Non-invasive estimation of localized intraluminal pressure in the artery by an ultrasound elastographic imaging framework

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Arterial wall deformation (ε), stiffness (μ) and intraluminal pressure (P_i) are recognized predictors of cardiovascular diseases but interdependent. Unlike ε and μ, noninvasive estimation of localized P_i deep in the body remains challenging. Current ultrasound-based noninvasive estimation methods mainly use pulse wave imaging or color Doppler imaging. They either neglect nonlinear elasticity of the artery walls or are angle dependent. This study thus aims to 1) develop a mathematical description for localized P_i as a function of ε and μ and 2) validate the proposed model *in vitro* using our ultrasound elastographic imaging framework (UEIF), comprised of our published vascular guided wave imaging (VGWI) and ultrasound strain imaging (USI) methods.

We consider the arterial nonlinear stress-strain behavior to be piecewise linearly-elastic. P_i for a transversely isotropic, nonlinear tubular wall is formulated as

$$P_i(t) = \sum_t \frac{(R+h)^2 - R^2}{(R+h)^2} \cdot \mu_T(t) \cdot [\varepsilon_\theta(t) - \varepsilon_r(t)],$$

where R and h are internal radius and wall thickness, respectively. Transverse shear modulus ($\mu_T(t)$), and radial ($\varepsilon_r(t)$) and circumferential ($\varepsilon_\theta(t)$) strains are time-varying. μ_T is estimated by VGWI (Fig. 1a), and ε_r and ε_θ are estimated by USI (Figs. 1b, c).

Two vessel-mimicking PVA phantoms (one with a 17% longitudinal pre-stretch) were pressurized by an AccuFlow-Q® flow pump. Stepwise constant flow and 1 Hz sinusoidal flow were used to provide static pressure at a 10-mmHg increment and dynamic pressure, respectively. Ground truth intraluminal pressure was measured by a commercial pressure meter. VGWI data were acquired by a Verasonics® system with an L7-4 probe at 8000 Hz. VGWI was performed 20 times with equal intervals over 2 consecutive cycles at the same position in each sample under dynamic pressure. The last compounded image of each VGWI event was used for USI to achieve simultaneous assessment of μ_T and strain.

Fig. 1d shows excellent agreement between P_i estimated by our model (dashed lines) and that measured by pressure meter (solid lines) in the static pressure scenario. Under dynamic pressure, UEIF-estimated P_i's (Fig. 1g, h: solid lines) were highly correlated with M-mode images (Fig. 1e, f) with high reproducibility. Results verified that our proposed formulation for P_i could be noninvasively estimated by UEIF. The human artery *in vivo* is being examined.

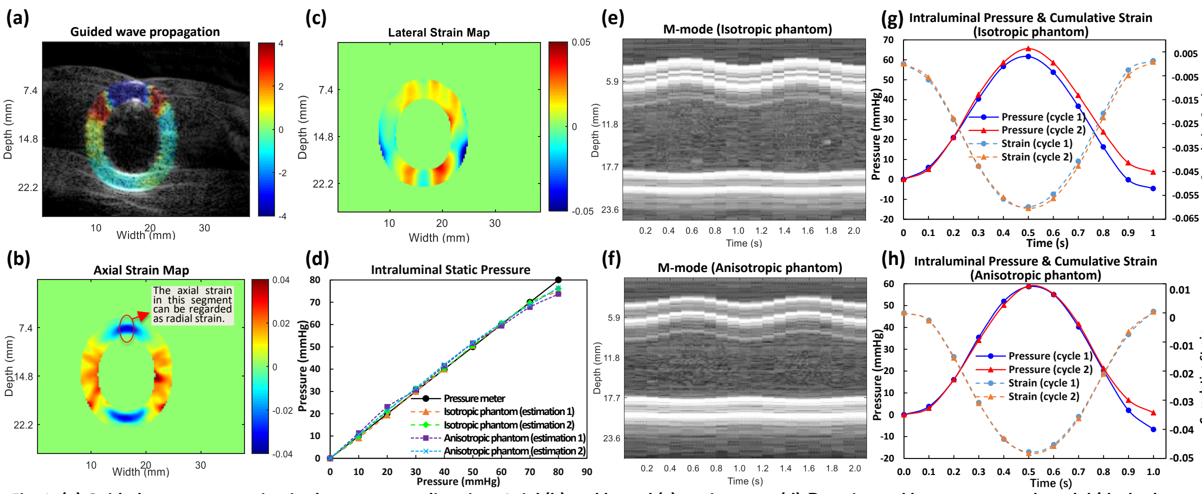

Fig. 1. (a) Guided wave propagation in the transverse direction. Axial (b) and lateral (c) strain maps. (d) P_i estimated by our proposed model (dashed lines) and by a commercial pressure meter (solid lines) in the static pressure scenario. M-mode images for isotropic (e) and anisotropic (f) phantoms in the dynamic pressure scenario. P_i estimated by our proposed model (solid lines) and cumulative radial strain (dashed lines) over 2 consecutive cycles of isotropic (g) and anisotropic (h) phantoms.