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Elasticity-based determination of isovolumetric phases in the human heart

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Abstract

Background/Motivation: To directly determine isovolumetric cardiac time intervals by magnetic resonance elastography (MRE) using the magnitude of the complex signal for deducing morphological information combined with the phase of the complex signal for tension-relaxation measurements.

Methods: Thirty-five healthy volunteers and 11 patients with relaxation abnormalities were subjected to transthoracic wave stimulation using vibrations of approximately 25 Hz. A *k*-space-segmented, ECG-gated gradient-recalled echo steady-state sequence with a 500-Hz bipolar motion-encoding gradient was used for acquiring a series of 360 complex images of a short-axis view of the heart at a frame rate of less than 5.2 ms. Magnitude images were employed for measuring the cross-sectional area of the left ventricle, while phase images were used for analyzing the amplitudes of the externally induced waves. The delay between the decrease in amplitude and onset of ventricular contraction was determined in all subjects and assigned to the time of isovolumetric tension. Conversely, the delay between the increase in wave amplitude and ventricular dilatation was used for measuring the time of isovolumetric elasticity relaxation.

Results: Wave amplitudes decreased during systole and increased during diastole. The variation in wave amplitude occurred ahead of morphological changes. In healthy volunteers the time of isovolumetric elasticity relaxation was 75 ± 31 ms, which is significantly shorter than the time of isovolumetric tension of 136 ± 36 ms ($P < 0.01$). In patients with relaxation abnormalities (mild diastolic dysfunction, $n = 11$) isovolumetric elasticity relaxation was significantly prolonged, with 133 ± 57 ms ($P < 0.01$), whereas isovolumetric tension time was in the range of healthy controls (161 ± 45 ms; $P = 0.053$).

Conclusion: The complex MRE signal conveys complementary information on cardiac morphology and elasticity, which can be combined for directly measuring isovolumetric tension and elasticity relaxation in the human heart.

Background

Times of isovolumetric contraction and relaxation and the resulting indices (e.g., Tei index) are frequently used to describe overall cardiac function [1]. The standard method for measuring cardiac time intervals is echocardiography, which exploits the opening and closing times of aortic and mitral valves [2]. Isovolumetric cardiac phases are characterized by changes in myocardial elasticity, while ventricular volume remains constant. Thus, the most direct determination of isovolumetric times combines measurement of both ventricular volume and myocardial elasticity. Cardiac volumes can be measured using ultrasound or magnetic resonance (MR) imaging. Myocardial elasticity can be measured noninvasively by elastography using either ultrasound or MR imaging and various mechanical stimuli such as time-harmonic vibrations [3-6], focused ultrasound pulses [7,8] or transient intrinsic cardiac waves [9]. In general, dynamic elastography relies on the evaluation of shear waves for recovering mechanical tissue parameters from amplitudes, wave lengths, or propagation speed. Classically, the wave equation is solved for elastic moduli using for example image-based algebraic Helmholtz inversion [10] or profile-based phase-gradient methods. Inversion techniques are well applicable in large organs such as the liver, brain, or larger groups of skeletal muscle. However, the complex anatomy of the heart requires consideration of finite geometries as proposed by Kolipaka et al. [11] and

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