Hemodynamic loading and intrinsic cardiac stiffness affect shear wave measurements: an in silico sensitivity analysis

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Background, Motivation and Objective

Previous work has shown that cardiac shear wave elastography (SWE) at end-diastole measures operational stiffness as represented by the local slope of the end-diastolic pressure-volume relationship. This means that shear wave speed (SWS) depends on hemodynamic loading and intrinsic stiffness properties, requiring the measurement of an additional parameter (such as transmural SWS gradient) to discriminate between both effects. To investigate the sensitivity of SWS and SWS gradient to pressure and stiffness, we built a finite element (FE) model of the left ventricle (LV).

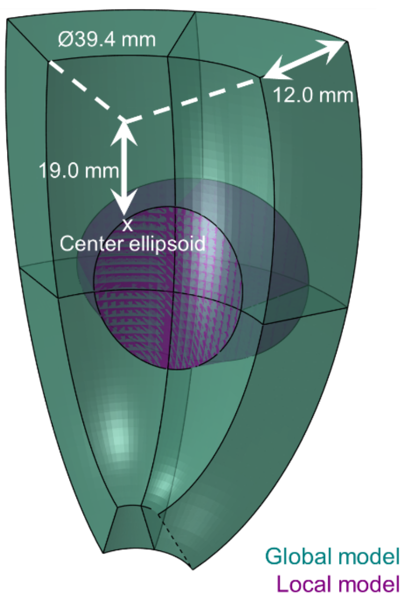
Statement of Contribution/Methods

The LV was modeled as a prolate spheroid with an isotropic nonlinear material model in the FE software Abaqus (Providence, RI, USA), as shown in fig. a. We considered three stiffness factors (1x, 2x, and 5x) and LV pressures (8, 20 and 30 mmHg), while pressure in the right ventricle was kept at 4 mmHg. After pressurizing the ventricle, shear waves were simulated in a local model by applying a body force for 250 µs. The resulting tissue velocities, shear stresses and strains were used in a transmural SWS and operational shear stiffness (µ) analysis for 10 equally spread anatomical lines across the cardiac wall in parasternal long axis view. SWS was estimated using the Radon transform and µ was obtained from the local slope of the stress-strain curve. Correlations were computed using Pearson's linear correlation coefficient.

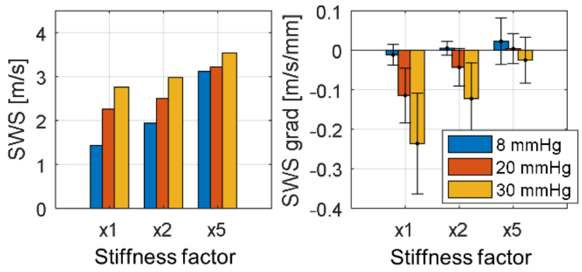
Results/Discussion

As expected, SWS at mid-wall (fig. b) increases when stiffness is elevated (+1.5 m/s when stiffness x5 at LVP of 8 mmHg), and when LVP rises (+1.4 m/s for ΔLVP of +22 mmHg at normal stiffness). Interestingly, for a given stiffness level, SWS gradient (fig. b) decreases when LVP increases (-0.23 m/s/mm for ΔLVP of +22 mmHg at normal stiffness), demonstrating its power to distinguish an SWS increase due to pressure or stiffness. However, its sensitivity decreases for stiffer materials (-0.18 m/s/mm at stiffness x5 compared to stiffness x1 for ΔLVP of +22 mmHg). Despite this limitation, the excellent correlation between SWS and µ (R=0.99; p<0.0001) and between SWS gradient and µ gradient (R=0.98; p<0.0001) in fig. c demonstrate the direct mechanical meaning of both SWE parameters. This highlights their usefulness for SWE analysis.

a) LV geometry



b) SWS at mid-cardiac wall and SWS gradient



c) Correlation plots between SWS and shear stiffness µ