Three dimensional three parameter direct inversion MR elastography of incompressible transverse isotropic media: Application to in vivo soleus muscle

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Target audience: Physicians and scientists interested in elastography of in vivo muscle.

Purpose: MR elastography (MRE) (1), of anisotropic elastic materials such as skeletal muscle requires adequate models for the inversion of the time harmonic wave equation. Here we introduce a curl-operator based model for reconstruction of three elasticity parameters, μ_{12}, μ_{13} and E_3 which fully represent the shear elastic coefficients of the incompressible elasticity tensor of a transverse isotropic (TI) material. We demonstrate this new direct inversion approach to anisotropic materials by in vivo MRE of lower leg muscles in healthy volunteers.

Methods: Ten healthy volunteers were investigated at 1.5 T scanner (Siemens, Magnetom Sonata) by multifrequency MRE (MMRE) with four harmonic frequencies (30, 40, 50 and 60 Hz) induced into the lower leg by a cylindrical transducer placed underneath the ankle. Full 3D wave fields were recorded by single-shot EPI-MRE in 30 axial slices with cubic voxels of 2.5 mm edge size. Postprocessing: After unwrapping based on the gradient method (2) and Fourier-transformation, the obtained spatial derivative components at drive frequency ω/2π were used for calculating the rotational field $\mathbf{q} = \nabla \times \mathbf{u}$ which was further solved for the shear moduli μ_{12} (plane of isotropy), μ_{13} (plane of symmetry) and the Young's modulus E_3 by inversion of the curl-based time-harmonic wave equation:

$$-\rho\omega\mathbf{q} = \mu_{12}\Delta\mathbf{q} + (\mu_{13}-\mu_{12})\left[\frac{\partial^2\mathbf{q}}{\partial z^2} + \begin{pmatrix} \frac{\partial^3 u_3}{\partial y\partial x^2}+\frac{\partial^3 u_3}{\partial y^3} \\ -\frac{\partial^3 u_3}{\partial x^3}-\frac{\partial^3 u_3}{\partial x\partial y^2} \\ 0\end{pmatrix}\right] + (E_3-3\mu_{13})\begin{pmatrix}\frac{\partial^3 u_3}{\partial y\partial z^2}\\ -\frac{\partial^3 u_3}{\partial x\partial z^2}\\ 0\end{pmatrix}.$$

We note similarity to (3), however, the third term with factor $E_3 - 3\mu_{13}$ is not given in (3) since the authors made the assumption that C_{3333}, the axial component of the elasticity tensor along the principal axis of a TI-material (z = x_3), is related to μ_{13}. Without this assumption, three independent parameters of elasticity are obtained consistent to other elastography studies of incompressible TI materials (4,5).

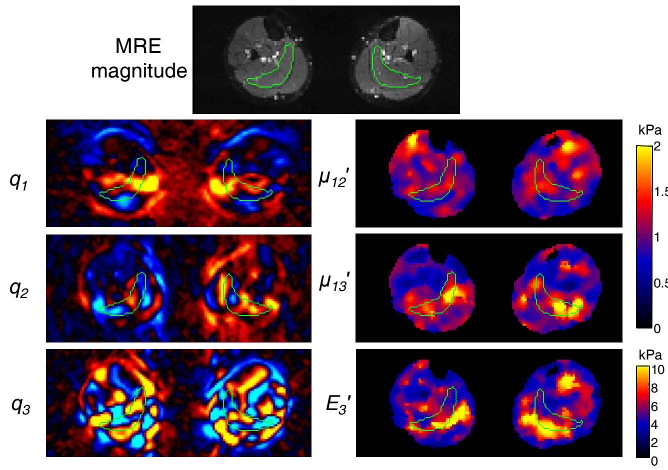

Fig.1: Magnitude of the MRE signal (gray), three curl components of the wave fields at 50 Hz vibration frequency and reconstructed μ'_{12}, μ'_{13} and E'_3 parameter maps in a central slice of one subject. The soleus region is outlined by green lines.

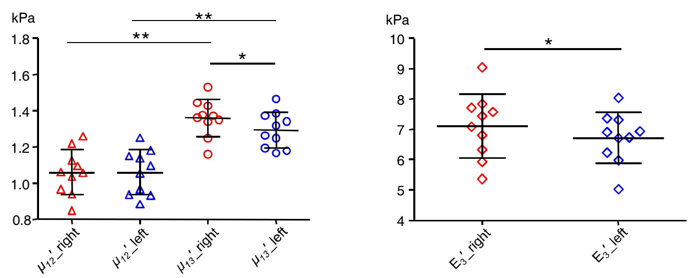

Fig.2: Spatially averaged elastic parameters μ'_{12}, μ'_{13} and E'_3 in the soleus of the left and right leg of 10 healthy volunteers, mean values and standard deviations. **P < 0.005, *P<0.05

Results: **Fig.1** shows MRE magnitude image, components of **q** at 50 Hz, real-part shear moduli μ'_{12} and μ'_{13} and Young's modulus E'_3 in one slice of one volunteer. μ'_{12}, μ'_{13} and E'_3 were analyzed for the soleus of left and right leg separately (**Fig.2**) revealing that μ'_{13} and E'_3 are higher in the right leg (1.4±0.1, 7.1±1.1 kPa) than in the left leg (1.3±0.1, 6.7±0.8 kPa, P <0.05). The shear stiffness is higher parallel to the fibers than perpendicular (μ'_{13}_right=1.4±0.1 kPa vs. μ'_{12}_right=1.1±0.1 kPa, P < 0.005; μ'_{13}_left=1.3±0.1 kPa vs. μ'_{12}_left=1.1±0.1 kPa, P < 0.005). Considering the imaginary part of MRE parameters reveals a difference between legs only in the loss-Young's modulus (E''_3_right=6.3±0.9 kPa vs. E''_3_left=5.9±0.7 kPa, P < 0.05). Consistently to the storage properties, μ''_{13} is always higher than μ''_{12} (right leg: 0.9±0.1 kPa vs. 0.4±0.1 kPa, P < 0.005; left leg: 0.9±0.1 kPa vs. 0.4±0.1 kPa, P < 0.005).

Discussion: Shear wave propagation in incompressible TI materials is governed by two eigenmodes, the so called fast transverse (FT) and slow transverse (ST) mode. While the ST-mode emanates in elliptical wave fronts with axes determined by the two shear moduli μ_{12} and μ_{13}, the FT-mode can involve more elaborate waveforms including caustics (backwards running waves) due to the involvement of a third elasticity parameter such as the Young's modulus E_3. Therefore, a complete MRE analysis of anisotropic shear wave propagation in TI-materials requires consideration of μ_{12}, μ_{13} and E_3 which – to the best of our knowledge - is proposed for the first time in this study. It is an intriguing result of current study that elasticity parameters associated with the fiber axis (μ_{13}) are higher in the right leg compared to the left leg. Since all volunteers were right-leg dominated these parameters are perhaps more sensitive to functional properties of the soleus than μ_{12}. Our study is limited in that we assumed a match of elasticity coordinate system with the imaging frame. This limitation may be overcome by using additional measures of the tissue fibers such as DTI for the determination of the local frame of the elasticity tensor in each voxel (3,6).

Conclusion: This is the first 3D three-parameter anisotropic inversion study of MRE in skeletal muscle. The elasticity values μ_{12}, μ_{13} and E_3 obtained for soleus muscle fully describe the anisotropic shear wave propagation in TI-materials.

Literature: (1) Muthupillai et al. Science 1995;269(5232):1854-1857. (2) Papazoglou et al. Physics in medicine and biology 2009;54(7):2229-2241. (3) Qin et al. J Magn Reson Imaging 2013;37(1):217-226. (4) Papazoglou et al. Magn Reson Med 2006;56(3):489-497. (5) Rouze et al. J Biomech 2013;46(16):2761-2768. (6) Romano et al. Magn Reson Med 2012;68(5):1410-1422.