AATS Aortic Symposium Workshop New York 2024

April 25 - 26, 2024

In Vivo MRI-based Parameters of Aortic Biomechanics Correlate with Aortic Tissue Properties Measured Ex Vivo

Jennifer Chung[1,2], Hijun Seo[2,3], Nitish Bhatt[1], Farshad Tajeddini[1,4], Maral Ouzounian[1], Kate Hanneman[1], Rifat Islam[1], Craig A. Simmons[2,3,4]

[1]Division of Cardiovascular Surgery University Health Network, [2]Institute of Biomedical Engineering University of Toronto, [3]Translational Biology and Engineering Program Ted Rogers Centre for Heart Research, [4]Department of Mechanical and Industrial Engineering University of Toronto, [5]Rogers Computational Program Peter Munk Cardiac Centre University Health Network, [6]Division of Vascular/Interventional Radiology, University Health Network

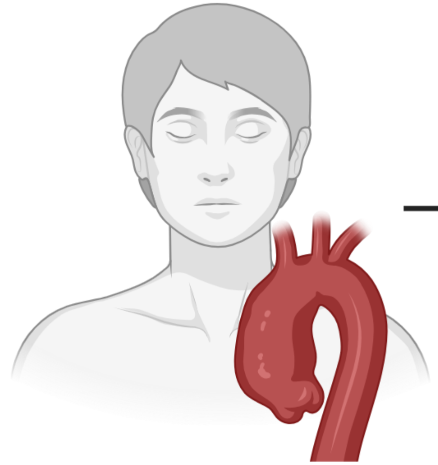
Introduction

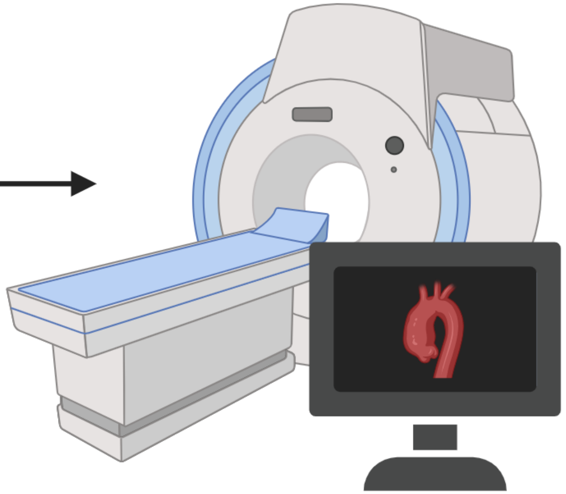
- Aortic event rates associated with aneurysms of the ascending aorta are low ~2%/patient year.
- Identifying those at elevated risk of dissection/sudden death and candidates for elective preventative surgery is challenging.
- The ability to measure an individual’s aortic biomechanics would be extremely helpful.
- Aortic biomechanics describe material properties of the ascending aorta, including its degree of fragility and risk of material failure.
- **We aim to validate MRI-based aortic biomechanics against ex-vivo tissue testing**

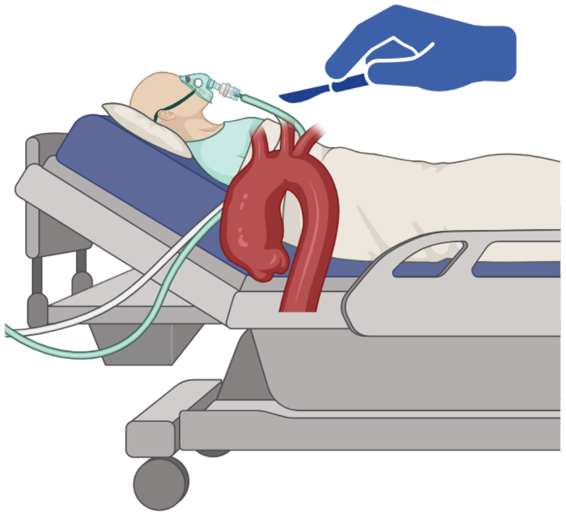
Methods: Workflow

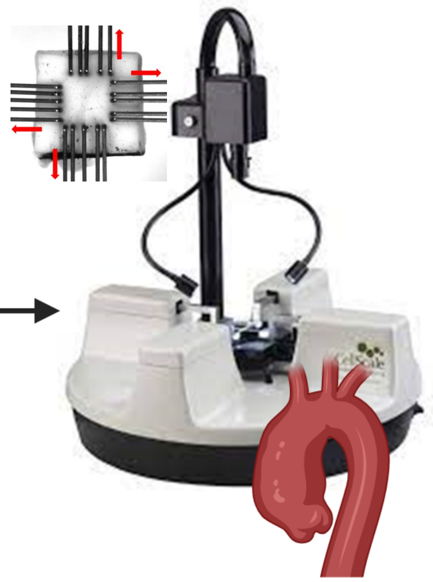
Patients undergoing elective ascending aortic surgery N=17

Healthy volunteers undergoing research MRI only N=4







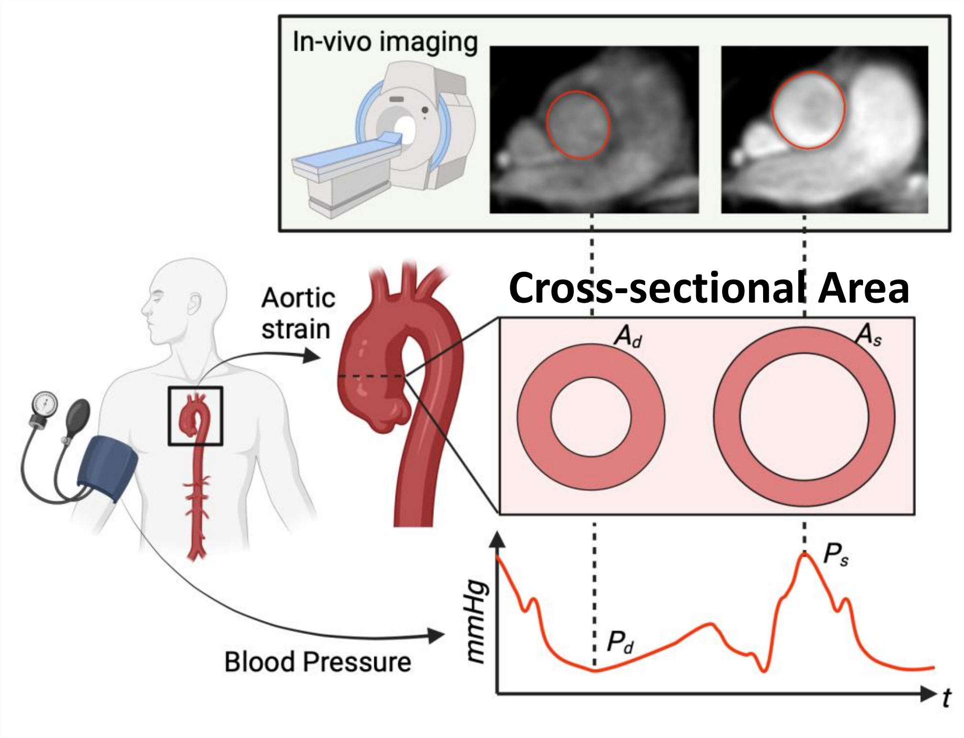


Several MRI-based aortic biomechanics parameters are derived:
- strain-based
- aPWV
- kinetic energy loss

Several ex-vivo aortic biomechanics parameters are derived:
- tangent modulus of elasticity
- energy loss
- delamination strength

Methods: MRI

- Stiffness: extent to which tissue resists deformation in response to hemodynamic loads

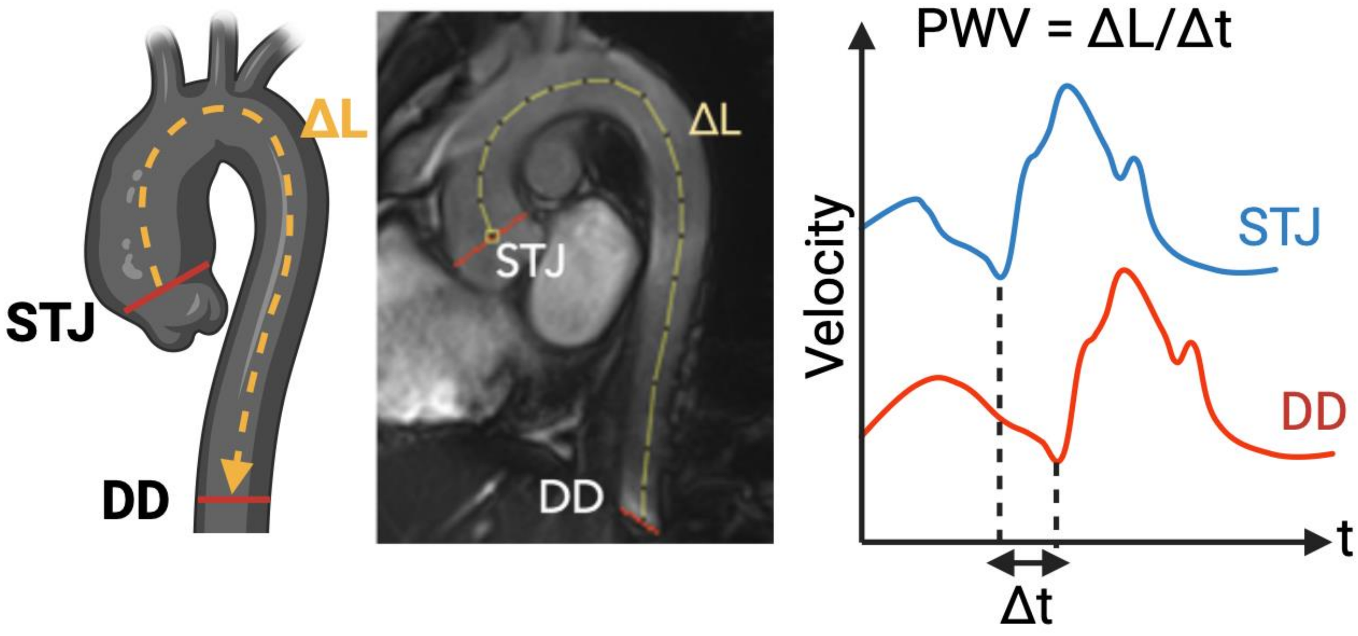


PARAMETER	EQUATION
STRAIN	$\frac{A_s - A_d}{A_d}$
DISTENSIBILITY (D)	$\frac{A_s - A_d}{A_s(P_s - P_d)}$
COMPLIANCE (C)	$\frac{A_s - A_d}{(P_s - P_d)}$
ARTERIAL STIFFNESS INDEX (β)	$\frac{\ln(\frac{P_s}{P_d})}{\frac{A_s - A_d}{A_d}}$

Parameters based on area and pressure

Methods: MRI

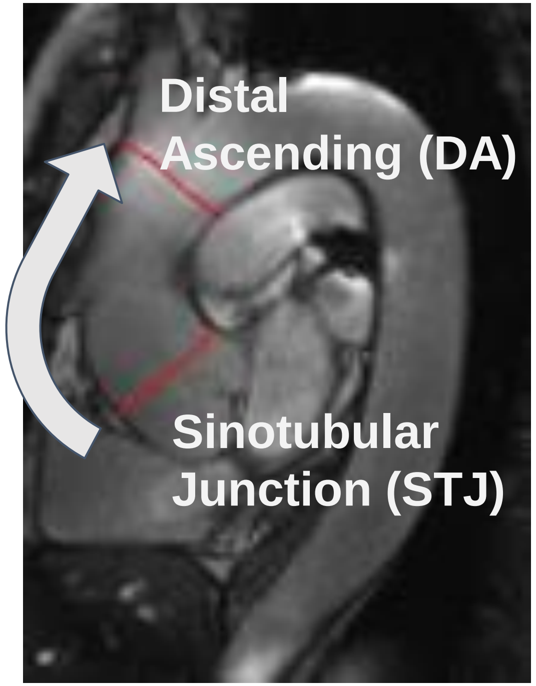
- Aortic Pulse Wave Velocity: Speed of fluid wave propagation through a vessel – related to stiffness

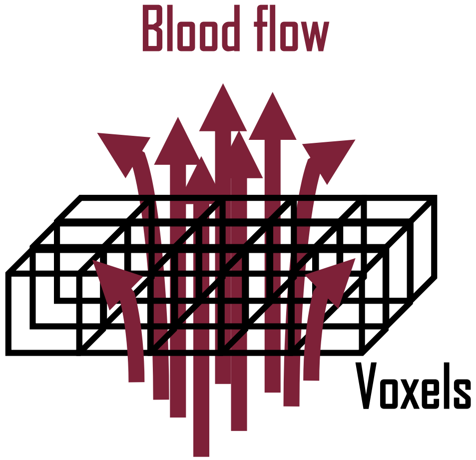


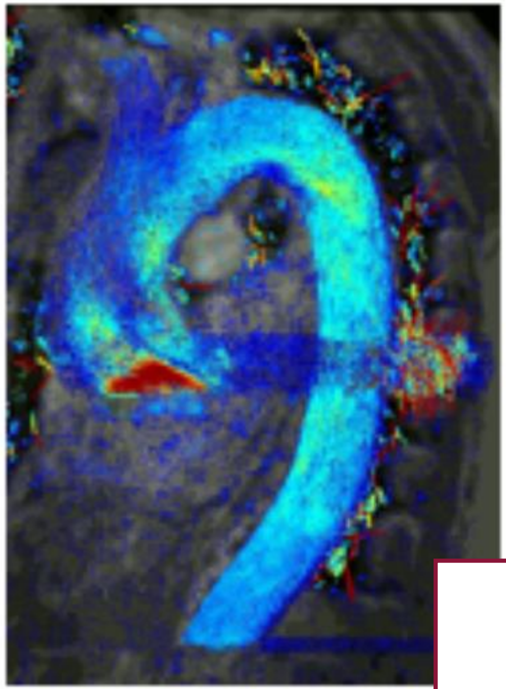
$$aPWV = \frac{\Delta L}{\Delta t}$$

Methods: MRI

- Kinetic Energy Loss (KEL): Fraction of energy dissipated between aortic loading and unloading (*efficiency of the elastic aorta*)







4D MRI

$$KE = \frac{1}{2}\rho \int v^2 dV$$

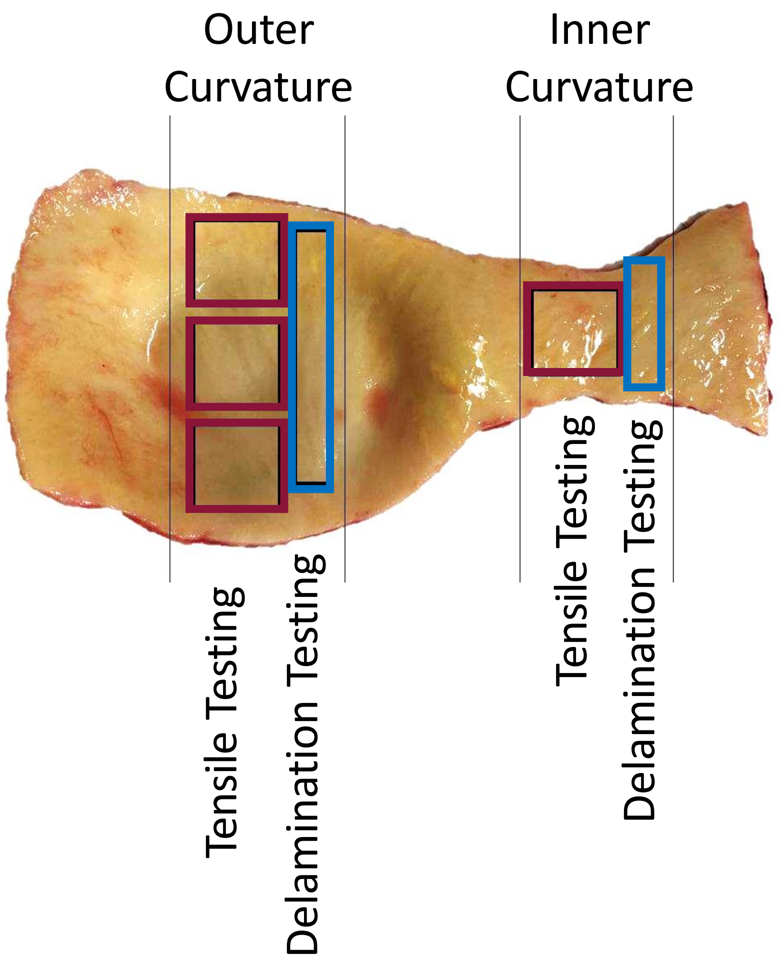
$$\rho = blood\ viscosity$$

⇩

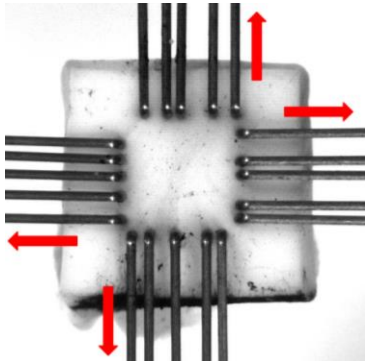
$$KE \approx \frac{1}{2}\rho \sum_{i=1}^{num\ voxels} v_i^2 \cdot V_{voxel}$$

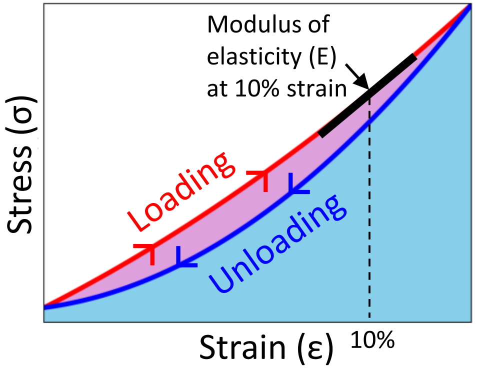
$$KEL = \frac{KE_{STJ} - KE_{DA}}{KE_{STJ}} \cdot 100\%$$

Methods: Ex-Vivo Biomechanics



Biaxial Tensile Testing

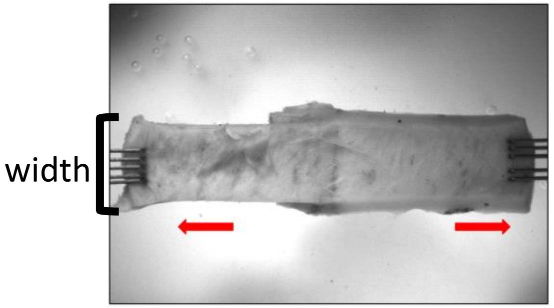


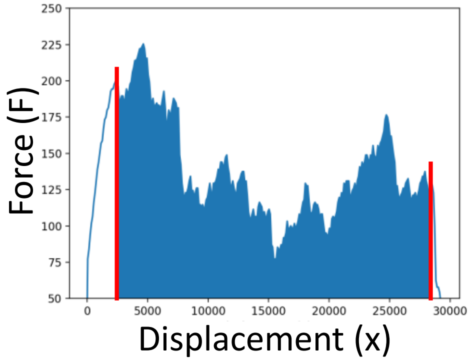


$$\Delta U_L = \frac{\int(\sigma_{loading} - \sigma_{unloading})d\epsilon}{\int \sigma_{loading}\, d\epsilon}$$

$$E = \frac{d}{d\epsilon}\sigma_{loading}(\epsilon_{10})$$

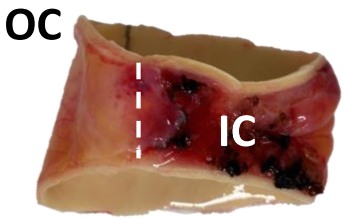
Delamination Testing

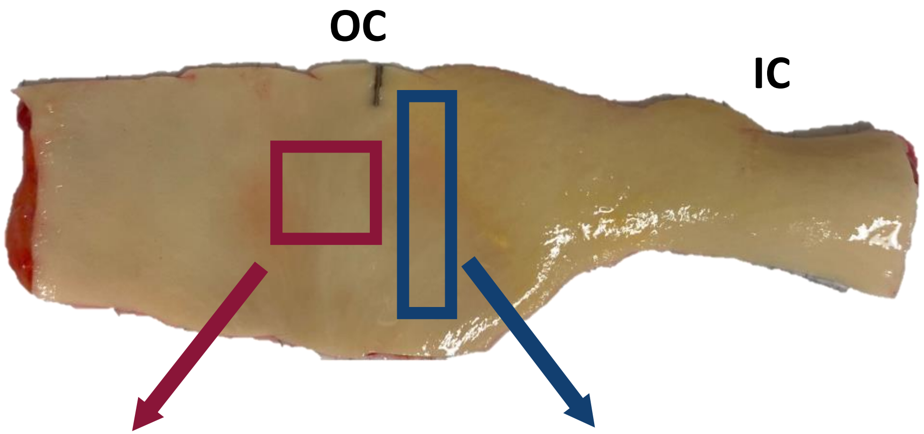


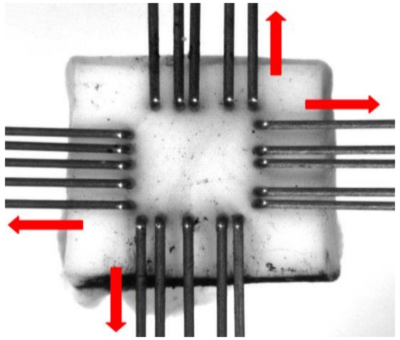


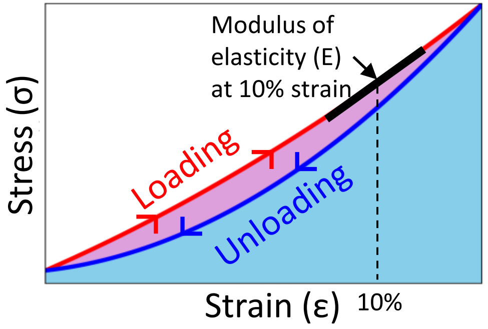
$$S_d = \frac{\int_{x_1}^{x_2} F\, dx}{(x_2 - x_1)(width)}$$

Methods: Ex-Vivo Biomechanics



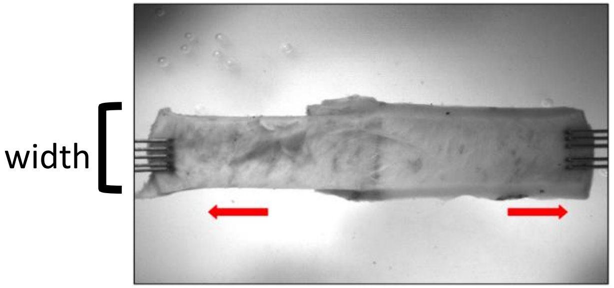


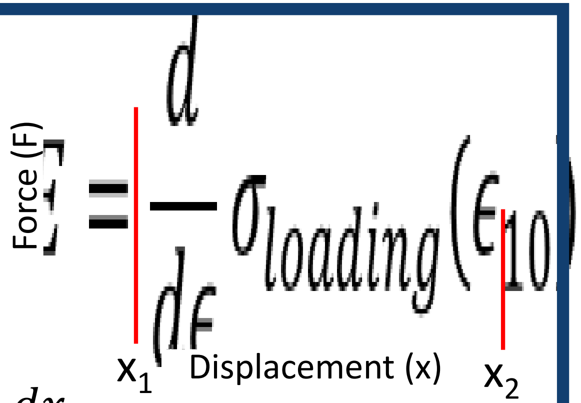




$$\Delta U_L = \frac{\int (\sigma_{loading} - \sigma_{unloading}) d\epsilon}{\int \sigma_{loading} d\epsilon}$$

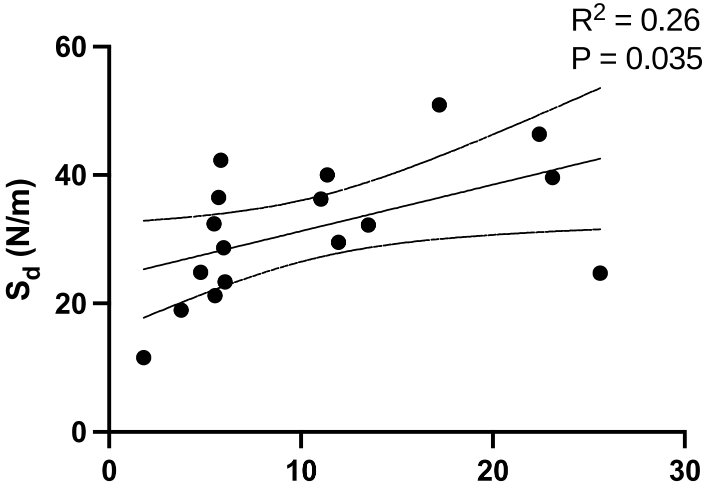
$$E = \frac{d}{d\epsilon} \sigma_{loading}(\epsilon_{10})$$

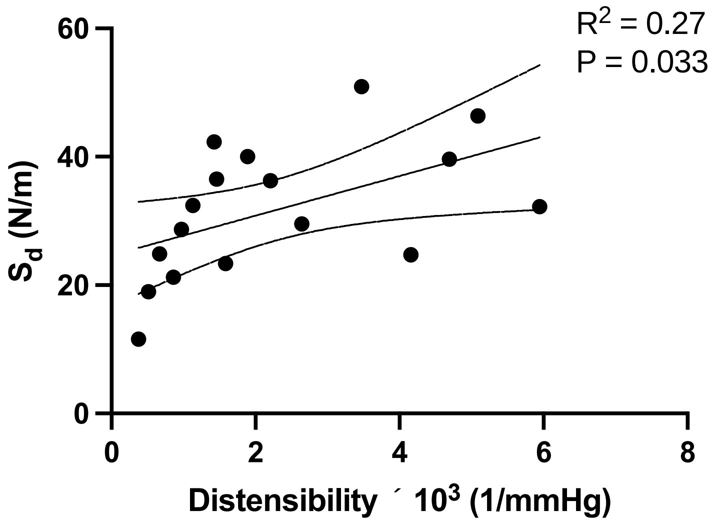


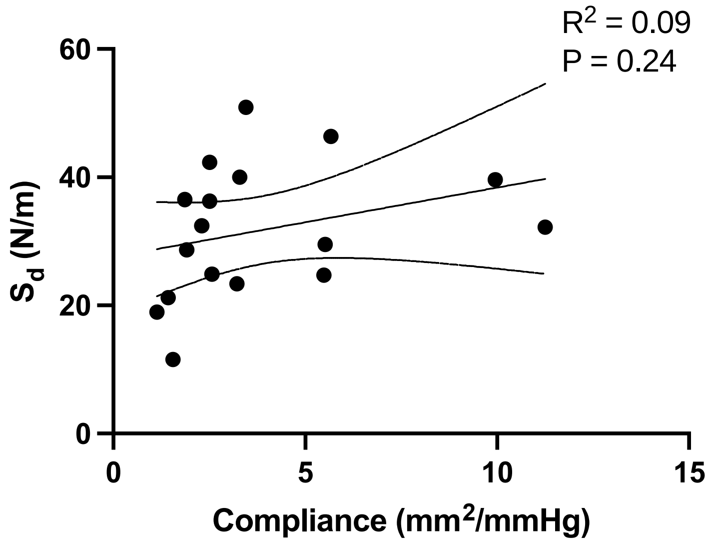


$$S_d = \frac{\int_{x_1}^{x_2} F\, dx}{(x_2 - x_1)(width)}$$

Association between Strain, Distensibility and Compliance and ex-vivo aortic biomechanics

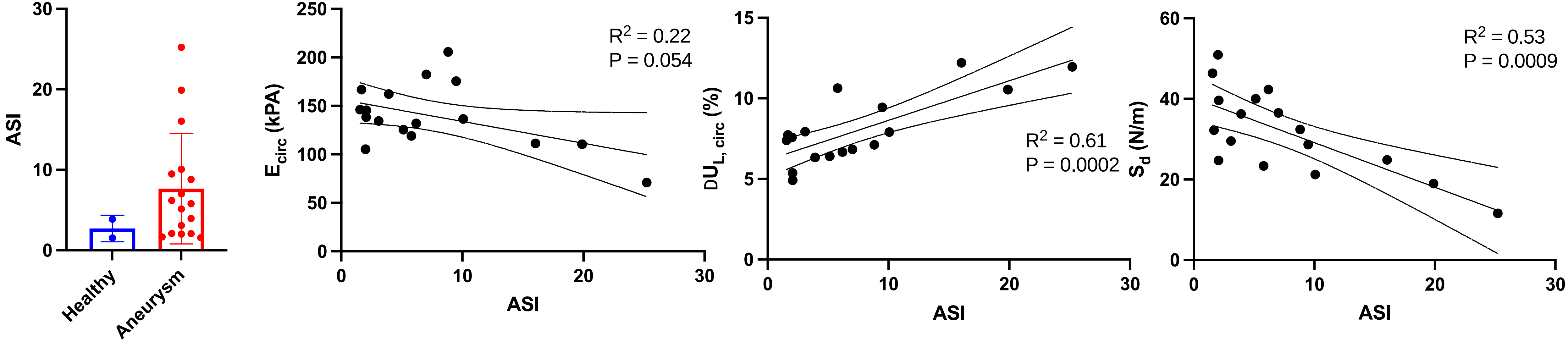






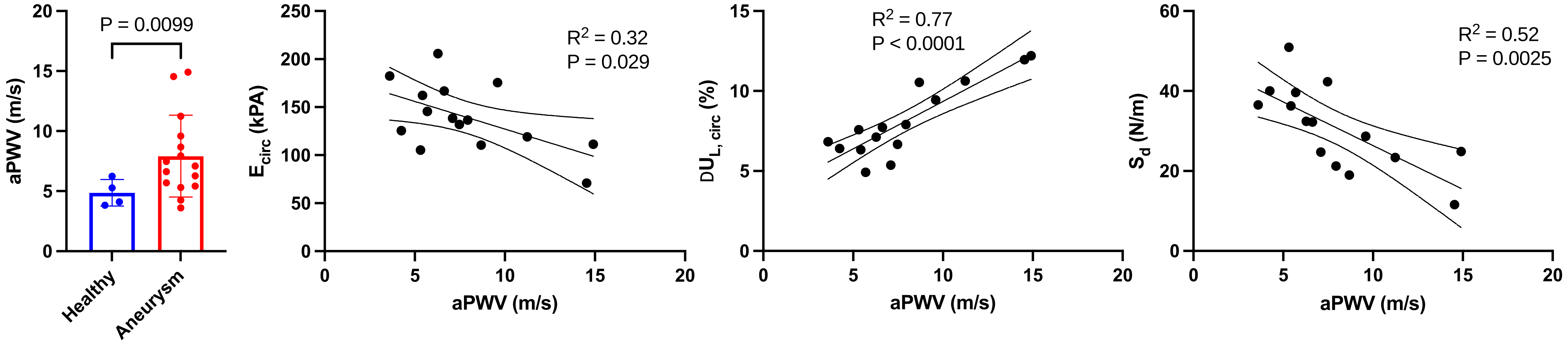
Weak correlations were found between Strain and Compliance versus Delamination strength but otherwise no other correlations were found.

Association between Arterial Stiffness Index and ex-vivo aortic biomechanics



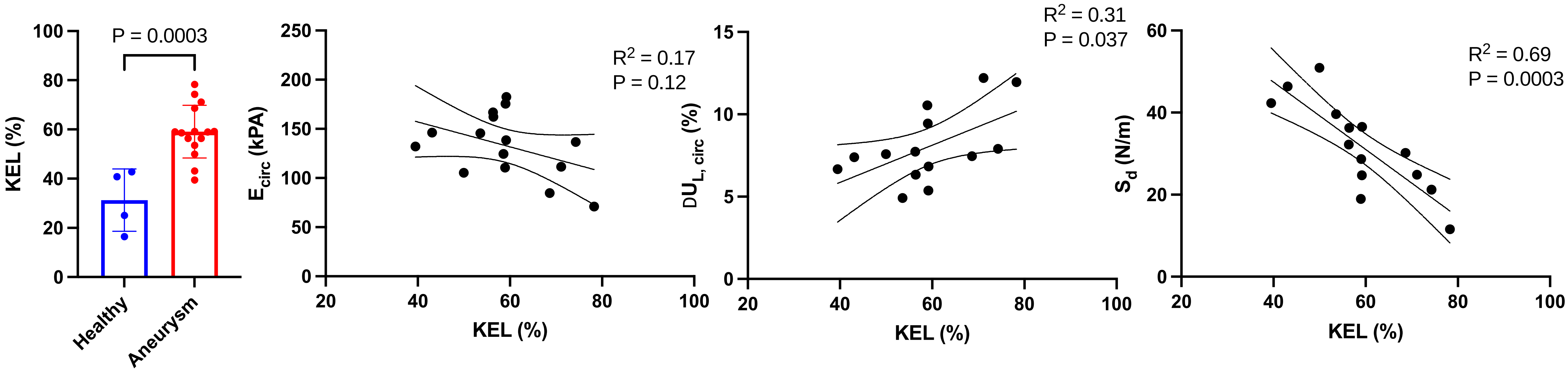
Greater ASI was associated with increased Energy Loss and decreased Delamination Strength

Association between Aortic Pulse Wave Velocity and ex-vivo aortic biomechanics



Greater aPWV was associated with decreased tangent modulus of elasticity, increased energy loss and decreased delamination strength

Association between Kinetic Energy Loss and ex-vivo aortic biomechanics



Greater KEL was associated with increased energy loss and decreased delamination strength

Conclusions

- For the first time, MRI-based aortic biomechanics have been validated against ex-vivo aortic biomechanics
- Most strain-based measurements of aortic biomechanics by MRI correlate weakly with ex vivo aortic biomechanics
- Arterial stiffness index, Aortic Pulse Wave Velocity and Kinetic Energy Loss are MRI-based aortic biomechanics that correlate very well with ex-vivo aortic biomechanics
- Future work will incorporate these 3 candidate MRI-based aortic biomechanical parameters into multivariable models for improving risk stratification of patients at risk of aortic dissection.