Phase Unwrapping for Absolute Cine-DENSE Myocardial Displacement Measurements using a 3D Guided Flood-Fill Algorithm

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Introduction: Displacement encoding with stimulated echoes (DENSE) (1) encodes myocardial tissue displacement into the phase of the MR image. To achieve enhanced motion sensitivity, relatively high displacement encoding frequencies are used and phase wrapping typically occurs. The purpose of this study was to develop algorithms to phase unwrap a time series of cine-DENSE images, thus enabling the computation of absolute myocardial motion trajectories (3). The unwrapping was implemented by extending a 2D quality-guided path following phase unwrapping method (4) to unwrap phase through time as well as space.

Methods: Let $\phi(i,j)$ be the wrapped phase and $\varphi(i,j)$ be the true, unwrapped phase. The coordinates i and j define the pixel position within the image. Phase wrapping can be defined as $\varphi(i,j) = \phi(i,j) + 2\pi k(i,j)$, where $k(i,j)$ are integers that force $\phi(i,j)$ to lie between $-\pi$ and π radians. Phase unwrapping entails determining all values of $k(i,j)$, and it can be done along a particular path by integrating the wrapped differences of the initially wrapped phases.

The 2D quality-guided phase unwrapping method uses a measure of phase "quality" to guide the path of unwrapping. A good measure of phase quality is a root-mean-square measure of the variances, within an $n \times n$ pixel region, of the spatial partial derivatives. The unwrapping path is guided by a region growing algorithm, which floods into regions of high quality phase before those with lower quality. Figure 1 captures six steps of the 2D quality-guided flood-fill procedure commencing from an arbitrary seed point in the myocardium, and using the phase quality map shown in Figure 2(c).

To obtain absolute phase measurements, it is necessary that the unwrapping path is initiated on a portion of tissue with known absolute phase. Very little cardiac motion takes place between the displacement encoding and the acquisition of the first frame of cine-DENSE data. It is therefore characteristic that no phase wrapping will have occurred on the first frame, and that all phase measurements in the myocardium will be absolute. Unwrapping the phase through time will thus result in measurements of absolute phase for all frames. This implicitly assumes that the true motion between frames for each pixel separated in time amounts to less than $|\pi|$ radians. This will always be the case given practical values of pixel size and displacement encoding frequencies. If the phase quality maps for a cine series are stacked on top of each other, then the quality-guided algorithm can easily be adapted to unwrap in 3D (one temporal and two spatial dimensions).

The following algorithm for unwrapping cine-DENSE phase images was implemented in MATLAB: Step 1. Calculate phase quality maps for all frames. Step 2. Manually place a seed point anywhere in the myocardium on the first frame. Step 3. Perform 3D quality-guided phase unwrapping, limiting the spatial unwrapping to a specified radius per frame. As soon as an unwrapped pixel appears on a particular frame, disallow all unwrapping for all previous frames. Step 4. Once unwrapped pixels are present on all frames, perform 2D quality-guided phase unwrapping for each frame independently, starting at the correctly unwrapped reference pixels.

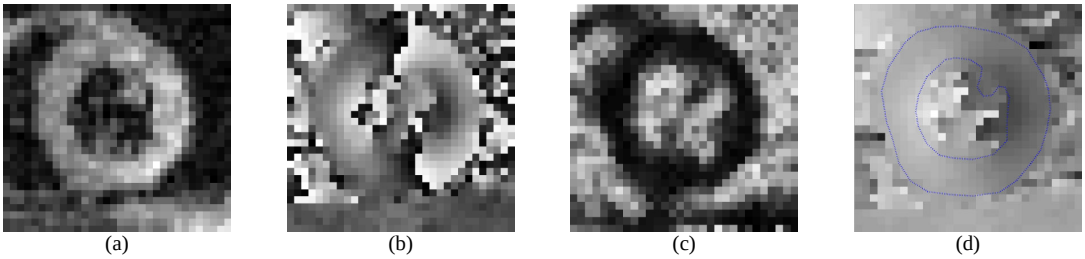
Step 2 serves to force the unwrapping through time using only high phase quality. If the 3D quality-guided flood-fill is used for the entire unwrapping process, phase inconsistencies are introduced at the later stages of the procedure due to temporal unwrapping between isolated regions of high quality phase in the noisy areas (lungs and ventricular cavities), and regions within the myocardium. The radius size is set based on the frame rate and the maximum expected amount of cardiac displacement per frame. It should be large enough to allow the 3D unwrapping to migrate spatially with the ventricle as it moves, but small enough to restrict the 3D unwrapping to relatively high values of phase. A radius of 2 pixels was used here.

A useful method for estimating where phase unwrapping errors may have occurred involves combining a map of unwrapped phase discontinuities with the phase quality map (3). The discontinuity map specifies the locations of pixels that differ from a neighbour by more than π radians. Unwrapping errors are likely to have occurred within regions isolated by the combined map. Eight sets of 12 frame cine-DENSE images with 2.81×2.81 mm pixel size were unwrapped. The combined maps were used to aid a visual inspection of the left ventricle (LV) for unwrapping errors. If a single error was encountered, then the image was deemed incorrectly unwrapped.

Results: An example of a cine-DENSE magnitude and phase image at end-systole is shown in Figure 2(a) and 2(b), respectively. Phase wrapping discontinuities are evident on the LV at 12 o'clock and 5 o'clock. The corresponding phase quality map is shown in Figure 2(c). The correctly unwrapped phase image, with superimposed LV borders, is shown in Figure 2(d). The method correctly unwrapped the LV phase in 191 out of the 192 of the images analysed (99.5%).

Conclusions: A reliable method of obtaining absolute phase measurements for cine-DENSE has been developed. The method will work for any view of the heart, and the only user interaction required is the selection of an initial seed point in the myocardium. Step 2 of the method could be improved by using 3D phase quality maps, whereby the variance of the partial derivatives of the locally unwrapped phase is obtained over an $n \times n \times n$ region of phase data. The method is also applicable for unwrapping harmonic phase (HARP) (4) images, although it is not very robust without masks of myocardial contours. These algorithms will help automate the analysis of cine-DENSE data, including the computation of absolute motion trajectories.

Figure 1. Progression of the guided flood-fill operation using the quality map in Figure 2(c). The calculation intervals are arbitrary.



(a) (b) (c) (d)

Figure 2 (a) Short axis DENSE magnitude image. (b) Wrapped DENSE phase image for horizontal motion. (c) Variance of the derivatives of the locally unwrapped phase for the four neighbouring pixels. (d) Unwrapped image with LV endocardial and epicardial contours superimposed.

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