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Fractional Encoding of Harmonic Motions in MR Elastography

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In MR elastography (MRE) shear waves are magnetically encoded by bipolar gradients that usually oscillate with the same frequency f_v as the mechanical vibration. As a result, both the repetition time (TR) and echo time (TE) of such an MRE sequence are greater than the vibration period $1/f_v$. This causes long acquisition times and considerable signal dephasing in tissue with short transverse relaxation times. Here we propose a reverse concept with TR $\leq 1/f_v$ which we call "fractional" MRE, i.e., only a fraction of one vibration cycle per TR, can be used for motion sensitization. The benefit of fractional MRE is twofold: 1) acquisition times in seconds can be achieved for a single-phase difference wave image, and 2) materials that combine low elasticity, high viscosity, and short T_2^* relaxation times show an increased phase-to-noise ratio (PNR). A twofold increase of the phase signal is predicted for liver-like materials. Volunteer studies performed in liver and biceps show the benefit of fractional MRE. Furthermore, we demonstrate the feasibility of the technique for in vivo myocardial MRE by visualizing transverse wave propagation in the interventricular septum (IVS). Magn Reson Med 57:388–395, 2007. © 2007 Wiley-Liss, Inc.

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Manual palpation is a sensitive means of detecting pathologically altered tissue near the surface of the body. The sensitivity of this method is related to the resistance of soft tissue to shear forces, which varies by orders of magnitude in the human body (1,2). Accordingly, elastography techniques have been developed to quantify the shear elasticity of living human tissue based on soft-tissue imaging techniques, such as ultrasound or MRI, using either static mechanical compression or acoustic strain waves (3–9). Since the acoustic approach in MR elastography (MRE) has made rapid progress in the last few years, it is now possible to examine the elasticity of tissue that is not palpable from the body surface. Dynamic MRE can map spatial and temporal shear wave fields that depend on heterogeneity, anisotropy, and nonlinearity of the elasticity (10–17).

Although pilot studies demonstrated the potential of MRE, it has remained a relatively slow technique compared to the rapid acquisition schemes of other flow- or motion-quantifying MRI methods (18–21). The extended time consumption of conventional MRE scans is due to the duration of bipolar gradients used to sensitize the sequence to slow mechanical vibration cycles (usually >5 ms, corresponding to vibration frequencies of $f_v < 200$ Hz). This frequency range is compelled by the high viscosity of most soft tissues that results in a rapid damping of the shear wave amplitude with the penetration distance (22). Current MRE methods encode the motion by oscillating gradients with a minimum duration of one vibration cycle. Thus, the repetition time (TR) of an MRE sequence is always greater than $1/f_v$.

In this work we propose the use of low-frequency shear vibrations with vibration cycles longer than the TR of the MRI sequence (TR $\leq 1/fv$). As a trade-off, only a fraction of one motion cycle can be magnetically encoded, and thus the phase difference signal is smaller. However, it will be shown that for soft and viscous materials with short transverse relaxation times this loss is more than compensated for by an increased signal resulting from reduced transverse relaxation. The short echo times (TEs) that are achievable with fractional motion encoding also enable MRE to be performed in the presence of blood flow or heart motion, which permits in vivo examinations of myocardial elasticity.

Although fractional motion encoding is feasible with any type of signal readout, all experiments in this study are based on a balanced steady-state free precession (bSSFP) experiment (i.e., all gradients are fully refocused within one TR) (23–27). Bieri et al. (28) recently introduced bSSFP-MRE based on intrinsic motion sensitization by readout gradients. The authors proposed the use of three half-motion cycles in one SSFP-TR to produce an oscillating steady state with acquisition of two images corresponding to the alternating offset of motion phase. In the present study, an extra motion sensitization gradient is employed such that the length of the SSFP-TR is adapted to one, one-half, or one-quarter vibration cycle. In the latter two cases, where TR $< 1/f_v$, an alternating steady-state is produced as described in Ref. 28.

In the following text we will first derive a theoretical expression for the motion phase in fractional MRE that accounts for NMR and viscoelastic parameters. The MRE phase signal for liver- and muscle-like materials is predicted based on this equation, and experimental parameters are proposed and validated by in vivo experiments on human biceps and liver. Furthermore, the feasibility of fractional MRE for detecting slow shear vibrations in the human heart is demonstrated on the interventricular septum (IVS) of a volunteer.

THEORY

bSSFP sequences require short TRs to minimize the effect of field inhomogeneities on the signal evolution that lead

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