In vivo MR elastography of the human heart: Initial results

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Introduction: Myocardial elasticity (heart stiffness) could play a key role in detecting early states of heart diseases and predicting the development of heart insufficiency. The stiffness of living myocardium can potentially ascertained by MR elastography which combines excellent 3D-MRI contrast with high sensitivity to externally induced vibrations [1].

Problem: Despite the success of MRE during the past several years it has remained a relatively slow technique compared to the fast flow or motion quantification in cardiac MRI. The increased time consumption in MRE is due to the need of applying slow mechanical vibration cycles (< 100 Hz) for achieving sufficiently large shear-wave amplitudes in highly viscous tissue. In classical MRE, such external vibrations are synchronized to the motion sensitization of the sequence causing large echo times which in turn prevent an adequate temporal resolution for heart-MRE.

Objective: Here, we propose a new method based on balanced SSFP-MRE [2] in combination with an alternating image reconstruction scheme [3] for measuring in vivo 50-Hz shear-vibrations in the human heart. We suggest aligning the image plane within the interventricular septum (IVS) and capturing out-of-plane deflections with a certain time resolution so that the shear wave speed can be determined by the phase propagation of the waves. Elastic parameters are then deducible considering the wave propagation through a viscoelastic plate [4]. First applications on three healthy volunteers indicate the presence of anisotropy similarly to the shear elasticity of skeletal muscles [5].

Methods: Shear waves were introduced into the heart using a carbon fiber rod connected to a custom-built acoustic actuator. The transducer was attached onto the solar plexus and vibrated in head-feet direction by an excitation frequency of 50 Hz. MR experiments were run on a 1.5T Siemens Sonata scanner. For image acquisition a balanced SSFP-MRE sequence was used as displayed in fig. 1. Two images were acquired (A and B) using an interleaved image reconstruction method so that the motion sensitization of A and B was synchronized to the vibration of the myocardium as shown in figure 1. The phase contrast images of A and B were subtracted from each other to eliminate static phase shifts and to increase the wave signal. The frequency of the motion encoding gradient (MEG) was 500 Hz yielding a *TR* of approximately 5 ms. The start of the image acquisition was triggered by the *R*-peak of an ECG-signal (fig. 2). The phase-encoding of the *k*-space was segmented into 16 times 8 lines, whereby the sequence was run 4 times during one heart cycle. This allowed 4 phase-difference images to be acquired at the end of 16 heart beats during which the volunteers maintained breath hold. The experiments were repeated 20 times for monitoring the evolution of waves by shifting the trigger to the wave generator with increments of 4*TR*/20. The image slice (thickness: 5mm) was aligned to be in plane with the IVS (fig. 2). For data evaluation 2D space-time (*x-t*) plots were interpolated from the 3D data by selecting profiles along different directions (fig. 3). An interactive edge detection routine directly yielded the desired shear wave speed from the slopes of the *x-t*-waves. The experiments were applied to 3 healthy, male volunteers with an average age of 34y.

Results and Discussion: The IVS was observable during the entire cardiac cycle in a single 2D image slice (fig. 2b). The major amplitude of the detected vibrations was introduced from the apex into the IVS. However, minor amplitudes were also observed running along the arrows ② and ③ shown in fig. 3a. The measured wave speeds corresponding to the given profiles are summarized in table 1. Shear waves along ② and ③ were resolvable in only two of three volunteers. These two volunteers displayed reproducible wave speeds in two follow-up studies at two different days. In the 3rd volunteer, low-amplitude waves were overlapped by the dominant fast running wave. The application of the model of an incompressible, vibrating plate yielded for the shear moduli 16 ± 8 kPa for the fast running mode and 2.25 ± 1.8 kPa along the directions ② and ③. With regard to elastographic studies on skeletal muscle we assign both elastic moduli to the shear stiffness parallel and perpendicular to fiber direction in the myocardium.

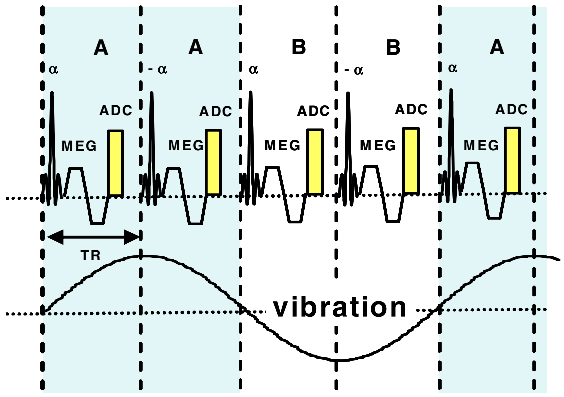

Fig. 1: The balanced SSFP-MRE sequence used for in vivo MR elastography on the human heart. The motion encoding gradient (MEG) was applied with the same phase for the images A and B along the direction of slice-selection. The external harmonic vibration (48.5 Hz to 51 Hz) was synchronized to 4*TR*.

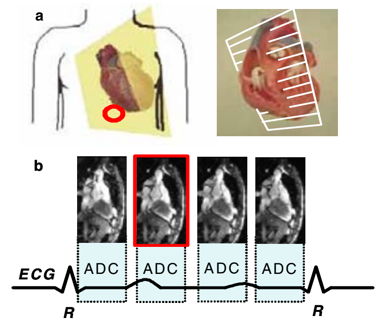

Fig. 2a: Positioning of the image plane in the human body. The red circle demarcates the approximate position of the transducer rod on the body surface. **b:** Anatomical SSFP-magnitude images acquired during different time intervals of the cardiac cycle. Wave images corresponding to the second phase (red boundary) are shown in fig.3.

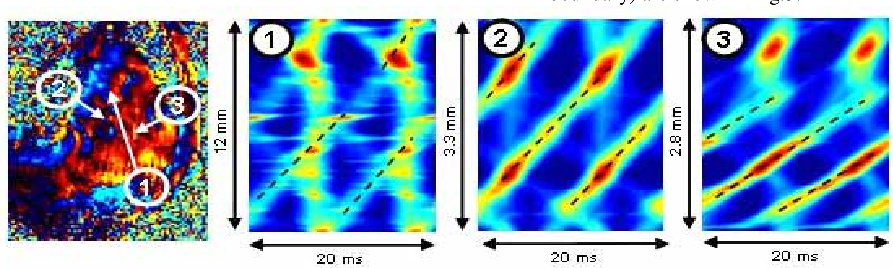

Fig. 3: Phase-difference wave image of the human interventricular septum after 50Hz shear wave excitation. **(1)-(3):** The wave propagation speed (the slope of the dashed lines) was quantified along the profiles ①, ② and ③ plotted against a temporal axis. The vertical stripes indicate the presence of a rapidly moving compression wave. The wave propagation is shown as an example of our data for volunteer 2, cardiac phase 2 (fig. 2b).

volunteer	①	② and ③
1	3.4 ± 1.5	1.6 ± 0.4
2	4.5 ± 1.0	1.1 ± 0.5
3	4.0 ± 1.3	-

Tab. 1: Shear wave velocities measured in the interventricular septum along the directions which are demarcated in fig. 3a. The values of the wave speeds are averaged over all phases of the cardiac cycle (1-4 in fig. 2b) since no significant change of the wave propagation speed was found.

Conclusion: Our study represents the first successful in vivo MR elastography experiments on the human heart. A new sequence design in SSFP-MRE enabled us to combine a low-frequency shear-wave excitation of the interventricular septum with fast motion sensitization and short MR-repetition times. First results on three volunteers indicate the feasibility of the method to measure anisotropic elastic parameters which are related to the fiber structure of the myocardium.

References:

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