Improved Detection of Phase Unwrapping Errors in 3D Tagged Cardiac Magnetic Resonance Imaging Data

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TARGET AUDIENCE: Scientists and engineers with research interests in cardiovascular MRI and phase unwrapping.

PURPOSE: Myocardial strains from tagged cardiac magnetic resonance imaging (cMRI) are important non-invansive parameters of cardiac mechanical function. Recently, phase unwrapping techniques have been proposed that can reconstruct 3D strain maps through the systolic and early diastolic phases of the cardiac cycle [1, 2]. These algorithms use branch cuts to correct for phase inconsistencies due to artifacts and noise. In [2], an algorithm for automatically placing branch cuts was presented along with an algorithm for detecting images where automatically placed branch cuts failed and manual inspection and correction was required. The detection algorithm is important because tagged cardiac imaging studies of the whole heart can have ~400 images that need unwrapping, and it is important to know which ones need manual inspection and editing and which ones do not. The algorithm in [2] used the phase difference between pixels to detect the images with phase unwrapping errors. In this abstract we propose an improved method for detecting phase unwrapping errors based on the spatial smoothness of the unwrapped phase image, which improves both the detection and false positive rates relative to the method in [2].

METHODS: The HARmonic Phase (HARP) image [3] can be represented as $\emptyset = w(r_{\perp} - u_{\perp})$, where w is the frequency, $r_{\perp}$ is the spatial position of the pixel, and $u_{\perp}$ is the displacement component perpendicular to the reference tag plane. Since the nonlinearity of the displacement field due to contraction is significantly lower than that caused by improperly placed branch cuts, we used the L^p norm of second order derivative of the unwrapped phase image to detect phase unwrapping errors.

Subjects: Two sets of cMRI studies were randomly selected from an existing database of cardiac studies. One set of 8 studies was used to optimize parameters (2 healthy volunteers (HV), 2 patients with pulmonary hypertension (PH), 2 patients with hypertension (HTN), and 2 patients with myocardial infarction (MI)). Another set of 5 studies was used for validation (2 HV, 1 PH, 1 HTN and 1 MI).

Image Acquisition: All subjects underwent tagged MRI. 8-12 slices of short axis view and 6 slices of 360° radial long axis view were acquired with a prospectively ECG gated fast gradient echo cine sequence with grid tags spaced 7mm apart. Scanning parameters were: FOV = 40×40cm, scan matrix = 256×128, 8mm slice thickness, flip angle = 10°, TE = 4.2ms, TR = 8.0ms, 20 frames per cardiac cycle, typical temporal resolution 50ms.

Procedure: Unwrapped phase was automatically computed in each study with the technique in [2]. Phase unwrapping errors were detected by the proposed L^p norm methods (p = 1, 2 or ∞) and compared to manual detection results from an expert user. ROC curves were then estimated for each choice of p and compared to the phase difference method in [2] separately for short axis and long axis images in the optimization set using MedCalc (MedCalc Software, Mariakerke, Belgium). Optimal choice of p and the optimal threshold were validated by applying the algorithm to the validation set.

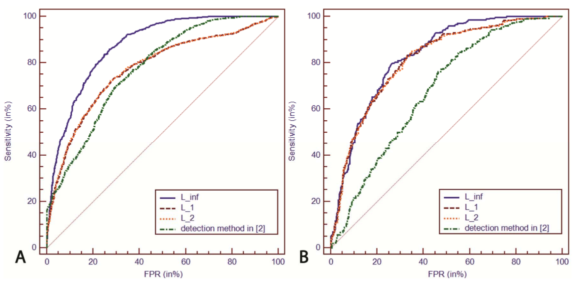

Fig. 1. Estimated ROC curves for phase unwrapping error detection in short axis (A) and long axis (B) tagged cardiac images for different L^p norms. The L^∞ norm (blue) out-performs the L^1 and L^2 norms and the phase difference method in [2].

RESULTS\DISCUSSION: Fig. 1 shows the estimated ROC curves. For short axis images, the phase discontinuity detection method gave an area under ROC curve (AUC) of 0.774, CI= (0.758, 0.789). The L^1 norm gave an AUC of 0.774, CI= (0.758, 0.789). The L^2 norm gave an AUC of 0.775, CI= (0.759, 0.790). The L^∞ norm gave an AUC of 0.875, CI= (0.862, 0.887). For long axis images, the phase difference method AUC = 0.679, CI= (0.648, 0.708). L^1 norm AUC = 0.814, CI =(0.788, 0.838), L^2 norm AUC = 0.813, CI =(0.787 0.837), and L^∞ norm AUC = 0.830, CI =(0.804, 0.853). The L^∞ norm method was statistically better than the phase difference method and L^1 and L^2 norm methods in short and long axis images. The L^∞ method and a threshold of 0.04 for both short axis and long axis images was applied to the validation set. The resulting averaged sensitivity/specificity for short axis and long axis were 0.69/0.80 and 0.87/0.67, respectively, which are improved relative to the phase difference method used in [2] (0.13/1 for short axis and 0/1 for long axis) .

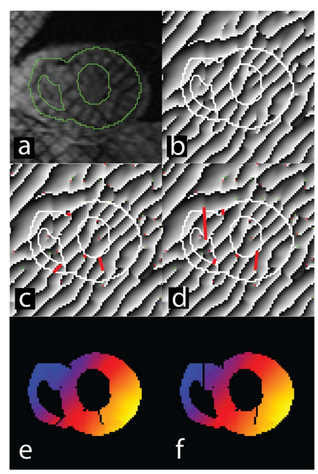

Fig 2. (a) Raw SPAMM image; (b) HARP phase image; (c,e) incorrectly placed branch cuts and unwrapped phase not detected by [2] but detected by the proposed method. (d,f) corrected branch cuts and unwrapped phase.

Fig. 3 shows the effect of phase unwrapping errors on mid-ventricular LV and RV strains and torsions. The red curves were computed from manually placed branch cuts. The other curves were computed from automatically placed cuts and performing manual correction only in images detected by either the phase difference method in [2] (green) or the proposed method (blue) as having phase unwrapping errors. Phase unwrapping errors undetected by [2] resulted in noticeable strain and torsion errors during diastole whereas almost all phase unwrapping errors were detected by the proposed method.

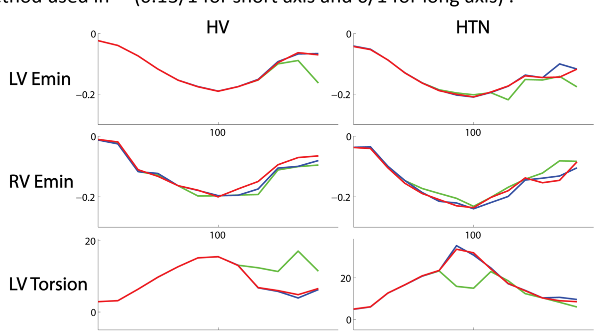

Fig. 3. Effect of phase unwrapping errors on mid-ventricular principal strains (Emin) and torsions vs % systolic interval for a normal volunteer (left) and a patient with hypertension (right). Red: branch cuts manually placed in all images. Green/Blue: branch cuts automatically placed and manually corrected in images detected by either the phase difference method in [2] (Green) or the proposed method (Blue)

CONCLUSION: Unwrapping errors can be detected based on spatial smoothness of the unwrapped phase image. The L^∞ norm performs the best of the three norms tested and performs better than the phase difference detection method in [2].

REFERENCE: [1] Ambale, et al. *JMRI* 2011; [2] Li, et al. *ISMRM* 2013; [3] Osman and McVeigh. *IEEE Trans Med Imaging* 2000