Significance of passive material parameters in mechanical models of the heart

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INTRODUCTION Medical images are taken at non-zero internal pressures, while mechanical models of the heart assume an initial stress free state. An unloaded reference geometry can be computed, but this will depend strongly on the passive material properties of the tissue. We investigate the effect on stress and strain in the heart cycle, when the initial geometry has been unloaded based on different stiffness parameters.

METHODS We constructed a human left ventricular (LV) mesh from echo images of end diastole (ED), expressed with two types of finite elements; linear tetrahedral (6960 elements, 2153 nodes) and quadratic tetrahedral (6917 elements, 13112 nodes). For fibers we used the rule-based algorithm from Bayer et al. 2012. We used a slightly compressible version of the strain energy function from Guccione et al. 1991, and tested 21 different sets of material parameters from the literature;

$$W = \frac{C}{2}(e^{Q}-1)+C_{comp}(J\ln J-J+1), \quad Q=b_{ff}E_{ff}^2+b_{xx}(E_{cc}^2+E_{ss}^2+E_{cs}^2+E_{sc}^2)+b_{fx}(E_{fc}^2+E_{cf}^2+E_{fs}^2+E_{sf}^2).$$

The passive model was coupled to an active contraction model by Nash and Panfilov, 2004. For each set we computed the unloaded geometry, assuming an ED pressure of 12mmHg. A simple fixed point iteration to compute the unloaded geometry, and the fiber generation was redone on the unloaded geometry.We estimated the force of the active contraction (T_{ref}) for each parameter set in an iterative process to obtain a matching end systolic volume. The results were obtained without varying the outflow parameters.

RESULTS Figure 1A shows that when the ED is used as the initial unloaded geometry, the parameters yield very different pressure-volume (PV) loops. In panel B, the correct unloaded geometry is used, resulting in closely matching PV loops. At the end of iso-volumetric contraction (300ms) we observe that qualitatively the strain field is fairly different, since the initial geometry is different, but the stress is less affected, Figure 1C and D.

DISCUSSION Our results indicate that the unloaded initial geometry significantly affects the results of mechanical models of the left ventricle. Furthermore, when the geometry is unloaded to a stress free initial state, the tissue fiber stress becomes less dependent on the passive material parameters. Significantly different parameter sets can yield identical PV loops by adjusting a single parameter (T_{ref}), and the computed stress fields are qualitatively very similar. The low sensitivity of the stress field to material parameters has implications for the feasibility and importance of estimating passive material parameters accurately in mechanical models of the heart.

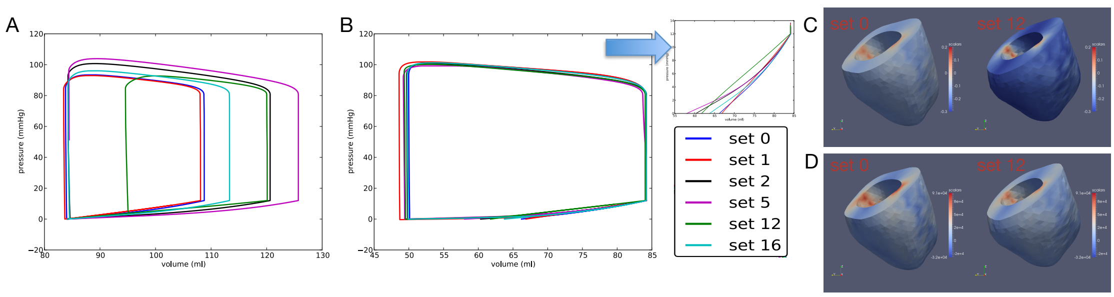

Figure 1: Linear tetrahedrals, LV fibers were used. A: PV loops starting from the original geometry, and T_{ref}=80000. B: PV loops starting from the unloaded geometry, T_{ref}s estimated range [80000-131333]. C: Strain in fiber direction at 300ms, from unloaded. D: Stress (Pa) in fiber direction at 300ms, from unloaded