Cerebral MR elastography for measuring poroelastic properties of the brain

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Background: Cerebrospinal fluid (CSF) filtration and microvascular flow within neuronal tissue is a key point for understanding various neurological disorders. Soft biological tissue has both fluid and solid phases which determine its mechanical behavior. Based on linear biphasic theory, the solid tissue matrix may be regarded as a fluid-saturated sponge with the fluid phase consisting of vasculature and interstitium [1]. MR poroelastography (MRPE) [2] is based on 3D tensor MR elastography (MRE) [3] and has been demonstrated on phantoms to be capable of measuring fluid pressure-field related parameter maps.
Problem: MRPE requires acquisition of 3D wave fields with high spatio-temporal resolution which easily extends measurement times beyond 30 min with continuous head stimulation. Furthermore, blood pulsation and CSF filtration influence the recovered mechanical parameters [4]. Finally, for fast and robust data processing, direct inversion-based recovery of poroelastic parameters is desirable.
Objective: An MRPE-method based on single-shot multi-slice echo-planar imaging is introduced. A full time-resolved 3D-wave field consisting of 30 slices is acquired within 3 min. Gated data acquisition by pulse trigger is demonstrated. Two complex mechanical moduli, λ and μ, are recovered using a direct 3D-harmonic field inversion. While μ corresponds to the shear modulus measured in previous studies of cerebral MRE, a new parameter, λ_p, is related to dilatational deformation occurring in biphasic soft tissue and is thus determined by microscopic fluid filtration.

Theory: According to Biot's law, the displacement field **u** of a matrix built from an incompressible material and soaked with an incompressible fluid is governed by two coupled balance equations (assuming local homogeneity):

$$\rho\ddot{\mathbf{u}} = (\lambda - p + \mu)\nabla(\nabla\cdot\mathbf{u}) + \mu\Delta\mathbf{u} \qquad (1)$$

$$\nabla\cdot\dot{\mathbf{u}} - \nabla\cdot(\kappa\nabla p) + \chi p = 0 \qquad (2)$$

(1) is Navier's equation where λ and μ represent Lamé's constants while p is the fluid pressure. (2) governs the fluid in the interstitium which is coupled by the divergence of $\dot{\mathbf{u}}$ to its linear momentum given by (1). χ and κ are coefficients of fluid filtration and percolation. The latter is regarded as being negligible on the time scale of dynamic MRPE. This assumption combined with harmonic motion reduces the fluid pressure to $p = -i\omega/\chi\,\nabla\cdot\mathbf{U}$ with **U** being the temporal Fourier transform of **u**. In the following we combine λ and p to λ_p, whose imaginary part yields a phase shift related to the porous pressure field. μ and λ_p are calculated by inversion of

$$\begin{bmatrix} \partial(\nabla\cdot\mathbf{U})/\partial x + \Delta U_1 & \partial(\nabla\cdot\mathbf{U})/\partial x \\ \partial(\nabla\cdot\mathbf{U})/\partial y + \Delta U_2 & \partial(\nabla\cdot\mathbf{U})/\partial y \\ \partial(\nabla\cdot\mathbf{U})/\partial z + \Delta U_3 & \partial(\nabla\cdot\mathbf{U})/\partial z \end{bmatrix} \begin{bmatrix} \mu \\ \lambda_p \end{bmatrix} = -\rho\omega^2\mathbf{U} \qquad (3)$$

Methods: Three healthy volunteers (2 males, mean age 26 years, SD 2 years) were examined by cerebral 3D tensor MRE. Experiments were run on a standard 1.5T clinical MRI scanner (Siemens, Erlangen, Germany). A head-cradle extended-piston driver was used for 25 Hz and 50 Hz harmonic head stimulation. A single-shot spin-echo EPI sequence was used for acquiring three Cartesian components of the wave field in 30 adjacent transversal slices and four time steps over the vibration period. Further sequence parameters: 2x2x2 mm^3 isotropic image resolution, 2 averages, motion encoding gradient: 60 Hz, 3 cycles with trapezoidal shape and first gradient moment nulling. For pulse-wave gated acquisition, a pulse oximeter trigger was attached to the finger of the volunteer. Vibration frequency was 25 Hz. Five slices, three wave components and four dynamics were consecutively acquired in increments of 100 ms relative to the pulse wave.

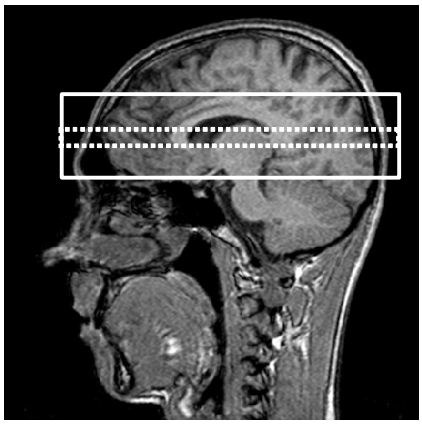

Fig. 1

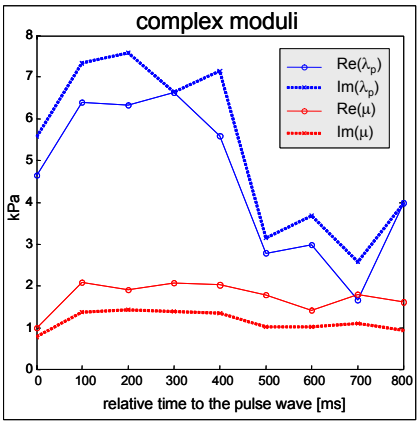

Fig. 2

parameter X	X @ 25 Hz in kPa	X @ 50 Hz in kPa	max(X[t])/ min(X[t]) @ 25 Hz
Re(λ_p)	3.05±0.87	6.32±2.15	3.61±0.70
Im(λ_p)	3.33±0.68	6.37±1.84	3.03±0.13
Re(μ)	1.10±0.23	2.08±0.19	1.57±0.46
Im(μ)	0.67±0.20	1.24±0.24	1.68±0.40

Table: Interindividual mean values and standard deviations from poroelasticity inversion of brain MRE.

Fig.1: Slice positioning for full 30-slice 3D MRE (not pulse-gated, solid line) and 5-slice reduced 3D MRE for time resolved pulse-gated poroelasticity imaging (dashed line)

Fig.2: Variation of complex moduli over the blood pulse wave in the brain of one volunteer. While the complex shear modulus appears fairly constant with time, the pressure-related λ_p presents a distinct variation upon brain pulsation.

Results and Discussion: The shear modulus values derived from 3D tensor MRE (s. table) are consistent with data acquired by 2D MRE at 25 and 50 Hz [5]. λ_p is a new parameter in cerebral MRE related to the dilatational component of the wave field. Regarding brain tissue as poro-viscoelastic material, λ_p suggests that the solid tissue matrix undergoes significant volumetric changes over a vibration period. As a result $|\nabla\cdot\mathbf{U}| > 0$, which yields the first Lamé parameter being much smaller than expected for monophasic incompressible materials. The observed low λ_p values indicate that the major portion of fluid motion imposed by tissue compression in the applied dynamic range occurs on small length scales below the voxel size. This fluid motion is apparently influenced by the blood pulse wave propagating through the vascular system (Fig.2) of the brain. An increased fluid pressure inside micro capillaries seems to reduce λ_p – which might either be due to an increased filtration of fluids between microvessels and interstitium or an increased blood motion in enlarged capillaries. Regardless of the underlying mechanism we believe that poroelasticity-based MRE reveals important physiological properties of brain tissue and might provide sensitive diagnostic markers for a variety of neurological disorders.

Literature:
[1] Leiderman at al. Phys Med Biol 2006;51(24):6291-6313. [2] Perrinez et.al. IEEE Trans Med Imaging 2010;29(3):746-755. [3] Muthupillai and Ehman. Nature Med 1996;2(5):601-603. [4] Pattison et.al. Proc 19th Annual Meeting ISMRM; 2010: p. 3404. [5] Wuerfel et al. Neuroimage 2010;49(3):2520-2525.