Quantitative MRI as an indirect evaluation tool of the mechanical properties of cardiac tissues

Delphine Perie[1], Anthony Foudis[1], Gilles Beaudoin[2], Guillaume Gilbert[3], Nagib Dahdah[4], and Daniel Curnier[5]

[1]Mechanical Engineering, Ecole Polytechnique de Montreal, Montreal, Quebec, Canada, [2]Physics and Biomedical Engineering, CHUM Hopital Saint-Luc, Montreal, quebec, Canada, [3]MR Clinical Science, Philips Healthcare, Cleveland, OH, United States, [4]Cardiology, CHU Sainte-Justine, Montreal, Quebec, Canada, [5]Kinesiology, Universite de Montreal, Montreal, Quebec, Canada

INTRODUCTION

Heart failure, which is the result of a systolic and/or diastolic dysfunction, is a major health problem able to reach quasi epidemical proportions in industrialized countries and negatively impacting the health resources (more than 10 Billion $ in the US). Among individuals over 55 years old, one third will develop heart failure later in life. The estimated 5-year survival rate is 35% once heart failure is diagnosed. The early detection of heart failure is necessary, even essential, to reduce mortality. The diagnosis of heart failure is based mainly on the hemodynamic parameters, estimated by echocardiography. The long-term objective is to develop a more sensitive and non-invasive technique allowing early detection and guiding follow-up of the mechanical property changes of the cardiac tissue with cardiomyopathy, and consequently tailoring patients' therapeutic and preventive strategies. The hypotheses are 1) the mechanical properties of cardiac tissues are biomarkers of cardiomyopathy, and 2) the mechanical properties of cardiac tissue can be measured indirectly using quantitative magnetic resonance imaging (qMRI). It is established that MR parameters obtained by qMRI are linked to the mechanical properties and to the biochemical composition of soft tissues [1-10] and muscles [11]. From those studies, we hypothesized that a relationship exists between the mechanical properties and the MR parameters of cardiac tissue. The specific aim of this study was to develop an indirect evaluation tool of the mechanical properties of cardiac tissue using qMRI.

METHODS

Porcine hearts (n=12) were obtained from a local slaughterhouse within 2 hours of death. Isolated hearts were placed in a chamber filled with a tyrode saline solution, and submitted to a qMRI acquisition followed by a uniaxial tensile test. For the qMRI acquisition, the chamber was placed within the head coil of a 3T whole body system (Philips Achieva X-Series). A single slice, 5mm thick, was taken centered within the left ventricle wall. The relaxation times were determined using a multiple IR-TSE sequence for T1, and, respectively, SE and GE sequences with multiple echo times for T2 and T2*. The diffusion tensor was extracted from a SE-EPI diffusion-weighted sequence, with 15 non-collinear diffusion encoding directions. The MT images were obtained using a GE sequence with and without a magnetization transfer saturation pulse. T1, T2, T2*, apparent diffusion coefficient (ADC) and fractional anisotropy (FA) were extracted from the signal intensity by non-linear regressions to their respective signal expressions. For the mechanical test, the heart tissue from the left ventricle was cut into samples of 5cm*1cm*1cm (L*W*H), which were submitted to a uniaxial tensile test until failure with a constant speed of 1mm/s (micro-mechanical testing system Mach-1, Biomomentum Inc.). The Young's modulus E was calculated from the slope of the force-displacement curve in the linear part. The relationships between mechanical properties and MR parameters was performed using multiple linear regressions (SigmaPlot, Systat Software,Inc.) as a first approximation and kriging as a refined approach. For each combination of trends, covariances, distances, nugget effects and normalizations within the kriging model, the RMS error between the estimated E from the MRI parameters and the E measured from the mechanical tests was evaluated. The optimal kriging parameters were identified from the smallest RMS errors for 8 of the 12 hearts analyzed, and the optimal model was used to predict the E for the remaining 4 of the 12 hearts.

RESULTS

The maps obtained for the relaxation times T1 and T2 and for the diffusion parameters FA and ADC were mostly homogeneous. Mean values of 92±12kPa, 1457±20ms, 121±6ms, 51±6ms, 72±5%, $11.7\pm0.2\times10^{-4} m^2/s$, 67±4% were found for E, T1, T2, T2*, MTR, ADC and FA respectively. Multiple linear regressions exist between E, T1, FA and ADC (R^2=0.42, p=0.02), with T1 being the most important parameter in the equation. The optimal kriging parameters in the estimation of E from T1, FA and ADC were found to be a quadratic trend, a logarithmic covariance, a global normalization, a Norm-1 distance and no nugget effect. This optimal model was able to predict the Young's modulus from the MR parameters with a RMS error of 4.5kPa.

DISCUSSION

The significant relationship found between the Young's modulus E, as determined by a constant deformation tensile test until rupture, and the MRI parameters T1, FA and ADC, as determined by quantitative MRI, is the basis for the development of an indirect tool for the in vivo evaluation of the mechanical properties of cardiac tissues. The hypothesis that a relationship exists between mechanical properties and MR parameters of cardiac muscles is confirmed and Kriging is a powerful tool that optimizes these relationships. Kriging is known to be the best linear unbiased estimator. It keeps more information on the measured value than the multiple linear regression, pass by the measured value, and the equation is differentiable at every point.

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