**High-Resolution Multi-Shot MR Elastography of the Brain with Correction for Motion-Induced Phase-Errors**

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**INTRODUCTION:** There has been a resurgence of MR Elastography (MRE) as a means for quantifying the changes in mechanical properties of brain tissue *in vivo* associated with various age-related pathologies [1-3]. Many brain MRE studies utilize imaging sequences with single-shot EPI readouts for acquisition speed, but these sequences suffer from long echo times and large distortions in high-resolution protocols. A multi-shot sequence has been recently introduced to reduce the effects of $T_2$*-induced blurring and sensitivity to field inhomogeneities, allowing for higher resolution acquisitions [4]. However, multi-shot MRE has the drawback of introducing significant phase errors between shots, which lead to phase cancellation and image artifacts. These artifacts are well known in diffusion imaging, another displacement encoding method [5]. In this work, a correction is applied to each *k*-space shot to offset the phase errors prior to reconstruction, and the improvement in quality is demonstrated in both images and MRE stiffness maps after inversion. This combination of multi-shot imaging and phase error correction allows for 2mm isotropic data to be acquired, which, to our knowledge, is the highest reported resolution for brain MRE. Higher imaging resolution is a necessity for the future of brain MRE, as the effective resolution of mechanical estimates is significantly decreased owing to the smoothness effect of discretizing the wave equation

**THEORY:** In MRE, applied motion is mapped to the phase of the image and it is assumed to be the same for each acquired *k*-space shot. Any inconsistencies in this motion from shot-to-shot can result in phase errors and signal loss. In brain MRE there is a very large rigid body motion component that results in bulk phase across an image due to the motion encoding gradients. The applied motion from the actuator (which, in general, is imperfect [6]) is reflected directly in the bulk phase, as opposed to the shear waves at steady state. Similar to approaches in diffusion imaging, the phase offset, $\Delta\varphi$, for each shot must be estimated as the phase at the center of *k*-space. Variable-density spiral readouts are employed to oversample the center of *k*-space and ensure that the true center is sampled.

**METHODS:** Imaging was performed on a healthy volunteer using a multi-shot, spin-echo variable-density spiral MRE sequence with twelve *k*-space interleaves [4]. Imaging parameters: shots=12; TR/TE=1000/65 ms; FOV=256 mm; matrix=128x128; slices=10 (2 mm thick). Actuation was driven at 50 Hz, using a head rocker system [7], and eight dynamics were acquired for each of three encoding directions. The acquisition resulted in a 2x2x2 $mm^3$ isotropic resolution, and the total acquisition time was 9 min 36 sec. ***Phase Error Correction*:** For each image, the phase offset for each shot, $\Delta\varphi$, was estimated as the phase at the *k*-space point with maximum energy. This phase offset was registered between shots prior to gridding and image reconstruction [5]. ***Inversion:*** Elastographic inversion was performed using the iterative, finite-element subzone based non-linear inversion (NLI) algorithm [9]. A Rayleigh damped material model was used as an alternative to general viscoelastic models for describing attenuation.

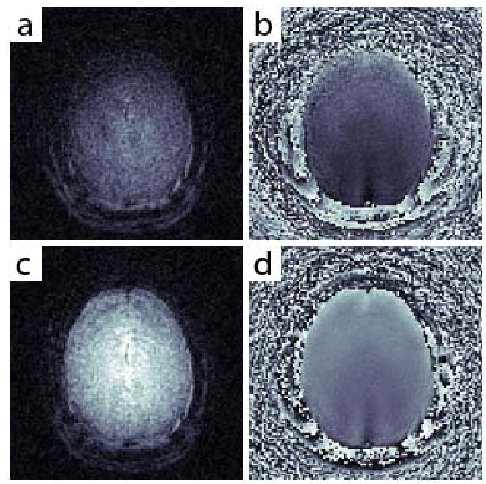


**FIG. 1**: example of mag and phase images without (**a,b**) and with (**c,d**) correction

**RESULTS:** The phase error correction resulted in a significant improvement in image quality, as shown in the example of Figure 1. To quantify this improvement, we compared the octahedral shear strain-based SNR (OSS-SNR) [8]. The OSS-SNR maps for the uncorrected and corrected data are given in Figure 2. The average OSS-SNR for the uncorrected data was *2.66* while correction increased the value to *5.52*, with Figure 2 demonstrating that the SNR is high even in the center of the brain, which inevitably suffers from attenuation of the shear waves. It has been shown that an OSS-SNR of approximately 3-4 is needed for a reliable inversion [8]. Real shear moduli (shear stiffness) were calculated using the NLI algorithm [9], and the results are shown in Figure 3. It is clear that the uncorrected data is prone to poorer identification of anatomical structures such as the ventricles, and also returns regions of artificially high stiffness resulting from model-data mismatch (Figure 3, arrow).

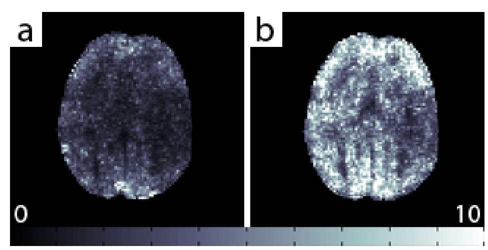


**FIG. 2**: OSS-SNR distributions for MRE data without (**a**) and with (**b**) correction

**CONCLUSIONS:** We have presented a method for correcting phase errors between shots in multi-shot imaging for MRE, thus allowing for high-resolution brain MRE acquisitions. Such phase errors stem from differences in applied motion across *k*-space shots, and can result in signal loss and artifacts in the image. It is demonstrated here that correcting for this effect leads to an improvement in image quality, OSS-SNR, and MRE inversion. We have achieved a 2mm isotropic imaging resolution for brain MRE, which results in reliable stiffness estimates for brain tissue with the NLI algorithm.

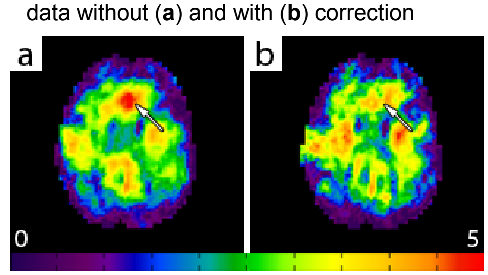


**FIG. 3**: real shear moduli (kPa) from NLI algorithm without (**a**) and with (**b**) correction

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