In vivo myocardial MR elastography: Observation of stiffness-related shear-wave amplitude variations

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Introduction: Many cardiovascular diseases and disorders cause hemodynamic dysfunction. The ability of the heart to pump blood through the vascular system strongly relies on variations in myocardial elasticity] [1-3]. Magnetic resonance elastography (MRE) [4] is a technique to measure elastic parameters of living soft tissue that is based on phase-sensitive MRI and externally induced shear waves. Here it is proposed that in vivo time-resolved cardiac MRE enables noninvasive assessment of myocardial pressure changes. Therefore, an experiment was developed that identifies variations in myocardial stiffness during the cardiac cycle by measuring changes in externally induced shear wave amplitudes.

Problem: External shear wave excitation of the heart requires the use of low vibration frequencies in order to compensate for the mechanical shielding and the viscosity of the wave-transmitting tissue. Therefore, shear wavelengths in the myocardium are too large for reconstructing elastic parameters by wave inversion.

Objective: Time-resolved detection and analysis of external oscillations in the myocardium is proposed to derive an estimate of the evolution of elasticity during the cardiac cycle. Therefore, a cine gradient echo (GRE-)MRE sequence was developed for capturing shear vibrations in left ventricular myocardium with high temporal resolution (5.8 ms). For data analysis a sliding-window Fourier transform was applied to obtain wave amplitudes in all spatial directions.

Methods: Six healthy male volunteers underwent in vivo cardiac MRE on a 1.5 T scanner (Siemens Sonata, Erlangen, Germany). An ECG-gated, nonbalanced (GRE) steady-state imaging sequence with a flip angle $\alpha = 15°$ and radiofrequency (RF) spoiling was used for acquiring phase-contrast (PC) wave images. Motion sensitization was achieved by a 2-ms long single-cycle trapezoidal motion encoding gradient (MEG) between phase-encoding and read-out. One line of *k*-space was acquired per ECG-trigger. Twofold GRAPPA acceleration combined with an interpolation of *k*-space data from 64 phase-encoded lines to a 128x128 matrix (FOV: 320 to 340 mm, slice thickness 5 mm) resulted in a total of 34 segments for a full scan. 360 wave images were acquired in 1.86 s with a repetition time (*TR*) of 5.16 ms. A respiration gate of 2.5 s was left after each segment. Total scan time was approximately 2½ minutes. Our standard protocol consisted of one reference experiment without vibration by sensitization along slice selection, three MRE experiments with consecutive sensitization of all components of **u** and one conventional cine SSFP-MRI sequence for comparison of wave data to intrinsic heart motions. This protocol was applied twice in each volunteer using an apical and a medial image slice position in the short-axis view.

A remote oscillator was used to vibrate the subject's chest as sketched in figure 1. The 2.5-3.0 m long transducer rod was mounted in the center of the oscillator membrane while the proximal end was kept in place in the center of the volunteer's chest solely by its own weight (≈ 1.5 kg). The vibration was synchronized to the MRI sequence with one sinusoidal burst 41.28 ms in length (24.3 Hz) after every eighth *TR*. The vibration amplitude was approximately 1.5 mm on the chest surface.

Results: Figure 2a demonstrates phase signal oscillations induced by the external vibrator acquired with through-plane motion sensitization in one volunteer. $\phi(t)$ was spatially averaged within two *ROIs* of similar size, one located in subcutaneous tissue of the upper chest and the other corresponding to the systolic circumference of the left ventricle (LV). The non-vibration reference signal is superposed on the oscillations. The time resolution is equal to the *TR* of 5.16 ms. Quantification of the wave deflection is demonstrated in figure 3. *Uj* was derived from $\dot{\phi}(t)$ using a signal correlation with a time-harmonic function of frequency equal to the vibration frequency (24.3 Hz) yielding a time resolution of 41.28 ms (=8*TR)*. The largest deflection component in the chest is along the phase-encoding direction. Wave polarization changes in the heart but there are large individual variations. The magnitude wave amplitude variation reveals a change in myocardial shear elasticity by a factor of about 37.7 ± 9.6 (interindividual mean ± SD).

Discussion and Conclusion:

We for the first time demonstrate time-resolved in vivo measurement of myocardial stiffness variations during the heart cycle. The excellent time resolution of the cine GRE-MR phase signal enables measurement of wave amplitude variations over the cardiac cycle. The measured wave amplitude variation was found to be significant in each of the six volunteers ($P < 0.05$). The resulting change in myocardial elasticity is the first directly measured elasticity variation over the cardiac cycle. In conclusion, amplitude-based in vivo heart MRE might be a valuable modality to detect cardiac dysfunction. In the future, low frequency vibrations might be used in cardiac PC-MRI for evaluating the rigidity of the heart during the cardiac cycle.

References:

[1] Sinkus R et al, ISMRM 2006, 77 ;

[2] Rump J et al, ISMRM 2006, 149

[3] Kolipaka A et al, ISMRM 2006, 796

[4] Muthupillai R et al, Science 1995; 269: 1854-1857

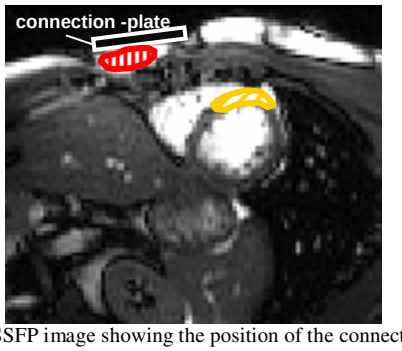

Fig.1: Short-axis SSFP image showing the position of the connection plate of the actuator and the two regions of interest in the chest wall (red) and left ventricular myocardium (yellow).

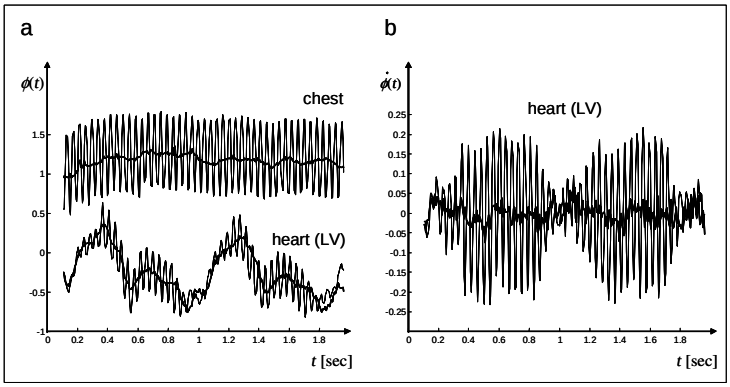

Fig. 2a: Phase signal oscillations due to external vibrations seen in the heart and subcutaneous tissue of the upper chest of one volunteer ($\zeta = 0.9$). **b:** Time derivative of $\phi(t)$ of the heart shown in (a).

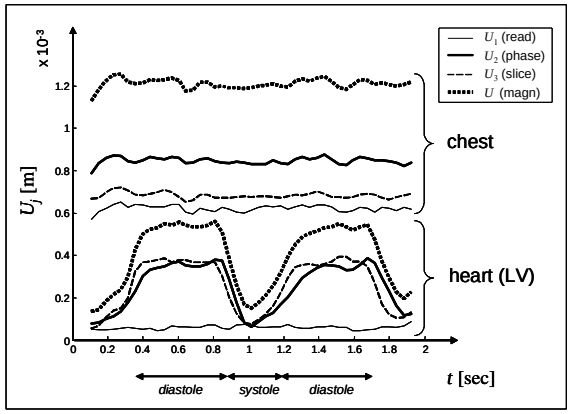

Fig.3: Wave components in chest and heart corresponding to fig.2. The U_3-deflections were derived by the $\phi(t)$-signals shown in figure 2a.