Elucidation of in vivo anisotropic elasticities by MR elastography: Application to skeletal muscle

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Introduction The determination of mechanical properties is of principal interest in medicine and biomechanics [1]. Due to its ability to selectively measure polarized tissue vibrations in any desired direction, MR elastography is particularly useful for the determination of anisotropic properties of in vivo tissue. The patterns of such polarized shear vibrations (see **fig. a**) reflect the elastic properties of the material [2] including all the information about the anisotropy of the material. This opens the perspective to determine anisotropic elatic coefficients from a single 2D displacement image. The purpose of this work is to provide a method for the evaluation of wave patterns and their direct conversion into elastic moduli.

Theory The eigenfrequencies ω_i of small vibrations in a linear, homogeneous elastic solid are given by the solutions of the secular equation

$$\left|\sum_{k,l=1}^{3} C_{jklm} k_k k_l - \rho\omega^2 \delta_{jm}\right| = 0, \qquad (1)$$

where C_{jklm} is the elastic tensor, k_l are the Cartesian components of the wave vector, ρ is the density of the material and δ_{jm} denotes the Kronecker delta. In general, three different modes exist corresponding to each direction of wave polarisation. Two of them are quasi-transverse modes (slow transverse: ST and fast transverse: FT) and one is quasi-longitudinal (L). The slowness vector $\mathbf{s}=\mathbf{k}/\omega(\mathbf{k})$ defines surfaces, which can be evaluated to obtain information about the anisotropy of elasticity. A transversely isotropic setting is a natural choice for modelling the elastic properties of muscle tissue [1]. In this case the elastic tensor comprises five independent moduli. Incompressibility reduces their number to three. The corresponding engineering quantities are the Young's modulus and the shear modulus along the fibres Y_L and μ_L, respectively, and the shear modulus perpendicular to the fibres μ_T, which is related to the transverse Young's modulus by $Y_T=3\mu_T$.

Methods The slowness curve of the ST mode was fitted to a squared elliptic equation (see **fig. b**). Moreover, finite difference simulations were performed (**fig. c**) using a transversely isotropic planar stress scenario to establish two thresholds. Experimental data (**fig. a**) were acquired on a 1.5 T Siemens Magentom Vision scanner using a modified gradient echo imaging sequence. For mechanical excitation 7 cycles of 200 Hz oscillations were applied and motion encoding was achieved by bipolar gradients applied in x-direction.

Fig. a) Shear wave patterns in a human biceps as observed in MRE experiments (right) with anatomical MR image for comparison (left). The actuation of the biceps was focally applied to the tendon (triangle) by a rocker unit vibrating in x-direction at 200 Hz. Physical coordinates were assigned to the scanner system with x:l→r, y: a→p and y: h→f. The z-axis is aligned parallel to the muscle fibres. (right) Direction of propagation is top to bottom.

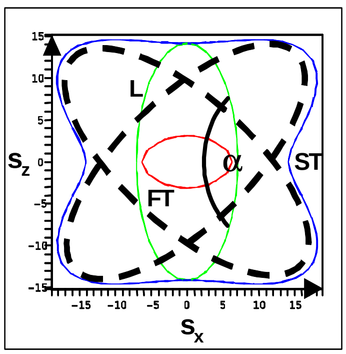

Fig. b) Cut through the slowness surface at k_y=0 for the three elementary modes FT, ST, and L emerging from eq. (1). In the elliptic approximation the ST mode is approximated by two tilted ellipses (dashed lines). The angle between the experimentally observed wave fronts is found to be represented by

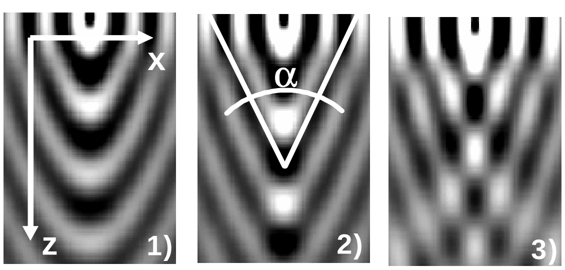

Fig. c) Finite difference simulations of the displacement field in x-direction at a fixed ratio Y_T/Y_L such that the resulting angle is α=55°. The numbers in the lower right corners refer to (**fig. d**).

Results The shear modulus μ_L was derived by evaluating the wave number along the z-direction. In the elliptic approximation the angle was found to be given by

$$\alpha = 2\tan^{-1}\left[\left(\frac{Y_T}{Y_L}\right)^{1/4}\right] \qquad (2)$$

Finite difference simulation reproduced the V-shape within two thresholds R and R', which were derived by taking into account curvature (R) and internal diffraction (R'). Using these thresholds it can be deduced from (**fig. d**), that the ratio between the Y_T and Y_L equals 1/16. This results in a ratio 1/4 for the corresponding wave speeds c_T and c_L.

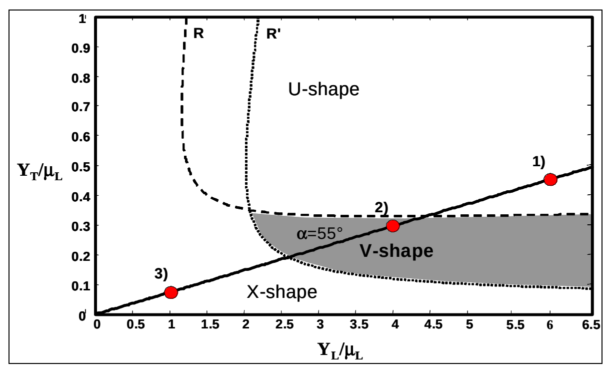

Fig d) The two wave-shape thresholds R and R' as function of elastic parameters. The straight line shows all Young's moduli which yield α = 55°. The numbered spots 1), 2) and 3) refer to the wave images shown in **fig. c).** V-shaped waves occur only inside the gray patch.

Discussion From the elliptic approximation of the slowness curve of the ST mode it is possible to derive a simple analytic expression for the angle enclosed by the straight wavefronts (see eq. 2). However, it was necessary to employ two more parameters R and R', since the ST mode allows a wider range of wave patterns and not only the observed V-shaped waves. For the same ratio Y_T/Y_L waves could appear U-shaped or X-shaped, respectively, according to the magnitude of R and R'. For the V-shaped waves (**fig a**) and (**fig. c**, image in the center) the angle provides an additional tool to determine the anisotropic elastic coefficients. The ratio c_T / c_L = ¼ determined using the elliptic approximation is supported by ultrasound elastography [3].

Conclusion In the present work a method is proposed to straight forwardly obtain three elastic parameters from a single 2D wave image i.e. the shear moduli parallel and perpendicular to the fibres, as well as the Young's modulus parallel to the fibres of the tissue.

References **[1]** Fung, Y. 1993. *Biomechanics: mechanical properties of living tissue*. Springer Verlag, New York. **[2]** Sack, I., Bernarding, J., Braun, J. Magn. Reson. Imaging 2002, 20, 95-104 **[3]** Gennisson, J. L., Catheline, S., Chaffai, S., Fink, M., J. Acoust. Soc. Am., 114, 536-541