Aortic Stiffness Estimation via Pulse Wave Imaging in Patient-Specific Simulated and Silicone Phantoms
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Introduction: Aortic stiffness has widely been reported as an independent indicator of all-cause mortalities and cardiovascular diseases. Traditional methods to measure arterial stiffness in vivo are either invasive or provide a global average estimate. An attractive alternative for noninvasive estimation of local arterial stiffness is based on pulse wave imaging (PWI), a method for pulse wave visualization and pulse wave velocity (PWV) measurement. In this study, PWI was used in patient-specific simulations and silicone phantoms for PWV and stiffness estimation and the results were compared against mechanical testing.

Materials and Methods: A patient-specific geometry of a normal aorta was considered to construct both the simulation models and silicone aortic phantoms. Finite-element simulation of the arterial wall under pulsation was implemented on Abaqus 6.10-1. Wall material properties were set to be the same as those of the silicone phantom, obtained by extracting sets of circumferential specimens of size 7.5 × 2 mm² and testing them under tensile loading to obtain the true Young’s modulus, E. Also, a 2D digital image correlation-based noninvasive strain measurement system was concurrently employed to determine the Poisson’s ratio, ν. Water material properties were used for nonviscous fluid modeling with a nonslip surface interaction against the phantom wall. The two ends of the aortic phantom were constrained to avoid global rigid body motion while allowing free propagation of the pulse wave along the phantom. A free inflow and initial fluid velocity were applied at the lumen to model the inlet pulsation, and a nonreflecting outflow was applied at the lumen outlet to minimize the pulse wave reflection. Coupled Eulerian-Lagrangian (CEL) and computational fluid dynamic (CFD)/explicit co-simulation solvers were separately used. On the displacement output, the axial position of the pulse wavefront was registered at consecutive time-points and the slope of the linear fit of time vs. position curve was measured to yield the PWV. To verify the simulation results, a customized laboratory setup was prepared to implement PWI on the silicone phantom under pulsatile flow. A linear-array ultrasound transducer was used to image the phantom wall with 16 beams at 950 fps. A 1D cross-correlation method was applied to estimate the spatiotemporal variation of the wall displacement and the PWV. The PWV estimates were inserted into the Moens-Korteweg equation, \( E = 2(1 - v^2) \rho PWV^2/t \), where \( r \) and \( t \) are respectively the internal radius and wall thickness.

Results and Discussion: True material properties were obtained with mechanical testing as follows: \( E = 2.56 ± 0.15 \text{ MPa} \) and \( v=0.48 \). Estimated PWV and E based on simulations and silicone phantoms PWI are given in rows 1 and 3 of Table 1, respectively. The large difference ratio between the simulated modulus and the true value from mechanical testing could be due to differences in fluid-solid interaction boundary conditions between simulations and experiments. It was observed that the dynamic convergence was dependent on factors such as friction at fluid-solid interaction surfaces, as well as fluid boundary conditions on the lumen inlet/outlet. The pulse propagation was also found to be sensitive to the Reynolds number. The estimated PWI modulus from silicone phantom indicates a very small difference to that of mechanical testing. Also, as shown in the second row of Table 1, the estimated PWV and E in a simulated phantom with double the previous stiffness (i.e., input stiffness of \( E = 5.12 \text{ MPa} \)), further supporting the dependence of the wall stiffness on the simulated PWV. It should be noted that sources of inaccuracy associated with mechanical testing may also incur errors in material parameterization. Nevertheless, the high correlation between mechanical testing and PWI indicates the reliability of the latter in estimating the material stiffness.

Table 1- PWV and E estimation in simulations and experiments with PWI. Estimated stiffness values are compared to true stiffness obtained from mechanical testing (the true stiffness for the second simulation was used as the material input parameter).

<table>
<thead>
<tr>
<th></th>
<th>Estim. PWV (m/s)</th>
<th>Estim. E (MPa)</th>
<th>True E (MPa)</th>
<th>Difference Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated Phantom</td>
<td>19.12 (( r^2=0.99 ))</td>
<td>3.54</td>
<td>2.56</td>
<td>38.28</td>
</tr>
<tr>
<td>Experiment Phantom</td>
<td>25.60 (( r^2=0.98 ))</td>
<td>6.35</td>
<td>5.12</td>
<td>24.02</td>
</tr>
<tr>
<td>Experiment Phantom</td>
<td>15.66 (( r^2=0.91 ))</td>
<td>2.38</td>
<td>2.56</td>
<td>-7.03</td>
</tr>
</tbody>
</table>

Conclusions: Reliable noninvasive measurements of pulse wave velocity can be of paramount significance in estimating the change in stiffness and material composition of vessels and enhancing the prognosis of vascular disease. In this study, PWI in simulated and silicone aortic phantoms were shown to yield accurate estimates of the regional pulse wave velocity and stiffness noninvasively. This ultrasound-based methodology could be easily applicable and will be tested in a clinical setting.

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