An Integer Optimization Technique for Measuring Biventricular Cardiac Strain from Tagged MR Images

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TARGET AUDIENCE: Cardiologists, cardiovascular physiologists, scientists and engineers with research interests in cardiovascular MRI.

PURPOSE: Quality guided phase unwrapping, which is used in HARmonic Phase (HARP) unwrapping [1] and DENSE imaging [2], is a path-dependent unwrapping technique that is sensitive to phase inconsistencies (residues) [1]. In [1], phase inconsistencies were corrected using manually placed branch cuts (mSUP). However, due to the number of images with residues, ~ 1 hour of constant manual operation was required for a typical biventricular cardiac study with this method. Recently, a path-independent automated phase unwrapping based on the wrap count unwrapping and graph cut optimization was proposed for left ventricular strain analysis [3], which is considerably less sensitive to phase inconsistencies and provides unwrapped images that are both spatially and temporally smooth. In this abstract, we extend this method (Strain from Unwrapped Phase with Integer Optimization – SUPIO) to biventricular strain analysis.

METHODS: *Contour segmentation*: Myocardial contours were manually drawn for tagged image at end-diastole and end-systole. Then contours were automatically propagated to other time frames using a non-rigid registration method [4].

Automated phase unwrapping [3]: Each HARP image ψ was unwrapped by estimating the wrap count image *k* such that the unwrapped phase $\phi = \psi + 2k\pi$ was spatially and temporally smooth. *k* was obtained by minimizing the energy function:

$$E(k^t|\psi^t,\phi^{t-1}) = \sum_{i\sim j}|2\pi(k_i^t - k_j^t) + \psi_i^t - \psi_j^t|^2 + \alpha\sum_i|2\pi k_i^t + \psi_i^t - \phi_i^{t-1}|^2$$

Where ψ^t is the wrapped phase at time *t*, ϕ^{t-1} is the unwrapped phase at time *t*-1, *i* and *j* are neighboring pixels of the 4-neighborhood system, α is the weight of the unary term, which was set to be 0.01 in this abstract. After initialization (*k*=0), the solution of *k* could be found by iteratively optimizing a binary image $\delta \in \{0,1\}^{MN}$ or $\delta \in \{0,-1\}^{MN}$ and adding this binary image to the temporal *k*. The binary optimization at each step was solved using graph cuts.

Error Correction: Unwrapping errors mostly occurred on the right ventricle (RV), which has a relatively thinner wall. In addition to problems with through plane motion and noise, contrast at the RV free wall epicardium and endocardium makes these boundaries difficult to be distinguished from tag lines in the phase map. To correct the erroneous unwrapped phase, we used the manual branch cut placement method described in [1].

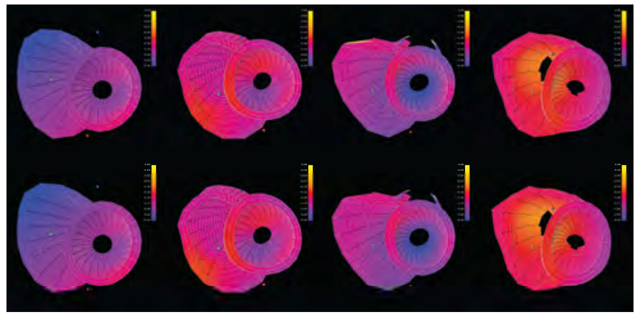

Fig 1. Representative end-systolic minimum principal strains computed using mSUP (top row - 2 min of quality guided unwrapping + ~1 hour manual processing time) and SUPIO (bottom row – 5min of automated phase unwrapping + ~15 min manual processing time) for (left to right) a normal volunteer, and patients with myocardial infarction and diabetes, resistant hypertension, and pulmonary arterial hypertension. An additional 30 min per study was required to draw LV and RV contours. Strain ranges from blue (25% contraction) to yellow (no change).

Strain Reconstruction: After all HARP images were unwrapped, 1D displacement at each pixel along the tag line normal direction was computed. These displacements were used to compute a 3D dense displacement field using a discrete model-free method [5]. Strains and torsion were computed from this 3D displacement field.

Patient Population and tMRI Protocol: A cohort of 30 studies (10 healthy volunteers (NL), 5 diabetic patients with myocardial infarction (DMI), 8 hypertensive patients (HTN), and 7 pulmonary arterial hypertensive patients (PAH)) were used as the validation dataset to compare the computed strains and torsion from the proposed method (SUPIO) to those from a feature-based method (FB) [5] and an unwrapped phase based method with manually placed branch cuts (mSUP) [1]. 8~12 short axis slices with grid tags and 6 long axis slices with line tags were acquired with a prospectively ECG gated fast gradient echo cine sequence. Tag spacing=7mm, FOV=40*40cm, scan matrix=256*128, 8mm slice thickness, flip angle=10°, TE=4.2ms, TR=8ms, 20 frames per cardiac cycle, typical temporal resolution=50ms.

Table1. Comparison of mid-ventricular strains and torsions computed from SUPIO and FB, or from SUPIO and mSUP at end-systole.

	SUPIO-FB				SUPIO-mSUP			
Strain	Differences	p	ρ	CV	Differences	p	ρ	CV
Ecc	0.011±0.002	0.16	0.95	0.02	0.002±0.001	0.83	0.97	0.01
Ell	0.007±0.002	0.49	0.95	0.02	0.001±0.001	0.88	0.98	0.01
Emin	0.006±0.002	0.48	0.95	0.01	0.002±0.001	0.80	0.99	0.01
Torsion	-0.983±0.148	0.11	0.96	0.03	-0.090±0.073	0.87	0.98	0.02
Ecc (RV)	0.021±0.003	0.02	0.87	0.03	0.003±0.003	0.70	0.85	0.04
Ell (RV)	0.016±0.002	0.10	0.94	0.02	0.002±0.002	0.80	0.97	0.02
Emin (RV)	0.017±0.002	0.07	0.94	0.02	0.005±0.001	0.61	0.98	0.01

Table2. Comparison of strains and torsions computed using SUPIO and mSUP.

Strain		Differences	p	ρ	CV
Emin	Peak	0.002±0.000	0.79	0.99	0.01
	Sys Rate	0.009±0.003	0.86	0.93	0.02
	E Dia Rate	0.016±0.006	0.81	0.74	0.07
Emin (RV)	Peak	0.006±0.001	0.52	0.91	0.02
	Sys Rate	0.003±0.007	0.96	0.65	0.06
	E Dia Rate	-0.072±0.007	0.25	0.62	0.08
Torsion	Peak	-0.213±0.021	0.81	0.98	0.01
	Sys Rate	-0.848±0.143	0.84	0.97	0.02
	E Dia Rate	2.153±0.246	0.68	0.94	0.04

RESULTS: The algorithm was implemented with MATLAB on a computer with a dual core 2.67GHz processor. For a typical biventricular study with 320 images, the automated phase unwrapping took 5 min, followed by 15 min of manual intervention. For SUPIO, 6.25% of the images required manual branch cuts compared to 84% with mSUP. Comparisons between mid-ventricular strains (unitless) and torsions (degree) at end-systole from SUPIO and FB (SUPIO and mSUP) are shown in Table 1. Table 2 shows a comparison of peak strains (unitless), strain rates (sec^{-1}), peak torsions (degree), and torsion rates (degree/sec) between SUPIO and mSUP. Differences are mean ± standard deviation, p is the p-value of the paired t-test, ρ is the correlation coefficient, and CV is the coefficient of covariance. P-values of all correlations are less than 0.001. Figure 1 shows the plots of minimum principal strains at end-systole for a representative from each subject group using SUPIO and mSUP. Qualitatively, the strains from SUPIO and mSUP are quite close even though SUPIO requires ¼ the manual processing time.

CONCLUSION: The proposed SUPIO method can accurately and efficiently reconstruct the 3D+time biventricular strain with considerably less time and manual intervention.

REFERENCE: [1] Venkatesh, et al., JMRI 2011; 34(4):799-810; [2] Gilliam and Epstein, IEEE TMI 2012; 31(9):1669-1681; [3] Li, et al., MICCAI 2014; 578-585; [4] Feng, et al., JCMR 2009; 11(30); [5] Denney and McVeigh, JMRI 1997; 7(5):799-810