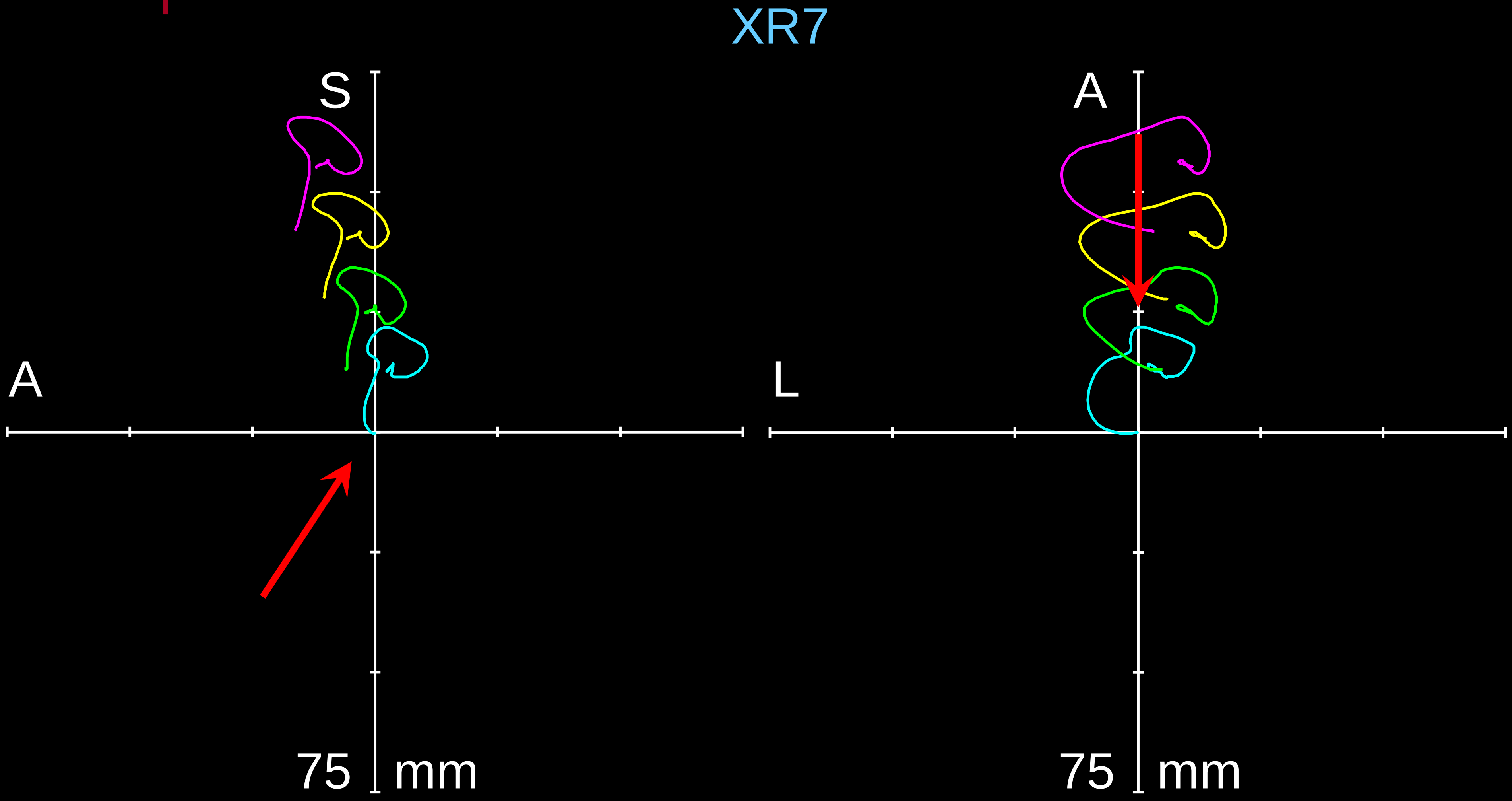




anterior and slightly superior; right toward and around the spine

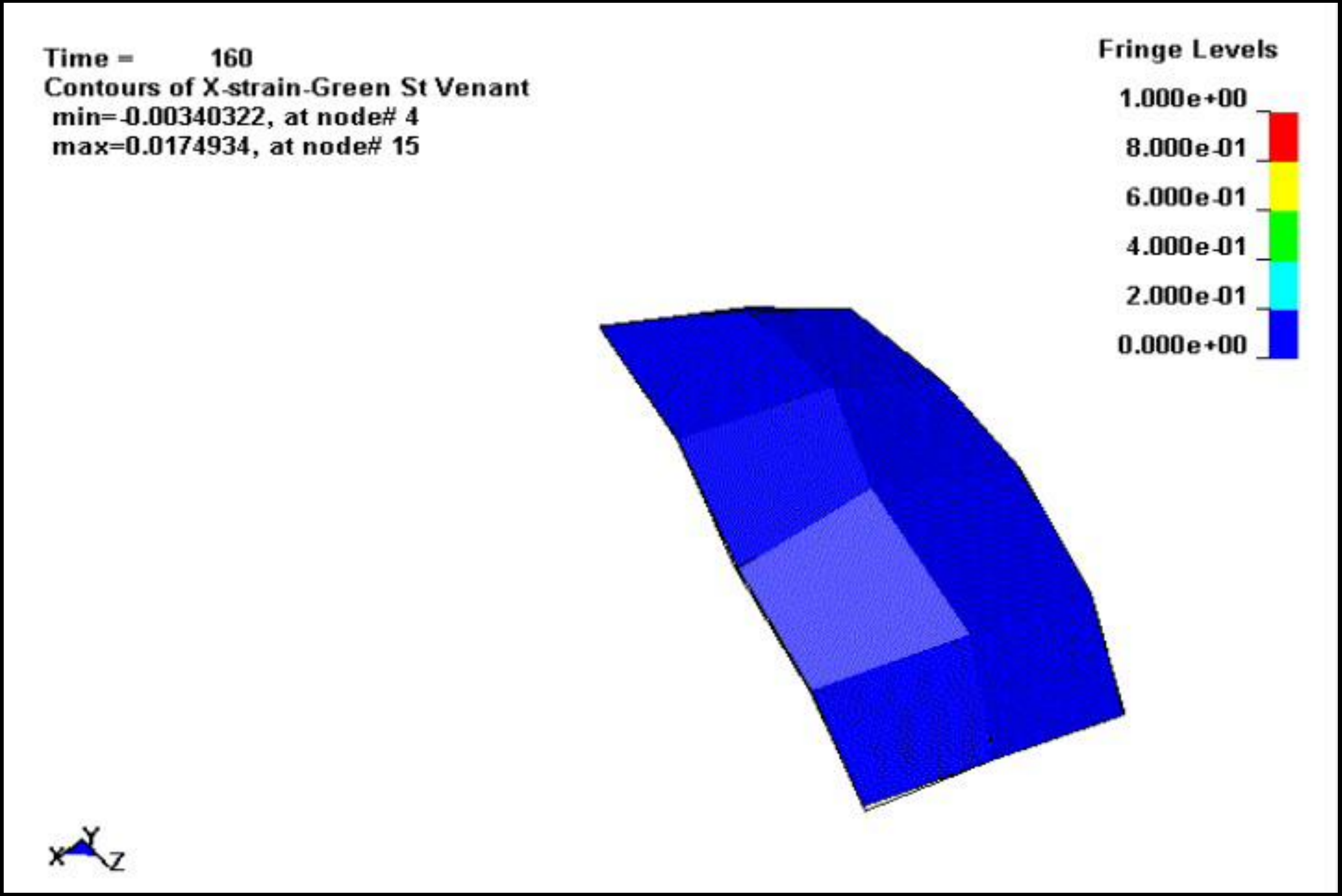
anterior and slightly inferior; right toward the spine

Kinematics: Submarining



superior and moderately posterior; slightly lateral, right and left

Deformation Patterns



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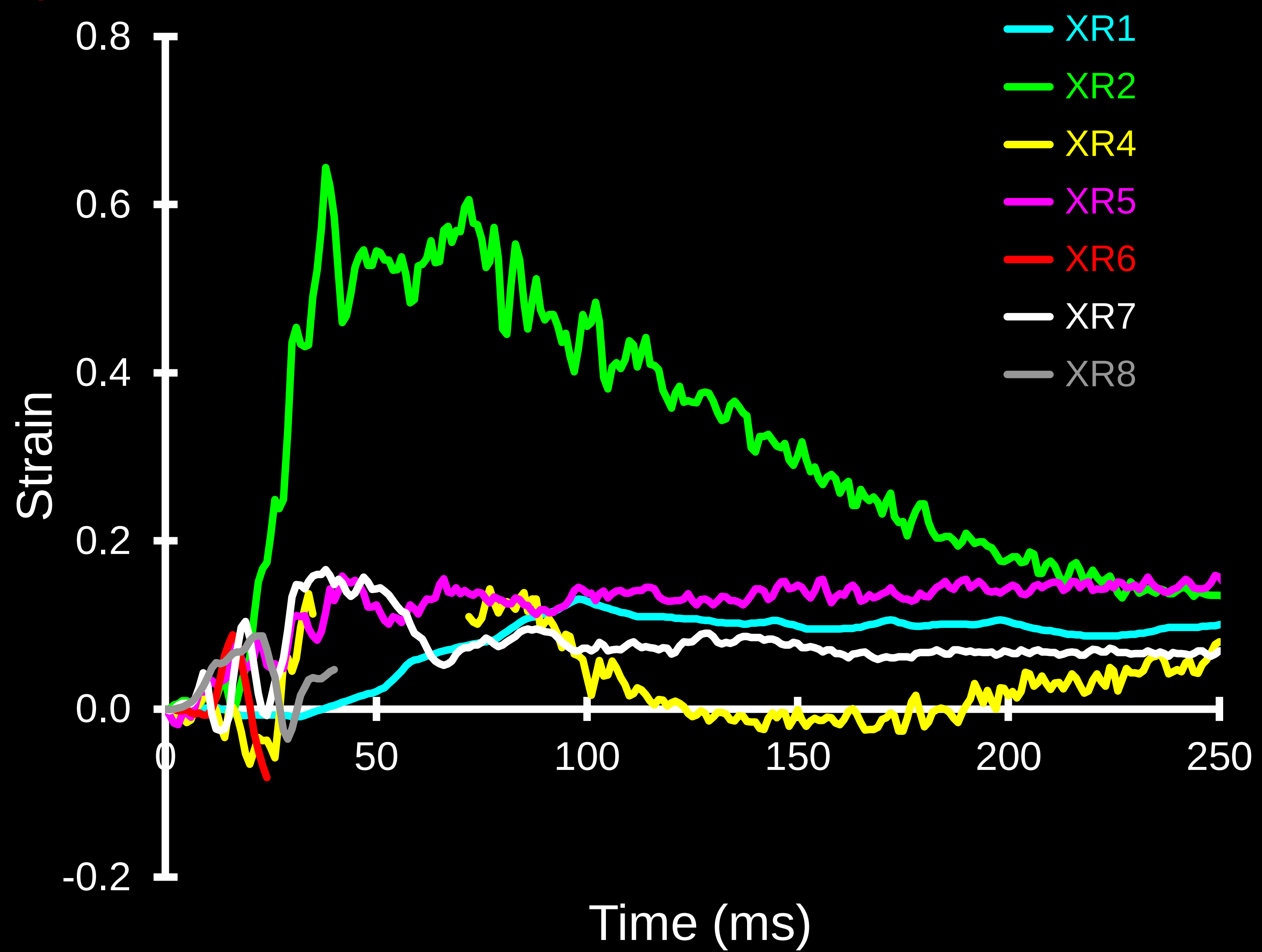
Avg. Longitudinal Strain



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Peak Avg. Longitudinal Strain

Center Target	Shoveling		Side Impact			Belt	Comb
	XR1	XR2	XR4	XR5	XR6	XR7	XR8
0	-	-	0.072	0.158	-	-	-
1	0.088	0.350	0.022	0.067	0.041	0.166	-
2	0.075	0.301	0.073	0.042	0.032	0.127	-
3	0.093	0.188	0.093	0.013	0.026	0.154	0.081
4	0.021	0.356	0.076	0.022	0.088	0.095	0.075
5	0.050	0.644	0.137	0.130	-	0.062	0.073
6	0.107	-	-	0.153	0.009	0.056	0.087
7	0.131	-	-	-	0.001	0.067	0.077
8	-	-	-	-	-	-	0.074

0.217 ± 0.137 (Shah, 2007)

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Atherosclerosis

- **Atherosclerosis potentiates TRA (Viano 1978).**
- **A number of the damage sites observed in this study correspond to regions of plaque.**
- **The greater the plaque, the greater the damage.**
- **Failure strain is lower when plaque is present.**

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Rib Fracture

- **Bertrand et al. (2008):**
  - **79.1% of TRA victims had associated rib Fx,**
  - **68% suffered multiple bilateral rib Fx,**
  - **Typically, ribs 2 - 7 were involved,**
  - **Minor or no rib fracture was related to age.**

- **The most prevalent concomitant injury seen throughout this study was multiple bilateral rib fractures. Test TR7 produced liver fractures.**

Intraluminal Pressure

- **Bass et al. (2001):**
  - **Pressure-based injury index,**
  - **101 kPa for 50% injury risk,**
  - **TRA was longitudinal, circular, or in the arch,**
  - **Extraluminal pressure was atmosphere.**

- **Forman et al. (2008):**
  - **Pressure > 101 kPa for half of the tests,**
  - **No TRA was observed,**
  - **Differential pressure << 101 kPa.**

Intraluminal Pressure

- **TRA can occur without any pressure effects (Roberts et al., 1966 and Hardy et al., 2006).**
- **TRA is not longitudinal:**
  - σ_u **transverse /** σ_u **longitudinal < 2,**
  - **Mohan and Melvin (1982):1.23 to 2.04,**
  - **Shah et al. (2006): 0.78 to 1.24.**
- **This study generated 34 to 165 kPa (68 kPa):**
  - **Mohan and Melvin (1983) needed 800 kPa.**
- **Pressure influences aortic turgor and geometry, and possibly the extent of damage/injury.**

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Inertial Components

- **Stapp (1957):**
  - **Linear AP acceleration to 45 g tolerated.**
- **Roberts et al. (1966):**
  - **Whole-body acceleration not required.**
- **Melvin et al. (1998):**
  - **51 g in frontal, 53 g in side.**
- **Forman et al. (2008):**
  - **169 ± 35 g,**
  - **7% chest compression.**
- **Whole-body acceleration does not cause TRA.**

Ligamentum Arteriosum

- TRA occurs with and without LA involvement.
- Convenient anatomical landmark:
  - Relatively weak peri-isthmic region.
- Local change in properties at the anastomosis that could result in stress concentrations.
- No pulmonary artery damage:
  - Interstitial tissue provides strain relief,
  - Mediastinal distortion is primary

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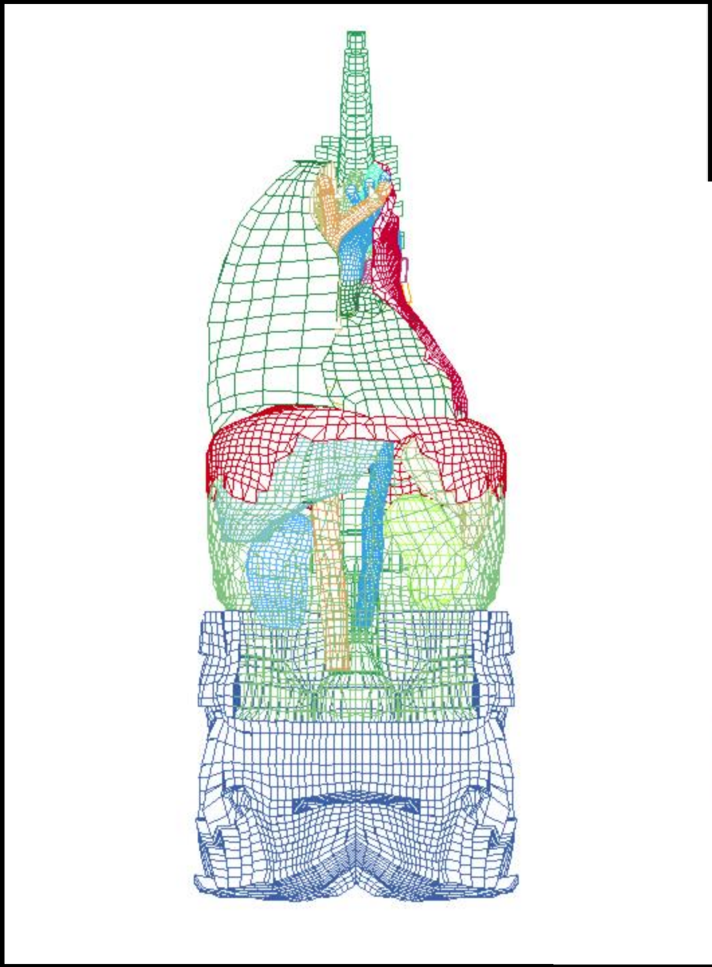
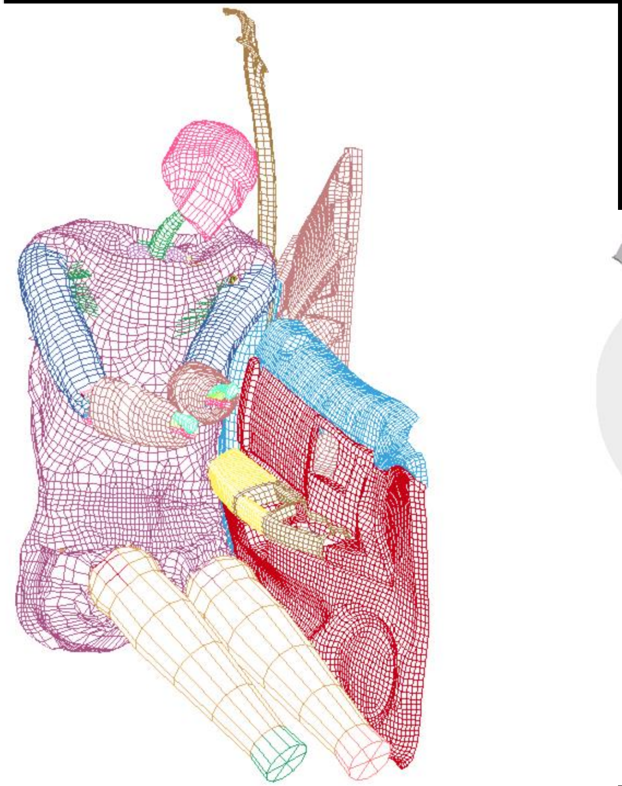
General Mechanisms

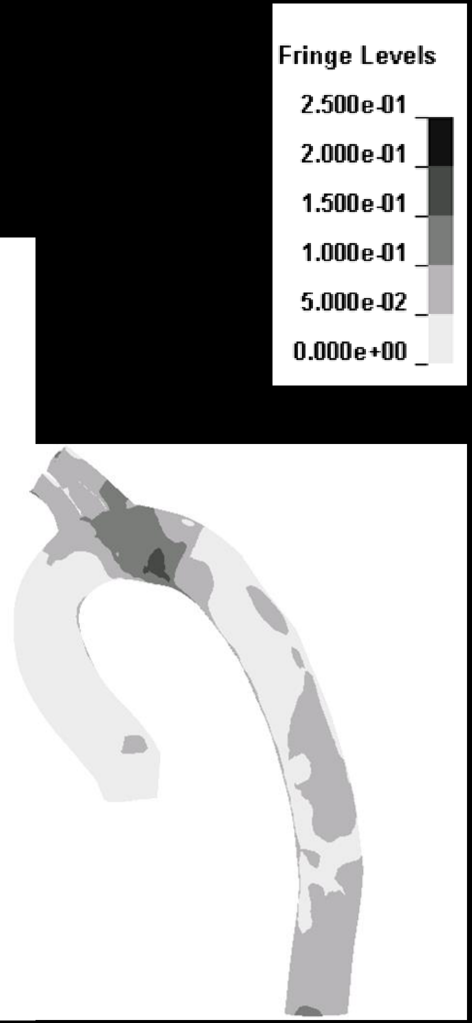
- **Relatively mobile arch and heart.**
- **Pericardiosternal ligaments, central tendon.**
- **Pleura tethers descending thoracic aorta.**
- **Nominal levels of axial tension.**
- **Straightening of inferior arch.**

FE Applications

Shah et al. (2007)







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Conclusions

- Clinically relevant TRA can be generated in the cadaver using the experimental techniques developed for this study,
- 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,

Conclusions

- 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,

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Conclusions

- **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,**
- **Deformation of the thorax is required for TRA.**

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Acknowledgments

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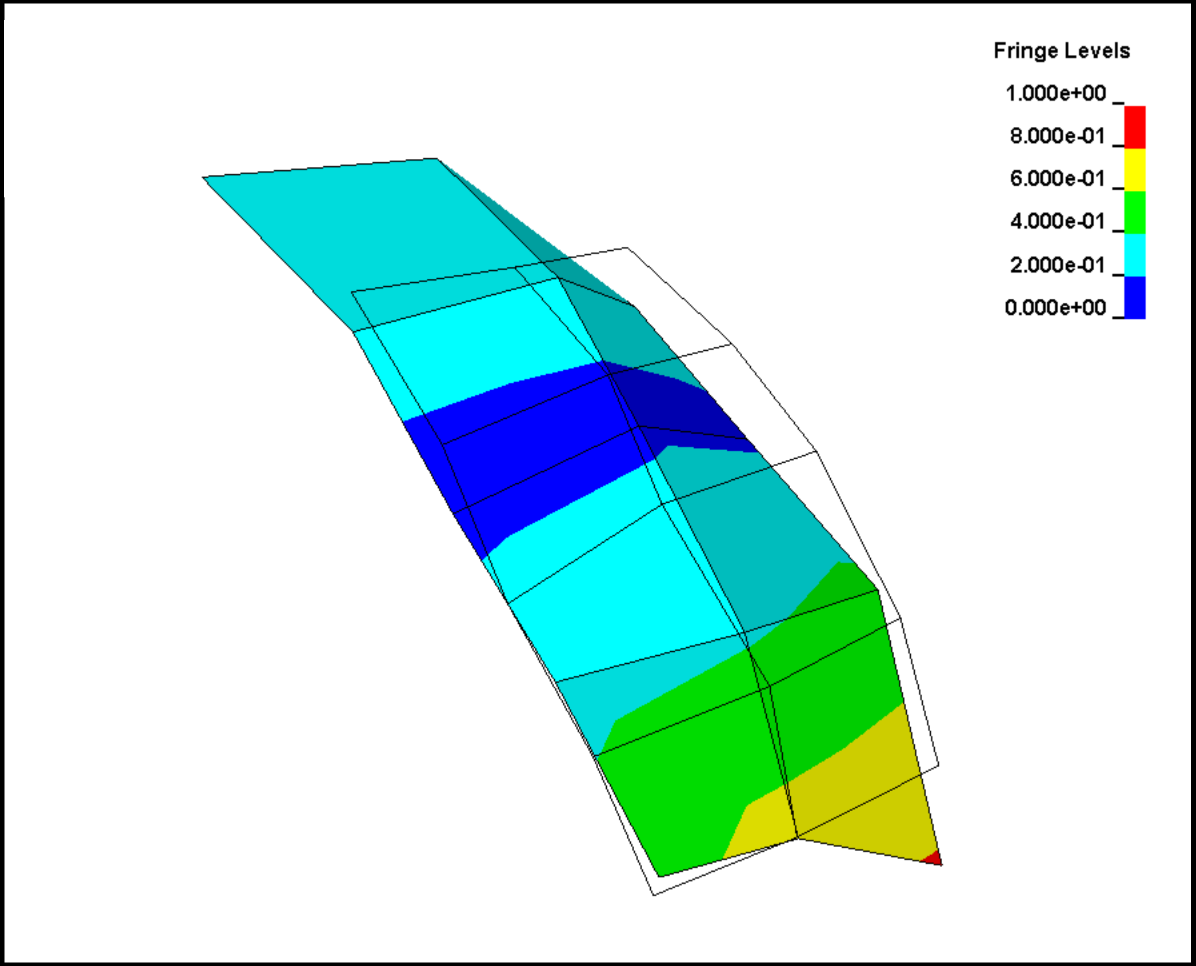
The authors wish to thank the research staff at the Bone and Joint Specialty Center of the Henry Ford Health System for their ongoing assistance.

The 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.

This research was supported in part also by the National Highway Traffic Safety Administration through the Southern Consortium for Injury Biomechanics of the University of Alabama at Birmingham.

Thank You!



Fringe Levels
1.000e+00
8.000e-01
6.000e-01
4.000e-01
2.000e-01
0.000e+00

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Experimental Considerations

- **Prep damages structures surrounding aorta.**
- **Not all of the markers could be tracked.**
- **Some markers were scrubbed off of the aorta.**
- **The markers were not typically located at the tears.**
- **Strain was taken along a 3D line between markers.**
- **The aorta could fold along its axis.**

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Mediastinal Motion

- **Dorsocranial motion was generated during shoveling impacts and submarining.**
- **Motion to the right side away from the impact was generated for the lateral blows.**
- **The aorta moved anteriorly during side impacts.**
- **The aorta moved more anteriorly and further around the spine when both arms were engaged than for direct impact to the**

TRA Characteristics

Test	Direction	Depth	Length (mm)	From LA (mm)	From LSA (mm)
XR 1	transverse	media	12 5 -	10 64 -15	25 79 0
XR 2	transverse	adventitia media	17 6	5 -5	30 20
XR 3	none				
XR 4	transverse	adventitia media	21 7	10 0	20 10

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TRA Characteristics

Test	Direction	Depth	Length (mm)	From LA (mm)	From LSA (mm)
XR5	transverse	media media	25 3	-20 0	0 20
XR6	oblique	media	21	0	5
XR7	transverse	media	8	-2	5
XR8	transverse	intima	8	14	37

Peak Avg. Longitudinal Strain

Center Target	Shoveling		Side Impact			Belt	Comb
	XR1	XR2	XR4	XR5	XR6	XR7	XR8
0	-	-	0.072	0.158	-	-	-
1	0.088	0.350	0.022	0.067	0.041	0.166	-
2	0.075	0.301	0.073	0.042	0.032	0.127	-
3	0.093	0.188	0.093	0.013	0.026	0.154	0.081
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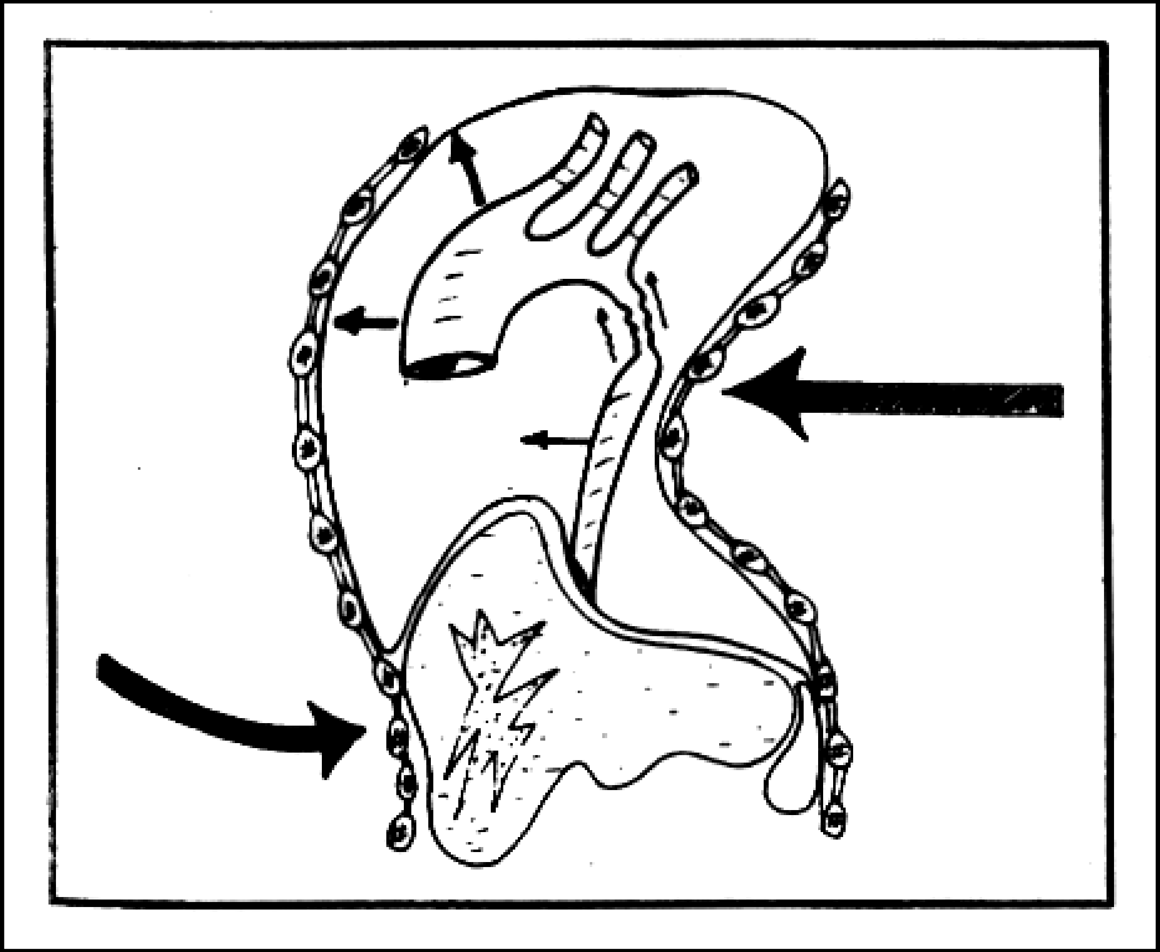
7	0.131	-	-	-	0.001	0.067	0.077
8	-	-	-	-	-	-	0.074

Deformation Patterns



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Inertial Components

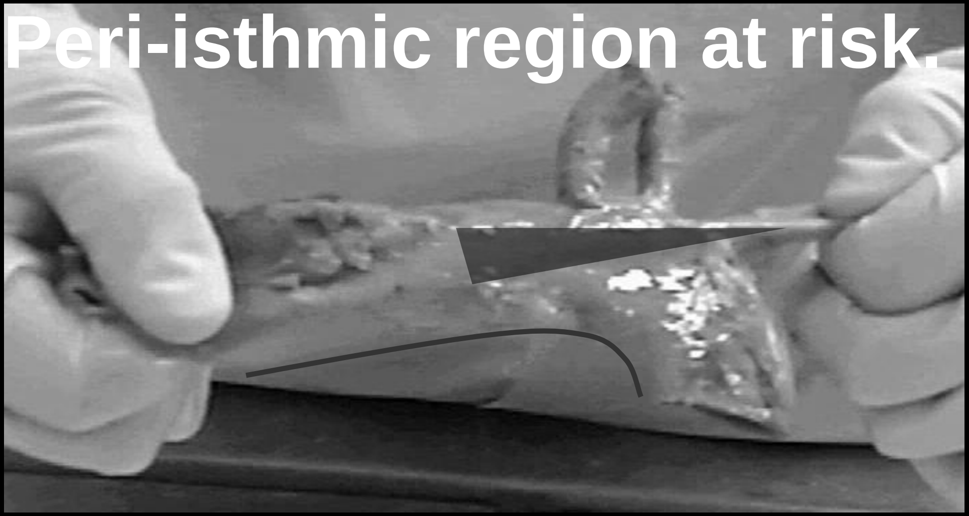
- **Bertrand et al. (2008):**
  - **Minimization of chest compression is important.**
- **The cadavers were fixed in space for this study and some form of TRA was observed in 7 of 8 tests.**
- **Whole-body acceleration does not cause TRA and is not needed for TRA.**
- **Thoracic deformation is essential for TRA.**

General Mechanisms

Hardy et al. (2006)
Shah et al. (2006)

Hardy et al. (2008)

- **Nominal levels of axial tension.**
- **Straightening of inferior arch.**
- **Peri-isthmic region at risk.**



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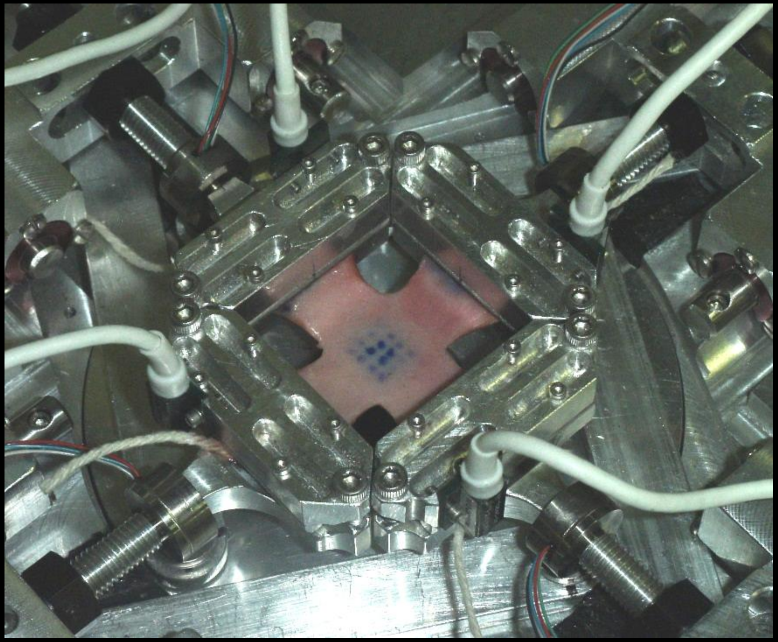
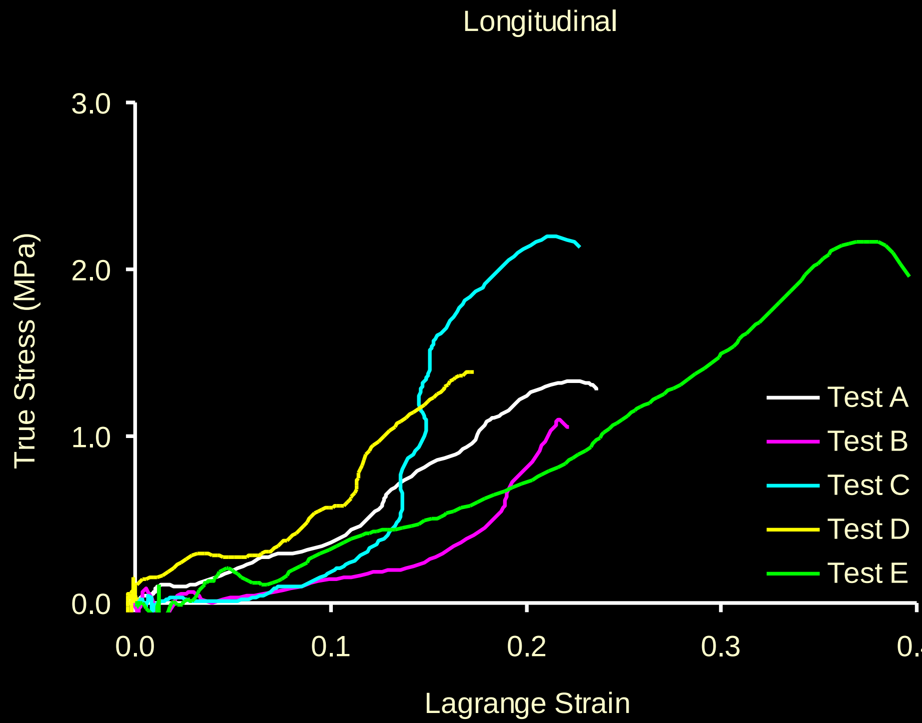
Injury Consequences

- **Clinically, TRA is observed within the peri-isthmic region (Parmley et al., 1958).**
- **Typically, TRA involves the intima and the media (Cammack et al., 1959).**
- **TRA is nearly always transverse to the axis of the vessel (Zehnder, 1960).**
- **The TRA damage generated within this study mimics that seen clinically.**

Tissue Testing

Mason et al. (2005)
Shah et al. (2005, 2006, 2007)

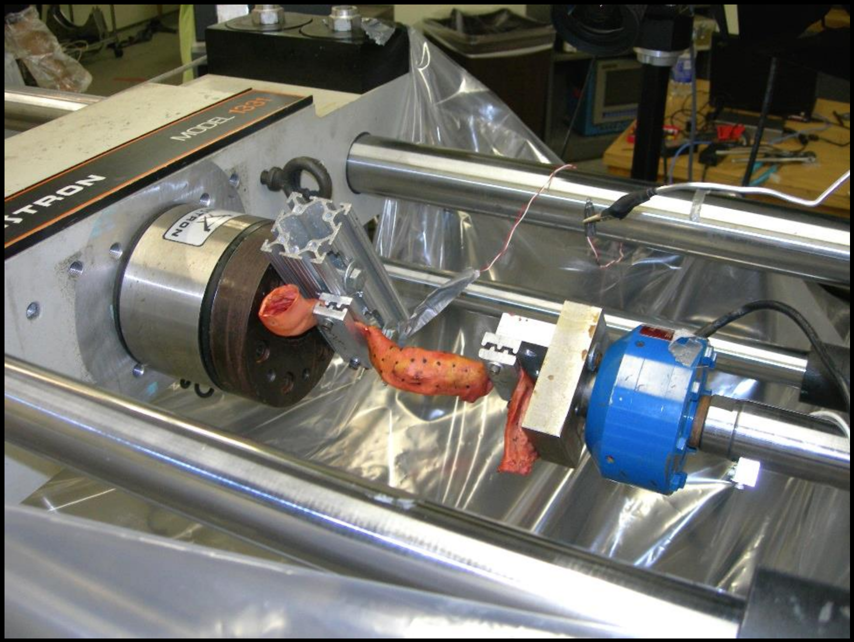




Region	Strain Rate (s^{-1})	Failure Strain
Ascending	**100.94 ± 31.34**	**0.277 ± 0.126**
Descending	**72.51 ± 49.24**	**0.244 ± 0.044**
Isthmus	**89.68 ± 58.18**	**0.217 ± 0.137**
Overall	**84.97 ± 48.07**	**0.244 ± 0.100**

Structure Testing

Shah et al. (2006)



Test	Strain Rate (s^{-1})	Load (N)	Failure Strain
LS2	17.0	82	0.174
LS3	13.0	91	0.319
LS4	11.0	96	0.222
LS6	6.0	98	0.170
Avg.	**11.8 ± 4.6**	**92 ± 7**	**0.221 ± 0.069**

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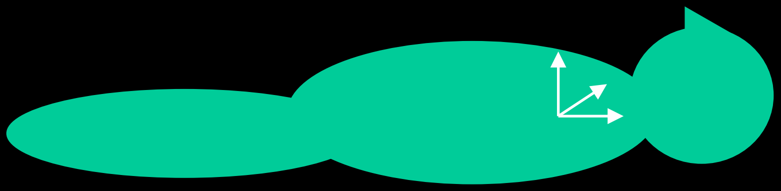
In Situ Testing

Hardy et al. (2006)



Test	Cadaver	Load (N)	Stretch (%)
TR2	31907	133	30
TR3	32065	153	27
TR4	571	159	33
Avg.		**148**	**30**