BIOMECHANICAL MODELING OF THE TRABECULATED EMBRYONIC HEART: IMAGE-BASED GLOBAL FE MESH CONSTRUCTION AND MODEL CALIBRATION

Wenjie Xie (1), David Sedmera (2), and Renato Perucchio (1)

(1) Department of Mechanical Engineering and of Biomedical Engineering
University of Rochester
Rochester, New York

(2) Department of Cell Biology and Anatomy
Medical University of South Carolina
Charleston, South Carolina

INTRODUCTION

Ventricular trabeculation of the embryonic tubular heart is an important developmental event in the formation of a normal four-chambered heart. Investigating the biomechanics of trabeculated tubular heart is essential for understanding how mechanical factors, such as stresses and strains, regulate cardiac development. We use the chick embryo model for its close similarity to the mammalian embryo at early stages of development. The focus of the present work is on Hamburger-Hamilton stage 21 (HH21), when the primary trabeculation of myocardium is fully developed. Due to its trabecular structure, the HH21 heart is characterized by an extremely complex geometrical configuration, which cannot be accurately represented in a computational environment by standard surface modeling procedures and finite element (FE) meshes. In order to perform systematic computational studies on HH21 heart we follow a local-global multi-scale nonlinear FE modeling approach. In [1] we introduced a novel material homogenization procedure for deriving strain energy density functions for the trabeculated myocardial tissue. The geometrical algorithms for modeling the trabeculated tissue at local level are given in [2]. In the present paper we focus on the construction and calibration of the global FE model representing the entire HH21 heart. The global results of the multiscale nonlinear FE simulation are discussed in a companion paper [3].

IMAGE-BASED GEOMETRICAL MODELING

A 3D FE mesh of a complex structure is usually constructed on the basis of its accurate boundary surface representation in a solid modeling system. In our approach, the HH21 global model and mesh do not need to include a direct geometric representation of the trabeculae since their biomechanical effect is already incorporated in the effective material properties derive al local (tissue) level [1]. Thus, the HH21 ventricle is modeled as a U-shaped tube with smooth walls composed of two distinct material layers: an external thin layer of compact myocardium and an internal thick layer representing the trabecular myocardium.

We reconstruct the HH21 heart solid model from a 3D digital image, consisting of a series of parallel confocal microscopic digital images. In conventional contour-line approaches, the 3D geometry is reconstructed from a sequence of 2D planar contours, interpolated in space by free-form surfaces. Sets of boundary-defining contours are constructed on each plane by connecting control points with cubic splines. The contour topology must not change from plane to plane in order to avoid major numerical difficulties in the surface reconstruction. Because of the HH21 heart U-shaped configuration, contours constructed on the parallel planes of confocal sectioning do not satisfy the topological requirement. In practice, regardless of the confocal sectioning orientation, direct contouring of the 2D confocal images yields topologically different contours. We overcome this problem by radially re-sectioning the original 3D digital image as shown in Fig.1. The U-shaped HH21 heart is located on the coronal plane (the xy plane in Fig.1). By inserting radial re-sectioning planes perpendicular to the coronal plane, we generate a set of new 2D sectional images on which we perform contour acquisition. Three sets of topologically identical contour lines are obtained to represent respectively the outer surface of the ventricle, the interface between compact and trabecular layers, and the inner lumen.

We use the ACIS Solid Modeler (Spatial Technology Inc.) for generating solid models from the radial contour sets. First, we create three intermediate solid models by surface interpolating (skinning) and enclosing the three contour sets. We then perform non-regularized Boolean operations on the intermediate solid models to generate the final HH21 global solid model representing the desired two-layered structure.

FINITE ELEMENT MESH GENERATION

We use Altair HyperMesh (Altair Engineering Inc.) for generating hexahedral FE meshes from the two-layered solid model, Fig. 2. The mesh is segmented into element sets according to functional and anatomical classifications. Notice that, since we focus on modeling the ventricle, both conotruncus and atria are modeled as elongated elastic extensions built on top of the ventricular openings.

Boundary conditions are specified on these two extensions to simulate the *in vivo* attachment of the heart to the embryo. We apply internal pressure to represent the blood lumen pressure. The pressure magnitude is derived from available experimental measurements [4]. Time-dependent activation is applied over the entire myocardial layer to generate periodic contraction and relaxation of the muscle fibers in the ventricle.

With reference to Fig.2, the compact layer consists of a combination of homogeneous and isotropic passive matrix and circumferentially oriented active fibers. The trabecular layer is inhomogeneous and anisotropic. The effective constitutive relations for the trabecular layer are determined through local material homogenization [1].

MODEL CALIBRATION

The major obstacle to biomechanical modeling of the tubular embryonic heart – and of the HH21 heart in particular - is the paucity of experimental data for passive and active material properties. For the present work, the effective material properties and activation strength of the trabecular myocardium are derived from available HH16 tissue-level properties [1]. In order for the global FE model to yield correct predictions on the mechanics of a HH21 heart, we determine a set of appropriate FE model parameters through a systematic calibration process based on experimental ventricular pressure volume (PV) data [4]. Using the end-diastolic PV relation, we first obtain the passive material constants. Then, from the end-systolic PV relation, we determine the active material constants and the activation strength. This calibration procedure is based on a set of rigorously defined mechanical assumptions. The calibrated model is verified by comparing the FE results for the contraction of an excised heart – modeled with the calibrated material properties in place – with experimental results.

CONCLUSION

We present a systematic modeling process for building the continuum FE model of the entire HH21 chick heart. The image based modeling procedure allows for the accurate reconstruction of the heart geometry. The model calibration yields material parameters essential for the correct biomechanical modeling of the HH21 heart. A systematic FE investigation on the mechanics of the trabecular HH21 heart based on the 3D calibrated global model is discussed in [3].

ACKNOWLEDGMENTS

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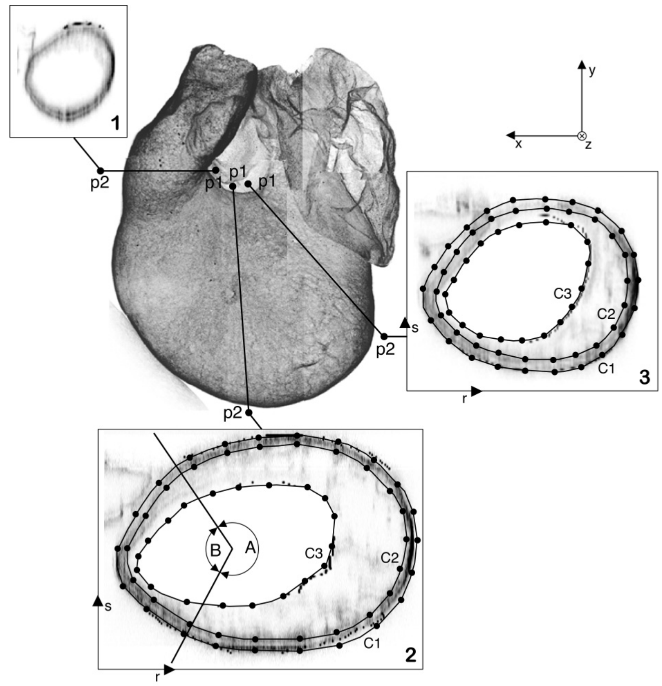

Figure 1. Radial re-sectioning and contour points acquisition. Contours C_1, C_2, and C_3 denote the external surface of ventricle, the interface between compact and trabecular layers, and the internal lumen, respectively.

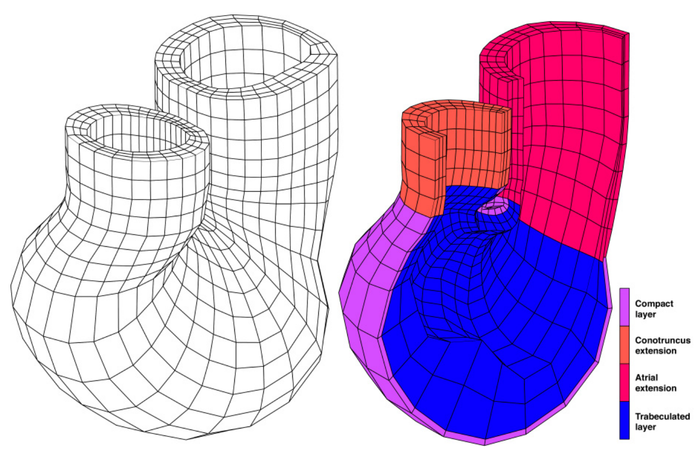

Figure 2. Global FE mesh of the HH21 heart: (a) complete hexahedral mesh; (b) coronal plane cutout to reveal internal smooth walls. Colors denote element sets representing different functional and anatomical components.