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Automated Aortic Strain Mapping with Spectral Robustness Quantification from 4D CT

Tricia Lobo, MS, University of Pennsylvania; Wensi Wu, PhD, MS; Harold I. Litt, MD, PhD; Melanie Freas, DNP, CRNP; Victor Ferrari, MD; Joseph E. Bavaria, MD; Nimesh D. Desai, MD, PhD; Alison M. Pouch, PhD

Introduction/Background

Spatially resolved aortic strain mapping has the potential to characterize vessel-wall mechanics beyond conventional diameter measurements. Deep learning-based segmentation and automated strain analysis may enable time-resolved aortic strain estimation on timescales increasingly compatible with clinical workflows. We present a largely automated framework for estimating patient-specific ascending-aortic areal strain maps from routine ECG-gated 4D CT. Because aortic strain estimates are sensitive to segmentation variability, we quantify reproducibility across segmentation sources and spatial scales by reconstructing strain using varying numbers of Laplace-Beltrami (LB) modes.

Methods/Intervention

ECG-gated 4D CT images from 14 patients in a bicuspid aortic valve (BAV) study were processed sequentially using nnU-Net segmentation, optimized surface remeshing, deformable registration, and mesh-based strain estimation to compute patient-specific strain maps. Patient-specific finite-element (FE) simulations generated synthetic image sequences with known deformation fields for registration tuning and validation. Segmentation-source robustness was quantified by projecting strain fields onto geometry-derived LB eigenfunctions, allowing comparison across progressively finer spatial scales.

Results/Outcome

Across FE validation analyses, estimated and ground-truth median strain showed near one-to-one agreement, with low mean bias for both semi-automated and nnU-Net-derived segmentations. Across segmentation sources, median strain agreement was excellent (Pearson r = 0.991 interobserver; r = 0.993 nnU-Net versus observer). LB spectral analysis showed preferential preservation of low-frequency strain organization, with K=5 reconstructions reducing segmentation-related disagreement by 52-56%, indicating greater reproducibility of broad, low-frequency strain patterns than of higher-frequency local features.

Conclusion

Automated strain mapping from routine ECG-gated 4D CT is reproducible across segmentation sources, particularly for broad regional strain patterns captured by low-order LB modes. The framework enables robust patient-specific characterization of aortic deformation while providing a general approach for identifying the spatial scales at which regional strain patterns remain reproducible.

Statement of Impact

We developed a reproducible, largely automated framework for aortic strain mapping that integrates deep learning-based segmentation, FE-based validation, and LB spectral analysis. The approach demonstrates that low-frequency regional deformation patterns are substantially more reproducible across segmentation sources than higher-frequency localized strain features, providing a framework for evaluating the reliability of spatially resolved strain that may generalize to other cardiovascular imaging applications.

Tables and Figures

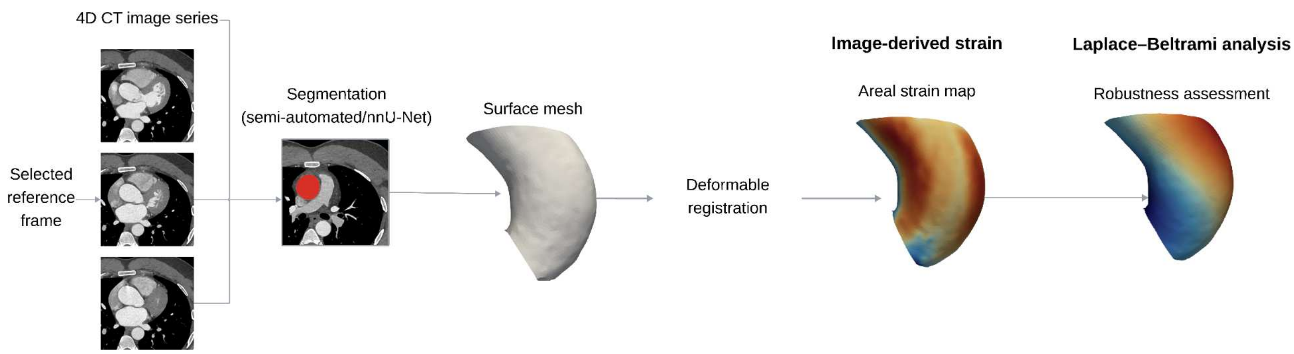

Figure 1. Overview of the proposed pipeline for automated aortic strain estimation and intrinsic spectral analysis. 4D CT images are segmented, registered, and used to compute dense areal strain maps, which are subsequently analyzed in the Laplace–Beltrami basis to evaluate the robustness of strain organization.

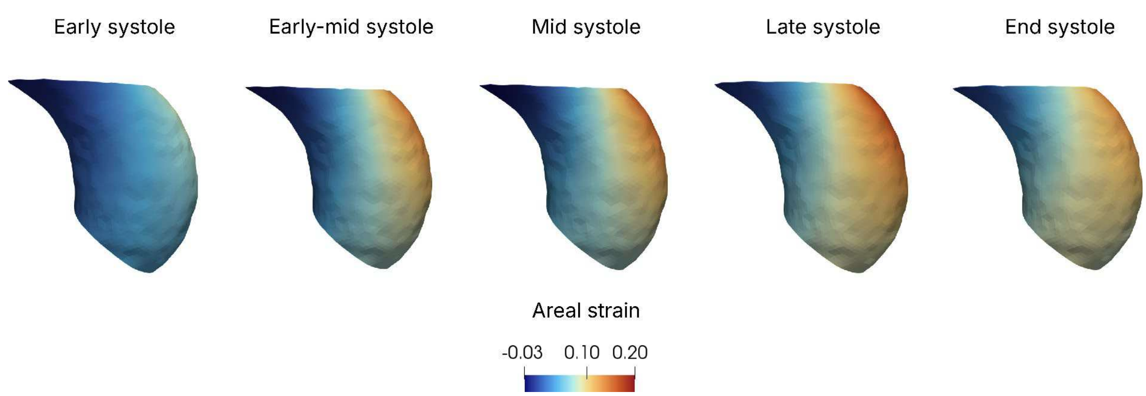

Figure 2. Temporal evolution of a representative ascending-aortic areal strain pattern across systole in a patient with bicuspid aortic valve. Strain maps were reconstructed using the first five Laplace–Beltrami modes and are shown at early, early–mid, mid, late, and end systole using a common color scale.

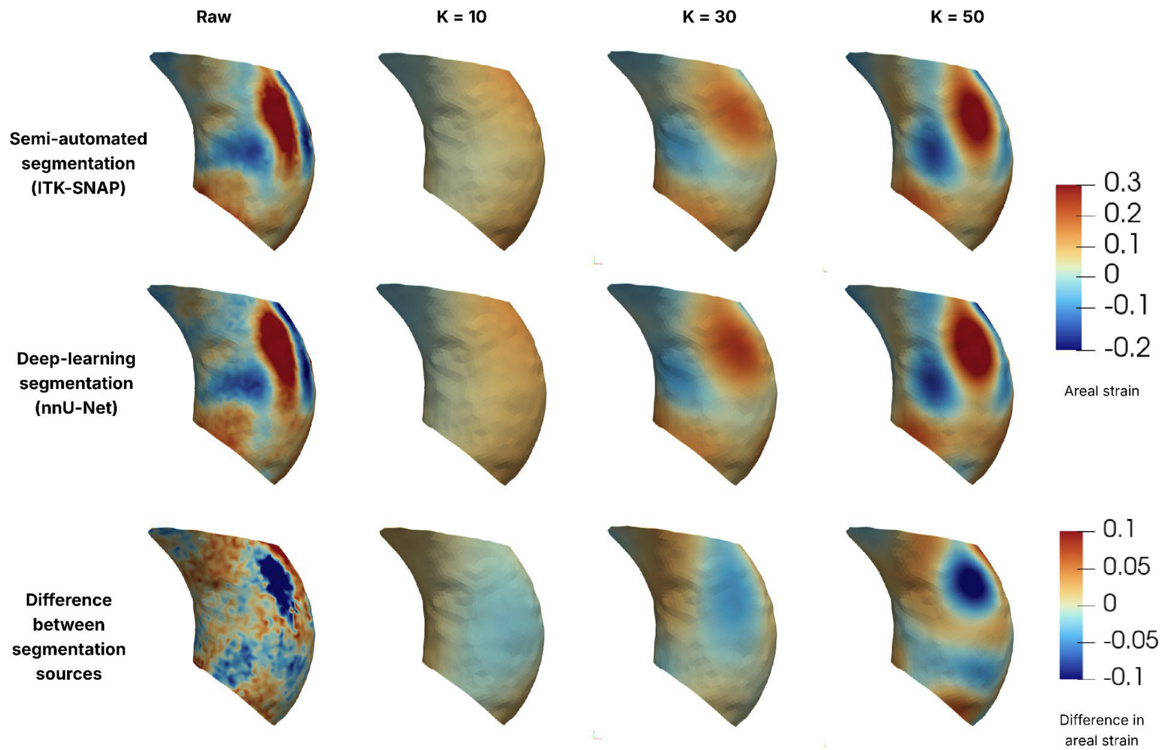

Figure 3. Spectral reconstruction reveals scale-dependent robustness of aortic strain across segmentation sources. End-systolic areal strain maps derived from semi-automated active-contour segmentation in ITK-SNAP (top row) and fully automated nnU-Net segmentation (middle row) are shown at full spatial resolution and after reconstruction using the first 10, 30, and 50 Laplace–Beltrami eigenfunctions. Increasing K permits reconstructions of progressively finer-scale spatial variation. The first two rows are displayed using a common color scale to permit direct comparison. After projection of the nnU-Net-derived strain field onto the semi-automated reference surface, difference maps were computed pointwise as semi-automated minus nnU-Net strain (bottom row). Difference maps are displayed using a common color scale to permit direct comparison across spectral resolutions. Low-order reconstructions showed greater consistency across segmentation sources, while finer-scale differences became increasingly apparent as additional modes were retained.