Computational Seal Zone Mechanics Model For Predicting EVAR Failure In Neck Fixation And Seal: Value And Correlation With Real Results

Luka Pocivavsek, MD, PhD and Ross Milner, MD

45th Annual VEITH Symposium
Center for Aortic Diseases
November 17, 2018

Goals

- Identify patients that are at high risk for device failure

- Appropriate device selection/sizing

Disclosures

- Consultant – Medtronic; WL Gore
Goals

• Identify patients that are at high risk for device failure
• Appropriate device selection/sizing
• Evaluate mechanisms of “interface” adhesion for current technology and new device development

What is Computational Seal Zone Mechanics

Case: 81 AAF with a history of HTN presenting with abdominal pain, found to have a ruptured 5.3 cm juxta-renal AAA. No pre-rupture CT data available. Carry out standard biomechanical analysis using published methodology:

Segmentation, part (AAA/ILT) definition, contact, meshing

Load and Boundary Conditions

Key Points:
1. Semi-automatic geometry segmentation allowing for aortic wall thickness variation, ILT contact definition
2. High density three-dimensional meshing (1.6 million element model) (Simpleware Technology)
3. Hydrostatic cyclical pressure loading – no flow

Computational thought experiment: assuming global aortic geometry at an infinitesimal time point prior to rupture is the same as geometry at rupture does area of rupture correlate with high wall stress?

Max stress = 0.15-0.4 MPa
Max/Min Stress Ratio > 4

Defined Aortic Wall in DANGER ZONE for rupture -> computational analysis validated

Case 2: ELF with ruptured 5.3 cm juxta-renal AAA and difficult neck anatomy.

Geometric Parameters
• Neck angulation (> 60°) (patient 45°)
• Neck length (< 15 mm) (patient 11 mm)

Simulation Workflow:
1. Aorta (A) with CT derived variable thickness, ILT, and continuous EG parts assembled and meshed
2. Contact element domains defined from CT: A/EG, A/ILT, EG/ILT
3. Literature based constitutive models for A, ILT, and EG
4. Uniform cyclical pressure load
5. Fixed proximal and distal boundary conditions on aorta, EG with no defined b.c.
6. Contact modeling: Cohesive Zone Method (CZM) with surface-based cohesive connections with damage modeled using a linear traction-separation law:

By continuity condition aortic wall stress equal to or less than interfacial stress. As such criterion for A/EG interfacial failure (graft separation) is wall stress equal to adhesion strength density.

Experimental data available in literature for average complete displacement forces of endografts:

\[ G_c = \frac{F_{\text{max}}}{d} \]

Total neck zone contact area between EG and aorta – computed from patient geometry.

Linear displacement of A/EG interface prior to macroscopic graft migration ~ 5 mm

By continuity condition aortic wall stress equal to or less than interfacial stress. As such criterion for A/EG interfacial failure (graft separation) is wall stress equal to adhesion strength density.
Areas of separation (interfacial failure) corresponded to zones of high stress (~10 MPa) within the aortic wall, approaching wall stresses where rupture can occur.

Coupling of Pressure Field and Downward Force

1. Truncated geometry – 5–8 mm below celiac artery, allows for more robust meshing and focus on the proximal neck seal zone.
2. Load: pressurization 0 to 220 mm Hg
3. Boundary Condition: downward graft force applied to distal end and fixed proximal and distal aorta/ILT
4. CZM at contact interface

Potential Mechanism of Neck De-Adhesion (loss of seal)

Danger zone: dynamically adhering and re-adhering EOA/neck generating transient and spatially fluctuating area of high stress much greater than mean wall stress:
• Could this transient high stress lead to further neck aneurysmal degeneration?
• Could the transient loss of seal be the source of transient type 1 leaks?

Proposed mechanism of de-adhesion balances stored elastic energy in aorta with adhesion strength. If validated, provides a target for graft/device optimization. Possible role of adjuncts like endo-anchors?

Computational Phase Diagram of EVAR Neck Stability

Input Parameters:
1. Geometry > exact via segmentation
2. Boundary > semi-exact, simplified
3. Load – pressure P(t) and force F(t) > simplified
4. Interfacial strength/CZM > computationally implementable but input parameters need to be experimentally defined

Output Parameters:
1. Aortic wall strain/stress
2. Interfacial stability (contact area, critical contact area prior to fracture)
3. Migration stability

Derived Parameters:
1. Aortic neck strain energy/adhesion strength
2. Critical length over which fracture propagates
3. Non-linear geometric constraints on propagation given non-uniform coaxial cylindrical geometry
Case 2: ELF s/p EVAR repair of juxtarenal AAA, presented at 1.5 year follow up with type 1 endoleak. CT showed aneurysmal dilation of neck, with complete loss of contact posteriorly between neck and EG. FEA shows that current graft configuration highly unstable, with severe graft displacement with pulse pressure. Strong correlation between magnitude of graft displacement and degree of systolic hypertension. Repair of type 1 leak with proximal cuff extension and bilateral renal chimneys.

Conclusions
- Aortic computational mechanics studies are easily implemented for native patient anatomy using commercial segmentation and finite element codes. This is largely due to the rich foundational work done 15 years ago.
- Aortic rupture (fracture mechanics) simulations are still in developmental phase, with large material (constitutive relations) and structural challenges.
- EVAR stability presents a novel problem where computational studies can help define mechanisms of EVAR failure specifically type 1 endoleaks. Two-dimensional EG/A interfacial fracture problem more tractable than aortic rupture.

Collaborators
The University of Chicago
- Dr. Luka Pocivavsek (vascular)
- Dr. Christopher Skelly (vascular)
- Dr. Trissa Babrowski (vascular)
- Prof. Thomas Witten (physics)
- Prof. Binhua Lin (ANL/physics)

University of Illinois – Chicago
- Prof. Mark Schlossman (physics)

USACH
- Prof. Enrique Cerda (physics)