Group-velocity inversion in MR elastography on skeletal muscles

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Introduction: The anisotropy of the elastic constants of living muscle might indicate a variety of muscle dysfunctions at an early state of the disease [1]. MR elastography (MRE) allows to monitor the full vector-field of a harmonic displacement which in turn provides information about anisotropic elastic parameters of the investigated tissue [2]. Here, a strategy is introduced for deducing two independent shear moduli from 2D wave images in MR elastography based on group velocity of bulk shear waves. The approach is based on fast balanced SSFP-MRE experiments and an automatic determination of direction-dependent wave velocities. The new method is demonstrated on an agarose phantom and applied to the biceps brachii of 5 healthy volunteers for measuring the shear moduli parallel and perpendicular to the muscle fibers.

Theory: In anisotropic elastic media the shear wave velocity generally depends on the direction of wave propagation. Thus, shear wave images can display different wave numbers k even in homogeneous elastic materials. This phenomenon is described by a vector of group velocity derived from the scalar phase velocity c and wave front normal $\vec{n}$ (with $\vec{n}=\vec{k}/|\vec{k}|$) by

$$\vec{v} = \partial c / \partial \vec{n} \qquad (1)$$

For this reason, in elastography of anisotropic elastic materials, wave numbers need to be determined dependent on the wave propagation direction. This can be achieved using a point source for wave excitation and measuring the wave speed along profiles $\vec{r}$ rotated around φ in the image plane. The obtained group velocity $\vec{v}(\varphi)$ can be analyzed using eq.1 combined with the slow-transverse phase velocity that is given in k-space for incompressible, hexagonal materials [3] by

$$\rho c^2 = \mu_{12}\left(n_1^2 + n_2^2\right) + \mu_{13} n_3^2 \qquad (2)$$

yielding an expression $\vec{v}(\theta)$, that is dependent on the direction of the wave normal (fig.1). To simulate the experiments $\vec{v}(\theta)$ is mapped onto $\vec{v}(\varphi)$ by

$$\vec{v}(\varphi) = \vec{v}(\varphi + \Delta) \text{ with } \cos\Delta = \left\{1 + \frac{\left(\mu_{12}-\mu_{13}\right)^2 n_3^2 \left(n_1^2+n_2^2\right)}{\left[\mu_{12}\left(n_1^2+n_2^2\right)+\mu_{13}n_3^2\right]^2}\right\}^{-1/2} \qquad (3)$$

ρ is the material density and μ_{12} and μ_{13} denote the shear moduli perpendicular and parallel to the muscle fiber direction, respectively. Thus, these parameters are the only constitutive constants which determine the group velocity by the proposed inversion.

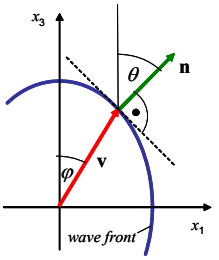

Fig. 1) Sketch of a sample wave front due to a point source located at the origin in an anisotropic medium. The two angles φ and θ are associated with the group velocity and the wave normal, respectively.

Methods: MR experiments were performed on a 1.5 T scanner (Siemens Sonata, Germany). Shear vibrations were introduced to the phantom at 205 Hz using an electromechanical actuator. For in vivo experiments an electromechanical rocker unit was attached to the distal tendon of the biceps of 5 healthy male volunteers (averaged age 34) vibrating at 126.3 Hz. Vibration direction was out-of-plane, parallel to the direction of the motion encoding gradients. For image acquisition a modified b-SSFP [4] sequence incorporating oscillating motion encoding gradients in slice select-direction was used. Data processing of the phase–difference wave images is demonstrated in fig.2. Simulations of the resulting –curves are shown in fig.3.

Results: The shear elasticities μ_{12} and μ_{13} agarose and human biceps of 5 volunteers are summarized in table 1. It is visible that the median shear modulus along the muscle fibers in human biceps is about 5 times larger than perpendicular.

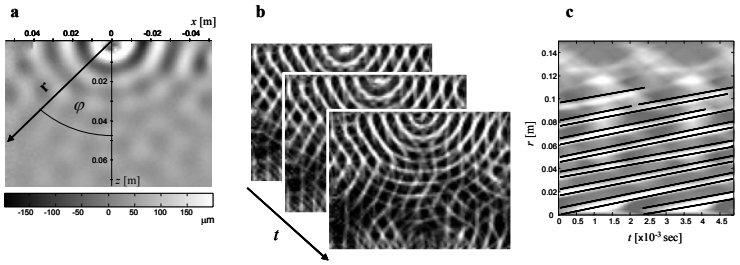

Fig. 2) Demonstration of the automatic group velocity determination on agarose:
1. 3D-Interpolation of $\vec{r}$ (fig.2a) from time resolved wave images which have been subjected to an phase-contrast enhancement (fig.2b).
2. Automatic detection of wave slopes shown by the r-t-images (fig.2c) using the Canny method of Matlab (The MathWorks, Inc., Natick, MA, USA).

	agarose	1	2	3	4	5	1-5
μ_{12}	9.49 (0.98)	5.48 (1.10)	5.07 (1.32)	5.51 (1.75)	5.50 (1.20)	8.18 (2.60)	5.50 (1.10)
μ_{13}	8.72 (0.94)	31.21 (2.64)	24.99 (2.96)	23.66 (3.67)	16.11 (2.07)	29.21 (4.96)	24.99 (5.13)
μ_{13}/μ_{12}	0.94 (0.20)	6.03 (1.69)	5.46 (2.01)	5.02 (2.26)	3.17 (1.07)	4.19 (1.94)	5.02 (0.98)

Table 1: Anisotropic shear moduli [kPa] in agarose and human biceps (1-5).

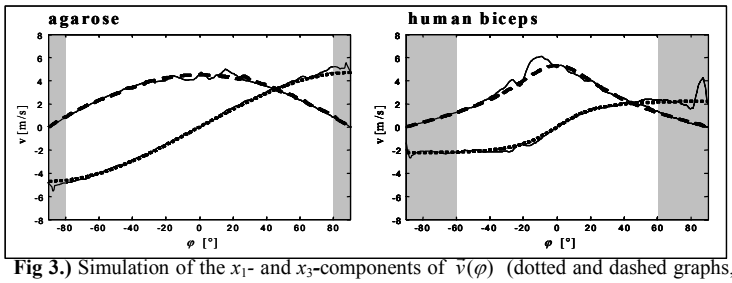

Fig 3.) Simulation of the x_1- and x_3-components of $\vec{v}(\varphi)$ (dotted and dashed graphs, respectively) for agarose and the biceps of volunteer #1. A fit was performed with considering solely the white area of φ for a least-square minimization wile varying μ_{12} and μ_{13} in eq.3.

Discussion and Conclusion: It was demonstrated that group velocity inversion is feasible for in vivo determination of anisotropic shear moduli. The proposed method is applicable to all MR elastography wave images, which show an out-of-plane deflection of the wave field emanating from a focal point-source. Only then, the slow-transverse wave mode (eq.2) is prevalent in wave images. This requirement is well achievable in MRE on skeletal muscles by exciting waves via tendon [5]. The results indicate a good interindividual reproducibility of muscle anisotropy. More detailed examinations are necessary to assess the dependency of the elastic anisotropy on mechanical workload and to use these results for diagnosing muscle dysfunctions in the clinic.

References:

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