Computational modeling of volumetric tissue growth: application to the cardiac left ventricle

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Application to the cardiac left ventricle

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Introduction

Local volumetric tissue growth is a fundamental aspect of cardiovascular tissue development and maintenance, affecting morphology and physiology of the organ. Computational modeling may provide additional insights in the relation between the local tissue stimulus and the local growth. Currently, however, no method is available to simulate volumetric growth in realistic cardiovascular geometries.

Objective

Develop a finite element (FE) based method that enables simulation of three-dimensional inhomogeneous volumetric soft tissue growth.

Materials and methods

Growth is assumed to plastically deform the unloaded tissue geometry based on a mechanical stimulus. Figure 1 shows the steps involved in a growth cycle.

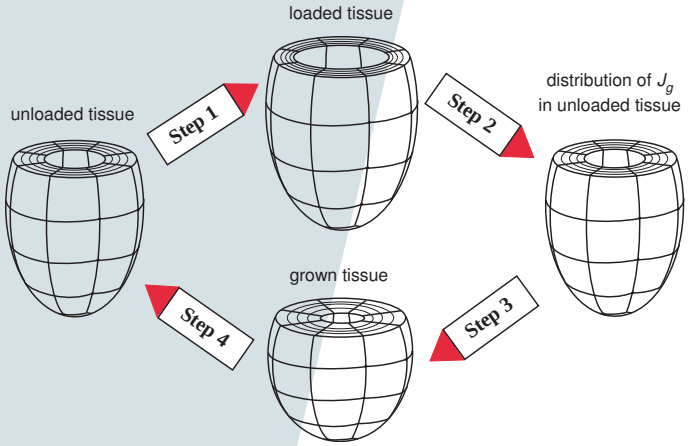

Figure 1. *Schematic overview of a growth cycle.*

- **Step 1: Determining the mechanical stimulus.** External pressure is applied on the inner surface, simulating diastolic filling. The tissue deforms, behaving transversely isotropic, non-linear elastic and nearly incompressible, as described by the strain energy density W_{stim} [1,2]:

$$W_{stim} = \Psi_{shape} + \Psi_{vol} \qquad (1)$$
$$\Psi_{vol} = \kappa(J^2 - 1)^2$$

with J the achieved volume change and κ the bulkmodulus. The equations of linear momentum that govern the tissue deformation are solved with a FE method.

- **Step 2: Determining the desired volume change.** The end-diastolic linear myofiber strain ε is translated into a desired local volume change J_g.

$$J_g = \frac{V(t+\Delta t)}{V(t)} = \beta(\varepsilon - \varepsilon_{hom})\Delta t + 1 \qquad (2)$$

with ε_{hom} the homeostatic myofiber strain, Δt the period of growth and β a rate constant.

- **Step 3 Determining the grown tissue geometry.** The volume change J_g is applied as internal load in the unloaded tissue. The tissue deforms, behaving isotropic and compressible (isotropic growth):

$$W_{growth} = \Phi_{shape} + \Phi_{vol} \qquad (3)$$
$$\Phi_{vol} = \kappa(J^2 - {J_g}^2)^2$$

- **Step 4 Updating the unloaded tissue geometry.** The grown tissue geometry is adopted as the new unloaded tissue geometry.

Results

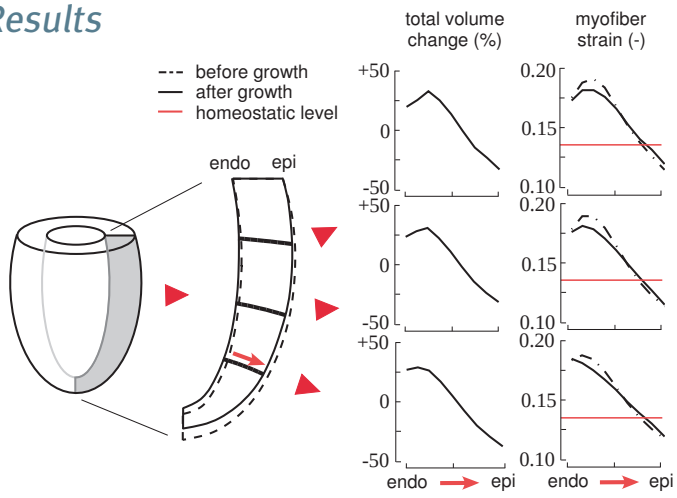

Figure 2. *The local volume changes and their effect on the transmural distribution of myofiber strain after 160 growth cycles.*

Conclusions

- A novel method has been developed to simulate 3D inhomogeneous volumetric growth.
- Adaptation of the cardiac left ventricle through inhomogeneous changes in wall volume of up to 30% successfully reduced heterogeneity in tissue strain.

References

[1] Bovendeerd PHM, et al. (1992) J Biomech 25:1129–1135.
[2] Kerckhoffs RCP et al. (2003) Ann Biomed Eng 31:536–547.