Cyclic Motion Encoding for Enhanced MR Visualization of Slip Interfaces

Y. Mariappan[1], K. J. Glaser[1], A. Manduca[2], and R. L. Ehman[1]

[1]Department of Radiology, Mayo clinic, Rochester, MN, United States, [2]Biomathematics resource, Mayo clinic, Rochester, MN, United States

Introduction: The presence of low-friction slip interfaces between tissue surfaces is critical to the normal functioning of many structures in the body. The loss of such interfaces, such as due to scarring, can lead to serious consequences. For instance, the development of "adhesions" between the visceral and parietal peritoneum in the abdomen following surgery can lead to acute conditions with catastrophic ischemic consequences. Unfortunately, the presence of adhesions between slip surfaces is very difficult to identify with standard imaging methods. We hypothesize that by applying external vibrations and mapping the relative motion between tissues on either side of the interface into the phase of the transverse magnetization, slip interfaces will be discernable in the magnitude images as local regions of signal loss due to intravoxel phase dispersion (IVPD) across the interface. This methodology is based on the technique of Magnetic Resonance Elastography (1) that has been developed to assess the mechanical properties of tissues and has emerged as a diagnostic tool for liver fibrosis and breast lesions (2, 3).The purpose of this work is to test this hypothesis in phantom experiments and to demonstrate the feasibility of the technique in a study on a normal human volunteer to distinguish muscle subcompartments.

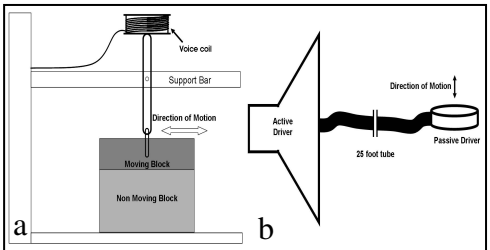

Figure 1: 1a. Experimental setup for the phantom study. 1b. A schematic representation of the pneumatic driver system used for the forearm volunteer study.

Theory: IVPD (4) is a phenomenon by which the magnitude signal of a voxel reduces due to the presence of significant phase variations inside that voxel. At a slip interface between a moving and a nonmoving object in a phase-sensitive MR acquisition, a large enough relative motion can create enough phase variation within the interface voxel to produce IVPD. The signal loss in the interface due to this phenomenon can be explained with the equation $R^2/N^2 = 1-4\alpha(1-\alpha)\sin^2((\theta_1-\theta_2)/2)$ based on a simple two-compartment model where R is the net magnitude signal of the voxel, N is the total number of (uniformly unit-magnitude) isochromats present in the voxel, α is the fraction of moving or nonmoving isochromats in the voxel, and θ_1 and θ_2 are the phases of the moving and nonmoving isochromats, respectively. According to this theoretical model, the magnitude of the interface reaches zero when α is 0.5 and the phase difference is π radians.

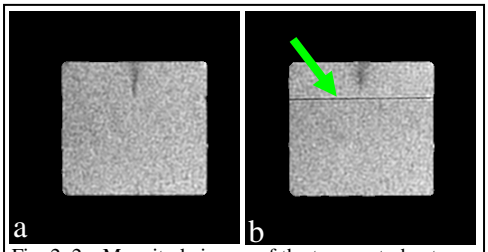

Fig. 2. 2a. Magnitude image of the two-part phantom without motion encoding. 2b. Magnitude image of the same phantom with cyclic motion encoding. A prominent "shear-line" of reduced signal intensity confirms the presence of a functional slip interface

Materials and Methods: A 1.5-T whole-body scanner (GE Signa, Milwaukee, WI) was used in all of the following experiments. A phantom study was first performed to test the hypothesis of IVPD based MR magnitude signal loss at slip interfaces. Two cylindrical wirosil silicone (Bego, USA) phantoms of equal radius were made and were placed one above the other as seen in the schematic representation of the experimental setup shown in fig. 1a.The bottom block was fixed to the base, whereas the top block could move in a shear-like motion with respect to the fixed block. A very thin layer of mineral oil was added between the two blocks to increase the slipperiness of the interface. A voice coil driver oscillating at 50 Hz was used to vibrate the top phantom. A spin-echo MRE pulse sequence was used with one 20-ms cyclic motion-encoding gradient pair sensitive to motion in the SI direction (the horizontal direction in fig. 1a) whose amplitude was adjusted from 0 to 4 G/cm to encode an increasing amount of phase into the transverse magnetization of the moving phantom. Other imaging parameters were FOV = 14 cm, acquisition matrix = 256x64, frequency-encoding direction = SI, TR/TE = 300/46 ms and slice thickness = 10 mm. For the IRB approved human volunteer experiments, a pressure activated MRE driver system with a small passive driver that can selectively vibrate any one finger of interest was used (as indicated in fig. 1b). Cross-sectional images of the forearm were acquired similar to the phantom experiment but with 60-Hz motion and a 16.7-ms through-plane motion-encoding gradient.

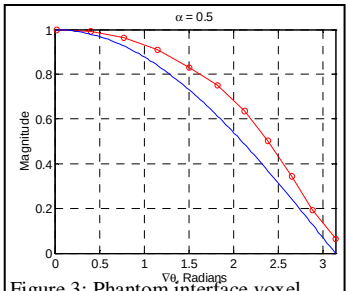

Figure 3: Phantom interface voxel signal vs. phase difference across the interface compared to the theoretical prediction of the signal based on the two-compartment model

Results and Discussion: Fig. 2a shows the MR magnitude image of the two blocks during the application of the motion, but with the motion-encoding gradient amplitude set at zero. From this image, the interface between the blocks is not evident. Fig. 2b shows the magnitude image with the same amount of motion but with the motion-encoding gradient amplitude set at 4 G/cm. The presence of a large phase discontinuity between the two blocks causes intravoxel phase dispersion resulting in the very low signal "shear line" (indicated by the arrow) at the interface. This localized signal loss is therefore an indication of a functional slip interface. There have been other efforts to assess the connectedness of tissue interfaces using MRE by analyzing the scattering of shear waves at these interfaces (5). However, with this proposed technique, the characterization of the interface is easier and less mathematically involved. Figure 3 shows that the experimentally observed change in the magnitude signal values at the interface (red) with an increasing phase difference across the interface were close to the theoretically predicted values (blue) based on the simple two-compartment model for an α value of 0.5. Figure 4 shows the results obtained from the volunteer study. Fig 4a shows a cross-sectional image of the forearm with the index finger being selectively vibrated, but with the motion-encoding gradient amplitude set to zero. Fig 4b shows the same image but with motion-encoding gradient set to 4 G/cm. The vibrations from the driver are transmitted through the flexor muscle of the index finger, producing a prominent low-signal shear-line where there is a large phase discontinuity between the functional index finger flexor muscle compartment and the other muscle groups.

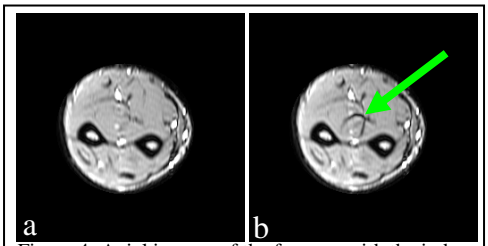

Figure 4: Axial images of the forearm with the index finger vibrating at 60 Hz with no motion encoding (4a) and through-plane motion encoding (4b). The shear line is indicated by the arrow.

Conclusion: From these results, it is concluded that the functionality of slip interfaces can be very sensitively visualized and assessed using applied acoustic vibrations and cyclic motion encoding gradients and that it is feasible to apply this technique in vivo. This technique will require further development and testing in humans, but if translation is successful, it may provide a new diagnostic option for detecting and localizing bowel adhesions and similar conditions. In cancer staging, the approach may also have potential for sensitive detection of tumor extension across organ interfaces

References:(1) Muthupillai et al., *Science* 269: 1854-1857, 1995. (2) Rouviere et al. Radiology 2006;240:440-448 (3) Sinkus et al. MRM 2005 ;45 :1579-1590 (4) Glaser et al. MRM 2003; 50:1256-1265 (5) Papazoglou et al. Phys Med Biol 2007 ; 52 :675-684