Phase Correction for Interslice Discontinuities in Multislice EPI MR Elastography

Matthew C Murphy[1], John Huston, III[1], Kevin J Glaser[1], Armando Manduca[2], Joel P Felmlee[1], and Richard L Ehman[1]
[1]*Department of Radiology, Mayo Clinic, Rochester, MN, United States,* [2]*Department of Physiology and Biomedical Engineering, Mayo Clinic, Rochester, MN, United States*

Introduction:
Magnetic resonance elastography (MRE) is an MR technique for noninvasively measuring tissue stiffness [1]. MRE is a three step process beginning with the introduction of shear waves via an external vibration source. The shear waves are then imaged with a phase-contrast MR pulse sequence with motion-encoding gradients synchronized to the motion. The shear wave images are then mathematically inverted to calculate tissue stiffness. Some applications, such as the brain, require a volumetric acquisition and 3D inversion because of through-plane wave propagation. An EPI pulse sequence is useful for such an application because it can acquire a volume of data with short acquisition times. However, slice-to-slice discontinuities in the phase of the EPI images can arise will bias the final inversion results. These discontinuities are low frequency in the imaging plane but high frequency in the slice direction, leading to an underestimate of the true stiffness. The discontinuities are also amplified when calculating the curl of the phase difference images, which is useful for isolating shear waves from the collected displacement images. The purpose of this work is to present a filtering method that removes these slice-to-slice discontinuities, and as a result improves MRE repeatability.

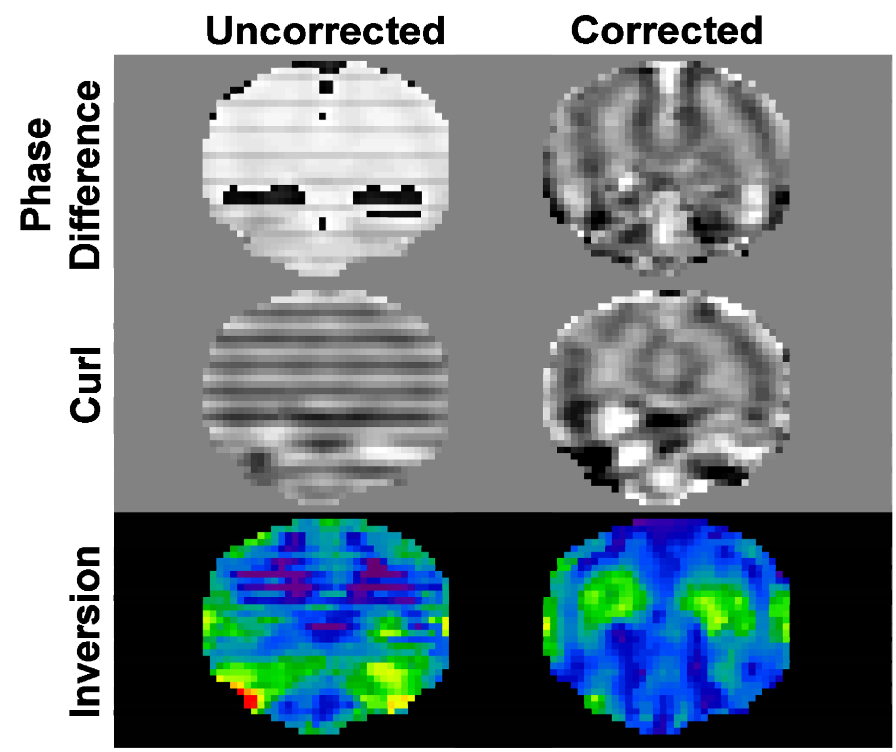

Figure 1. Example images reformatted into the coronal plane. Each row of the images represents a slice of the acquisition. Phase difference images are shown in the top row, the x component of the curl is shown in the middle row and the resulting inversion is shown in the bottom row. Images before correction are shown on the left and images after correction are shown on the right.

Methods:
MRE data were collected with a modified spin-echo EPI pulse sequence on a 3T MR imager (SIGNA Excite, GE Healthcare, Waukesha, WI). Shear waves at 60 Hz were introduced with a soft pillow-like driver placed under the head and imaged with the following parameters: TR/TE = 1500/61 ms, FOV=25.6 cm, 60x60 imaging matrix reconstructed to 64x64, 3x ASSET acceleration, 36 4-mm slices, one 4-G/cm motion-encoding gradient on each side of the refocusing RF pulse, x, y, and z motion-encoding directions and 4 phase offsets over one period of motion. For each slice, complex-valued images with a record of the shear motion in the image phase are produced with positive and negative motion-encoding gradients. These images are combined using a complex conjugate product to produce complex phase-difference images (the phase of which is the wave data typically processed in MRE). To filter the EPI wave images, the complex phase-difference images were first low-pass filtered in 2D with a 3x3 rectangular window function in k-space to estimate the constant phase shift or slowly varying phase for each slice. A second set of phase-difference images was then calculated between the original phase-difference images and the low-pass filtered images. The curl of the wave images was calculated and stiffness was determined with a direct-inversion algorithm [2]. The MRE exam was repeated a total of 4 times over 2 days to assess repeatability.

Results:
Example images with and without the proposed correction are shown in Figure 1. The images collected in the axial plane have been reformatted to the coronal plane so that each row of the image represents a slice of acquired data. The chosen example is the worst case observed. With no correction, the coefficient of variation (COV) for global brain stiffness over the four MRE exams was 7.72%. After correction, the COV improved to 2.26%.

Discussion:
When through-plane shear wave propagation is present, a 3D inversion algorithm is necessary to calculate an accurate stiffness. However when using a 3D inversion, the shear wave images must be free of slice-to-slice discontinuities to avoid artifacts in the calculated stiffness map. Some multislice EPI protocols contain these phase discontinuities, which can be further amplified by postprocessing and create artifacts in the inversion. Any volumetric data to be used for 3D inversion should be inspected for slice-to-slice discontinuities. The filtering method proposed here significantly reduced the artifacts in the phase difference images, the curl images and the inversions. The filtering also significantly improved the repeatability of the MRE exam in this subject.

References:
[1] Muthupillai et al. Science 1995. 269 (5232): 1854. [2] Oliphant et al. Magn Reson Med 2001. 45: 299.