Compliance weighted imaging in MR elastography

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Background: The shear elastic behavior of living soft tissue can sensitively indicate pathologic tissue changes. In MR elastography (MRE) [1] shear waves are used for testing elastic parameters of human organs. Traditional MRE is based on the inversion of shear wave images for calculating elasticity images (elastograms).

Problem: Wave-inversion often suffers from noise and unknown boundary conditions which degrade the spatial resolution of elastograms [2]. In general, the quality of stiffness contrast in MRE is related to the lengths of the shear waves and their amplitude-to-noise-ratio. Since short wavelengths improve the resolution in elastograms high amplitudes at high driving frequencies are experimentally desired. However, the higher the frequency of shear waves the stronger is their damping which is a result of viscous properties of biological tissues. Thus, the spatial resolution of mechanical information in MRE has been limited by the inherent viscosity of tissue under investigation.

Our approach: Compliance weighted imaging (CWI) is introduced that uses mechanical low-frequency excitation in the order of 10 Hz. As a result, viscous damping is negligible which allows the approximation of a constant strain energy averaged over one oscillation period. Using first-derivative data-processing yields a new contrast that is scaled by the inverse stiffness (compliance) of the material. The spatial resolution in CWI-MRE is comparable to that of standard MR images which considerably improves the detail resolution in MRE. CWI-MRE of the brain allows mapping the anatomical structure of the brain based on its mechanical properties. The method can for example further be used to examine noninvasively the consistency of tumors prior to intervention.

Methods: The theoretical concept of CWI-MRE is based on a locally constant expectation value of the shear strain-energy density over one vibration period:

$$\langle E \rangle = \mu \int_0^\tau W dt \cdot \qquad (1)$$

μ is the shear modulus and τ is the duration of an oscillation period. W denotes the squared strain tensor which is simplified to

$$W = \frac{1}{2}\left(\left[\frac{\partial w}{\partial x}\right]^2 + \left[\frac{\partial w}{\partial y}\right]^2 \right) \qquad (2)$$

by considering the through-plane component $w(x,y)$ of the wave field and assuming in-plane components to be zero. In our current setup W is measured using a single-shot spin-echo EPI sequence with motion encoding gradient in variable direction. 10-Hz-vibrations are introduced into the brain by a head-rocker actuator. The phase of the vibration relative to the motion encoding gradient is varied between 20 to 40 times for time integration. The acquired phase images are subjected to spatial gradients according to eq.2 followed by temporal averaging.

Results and Discussion: Figure 1 demonstrates CWI-MRE in comparison to inversion-based (traditional) MRE. A gel phantom with three inclusions was used. The stiffness of the inclusions decreased from 1 to 3 (first image). 50-Hz vibrations were used which ensured the absence of viscous damping within the region-of-interest (second image). However the large wavelength at 50 Hz prevents the resolution of stiffness-details in the elastogram (third image). In contrast, CWI-MRE is able to display the correct ratios of relative elasticities of the inclusions and the matrix (forth image). Figure 2 displays in vivo CWI-MRE of the brain. Our current actuator mainly induced vibrations in the head-feet direction and thus significant elastic strain only occurred in this component. The resulting CWI-contrast reveals the mechanical heterogeneity of the brain which corresponds to the anatomical structure: Basal ganglia, thalamus, genu and splenium of the corpus calosum are well distinguishable from the internal capsule. Cerebrospinal fluid (CF) appears dark due to MRI- and wave-signal obliteration caused by intravoxel phase dispersion (IVP) [3] and zero shear elasticity in liquids, respectively. Figure 3 shows the application of CWI-MRE to a patient with renal carcinoma and cerebral metastases. Bright T2w-signal of the peripheral edema is eliminated in CWI due to similar tissue compliance properties of the surrounding healthy brain matter. In contrast, the bright CWI-contrast on the edges of the metastasis strongly indicates a much softer mechanical tissue behavior than that of surrounding white matter. The CWI signal blank in the center of the metastasis suggests that the oscillatory shear stress is only supported by nonevanescent waves near boundaries. It is important to mention that the wave deflection in the patient study was about half of that of the volunteer experiments. Therefore, IVP is smaller in figure 3 causing the CF inside sulci to appear bright.

Conclusion: CWI-MRE allows the acquisition of high resolved images weighted by elastic information. Unlike in wave-inversion based MRE, ultra-low driving frequencies can be used which considerably improve the acceptance of brain MRE by patients.

References: [1] Muthupillai et al, Science 1995; 269: 1854-57 [2] Sack et al, NMR Biomed., 2007, DOI: 10.1002/nbm.1189 [3] Glaser et al, MRM 2006, 55-67

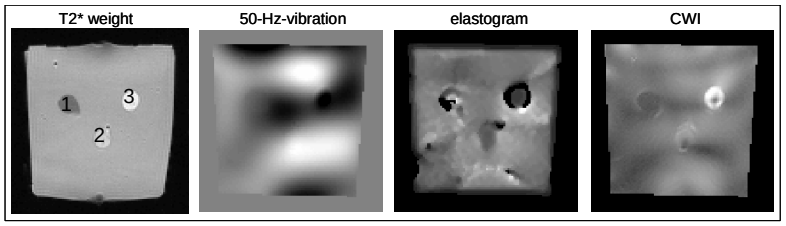

Fig.1: Comparison of inversion-based MRE and CWI-MRE.

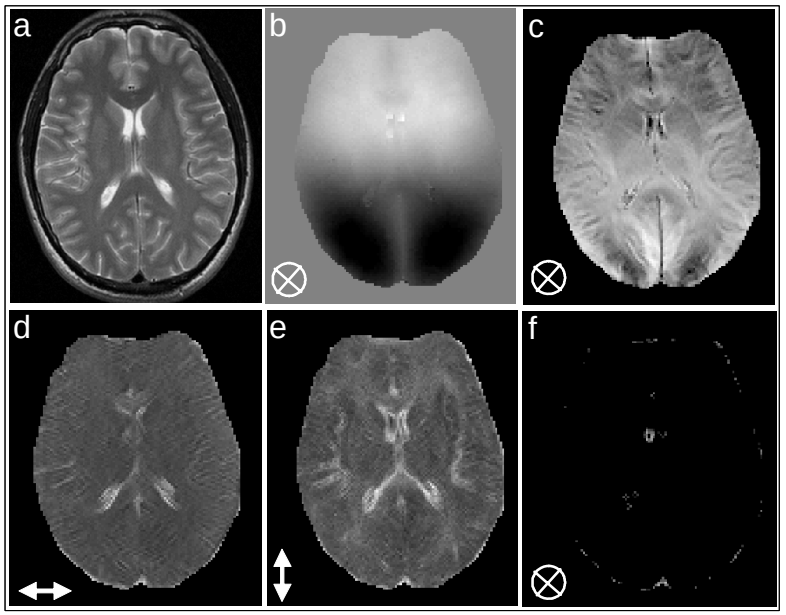

Fig.2: CWI-MRE on healthy human brain. The specific direction of the motion-encoding gradient used is given in the lower left corner of b-f. **a:** T2w-image for comparison. **b:** 10-Hz-wave image (maximum deflection ≈50 μm) and **c:** corresponding CWI-contrast. **d/e:** CWI-contrast acquired by in-plane motion encoding showing a constant gradient of rigid motion rather than elastic strain. **f:** CWI-experiment as shown in (c) but without vibrations. Images c-f are displayed with identical grayscale window.

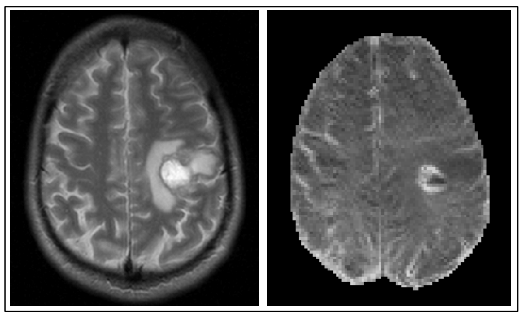

Fig. 3: CWI on a patient with cerebral metastasis and perifocal edema. Left-hand side: T2w-image contrast. Right: CWI contrast with high intensity inside the metastasis which reveals an almost liquid tissue structure. The dark centre of the lesion is due to wave obliteration inside a liquid medium.