

In Vivo Wideband Multifrequency MR Elastography of the Human Brain and Liver

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Purpose: To demonstrate the feasibility of in vivo wideband MR elastography (wMRE) using continuous, time-harmonic shear vibrations in the frequency range of 10–50 Hz.

Theory and Methods: The method was tested in a gel phantom with marked mechanical loss. The brains and livers of eight volunteers were scanned by wMRE using multislice, single-shot MRE with optimized fractional encoding and synchronization of sequence acquisition to vibration. Multifrequency three-dimensional inversion was used to reconstruct compound maps of magnitude $|G^*|$ and phase φ of the complex shear modulus. A new phase estimation, φ^* , was developed to avoid systematic bias due to noise.

Results: In the phantom, G^* -dispersion measured by wMRE agreed well with oscillatory shear rheometry. $|G^*|$ and φ^* measured at vibrations of 10–25 Hz, 25–35 Hz, and 40–50 Hz were 0.62 ± 0.08 , 1.56 ± 0.16 , 2.18 ± 0.20 kPa and 0.09 ± 0.17 , 0.39 ± 0.16 , 0.20 ± 0.13 rad in brain and 0.89 ± 0.11 , 1.67 ± 0.20 , 2.27 ± 0.35 kPa and 0.15 ± 0.10 , 0.24 ± 0.05 , 0.26 ± 0.05 rad in liver. Elastograms including all frequencies showed the best resolution of anatomical detail with $|G^*| = 1.38 \pm 0.12$ kPa, $\varphi^* = 0.24 \pm 0.10$ rad (brain) and $|G^*| = 1.79 \pm 0.23$ kPa, $\varphi^* = 0.24 \pm 0.05$ rad (liver).

Conclusion: wMRE reveals highly dispersive G^* properties of the brain and liver, and our results suggest that the influence of large-scale structures such as fluid-filled vessels and sulci on the MRE-measured parameters increases at low vibration frequencies. **Magn Reson Med 000:000–000, 2015.** © 2015 Wiley Periodicals, Inc.

Key words: wideband MRE; multifrequency dual elasto-visco MDEV inversion; three-dimensional; low-frequency harmonic tissue stimulation; liver; brain

INTRODUCTION

MR elastography (MRE) can image the mechanical properties of in vivo soft tissues (1,2). Recent developments in MRE aimed at making the measurement of shear wave fields (3–5) more efficient for high-resolution shear modulus mapping (6–10) and at sensitizing MRE to pressure and compression-related parameters (11–14).

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MRE research is motivated by the high sensitivity of elasticity, viscosity, and poroelastic properties to structural variations of biological tissues at multiple scales (15). Ideally, one would recover shear modulus, shear viscosity, and tissue pressure with high spatial resolution from one set of MRE data obtained at a single vibration frequency for probing the mechanical interactions between cellular, extracellular, and vascular components in the tissue. However, the hierarchy of structure elements in biological tissues is associated with a hierarchy of dynamic responses, which in turn gives rise to a pronounced frequency dispersion of parameters measured by MRE. For example, at low frequencies, the timescale of fluid motion is in the order of the exogenous stimulation in elastography, causing the tissue's mechanical response to be dominated by multiphasic poroelastic effects rather than monophasic viscoelastic properties (14,16–18).

Wideband multifrequency MRE (wMRE) with a range of vibration frequencies larger than one octave has so far only been applied to tissue samples in preclinical systems, where higher frequencies (> 200 Hz) are exploited, thus precluding a direct comparison with clinical MRE, which typically uses frequencies in the range of 50 Hz (19–21).

In this study, we investigate in vivo wMRE in humans by studying dispersion of complex-valued shear modulus G^* of the liver and brain using exogenous stimulation in a frequency range of 10 to 50 Hz. A frequency below 25 Hz has not been explored for this purpose before. We will further test if this low-frequency range (<25 Hz) is suitable for generating high-resolution maps of magnitude $|G^*|$ and phase angle φ of the shear modulus. Given the fact that shear waves at low frequencies have lower energy and are less damped than high-frequency vibrations (22), MRE in a range below 25 Hz could overcome damping problems or uncomfortable stimulation of sensitive body parts such as the head.

To this end, an ultrafast MRE sequence is developed based on fractional motion encoding and synchronization of image acquisition with the harmonic vibration phase. The method avoids transient mechanical effects, thus allowing us to encode arbitrarily long cycles of exogenous harmonic motion by short gradients as quantified by a fractional-encoding master equation derived for rectangular gradients in the next section.

The method is tested in a phantom made of ultrasound gel, which was previously shown to simulate dispersive tissue properties (23). In the current study, we characterized this phantom by shear oscillatory rheometry. These experiments led us to a revised calculation of phase angle φ to account for systematic bias due to noise and