AN EXPERIMENTAL AND THEORETICAL MODEL FOR THE PASSIVE BIOMECHANICAL PROPERTIES OF THE INTACT HEART

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ABSTRACT

Previous attempts to model the biomechanics of the heart have either imposed restrictive simplifications on geometry or have ignored the inherent complexities of the tissue. The present work intends to capitalize upon advances in cardiac imaging and material modelling to overcome some of these limitations so that the passive biomechanical properties of the intact heart may be quantified in-vivo.

State-of-the-art nuclear magnetic resonance imaging (MRI) has made it possible to image the beating heart in extraordinary detail. This technology has been employed in obtaining three-dimensional intact measurements of cardiac geometry synchronized with ventricular pressure. Fiducial markers suitable for cardiac MRI have been developed to assist the determination of motion from MR images. The present research also initiates a systematic formulation of constitutive equations for the passive mechanical behavior of intact myocardium – based on first principles of continuum mechanics. This will serve as a sound foundation upon which more comprehensive models may be built, and will hopefully lead to improved understanding, diagnosis, and management of cardiac disease.

INTRODUCTION

Multifarious models have been proposed to better quantify the working parameters of the heart, in health and disease. Parallel histological and morphological research has disclosed more and more of the complexities of the myocardium, thus exposing the shortcomings of previous mathematical attempts to characterize this tissue. Ongoing experiments as well reveal the inadequacies of the existing techniques and models, and the current understanding of heart function.

It is hypothesized that an accurate biomechanical model for myocardium, applied to the intact heart, will lead to improved diagnosis of disease – with increased reliability, expediency, and greater detail. The current research initiates the development of such a model by initially focusing upon the passive elastic characteristics of myocardium during diastasis. Constitutive equations are presented — based on well founded principles of continuum mechanics — for modelling the nonlinear, orthotropic, compressible properties of intact heart tissue. Experimental techniques are developed to obtain the three-dimensional boundary conditions required for assessing the validity of these equations in-vivo.

In the next phases of this work, the mathematical model will be solved numerically using finite element analysis and validated using intact experimental data which was collected by MR imaging.

THEORETICAL MODEL

The myocardium, in its passive state, will be described as a compressible, non-linearly elastic material possessing orthotropic material symmetry. No assumptions are made upon the type of deformations or the relative significance of shear strains. Body forces will be ignored as well as inertial and viscous effects as these will be dominated by nonlinear elastic effects. Explicit constitutive equations are derived considering a homogeneous material consisting of one (solid) phase; however, the mobility of the fluid within the tissue is accounted for by allowing overall compressibility. Orthotropy has been selected for at least two reasons. First, the evidence provided by the abundant microstructural data suggests that such symmetry may exist. Second, in light of the postulated 'stress-adaptive' behavior of biologic tissues, the three-dimensional stress fields which occur in the intact heart should accordingly give rise to "three-dimensional" material properties.

The present set of constitutive assumptions are summarized in the table below.

Property	Proposed
Overall Geometry	3-d reconstruction
Material Symmetry	orthotropic
Aeleotropy	direct measurement
Nonlinearity	polynomial
Compressibility	compressible
Deformation Field	unrestricted

Table 1: Constitutive Assumptions.

The specific form for the strain energy density function is derived from a Taylor expansion in the orthotropic invariants of the Green-Ste. Vénant strain tensor, **E**, and is presented below:

$$W = A_0(E_{11} + E_{22} + E_{33}) + A_1E_{12}^2 + A_2E_{13}^2 + A_3E_{23}^2 + A_4E_{11}^2 + A_5E_{22}^2 + A_6E_{33}^2 + A_7E_{11}E_{22} + A_8E_{11}E_{33} + A_9E_{22}E_{33} - \frac{A_0}{2}(I_3 - 1).$$

Here, I_3 is the third invariant of the right Cauchy-Green strain tensor ($I_3 = \det \mathbf{C}$) and the coefficients $\{A_0 \ldots A_9\}$ are orthotropic material constants. The ensuing expression for stress is

$$T_{ij} = \rho \left\{ \begin{array}{l} (A_0 + 2A_4E_{11} + A_7E_{22} + A_8E_{33})F_{j1}F_{i1} \\ +(A_0 + 2A_5E_{22} + A_7E_{11} + A_9E_{33})F_{j2}F_{i2} \\ +(A_0 + 2A_6E_{33} + A_8E_{11} + A_9E_{33})F_{j3}F_{i3} \\ + A_1E_{12}(F_{i1}F_{j2} + F_{j1}F_{i2}) \\ + A_2E_{13}(F_{i1}F_{j3} + F_{j1}F_{i3}) \\ + A_3E_{23}(F_{i2}F_{j3} + F_{j2}F_{i3}) \\ - A_0I_3\delta_{ij} \end{array} \right\}$$

$_{,j}$ above are the components of the deformation gradient tensor.

EXPERIMENTAL MODEL

Eventually, a finite element solution is sought for the present problem wherein material parameters are determined through a parameter optimization proceedure. With this solution scheme in mind, experiments were conducted to acquire the appropriate data. This includes (1) the three-dimensional, in-vivo geometry of the endo- and epicardial surfaces of the heart, (2) the associated ventricular pressures, and (3) a localized estimate of strain within a region of the myocardium. These data are acquired at two or more points during diastasis.

The first goal was accomplished by gated cardiac MR imaging on an instrumented canine subject. All imaging was conducted with a 4.7 Tesla Brüker imaging system employing a 25 cm General Electric proton imaging coil. To the best knowledge of the author, these experiments represent the first use of a 4.7 Tesla imaging system for cardiac imaging.

For the second goal, ventricular pressures were monitored during cardiac imaging by special non-magnetic transducers (Millar) coupled with noise-insensitive instrumentation. A pressure accuracy of approximately 0.5 mmHg and temporal resolution of 5 ms were achieved.

Customized instrumentation and computer algorithms were developed to assure proper synchronization of image acquisition during diastasis. Various modalities for reliably synchronizing image acquisition to diastasis were investigated. A PC-based system was developed for (a) analyzing various physiological signals for their variability and efficacy for a particular gating application, and (b) providing a selection of gating strategies for triggering the MR imaging system. Among the physiologic signals investigated were (a) EKG, (b) LVP_{max}, (c) LVP_{min}, (d) dP/dt_{max}, and (e) dP/dt_{min}. Of these, left ventricular pressure was found to provide a reliable signal in the presence of the noisy MR environment.

The third goal was accomplished by implanting several fiducial markers into the myocardium prior to imaging. These microencapsulated copper sulfate spheres are approximately 2-3 mm in diameter and appear as bright marks in the images – which contrast well with the adjacent tissue (Figure 1). The displacement of these points provide a first-order estimate of strain and will assist the numerical optimization scheme in converging upon a unique solution for the governing equations. To the best knowledge of the author, such myocardial markers have not been described elsewhere in the literature.

Figure 1: Gated cardiac image of the canine heart. This scout image revealed three coplanar markers, identified as Nos. 1, 2, and 3 (counter-clockwise, from the arrow.) [MR imaging parameters: FOV=20 cm , matrix=256x256, TE=34, TR≃500].

Following MR imaging, the animal's heart was fixed in-situ to be subsequently subject to morphometric analysis. Measurements were performed on the fixed heart to determine the distribution of fibers, and validate the position of myocardial markers and cardiac boundaries.

SUMMARY

An experimental and theoretical model for the passive biomechanical properties of the intact heart has been presented.

Constitutive equations for passive cardiac tissue, based on first principles of continuum mechanics and incorporating the structural features of the material has been described.

Results of MR imaging experiments with a canine subject have demonstrated the feasibility of imaging the intact heart and implanted markers at designated phases of diastasis, while concurrently measuring ventricular pressure as a reference.

Ultimately the experimental data will serve as input to a finite element routine, coupled with a nonlinear regression algorithm, to allow the determination of the nonlinear orthotropic material parameters inherent in the model assumptions.

It is hoped that this work will lead to yet more comprehensive models for the intact heart, the goal being to provide a functional experimental and theoretical strategy for comprehending the biomechanics of heart disease, and, ultimately, to improved clinical methods of diagnosis, management, and prevention.

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