INTRODUCTION

BACKGROUND
• Biomechanical factors important in maintaining normal vessel structure but can also impact congenital (coarctation) and acquired (atherosclerotic, hypertensive, aneurysmal) diseases.

OBJECTIVES
• Utilize 4D MRI analysis methods to characterize hemodynamic conditions and wall motion of the porcine and human thoracic and abdominal aorta.
• Develop improved techniques for quantifying vessel wall motion.

WORK IN PROGRESS:
• Biomechanical factors important in maintaining normal vessel structure but can also impact congenital (coarctation) and acquired (atherosclerotic, hypertensive, aneurysmal) diseases.
• Strong forms of the Navier-Stokes equations:
  \[
  \rho \frac{\partial v}{\partial t} + \rho (v \cdot \nabla)v = -\nabla p + \mu \nabla^2 v + f
  \]
  \[
  \nabla \cdot v = 0
  \]

RESULTS

QUANTIFICATION OF WALL MOTION USING 4D MRI

BACKGROUND:
• Mechanical environment of the thoracic aorta is largely unknown
• Designing and improved testing of new thoracic stent grafts

OBJECTIVE:
• Describe time- and location-dependent mechanics of the normal “young” and “mature” thoracic aorta

METHODS:
• 19 volunteers without history of cardiovascular disease were recruited and scanned according to a protocol approved by the Stanford University Institutional Review Board. Subjects were recruited into either a “younger” or “older” age group, which were defined as 20-35 years and 50-70 years, respectively. Young: n = 10; Mature: n = 9 (gender balanced).
• Contrast-enhanced MR angiogram obtained
• 4D volume of aortic motion (cardiac and respiratory resolved)
• ~12 aortic motion slices perpendicular to aorta

RESULTS:
• The distal thoracic aorta was found to have a smaller diameter but higher circumferential strain than the proximal aorta, and the direction of wall motion gradually rotated from the outer curvature in the proximal descending thoracic aorta to the inner curvature at the level of the celiac artery.

WORK IN PROGRESS:
• Developing improved techniques for quantifying vessel wall motion.
• Quantify aortic wall motion in subjects with congenital and acquired vascular diseases.

3D NANOSTRUCTURE OF MEDIAL LAMELLAR UNIT

• Serial block-face scanning electron microscopy [Denk, 2006]
• 3D lamellar boundaries at time points of minimum (blue curve) and maximum (red curve) equinodiameters. The image vectors point toward the inner curvature of the thoracic aorta.

• Elastic:
  \[
  \frac{\partial E}{\partial t} + \mu \nabla^2 E + f = 0
  \]

• Cytoplasm:
  \[
  \frac{\partial C}{\partial t} + \mu \nabla^2 C + f = 0
  \]

• Membrane:
  \[
  \frac{\partial M}{\partial t} + \mu \nabla^2 M + f = 0
  \]

• hydrodynamic boundary conditions
• linear membrane enhanced with traction of the fluid can be related through the elastodynamics

• Zero-velocity condition removed from the lateral surface of the vessel wall:
  \[
  \frac{\partial v}{\partial t} + (v \cdot \nabla)v = -\nabla p + \mu \nabla^2 v + f
  \]
  \[
  \nabla \cdot v = 0
  \]

MODELING AORTIC BLOOD FLOW & AORTIC WALL MOTION

• Developed a new formulation to simulate blood flow in deformable subject-specific models
• Computationally advantageous alternative to standard techniques for Fluid-Solid Interaction (FSI) phenomena
• Enables representation of wall motion, wall stress & wave propagation phenomena in the cardiovascular system
• Small increase in computational cost compared to rigid wall simulations

Strong Forms of the Navier-Stokes Equations

• Formulation Features:
  Zero-velocity condition removed from the lateral surface of the fluid domain & replaced with a traction condition

• Using a thin wall approximation, this unknown interface traction can be related to a body force, for the vessel wall (Womersley)

• Traction of the fluid can be related through the elastodynamics equations with the mass and stiffness terms of the vessel wall

• Membrane formulation used to describe mass and stiffness terms of the solid

• Strong coupling approach is used whereby degrees-of-freedom of vessel wall & fluid boundary are same (i.e., no rotations) – solid momentum contributions are embedded into fluid equations using same degree-of-freedom

• Linearized kinematics approach adopted for coupled problem – enables representation of solid equations using the same Eulerian frame as in fluid equations

• Linear membrane enhanced with transverse shear modes used due to lack of stability of linear membrane under transverse loading

• SUMMARY: Pressure waves show significantly larger pulses in the rigid case, whereas outflow waves present larger values in diastole and smaller values in peak systole for the deformable case.

DISCUSSION

• Image-based computational methods essential for quantifying biomechanical forces and elucidating structure-function relationships in blood vessels from nano- to macro-scales.
• Computational methods could be used to design novel therapies (pharmacologic, catheter-based, surgical) for aortic diseases.

FUTURE CHALLENGES
• Development of automated techniques for creating (i) time-varying imaging-based models from 4D MRI data, (ii) microstructural computational models from 3D microscopy data
• Development of nonlinear homogenization techniques to infer macroscale tissue properties from microscale data
• Incorporation of external tissue support in coupled blood flow – vessel deformation simulations.

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