Feasibility of a new actuator type for magnetic resonance elastography based on transient air pressure impulses

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Target audience: physicists and physicians interested in elastography.

Background: MR elastography (MRE) [1] is an emerging clinical imaging modality for the diagnosis of many diseases such as hepatic fibrosis which are associated with altered viscoelastic tissue properties [2]. Despite recent success of MRE in clinical studies there is still need for improving MRE drivers with regard to high vibration amplitudes particularly in obese patients, patient comfort as well as reproducibility, consistency and optimization of driver handling in the clinic [3].

Purpose: To develop and demonstrate a new type of MRE actuators based on transient air pressure impulses.

Methods: The new actuator is sketched in Fig.1. It was driven by medical compressed air supplied inside the scanner room of a 1.5-T MRI system (Siemens, Erlangen). Maximum air pressure was 5 bar which was reduced to 0.5 bar prior to being fed into a fast switching electromagnetic two-way valve (Festo, Esslingen, Germany). The valve was controlled by a function generator which was triggered by the MRI scanner. To demonstrate the system for brain MRE, a bellow cylinder was placed under the shoulders of a volunteer. The actuator was connected by a tube of 1 cm diameter to the air pressure valve. During activation, the valve was repeatedly opened to supply short pressure bursts to the actuator with a periodicity of the desired MRE frequency. Therewith vibrations were generated in the thorax which propagated as shear waves from the thoracic spine into the head. To minimize damping, very low frequencies of 15, 20 and 25 Hz were applied. To extract the first harmonic, 16 time points over one vibration cycle were captured in 15 contiguous axial slices through the brain using spin-echo EPI [4]. Further imaging parameters: TR: 2300 ms; TE: 99 ms; FoV: 176×192 mm^2; resolution 2×2×2 mm^3. Elasticity reconstruction was based on multifrequency dual elasto visco (MDEV) inversion [4] providing two parameters, the magnitude |G*| and the phase angle φ of the complex shear modulus G*.

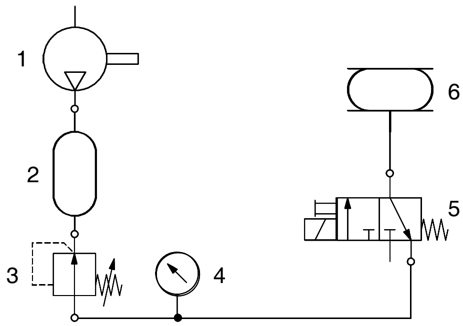

Fig. 1: Setup of the actuator system. (1) compresor, (2) holding tank, (3) pressure reducing valve, (4) manometer, (5) two way magnetic valve, (6) bellow cylinder.

Results: Fig 2 shows unsmoothed curl components for each driving frequency and motion-encoding direction before MDEV-inversion. Shear waves penetrate the brain uniformly. Fig.3 shows high resolution maps of |G*| for 15 contiguous slices of the brain of a healthy volunteer averaged over all vibration frequencies. |G*| is higher for white matter regions (1200-1500 Pa) and lower for gray matter (600-800 Pa) consistent with previous work [4,5].

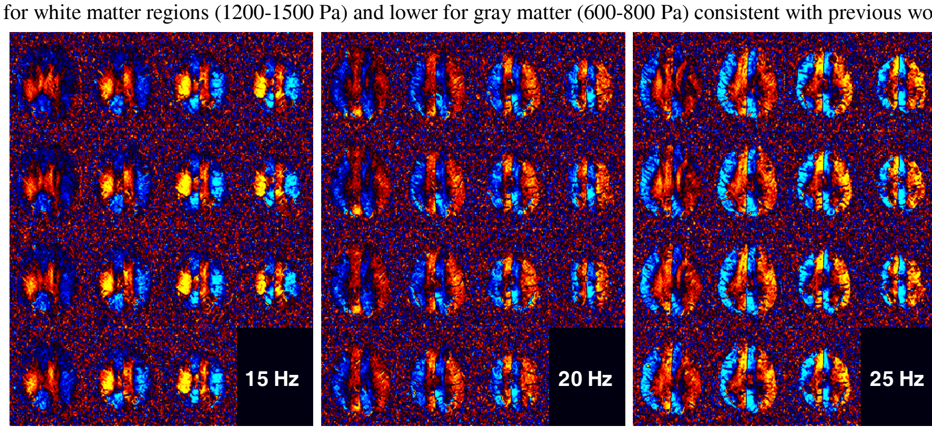

Fig. 2: In-plane curl component ($\partial u_2/\partial x_1$-$\partial u_2/\partial x_1$) for driving frequencies of 10, 25, and 25 Hz (unsmoothed).

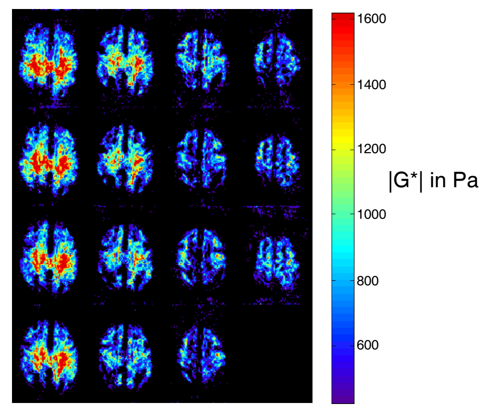

Fig. 3: |G*| calculated by MDEV inversion.

Discussion: The new actuator concept allowed the quantitative determination of viscoelastic parameters of human brain with remote actuation. No image distortions were observed despite valve operation inside the scanner room. Preliminary results for viscoelastic parameters of the brain are in good agreement with data acquired by the same sequence and inversion method but using a conventional head cradle actuator and employing a higher dynamic range [3,4]. The following main differences to conventional approaches of vibration generation in MRE exist: (i) Transient bursts of acoustic energy are generated independently of the desired frequency. (ii) Therewith acoustic force and waveform control are separated from each other, i.e. for MRE only waveform control (switching the valve) has to be retained. (iii) Given an air pressure supply of 5 bar of which only 0.5 bar were used, the proposed actuator features adequate power reserves and flexibility for applications to obese patients, MR-systems with limited gradient power or remote actuation. (iv) The applied range of low frequency vibrations warrant low damping of the shear waves on their way from the source into the tissue of interest. Nevertheless, as seen in Fig.3, high-resolution elastograms were obtained, which encourages further investigations of MRE at this very low dynamic range. At the current state of the development our feasibility study is limited by the lacking systematic analysis of vibration amplitudes in different organs and at higher frequencies. Further optimization of the prototypical actuator system is addressed in ongoing work.

Conclusion: The presented actuator based on transient air pressure impulses is a feasible way of generating vibrations for in vivo MRE. The produced thoracic vibrations in the frequency range between 15 and 25 Hz were strong enough to be detected in the human brain, thus enabling us to perform cerebral MRE by remote actuation. The system was tested robust, powerful, and easy to handle and might therefore support further dissemination of MRE in the clinic.

References: [1] Muthupillai R, et al. Magnetic resonance elastography by direct visualization of propagating acoustic strain waves. Science. 1995, 269:1854-7. [2] Glaser KJ, et al. Review of MR elastography applications and recent developments. J Magn Reson Imaging. 2012; doi: 10.1002/jmri.23555. [3] Uffmann K, et al. Actuation Systems for MR Elastography. IEEE Eng Med Biol Mag. 2008; 27:28-34. [4] Guo J, et al. Towards an elastographic atlas of brain anatomy. PLoS One. 2013;8:e71807. [5] Braun J, et al. High-resolution mechanical imaging of the human brain by three-dimensional multifrequency magnetic resonance elastography at 7T. Neuroimage. 2014; 90:308-14.