Waveguide Magnetic Resonance Elastography of the Heart

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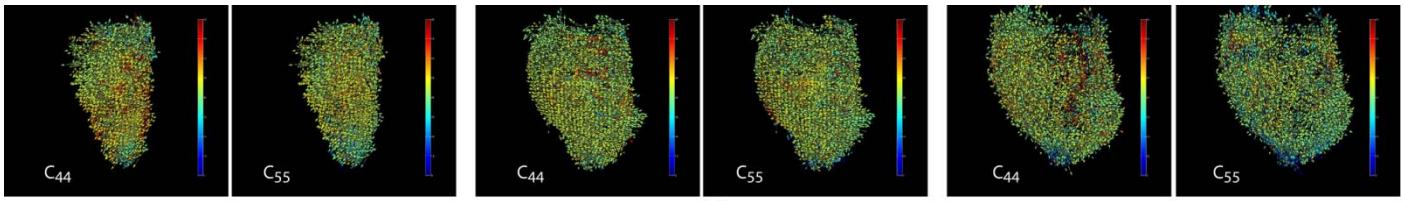
Targeted Audience: Biomedical engineers, cardiologists, radiologists, technologists, researchers and biomechanical engineers.

Introduction: Myocardial stiffness has been recognized as a central parameter of cardiac function and disease [1]. It is known that myocardial infarction (MI) alters regional stiffness, triggering left ventricular (LV) remodeling and heart failure with reduced ejection fraction (HFREF) [2]. However, *in vivo* assessment of LV stiffness relies upon invasive measurements of LV pressure and simultaneous assessment of LV volume [3,4]. The invasive nature of these measurements has severely limited the understanding of a variety of cardiac disease states which provides only global measure of stiffness. Furthermore, in case of LV myocardium undergoing remodeling, a more in depth understanding of myocardial fiber stiffness is needed for proper diagnosis and prognosis. It has been recently demonstrated that magnetic resonance elastography (MRE) [5] can be adapted to measure the shear stiffness of myocardium [6-9]. Since myocardium is anisotropic, however, the purpose of this study was to demonstrate the feasibility of using Waveguide MRE [10] to estimate the stiffness of myocardial fibers (i.e. in the subepicardial (outer), mid-myocardial and subendocardial (inner) layers).

Methods: ***Acquisition:*** In order to estimate the stiffness along the LV fibers, prior information of fiber directions are needed. Therefore, Diffusion Tensor Imaging (DTI) and MRE were performed on a formalin fixed (soaked in formalin for 4 months) ex-vivo porcine heart on a 3T-MRI Scanner (Tim-Trio, Siemens Healthcare, Erlangen, Germany) in the short axis view of the heart covering the entire ventricle. ***DTI:*** DTI was performed using a standard diffusion-weighted single-shot spin echo-based echo-planar imaging sequence. Imaging parameters included 256 diffusion encoding directions with isotropic resolution of 2x2x2mm; TE:90ms; TR:7000ms; imaging matrix:128x128; FOV:256mm; b-values:0,1000s/mm^2. ***MRE****:* MRE was performed using a standard gradient echo-based sequence. Imaging parameters included TE:21.4ms, TR:25ms; isotropic resolution:2x2x2mm; imaging matrix:128x128mm^2; FOV:256mm; excitation frequency:60Hz; 4 MRE time offsets; and a bipolar 16.67ms duration (60Hz) motion-encoding gradients (MEG) was applied separately in the x, y, and z directions to measure the in-plane and through-plane tissue motion. Positive and negative MEG amplitudes were used on alternate views and a phase-contrast reconstruction was performed to obtain images of tissue displacement. ***Analysis:*** DTI and MRE images were then masked to segment the LV myocardium. The DTI images were analyzed using FSL (FMRIB, Software Library) to obtain the principal eigenvectors and eigenvalues. The z-component of the principal eigenvectors is used to segment the individual myocardial fibers (i.e. inner, middle and outer layers). These individual fiber masks were used to track the displacements from MRE images for further stiffness analysis.

Provided with a knowledge of the position vectors of the fibers, a spatial-spectral filter was applied to the measured displacements in an attempt to identify only those waves which were traveling at particular angles to and along the fibers at every point. At this time as well, a Helmholtz decomposition was implemented which separates the total field into its longitudinal and transverse components. An Orthotropic inversion was then performed along the fibers to evaluate the complex stiffness values. By filtering along six specific directions within the local reference frame of the fibers, the equations of motion decouple allowing for each of the nine elastic coefficients to be solved for independently of one another. This approach allows for lower order anisotropic models (such as Hexagonal or Cubic, for example) to be exposed as valid by exposing redundancies in the Orthotropic coefficients.

Results: Below, we show the results of the application of our method to the three myocardial fiber structures. The first two images represent the real components of the shear stiffness C_{44} and C_{55} for the inner structure, the next two images the stiffness for the middle structure, and the last two images show the results for the outer structure. The color bars range from 0-80 kPa. As can be observed, the structures have a stiffness of around 50 kPa in the main bodies; however there is significant variation between the two coefficients indicating that these structures are, at a minimum, Orthotropic in nature.



Discussion: This study demonstrates the feasibility of determining stiffness along individual fibers in the LV myocardium. The stiffness values across the myocardial fibers appeared to be uniformly distributed as the fibers are fixed using formalin. Furthermore, we can observe the helical pattern of fiber orientations from the stiffness maps. More studies are warranted to determine the reliability of this technique and its applications for the diagnosis and prognosis of different cardiac diseases by understanding the remodeling of myocardial fibers.

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