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Shear Wave Group Velocity Inversion in MR Elastography of Human Skeletal Muscle

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In vivo quantification of the anisotropic shear elasticity of soft tissue is an appealing objective of elastography techniques because elastic anisotropy can potentially provide specific information about structural alterations in diseased tissue. Here a method is introduced and applied to MR elastography (MRE) of skeletal muscle. With this method one can elucidate anisotropy by means of two shear moduli (one parallel and one perpendicular to the muscle fiber direction). The technique is based on group velocity inversion applied to bulk shear waves, which is achieved by an automatic analysis of wave-phase gradients on a spatiotemporal scale. The shear moduli are then accessed by analyzing the directional dependence of the shear wave speed using analytic expressions of group velocities in *k*-space, which are numerically mapped to real space. The method is demonstrated by MRE experiments on the biceps muscle of five volunteers, resulting in 5.5 ± 0.9 kPa and 29.3 ± 6.2 kPa ($P < 0.05$) for the medians of the perpendicular and parallel shear moduli, respectively. The proposed technique combines fast steady-state free precession (SSFP) MRE experiments and fully automated processing of anisotropic wave data, and is thus an interesting MRI modality for aiding clinical diagnosis. Magn Reson Med 56:489–497, 2006. © 2006 Wiley-Liss, Inc.

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MR elastography (MRE) is capable of monitoring bulk shear vibrations in soft biological tissues (1–4). The interest of physicians in imaging shear vibrations is based on the possibility of quantitatively testing in vivo stiffness variations, which would enable the detection of pathologies at an early stage. In MRE the sensitivity of wavelengths to elasticity changes is usually exploited to map elastic heterogeneities (5–9). In this way, local variations of wavelengths are analyzed in terms of local variations of the isotropic shear modulus using inversion algorithms. It is an inherent prerequisite of such isotropic inversion techniques that the waves propagate at equal speed through homogeneous elastic parts of the material. This does not hold true for anisotropic elastic material, such as skeletal muscle (10–12). Here the wave velocity generally depends on the direction of wave propagation, and shear wave images can thus display different wave numbers even in homogeneous elastic materials. This phenomenon is well known in crystal acoustics, where it is described using a vector of wave group velocity that is aligned with the direction of energy flux from the wave source (13,14). This contrasts with the scalar phase velocity, which denotes the wave speed along the wave front normals and which is usually deduced by isotropic inversion techniques. The purpose of this study was to develop a method for measuring group velocities in MRE of strongly anisotropic materials, such as skeletal muscles.

Extensive research in the field of muscle activity measurements by MRI underscore the important role of muscle MR in neurophysiologic research, diagnosis, and therapy (15–19). Muscle MRE (11,20–24) is developing into a straightforward technique for detecting several diseases that affect muscle elasticity, such as hypogonadism (25) and obstructive pulmonary disease (26). Thus it is increasingly important to correctly deduce all information about muscle elasticity from MRE shear wave patterns. As previously shown, applying isotropic inversion techniques to anisotropic wave images may yield misleading results (27). On the other hand, additional information about the mechanical properties of a material beyond scalar phase velocities can be gained by taking into account the directional dependency of the wave group velocity (28). Such an analysis would exploit the fact that the anisotropy of elasticity generates characteristic wave patterns, assuming 1) elastic homogeneity or shallow heterogeneity (on the scale of one wavelength), 2) a point source of the waves, and 3) non-reflecting boundary conditions. As previously shown, the special experimental conditions of in vivo muscle MRE apply in good approximation to these prerequisites (24). A group velocity inversion method would thus be applicable to MRE of skeletal muscles, and could reveal interesting information about the anisotropy of the mechanical properties of living muscle tissue.

In the following, a strategy for automatically detecting group velocities will be introduced in theory and demonstrated in MRE experiments of isotropic agarose gel and muscle biceps brachii from five volunteers. The new method can be outlined as follows:

1. The relationship between elastic coefficients and group velocity is derived in three dimensions for incompressible media. By this means, analytical expressions of wave speeds in *k*-space are received that model the shear wave-based elastography of biological tissues.
2. The analytical wave speed functions of *k* are numerically transformed into spatial dimensions, where they are automatically fitted to experimental group velocities by varying elastic coefficients. The experimental group velocities were previously determined by applying symmetry enhancement and automatic edge detection to phantom data and in vivo human biceps MRE data from five volunteers.

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