Patient-specific Ventricular Remodelling: A Multiphase Approach

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ABSTRACT

The human heart beats on average 100 000 times a day, delivering 7000 l of blood to the body, and is often regarded as the most vital organ. Due to its complexity, the heart is susceptible to various life threatening diseases which are predicted to account for as many as 25 million deaths annually by the year 2020. Amongst these, dilated cardiomyopathies are evoked by molecular changes which affect cytoskeletal proteins and impact on the structural integrity of the heart. The proliferative response of cytoskeletal proteins to mechanical deformation and stress generally allows the heart to adapt its structure to maintain proper functioning. However, a prolonged volume overload leads to progressive chamber dilatation and wall-thinning, so-called eccentric hypertrophy, ultimately causing systolic heart failure.

In order to further the understanding of the mechanisms of the disease as linked to changes in the cytoskeletal architecture and hypertrophy of cardiac myocytes, a continuum bi-phasic multi-component model is formulated based on the theory of porous media (TPM). This makes it possible to account for interactions and contributions of multiple phases of constituent materials as well as concentrations of solved components, that is here a solid phase, the cardiac tissue, and a liquid phase, the blood and the interstitial fluid. Particular attention is paid to the strain-driven phase transition of the liquid to the solid phase. To this end, based on thermodynamical restrictions constitutive relations are proposed for stress, mass supply, seepage velocity of the fluid and interaction forces.

The approach is implemented in the in-house computational cardiac mechanics toolbox SESKA which makes use of finite element as well as meshfree approximations. It considers the passive orthotropic nonlinear elastic material behaviour of the myocardium as well as its active contraction response facilitating modelling of the entire heart cycle.

A patient-specific computational case study is conducted to elucidate the chronology of the disease and the strain-induced proliferative mechanisms as a result of chronic volume overload from the biomechanics perspective, making use of cardiovascular magnetic resonance (CMR) scans obtained over a period of two years from Groote Schuur Hospital, Cape Town, South Africa to generate geometrically realistic models.

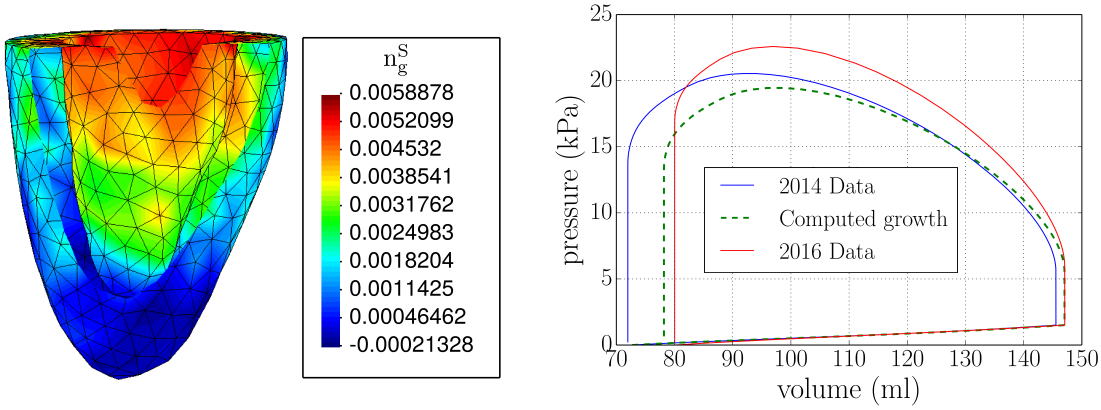

Figure 1: (Left) Distribution of the solid volume fraction n_g^S (cardiac tissue) of the left ventricle which has been added as growth (via mass exchange from the blood) after two years. (Right) Pressure-volume curves illustrating computational results obtained from 2014 and 2016 CMR data, along with the remodelled results obtained using the computational growth model.

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