Improved Spatial Resolution and Reduction of Artifacts in Strain-Maps with Phase-Unwrap HARP

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Introduction: Myocardial tagging such as CSPAMM [1] combined with harmonic phase-analysis (HARP) [2] is a powerful method to quantify myocardial motion with high temporal resolution. However, strain-maps obtained with HARP are often corrupted by visible artifacts ('zebra-patterns') caused by noise, Gibbs ringing and interference from other harmonic peaks. Improving contrast-to-noise-ratio (CNR) and/or spatial resolution at the cost of temporal resolution is limited by wraps in the HARP-phase. With other methods such as displacement encoding with stimulated echoes (DENSE) [3] this trade-off is possible and high-quality strain-analysis with high spatial resolution can be achieved. The use of the conventional peak-combination method [4], which has been proven to not only increase the SNR of the HARP-images but also to efficiently reduce artifacts caused by B0-inhomogeneity, yields even twice as many phase-wraps. In this work, an improved method for peak-combining HARP-images is introduced avoiding the increase of phase-wraps. Furthermore, by unwrapping HARP-images and applying a modified HARP method, robust tracking becomes possible even for data with very large motion between heart phases. The combination of these methods allows the generation of high-quality strain-maps with HARP.

Methods: In [4] an alternative peak-combination method is described, where the HARP-images originating from the two harmonic peaks (Fig.1b,c) are summed. This yields twice the spurious phase resulting from B0-inhomogeneity (Fig.1d). After dividing this B0-map by two and subtracting it from one of the HARP-images, spurious phases are removed but phase-wraps from the B0-map are still present (Fig.1e). To remove these phase-wraps, the B0-map has to be unwrapped (Fig.1f) and an artifact-free peak-combined HARP-image with the same number of phase-wraps is obtained (Fig.1g). For datasets with large motion between time frames, the peak-combined HARP-images are to be unwrapped likewise (Fig.1h) in order to make tracking possible. Furthermore, a modification of the HARP-method is necessary to avoid that the starting point of the HARP-search is located outside the myocardium due to large motion between time frames.

For phase-unwrapping, a modified 3D guided flood-fill algorithm which does not require any user-interaction was implemented based on ideas presented in [5-6]. Quality-maps for each time frame are obtained by calculating phase derivative variances and 2D phase unwrapping is performed by choosing the pixel with the best quality as the seed. Once all pixels with a phase quality above a certain threshold are unwrapped, the procedure is performed in the next time frame starting at the pixel with the best frame-to-frame quality. The threshold is decreased when all frames are completed and the procedure is continued until all pixels are unwrapped (Fig.1f,h).

To make HARP-tracking possible for datasets with large motion between time frames, the phase difference between the original phase of a landmark point and the phase value at each pixel in the new time frame is calculated (Fig.1i). The minimal difference within a masked region (threshold applied on the harmonic magnitude image) serves as the starting point for the HARP-algorithm in the new time frame.

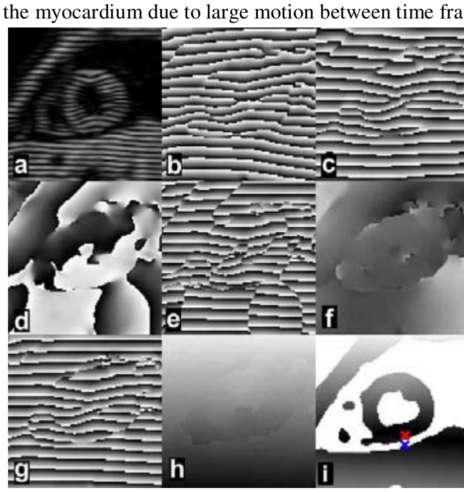

Figure 1: a) Tagged magnitude image. b, c) HARP-images of each harmonic peak. The phase is distorted due to B0-inhomogeneity, e.g. in the liver. d) (=b+c) B0-map. e) (=b-d/2) Peak-combined HARP-image: Phase wraps of B0-map are present, impairing HARP-analysis. f) Unwrapped B0-map. g) (=b-f/2) Peak-combined HARP-image: No phase distortions (wraps aligned with tag-lines) and no phase-wraps from B0-map. h) Fully unwrapped peak-combined HARP-image. i) Masked image showing the difference between the original phase of the landmark point (blue 'x') and the phase value at each pixel in the new time frame. The starting point of the HARP-search is moved from the blue to the red 'x').

Equatorial slice following CSPAMM images from a healthy volunteer were acquired in one breath-hold. An EPI-sequence was used on a Philips 1.5T scanner (Philips Medical Systems, Best, NL) (FOV:320mm, matrix:128x43, reconstructed:256x256, EPI-factor:9, ramped flip angles, total scan time:17s). Three scans were acquired with different tag distance and temporal resolution, requiring different post processing methods as described in Table 1. Color coded strain-maps were obtained by HARP-tracking 12 contours consisting of 120 landmark points and calculating the relative distance changes in circumferential direction. The HARP-filter was Hanning shaped to reduce Gibbs ringing and a radius at half maximum was chosen to be about 60% of the distance between the harmonic peak and k-space center.

Results: Fig.2 demonstrates the strong correlation of the zebra-patterns in the strain-maps with CNR of the tagging images. The phase unwrapping method reliably processed all datasets without any evident phase discontinuities inside the myocardium within or between time frames. HARP-tracking was robust and error-free applying the modified HARP-method. Fig.3 displays strain-maps 360ms after tagging preparation, i.e. at end-systole for the three different methods listed in Table 1. Compared to Fig.3a increased strain is visible in Fig.3c at the free wall and towards the endocardium.

	# phases	temp. res.	tag dist.	flip angle	HARP-analysis
scan 1	20	32 ms	8 mm	20°	Conventional peak-combination HARP, no phase unwrapping
scan 2	20	32 ms	5 mm	20°	Peak-combination using unwrapped B0-maps
scan 3	5	107 ms	5 mm	38°	As scan 2 & unwrapping of HARP-images & modified HARP

Table 1: Scan- and post processing parameters

Conclusions: The improved peak-combination technique for HARP allows decreasing the tag distance while maintaining the temporal resolution, which results in less peak interference and higher spatial resolution. By applying the proposed method of additionally unwrapping the HARP-images and using a modified HARP-tracking method, tagging images with a high CNR but low temporal resolution can be post-processed. Thus, high quality strain-maps with increased spatial resolution can be generated. An improvement of strain-map quality could be demonstrated both in the model and in-vivo.

References: [1] Fischer SE, et al., 1993, MRM 30: 191-200. [2] Osman N, et al., 1999, MRM 42: 1048-60. [3] Aletras AH, et al., 1999, JMR 140: 41-57. [4] Ryf S, et al., 2004, JMRI 20: 874-8. [5] Spottiswoode BS, et al., 2005, Proc. ISMRM: 2786. [6] Ghiglia DC and Pritt MD, *Two-dimensional phase unwrapping*, 1998, Wiley-Interscience

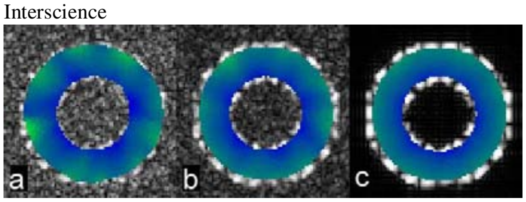

Figure 2: Strain-maps for a contracting & rotating ring (software model): a) CNR=15, b) CNR=30, c) CNR=∞.

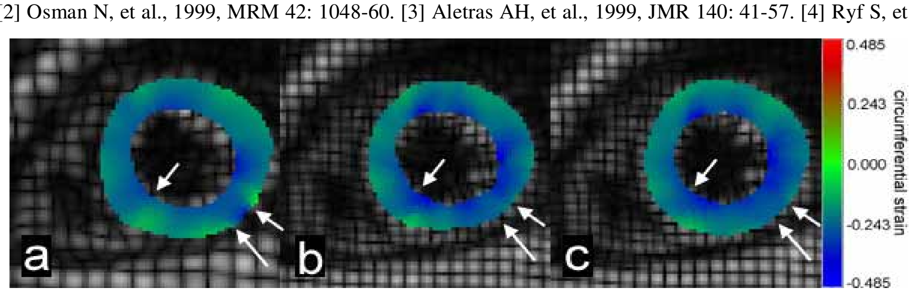

Figure 3: Circumferential strain-maps at end-systole: a) Scan 1, b) Scan 2, c) Scan 3. Arrows highlight artifacts in the strain maps which are reduced with increasing CNR in b) and c).