

# Position dependent shear wave group velocities in in vivo human biceps muscle

S. Papazoglou<sup>1</sup>, U. Hamhaber<sup>2</sup>, J. Rump<sup>1</sup>, D. Klatt<sup>1</sup>, J. Braun<sup>2</sup>, and I. Sack<sup>1</sup>

<sup>1</sup>Department of Radiology, Charité Berlin, Berlin, Germany, <sup>2</sup>Institute of Medical Informatics, Charité, Berlin, Berlin, Germany

**Introduction:** Muscle tissue is known to show strong elastic anisotropy [1, 2]. Recently, a shear wave based group velocity inversion has been proposed as a means to deduce anisotropic elasticities from MR elastography wave images of human skeletal muscle [3]. The method is based on the ability of MR to detect certain elliptic modes of wave propagation. This is achieved by an appropriate combination of image plane and direction of external vibrations as well as assuming a focal character of the source of waves. Group velocities are then deduced from measurements of the propagation velocity of transverse waves along the rays outwards from the source location. Therefore, the method appears to be sensitive to deviations in the estimated location of the source from its true position. Here, we study the geometric biases imposed to the group velocities determined in human biceps due to translations of the presumed source location along a Cartesian coordinate axis. It is shown that in contrast to agarose group velocities in human biceps are less effected by geometrical biases.

**Theory:** Consider an anisotropic wave form such as shown in fig.1. As demonstrated in [3], elliptic waves in a transversely isotropic medium that feature out-of-image-plane deflections are generally due to the slow transverse mode. They are described by two different wave speeds parallel and perpendicular to the muscle fiber direction. Considering a dislocation of the source by any vector  $\mathbf{r}_0$  (see fig. 2) the components of the apparent wave speed  $v_i'$  differs from the true  $v_i$  due to geometrical biases of the waves along  $x_i$ :

$$v_i' = \lambda_i' \frac{\omega}{2\pi} \quad \text{with} \quad \lambda_i' = \frac{x_i - x_{0i}}{N} \quad 1.$$

$N$  is the number of repeated waves along  $\mathbf{r}$  ( $N=x_i/\lambda_i$ ; no summation over  $i$ ) due to the continuous wave excitation. The distortions on the apparent wavelength along the  $x_i$ -axis  $\lambda_i'$  can be quantified in a straightforward way for elliptic wave patterns. We now relate  $\mathbf{r}_0$  and  $\mathbf{r}$  to the true wavelengths  $\lambda_i$  using:

$$\left[ \sum_{i=1}^3 \left( \frac{x_{0i}}{\lambda_i} \right)^2 \right]^{\frac{1}{2}} = N_0 \quad \text{and} \quad \left[ \sum_{i=1}^3 \left( \frac{x_i}{\lambda_i} \right)^2 \right]^{\frac{1}{2}} = N_0 + N \quad 2.$$

For the initial case of  $\mathbf{r}_0 \equiv |\mathbf{r}_0| = 0$  and  $\mathbf{r} \parallel \mathbf{e}_i$ , eqs.1 and 2 yield  $\lambda_i' = \lambda_i$ . The same results for  $\mathbf{r}_0 \parallel \mathbf{e}_i$  and  $\mathbf{r} \parallel \mathbf{e}_i$ , whereas a perpendicular dislocation requires the knowledge of  $x_j$  and  $x_k$  for deriving  $x_i$  ( $i \neq j, k$ ). For example with  $\mathbf{r}_0 \parallel \mathbf{e}_j$  and  $\mathbf{r} \parallel \mathbf{e}_i$ , we can write  $x_j = N_0 \lambda_j$ , so that the apparent wavelength follows with

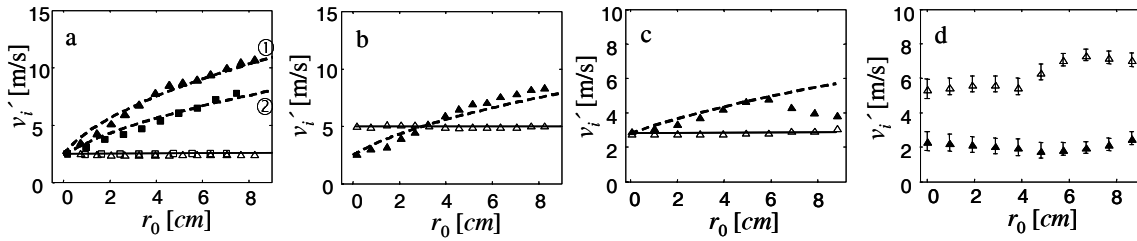
$$\lambda_i' = \lambda_i \sqrt{2 \frac{N_0}{N} + 1} \quad 3.$$

which is illustrated in fig.2. Eq.3 holds for any  $\mathbf{r}_0$  if the wave profile runs parallel to  $\mathbf{e}_i$ . The ratio  $N_0/N$  represents the dislocation over profile length, which equals  $\sqrt{x_{0j}^2 + x_{0k}^2} / x_i$  ( $i \neq j \neq k$ ). Consequently, the maximum bias occurs if  $\mathbf{r}_0 \perp \mathbf{r}$ . From eq.3 follows that the

apparent shear modulus depends linearly on  $N_0$ . Note that if  $\mathbf{r}_0 \neq 0$ , the apparent wavelength is always larger than the true wavelength and consequently the minimum of  $v_i'(\mathbf{r}_0)$  can indicate the location of the wave source.

**Methods:** MR experiments were performed on a 1.5 T scanner (Siemens Magnetom Sonata, Erlangen, Germany). For image acquisition a modified *b*-SSFP sequence incorporating trapezoidal oscillating motion encoding gradients (MEG) was used. The image plane was chosen so that external vibration direction corresponded to out-of-plane direction. Shear vibrations were introduced electromechanically. Experiments were performed on agarose phantoms and human biceps. The protocol for determining group velocities and the simulation of wave propagation used are described in detail in [3].

**Results:** The results are shown in fig. 3. For their description see the corresponding caption.

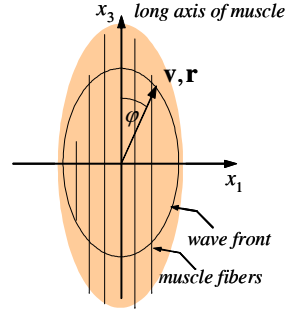


**Fig. 3:** Position dependent velocity components  $v_1'$  (closed symbols) and  $v_3'$  (open symbols) determined at  $\mathbf{r}_0=[0,0,x_3]$  **a:** wave speeds of synthetic isotropic waves emerging from a point source at  $x_i=0$  ( $\lambda_1=\lambda_3=0.0125$  m,  $v_1=v_3=2.5$  m/s). The solid line shows that  $v_3'$  is constant with  $v_3'=v_3$ . The increasing dashed lines were fitted to data received with  $r=0.75\lambda_3$  (⊙) and  $r=1.5\lambda_3$  (⊙). **b:** Components of  $\mathbf{v}'$  of synthetic anisotropic waves that are equivalent to (a) but  $\lambda_3=0.025$  m ( $v_3=5$  m/s). Inversion and simulation were performed using  $r=0.75\lambda_3$ . **c:** Experimental group velocities of agarose determined at positions  $\mathbf{r}_0=[0,0,x_3]$  away from the source location. The tolerances of  $\mathbf{v}'$  are within the symbol size. **d:** Biceps data at positions  $\mathbf{r}_0=[0,0,x_3]$  away from the distal tendon, that is here assumed to be the source. Here,  $v_1'$  is not increasing other than in (a), (b) and (c).

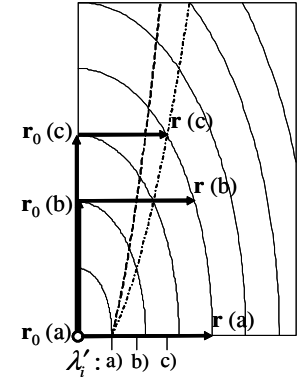
**Discussion and Conclusion:** The increase of  $v_1'$  observed by analyzing elliptic waves was not found for biceps data. There, the projection of the wave speed perpendicular to the muscle fibers remains constant along the muscle axis, as wave patterns repeat themselves parallel to that axis. This waveform is different to the model, which predicts elliptical or circular concentric wave fronts. However, even without revision of the underlying model group velocity inversion may benefit from the stability of the apparent wave speed in muscle. In case of image slices dislocated from the point of wave excitation correct wave speeds are found as long as  $\mathbf{r}_0$  lays on single principal axis of the muscle.

## References:

- [1] Fung Y. C., Biomechanics, Springer-Verlag New York, Inc.(1993)
- [2] Kruse S. A. et. al., Phys. Med. Biol. 45:1579–1590 (2000)
- [3] Papazoglou S. et. al., Magn. Reson. Med. 56:489–497 (2006)



**Fig. 1:** Exemplary 2D waveform due to a point source at the origin in a medium with two different shear wave velocities along the Cartesian axes (biceps muscle). The group velocity  $\mathbf{v}(\phi)$  is measured along the rays  $\mathbf{r}(\phi)$  outwards from the source.



**Fig. 2:** Two dimensional sketch of  $\lambda_i'$ -projections assuming elliptical wave fronts (solid lines) corresponding to a ratio of two between vertical and horizontal wave speeds. a) shows the coincidence of the origin of  $\mathbf{r}$  with the source of the waves ( $r=0$ ). Two examples are shown for dislocating  $\mathbf{r}$  parallel to the vertical axis:  $N_0=2; N=2$  (b) and  $N_0=3; N=1$  (c). The corresponding functions  $\lambda_i'(N_0, N=2)$  and  $\lambda_i'(N_0, N=1)$  are drawn with dashed and dash-dotted lines, respectively.