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Analysis of wave patterns in MR elastography of skeletal muscle using coupled harmonic oscillator simulations

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Abstract

The ability to study muscle elasticity in vivo would be of great clinical interest. Magnetic resonance elastography (MRE) has the potential to quantify noninvasively the distribution of the shear modulus in muscle tissue. Elasticity information may be derived by extracting frequencies from the wave patterns of phase-contrast MRE images. In a new approach, MRE wave patterns were reconstructed using 3D coupled harmonic oscillator calculations (CHO). To analyze in vivo MRE measurements of the biceps brachii of healthy volunteers, different anisotropic fibrous structures for the couplings between the muscle elements have to be assumed. V-shaped wave patterns as observed when excitation was applied on the tendon were reproduced by a model, where in a central band of stiff fascicles wave propagation was about twice as fast as that in surrounding tissue. Planar waves were observed for excitation near the muscle surface. They could be reconstructed by assuming a simultaneous wave excitation of all muscle fibers, where fibers along the main muscle axis were coupled more strongly than those perpendicular to the axis. The results show that CHO calculations provide a fast and reliable method for incorporating anatomical information of the investigated tissue in the reconstruction of complex wave patterns.

Keywords: In vivo MR elastography; Skeletal muscle; Biceps brachii; 3D coupled harmonic oscillators

1. Introduction

Tissue elasticity in vivo may differ strongly from the elasticity of excised tissue due to variations in hydrostatic pressure or biomechanical mechanisms such as muscle tension [1,2]. The qualitative correlation of function and elasticity appears most obvious in the case of skeletal muscle, where manual palpation has shown that maintaining load increases the muscle stiffness [3]. Surprisingly, only a few studies have been performed to elucidate quantitatively the elasticity of skeletal muscle tissue in vivo [4–6]. This may be due to the limited number of noninvasive techniques that allow the distribution of elasticity within a muscle to be monitored. Additionally, the easy and straightforward analysis of elastographic data is often hampered by the complex structure of skeletal muscle tissue that results in complex elastographic data [7].

In recent years, elastographic techniques such as ultrasound (US) [8–10] or magnetic resonance imaging (MRI) [11–15] have been developed that combine noninvasive imaging methods with a static or dynamic application of stress to the tissue. In vivo studies of skeletal muscle were performed using dynamic elastography of the quadriceps muscle at excitation frequencies between 30 and 120 Hz while maintaining different loads [5]. Experiments at the biceps brachii were achieved by dynamic MR elastography (MRE) applying 150 Hz acoustic frequency [6].

In contrast to ultrasound elastography, MRE enables the entire muscle to be studied and no limitations in penetration depth and maximum resolvable field of view are imposed. To extract elasticity information from MRE phase images, a local frequency estimation may be used [16,17]. Other approaches include the solution of complex tensor equations [18–22]. For isotropic Hookean materials, the shear modulus μ can be related directly to the shear wave speed c by

$$\mu = c^2\rho \qquad (1)$$

where ρ is the tissue density, which was found to be 1100 kg/m^3 for muscle tissue in the literature [6]. Following the terminology of [23], the shear modulus at a given frequency

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