MR Elastography of the Human Heart: Noninvasive Assessment of Myocardial Elasticity Changes by Shear Wave Amplitude Variations

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Many cardiovascular diseases and disorders are associated with hemodynamic dysfunction. The heart's ability to contract and pump blood through the vascular system primarily depends on the elasticity of the myocardium. This article introduces a magnetic resonance elastography (MRE) technique that allows noninvasive and time-resolved measurement of changes in myocardial elasticity over the cardiac cycle. To this end, low-frequency shear vibrations of 24.3 Hz were induced in the human heart via the anterior chest wall. An electrocardiograph (ECG)-triggered, steady-state MRE sequence was used to capture shear oscillations with a frame rate of eight images per vibration cycle. The time evolution of 2D-shear wave fields was observed in two imaging planes through the short axis of the heart in six healthy volunteers. Correlation analysis revealed that wave amplitudes were modulated in synchrony to the heartbeat with up to 2.45 ± 0.18 higher amplitudes during diastole than during systole (interindividual mean ± SD). The reduction of wave amplitudes started at 75 ± 9 ms prior to changes in left ventricular diameter occurring at the beginning of systole. Analysis of this wave amplitude alteration using a linear elastic constitutive model revealed a maximum change in the myocardial wall stiffness of a factor of 37.7 ± 10.6 during the cardiac cycle. Magn Reson Med 61:668–677, 2009. © 2008 Wiley-Liss, Inc.

Key words: cardiac MR elastography; shear waves; myocardium; heart mechanics; shear modulus

Heart failure is a progressive disorder in which damage to the heart causes weakening of the cardiovascular system. It has emerged as a growing health problem that is likely to reach epidemic proportions in developed countries. Among individuals aged 55 years, almost one in three will develop heart failure during their remaining lifespan. Heart failure continues to be a fatal disease, with a survival rate below 35% 5 years after the first diagnosis (1,2). Early detection of heart failure is an important prerequisite for reducing the mortality rate associated with cardiovascular impairment (3). Assessment of ventricular pressure dynamics has been found to be crucial for the diagnosis of heart failure and the prediction of cardiovascular health risks (4). While systolic function is described by the ability of the myocardium to actively contract and thus to generate pressure, diastolic heart function is characterized by myocardial relaxation. Systolic function can be easily assessed by calculating the ejection fraction using echocardiography or magnetic resonance imaging (MRI). It has been observed that in over 50% of patients with heart failure, diastolic cardiac function is limited, while systolic function is preserved (5). Diastolic dysfunction can be the result of a large variety of diseases ranging from hypertension, diabetes, and ischemia to infiltrative diseases such as myocarditis, amyloidosis, or restrictive cardiomyopathy (6,7). Presently, it is difficult to detect dysfunction of diastolic ventricular filling noninvasively. Echocardiography and MRI can accurately determine morphology, volume, and volume fractions of the heart together with their spatial and time derivatives, strain, and velocity (8–13). MRI also demonstrates alterations in tissue composition (edema, necrosis, scar) and perfusion (7). However, the most important functional characteristic of the heart—the alteration of ventricular pressure between systole and diastole—is not amenable to assessment without techniques capable of measuring forces in response to regional myocardial pressure (14). Shear-wave-based elastography allows noninvasive palpation of tissue deep inside the body in order to assess the tissue's shear modulus, which characterizes its shear deformation resistance to harmonically oscillating shear forces (15,16). Recently, Rump et al. (17,18) demonstrated the feasibility of observing externally induced shear vibrations in the living human heart using MRI elastography (MRE). This work was based on fractional encoding of shear oscillations in the frequency range of 50 Hz using balanced steady-state free precession (bSSFP) MRE. Although the propagation of shear waves through the interventricular septum was visualized in a time-resolved fashion, wave propagation speed (and thus myocardial elasticity) was difficult to determine. The deduction of elastic moduli from shear waves by inversion algorithms, as traditionally done in MRE, is often compromised by noise and unknown boundary conditions. These effects are mitigated by high wave numbers. However, high wave numbers require high driving frequencies, which in turn result in strongly damped wave amplitudes due to the viscous properties of soft biological tissues. For instance, a 50-Hz vibration would result in myocardial oscillations with wavelengths of about 10 cm assuming an isotropic shear elasticity of 30 kPa (19). Such large wavelengths are not suited for determining regional myocardial stiffness by inversion-based MRE.

To address this deficiency, a technique is introduced here that measures wave amplitude variations (WAV) resulting

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Grant sponsor: German Research Foundation; Grant number: Sa/901-3.

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Received 1 June 2007; revised 23 July 2008; accepted 8 October 2008.
DOI 10.1002/mrm.21878
Published online 18 December 2008 in Wiley InterScience (www.interscience.wiley.com).