Effects of the Wall Inclusion Size and Modulus Contrast on the Regional Pulse Wave Propagation Along the Arterial Wall In Silico

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Background: Arterial stiffness has previously been reported as an independent indicator of cardiovascular diseases such as aortic aneurysm. Existing stiffness measurements methods in vivo are either invasive (e.g. catheterization) or provide only an average global estimate (e.g. tonometry). Previous studies of pulse wave propagation along inhomogeneous arterial walls have shown that a global PWV estimate might not effectively detect the presence of local stiffness changes [1]. Pulse wave imaging (PWI) is a noninvasive and local estimation method [2-4] for regional pulse wave velocity (PWV) measurement and visualization. This study aims at examining the effects of size and modulus contrast of the arterial wall inclusion on the pulse wave propagation and reflection mechanisms.

Aims: Examining the effects of inclusion size and modulus contrast on the regional pulse wave propagation and velocity along the simulated arterial wall.

Methods: A full 3D FSI simulation of pulse wave propagation was performed in Coupled Eulerian-Lagrangian(CEL) explicit solver of Abaqus 6.10-1 (Simulia, RI, USA). The Lagrangian domain composed of a straight geometry tube (L=250 mm; r=12 mm; t=2.2 mm) with a linearly elastic wall (Ewall=5.12 MPa, ρwall=1050 kg/m³ and Poisson’s ratio ν=0.48). The Eulerian domain encompassed the Lagrangian tube, simulating the presence of a Newtonian fluid medium (ρfluid=1000 kg/m³, speed sound C0=1483 m/s and viscosity η=0.0001 Pa.s). The FSI was defined as a frictionless two-way coupling between the tube and the fluid medium. The tube inlet and outlet were fully constrained in x-y-z directions and a rectangular initial velocity (V0=5 m/s) was applied on the inlet as the driving force for the dynamic wall motion. The first simulation was performed on the homogenous wall (no inclusion) as the reference model. The effects of the inclusion size were examined based on a set of simulations of the wall containing a 2 and 10 mm long inclusion with a Young's modulus of 1.50 times the Ewall=5.12 MPa. To examine the effects of the inclusion modulus contrast, a set of simulations were performed on the wall containing a 2 mm long inclusion with a Young's modulus of 1.50 and 2.00 times the Ewall=5.12 MPa. The wall radial displacement along the entire tube length (axial spatial resolution of 5 mm) was measured at multiple time-points (temporal resolution of 0.375 ms) and the information was mapped onto a 2D spatio-temporal plane which allowed the visualization of the entire wave propagation.

Results: Figure 1 provides the spatio-temporal plots of the wall displacement for the homogenous wall (Fig. 1.A), and the inhomogeneous walls (Figs. 1.B-1.D). It is seen that a small portion of the main forward wave gets reflected at the site of the inclusion while the rest continues to travel forward beyond the inclusion site under a PWV which remains almost unaffected (not shown here, see [1]). However, the spatio-temporal plots further illustrate that the reflection quantitative and qualitative patterns depend on the inclusion properties. In particular, increase in both the inclusion size (Figs. 1.B & 1.C) and modulus contrast (Figs. 1.B & 1.D) was found to increase the reflection wave magnitude. Furthermore, the spatio-temporal plots also show that the low wall displacement at the inclusion site forms a standing wave whose width indicates the size of the inclusion (Figs. 1.B & 1.C).

Conclusions: This study of pulse wave propagation along the inhomogeneous arterial walls in silico highlighted the need for regional PWV measurements, such as those obtained by PWI, in order to detect the changes in regional wall stiffness. In particular, it was found that spatio-temporal plots of the wall displacement contain qualitative and quantitative information that can collectively be used to obtain the size and modulus contrast of the zone entailing the regional changes. Future studies will focus on examining the pathological conditions, such as the inhomogeneity in modulus and geometry seen in aortic aneurysm, in order to determine the implications in PWI in vivo.