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Observation of Nonlinear Shear Wave Propagation Using Magnetic Resonance Elastography

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MR elastography (MRE) is an MRI modality that is increasingly being used to image tissue elasticity throughout the body. One MRE technique that has received a great deal of attention is based on visualizing shear waves, which reveal stiffness by virtue of their local wavelength. However, the shape of propagating shear waves can also provide valuable information about the nonlinear stress–strain behavior of tissue. Here an experiment is proposed that allows the observation of nonlinear wave propagation based on spatial-temporal phase contrast images. A theoretical description of the wave propagation was developed that reflects typical MRE excitation, which involves excitation modes both parallel and perpendicular to B_0. Based on this model, it is shown that both odd and even higher harmonics are produced with their amplitudes dependent on the details of the actuator, imaging geometry, and the nonlinear tissue properties. With appropriate motion encoding, harmonic vibrations arising from nonlinear tissue response can be detected. The effect is demonstrated on an agarose gel phantom using a sinusoidal shear vibration of 150 Hz, and clearly shows the presence of harmonics at 600 and 750 Hz. Using an estimate of the strain energy of the phantom, we were able to determine the nonlinear tissue properties. Magn Reson Med 52: 842–850, 2004. © 2004 Wiley-Liss, Inc.

Key words: nonlinear wave propagation; MR elastography; shear waves; nonlinear harmonics; anharmonic vibrations

In recent years, MR elastography (MRE) has received considerable interest as a novel modality that is capable of imaging tissue elasticity in vivo. Originally based on ultrasound (US) imaging, elastography applications in MRI have made rapid progress. The highly-resolved soft-tissue contrast gained by MRI, combined with the shear modulus as a sensitive elasticity parameter, have led several investigators to employ MRE in a number of clinical applications, including the prostate (1,2), head (3–6), skeletal muscle (7–9), and breast (10–12). MRE is based on the detection of spin phase contrast arising from oscillatory motion in the presence of phase-locked magnetic field gradients (13). This allows the propagation of acoustic shear waves to be imaged along the direction of the applied motion-encoding gradients. To date, tissue stiffness has been examined in MRE in terms of the shear modulus μ as a linear elastic material property. The linear shear modulus can be analyzed by means of local wave speeds based on local frequency estimators (14,15), from inverse solutions of the Navier equations (11,16), or an iterative refinement of displacements (17,18). However, using real-time US, Catheline et al. (19–21) recently demonstrated that low-frequency (100 Hz) transverse waves can exhibit nonlinear propagation effects while traveling through agarose gel. Although such thermo-reversible gels have been found to be linear elastic under small static deformations, shear waves cause third-order nonlinear effects due to the high particle deflection speed relative to the low shear wave propagation speed. One can visualize the nonlinear effects by creating higher harmonic frequency components of the fundamental shear vibration, whose intensity ratios, shock speeds, and total amplitudes are sensitive to both applied strain components and the inherent nonlinear stress–strain function of the material (22). These nonlinear parameters may provide new information regarding tissue type, as previous rheologic experiments have shown that most tissues exhibit nonlinear constitutive properties (23). The goal of this study was to introduce a methodology that exploits the potential of MRE in demonstrating these nonlinear properties in an imaging experiment.

BACKGROUND

Temporal Resolution of MRE

In contrast to real-time US observation of nonlinear transverse waves (20), MRE acquires data by phase encoding each line in *k*-space with appropriate oscillatory motion-encoding gradients. Through the use of sinusoidal motion-encoding gradients, the final image selectively shows oscillatory wave motions, which occur with a frequency content that is dependent on the details of the gradient. Ideally, an MRE experiment would not be limited by tissue T_2, and hence long motion-encoding gradients could be applied. This would result in an image that would be selective only for motions that occur at the frequency of the gradient. However, due to the short T_2 times of tissues, these gradients are short (on the order of 10–200 ms), which broadens the spectral response of any practical MRE experiment. As such, MRE gradients serve to operate as a filter by which the spectral response of tissue motions will be scaled depending on the details of gradient encoding.

The resultant phase image reports the spatial distribution of motion, and the gradients act in a stroboscopic manner to capture the tissue motions. To achieve a time-resolved rendering of the shear wave progression, repetitive MRE acquisitions are required while the phase φ is incremented between the motion and gradient waveforms. As such, the time required to achieve time-resolved 2D

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