Modeling of Fiber Orientation in the Ventricular Myocardium with MR Diffusion Imaging

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Abstract

A numerical simulation of the electrical and mechanical behavior of the heart requires appropriate anatomical models. Suitable are models that describe the macroscopic anatomy including information concerning the averaged local fiber direction. This work describes methods to create anatomical, macroscopic models using different techniques of magnetic resonance (MR) imaging, i.e. proton density and diffusion tensor imaging, with techniques of digital image processing. An example model of canine ventricles is developed and presented using three dimensional visualization.

1. Introduction

Anatomical models of the human heart are of interest in many areas of cardiology, e.g. for numerical simulation of excitation propagation and mechanical deformation and for the development and optimization of medical devices like cardiac pacemakers and defibrillators. In some cases, the models are constructed from medical images obtained from computed tomography based on X-rays (CT) and magnetic resonance (MR) tomography using strategies of digital image processing. Besides the geometry, another important consideration is the assignment of material properties, needed for accurate modeling of electro-mechanical behavior. For example, the myocardium has both anisotropic elastomechanical parameters and electrical conductivities that depend on the local fiber orientation. New imaging techniques, such as diffusion tensor imaging, provide methods to extract the cellular orientation non-destructively.

In this work an anatomical model of the canine ventricles is developed using MR data sets. Two scans with sub millimeter resolution of the same heart form the foundation of the processing: a standard MR scan describing the anatomy and a scan delivering eigenvectors and -values of the measured diffusion tensors. To construct the model, different digital image processing methods are used to filter and segment the images to define the regions of interest, including the right and left ventricle and papillary muscles. Tools have been developed to interpolate the diffusion tensor data onto the anatomical structure. The final three dimensional anatomical model of the ventricles is out putted into a set of elements and material properties that can be used for numerical simulation.

2. Methods

2.1. Overview

In the following sections the modeling of the orientation and lamination of myocytes is restricted to a macroscopic, averaged perspective onto the discrete cellular geometry. This perspective is often taken in the modeling of complex, inhomogeneous structures, e.g. continuum modeling of electrophysiology and structure mechanics, and allows a simplified treatment, especially, if the microscopic inhomogeneity of attributes can be neglected.

The strategies for the modeling the orientation and lamination of myocytes can be divided into two groups. The first group uses direct measurement of the attributes, i.e. histological studies of surfaces of tissue sections and recently developed imaging techniques. The second group uses of rule based methods, based on anatomical studies.

An example of the first strategy is diffusion tensor imaging which provides information on the macroscopic, averaged orientation of myocytes in vitro [1, 2, 3, 4] and in vivo [5, 6, 7]. The assignment of the local fiber direction is based on the assumption, that the diffusion of water molecules by Brownian motion is larger in the direction of the cells than transverse to it. In general the motion is greater along fibers than across fibers, leading to an anisotropic diffusion tensor.

The assumption that the diffusion tensor scan yields the local fiber directions was tested by comparing histological measurements of paraffin-embedded and sectioned probes of rabbit left ventricles [3, 8] and right ventricular free wall of mongrel dog [2]. Comparisons showed an RMS

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difference of 5.3° and an averaged difference of $-2.3 \pm 0.98°$ in [3] and [2], respectively.

In addition to direct measurements, different rule based strategies can be used to assign the myocyte orientation and lamination. A strategy consists of a manual assignment of the attributes by a human expert at specific points [9, 10]. A further strategy uses knowledge delivered by anatomical studies [11, 12, 13]. The knowledge can be incorporated into a computer programs for automatic assignment of attributes. In both strategies an interpolation of the orientation and lamination be used to determine the attributes over the entire myocardial volume.

2.2. Imaging of Heart

An explanted canine heart was fixed and scanned using MRI.[1] Therefore, special pulse sequences were developed for the diffusion weighting. Images of the proton density and diffusion weighted scans were made (figure 1). The acquisitions were three dimensional, and the diffusion tensor scan was performed using a reduced encoding method, reduces the required scan time by a factor of 4.

The images were stored in three dimensional data sets, consisting of 256 x 128 x 128 voxels with a size of 0.4 mm x 0.8 mm x 0.6 mm. The proton density of each voxel was coded by a float value (4 $bytes$), the diffusion tensor by its three principal axes ($3 \times 3 \times 4$ $bytes$) and its three eigenvalues (3×4 $bytes$).

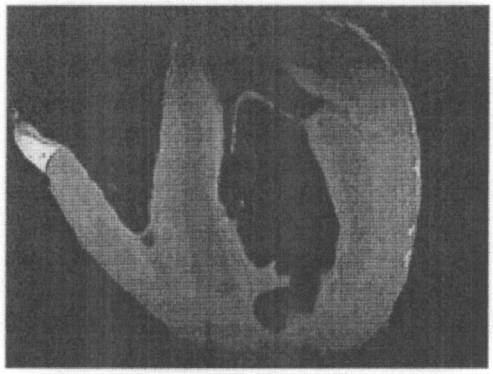
2.3. Preprocessing of Digital Images

The MR data sets were preprocessed to simplify the image segmentation and classification process. The proton density scans showed a significant decrease of signal intensity in apical and basal regions due to the sensitivity drop off near the ends of the radio frequency (RF) coil. This reduction in signal was detected and compensated using a scaling operation.

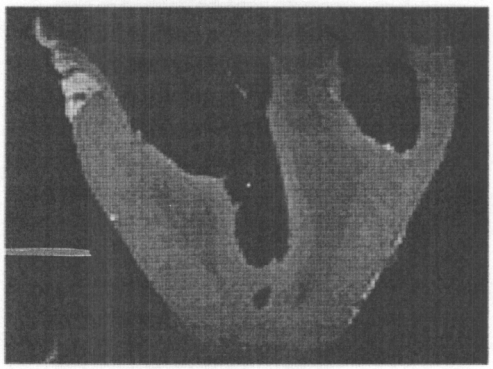
In addition, the proton density images were preprocessed by a sequence of morphological filtering to reduce measurement noise. The data format of the proton density scans was reduced to 1 $byte$.

The decrease of signal intensity in apical and basal regions was also found in the diffusion weighted images. The images show gaps of different size in the regions, which were filled by interpolation techniques taking neighboring values into account. Additional small artifacts in the diffusion weighted images were detected, erased and filled using interpolation.

[1]The imaging was done at the Center for In Vivo Microscopy, Duke University, Durham (USA).



(a)



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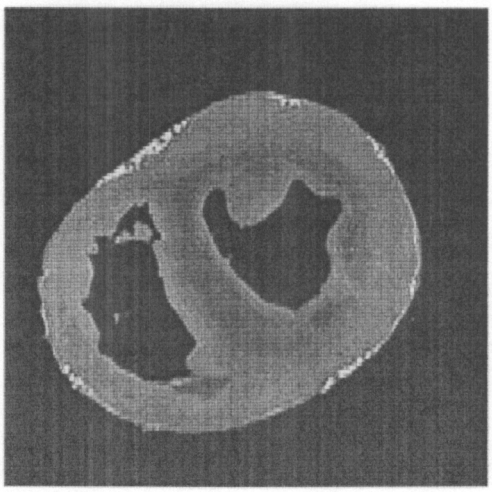


(c)

Figure 1. Slices of proton density weighted, three dimensional MR data set of an explanted canine heart: (a) frontal, (b) lateral, and (c) transversal.

2.4. Tissue Segmentation and Classification

The segmentation and classification of the three dimensional data sets were performed using different techniques of digital image processing, e.g. interactively deformable meshes, thresholding, region growing, and morphological operators [14].

The boundaries of the epicardial and endocardial myocardium as well as the septum were determined using interactively deformable triangle meshes [15]. Initial meshes were manually placed, oriented, scaled and subsequently deformed to the tissue boundaries. The boundaries served as a mask for thresholding.

Region growing on the three dimensional data sets was used to classify blood, papillary muscles, left and right ventricular myocardium. Sequences of morphological operators, i.e. median filtering as well as opening and closing, eliminated minor fail assignments.

3. Results

The eigenvector of the measured diffusion tensor with the highest eigenvalue served as a basis for the assignment of the local fiber orientation in canine ventricular myocardium. An averaging filter for orientations was applied to reduce noise and artifacts in the MR diffusion data.

The resulting data set has the same resolution and size as the tissue classified data set, i.e. 256 x 128 x 128 voxels with a size of 0.4 mm x 0.8 mm x 0.6 mm. Each voxel in the tissue data set is classified in one out of five different tissue classes. Therefore, a single byte is assigned to a voxel. Each voxel in the orientation data set includes 2 bytes, encoding two angles, ϕ, and θ, in the range of $[0 \ldots \pi]$.

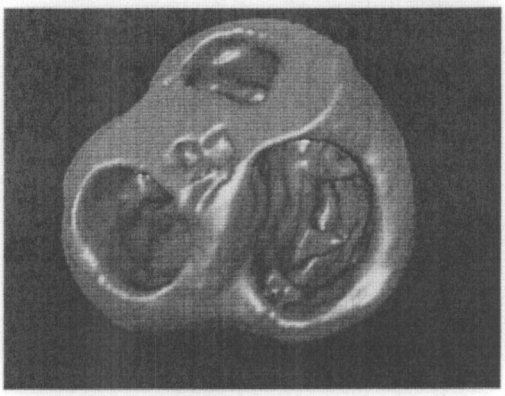
The tissue classified data set is illustrated in figure 2. An exemplary slice of the anatomical model in conjunction with the assigned cellular orientation is shown in figure 3.

4. Conclusions

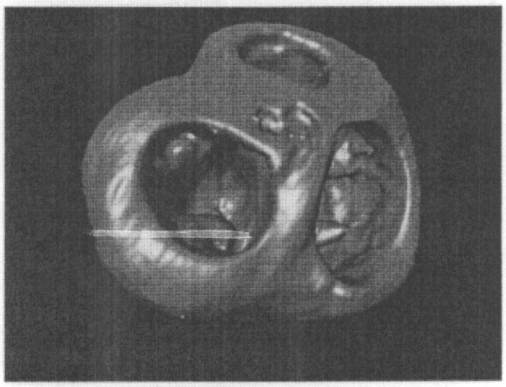
Using a series of digital image processing techniques on both proton and diffusion tensor MR data sets produced a high resolution, anatomic model of canine ventricles that is suitable for numerical simulations of the electrical and mechanical behavior of the heart. The methods can also allow for the direct, quantitative comparison of hearts for rapid phenotyping.

Future work will aim at the modeling of atrial fiber orientation and at an automation of the manual segmentation steps, which can be achieved e.g. by using of deformable models [16].

Of further interest is an acquisition of the lamination of the tissue, which is reported for ventricular myocardium [17]. The knowledge of the cellular orientation and



(a)



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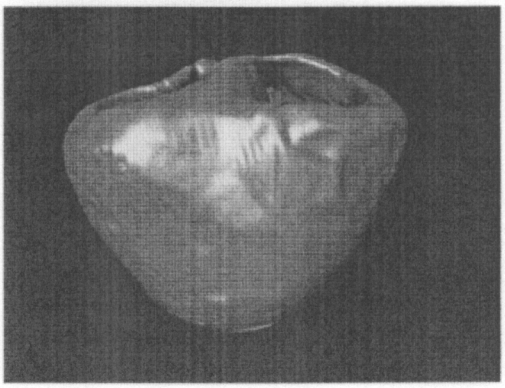

(c)

Figure 2. Anatomical model of canine heart viewed from the base of (a) the right ventricle and (b) the left ventricle as well as from (c) frontal. The ventricles and papillary muscles are segmented with interactively deformable meshes and thresholding techniques.

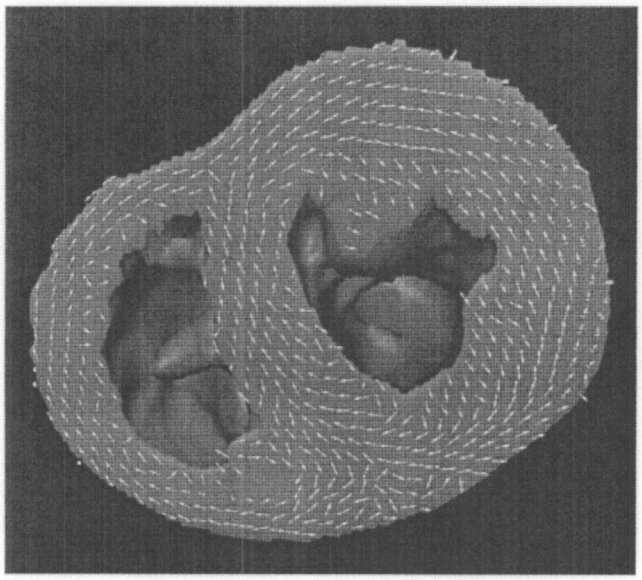

Figure 3. Anatomical model of canine heart with macroscopic orientation of myocytes in exemplary slice indicated by white arrows.

tissue lamination allows the usage of three dimensional anisotropic constitutive laws in continuum mechanics [18].

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