Temporal Phase Unwrapping Aids 3-D MR Elastography of Prostate Specimens

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Introduction: While recent studies have begun to specifically address the problems of phase wrap in 3-D datasets, there are issues that are particular to MR Elastography (MRE). MRE, an emerging technique for quantitating tissue mechanical properties (1), performed on ex vivo human prostate specimens (2) to determine the feasibility of depicting tumors in situ on the basis of stiffness measurements. Such MRE data is highly susceptible to phase wrap because MRE is a phase contrast method and because gradient echo scans can be contaminated with additional phase nonlinearities (3). MRE datasets typically have large variations in phase and phase difference over the entire field of view, so that some suggested corrections cannot be applied (4-5). MRE acquisitions commonly experience signal loss artifacts near electromechanical drivers and in areas of high wave amplitude, which can reduce the effectiveness of simple thresholding operations for defining the boundaries for a phase unwrapping algorithm. Two-dimensional phase unwrapping techniques are thus important for MRE, but have proved insufficient for some applications, notably this study. This work presents means to supplement 2-D phase unwrapping algorithms, including the use of the time dimension for additional information to regularize the data.

Methods: MR Elastography techniques described previously (1) were adapted for this study to assess tissue that heavily attenuates shear waves (2). Displacement data were acquired with a matrix of 256x64x16 using an 8 cm FOV and 3 mm thick sections for complete gland coverage. These snapshots of shear motion are captured at 4-8 points evenly distributed through one 350 Hz wave period. After initial 2-D unwrapping with a state-of-the-art algorithm, Flynn's minimum discontinuity routine (6-7), data were analyzed in the time direction. Displacement jumps in the time direction greater than 2 pi were corrected (the jump was reduced by 2 pi) if the fundamental of the time FT grew in relation to the higher temporal frequency components. The wave data were converted to a wavelength map by application of the Local Frequency Estimator (LFE) algorithm (8). Because the multiscale solution output of the LFE is subject to bias in the presence of large-scale attenuation, an amplitude-limiting operation was also applied. After the time FT (of the corrected data), any amplitude above a threshold value of pi radians was set to pi radians, while the phase of the FT components was maintained. The reconstituted wave data was then processed with the LFE, and the stiffness maps compared with histopathology data. Full amplitude equalization was also investigated for a subset of the specimen data. Three-dimensional unwrapping algorithms were not attempted because of the anisotropic spatial sampling.

Results: The time-direction unwrapping was useful for correcting errors at the locations of the 2-D algorithm's failures. The effect of this correction is best observed when comparing the phase difference values for a single pixel through time, as shown in the example in Figure 1. The time-direction unwrapping was unsatisfactory for datasets with only four timepoints. The datasets typically had greater than two orders of magnitude difference between the highest and lowest displacement amplitudes, but amplitude equalization was found to result in unacceptable artifacts due to noise amplification. The amplitude limiting operation assisted in controlling high stiffness values in areas of normal tissue, as in Figure 2. In a preliminary evaluation, these steps raised the specificity of MRE identification of prostate tumors at a threshold of 19 kPa by 8% without reducing the 85% sensitivity. This improved the ability to distinguish prostate cancer from normal tissue using stiffness maps from LFE wavelength estimates.

References 1) Muthupillai et al., Science, 1995. 2) Dresner et al., Proc. ISMRM 2002. 3) Bernstein et al., MRM 1998. 4) Friedlander et al., IEEE Trans. Signal Proc., 1996. 5) Xiang, JMRI, 1995. 6) Flynn TJ, J. Opt. Soc. Amer. A, 1997. 7) Strand and Taxt, Applied Optics, 1999. 8) Manduca et al., Med. Image Analysis, 2001.

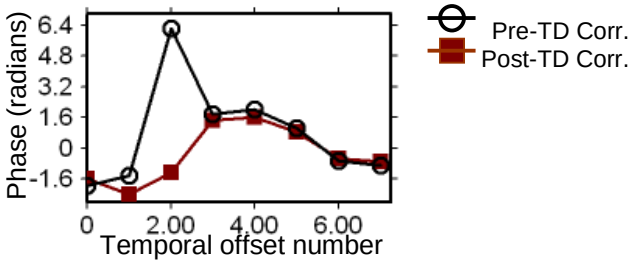

Figure 1. Phase difference values for a single pixel from a 3-D dataset as a function of time (steps through one wave period) before and after corrections for 2 pi discontinuities in the time direction (TD).

Discussion/Conclusions: The effectiveness of MRE for pathology detection through tissue stiffness measurements increased in this study by the use of complementary methods to control residual phase wraps. Prior shear stiffness reconstructions experienced artifacts due to unwrapping algorithm failures (resulting in image discontinuities) and displacement field inhomogeneity. It remains to be seen if more local shear wave inversions are as significantly affected by phase aliasing as the LFE, a multiscale solution. An ideal algorithm would take the time and spatial dimensions into consideration to perform a true 3-D unwrapping, or even 4-D if isotropic data acquisition was practical.

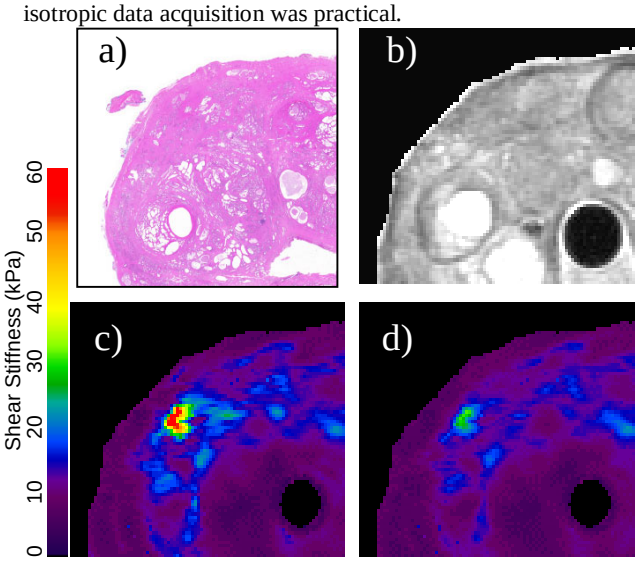

Figure 2. Inset images of a prostate specimen demonstrating the effect of the amplitude limiting operation result on a section of normal prostate tissue as determined by histopathology (a). FSE image (b) shows corresponding anatomy and LFE-derived shear modulus maps from data before (c) and after (d) amplitude limiting show reduction in this high stiffness reported for normal tissue.