Motion-guided Segmentation of the Left Ventricle for Cine DENSE MRI

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Introduction: Cine displacement encoding with stimulated echoes (cine DENSE) [1] allows myocardial motion to be tracked through the cardiac cycle at a pixel resolution [2]. Manually delineating the myocardium is currently the most time-consuming and labor-intensive component of cine DENSE image analysis. We introduce a novel segmentation method that makes use of the cine DENSE myocardial motion information to project a single manually drawn contour onto all cardiac phases.

Methods: Tissue displacement is encoded onto the phase of cine DENSE images. Figure 1a shows a 2D DENSE displacement field for a single frame of a short-axis view of the left ventricle (LV). The LV is evident contracting towards the center of the image. The phase data in the blood and surrounding pulmonary cavity is noisy, and the appearance of these vectors is random. Note that the vector tails all refer to the tissue position at the time of displacement encoding (t_0), and the vector heads, which lie on the pixel centers, refer to the position at the current frame. The aim here is to extract the myocardium from a time series of such displacement data.

If all or a portion of myocardium is manually defined on any frame, the position of this myocardium at t_0 is identified by the vector tails. These points can then be tracked through time using 2D distance-weighted interpolation of the cine DENSE displacement fields [2], thus identifying the position of the myocardium at all other frames. Since it is the phase of the cine DENSE image that is of interest, it is useful to draw the initial contour on a *phase quality map*. A suitable measure of phase quality is the root-mean-square of the variances, within a 4-nearest-neighbour region, of the spatial partial derivatives of the locally unwrapped phase. Figure 2a, b and c depict typical images of magnitude, phase and an inverted phase quality map, respectively.

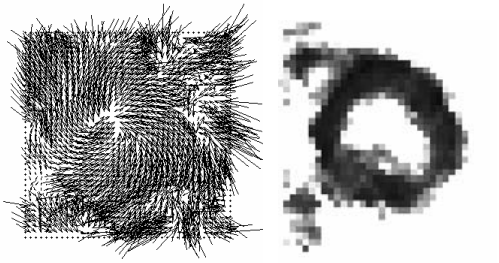
If all myocardial points at t_0 are tracked as described in [2], then frame-to-frame trajectories such as those shown in Figure 3a result. Many of these trajectories are incorrect because noisy vectors from the lungs and blood pools intrude into the myocardium and are inadvertently being used for the 2D interpolations. The effect of these noisy vectors can largely be removed with a *strain mask*, which is obtained by combining orthogonal spatial derivatives of the displacement fields. The strain mask corresponding to Figure 1a is shown in Figure 1b. By setting a threshold that excludes all strain values greater than those found in the human heart (70 % was used here), one can eliminate the majority of the noisy displacement vectors. Figure 3b shows the trajectories if these strain masks are used prior to applying the tracking.

Further noisy vectors can now be removed based on their deviation from the mean magnitude and angle of nearby vector tails. Using the 9 closest vector tails, vectors with angle deviation $> \pi/6$ radians and magnitude deviation > 0.7 are ignored. Figure 3c portrays the improvement offered by these heuristic rules. A binary mask for each frame can be obtained by representing each trajectory position by a 2D Gaussian function with an area of unity and a spread of 1.25, and then thresholding this image at 0.5. Contours can easily be extracted from these binary images. The periodic contours in the short axis LV view are then smoothed using 4th order Fourier basis functions, and the temporal evolution of contour shapes are restrained by assuring that the Fourier harmonics for adjacent frames are similar.

The algorithm was written in MATLAB and tested on 14 cine DENSE datasets, each with 25 cardiac phases. For each dataset, the epicardial and endocardial borders were manually contoured for a single cardiac phase in early systole. Based on the sum of false positive and false negative area measures, the automatic contours were compared to manually-drawn contours from two independent observers. Inter-observer variability was also investigated.

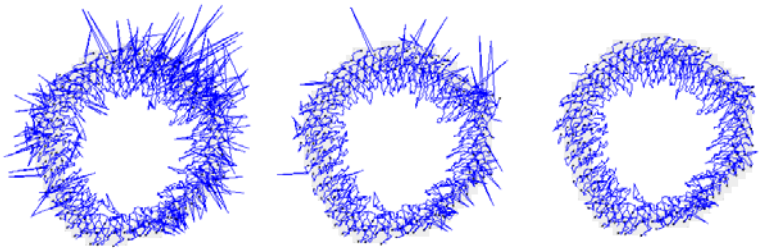
Results: Figure 2d, e and f show an example of motion-guided contours depicted on inverted phase quality maps for a few cardiac phases. A papillary muscle has also been contoured using the same algorithm. Epicardial and endocardial contours were successfully extracted from the binary masks in 332 out of 336 images (98.8%), and the mean processing time per frame was 2.19 seconds on a 2.8GHz Intel Celeron with 256MB of RAM. The 4 errors were due to transmural discontinuities in the binary mask, which can occur where the myocardial width spans only 1- 2 pixels. In these cases, active contour models could be applied to bridge the gaps. Segmentation inaccuracies can also occur when encoded tissue moves through the image plane. Visual inspection with reference to the phase quality maps showed these effects to be adverse in 12 out of the remaining 332 images (3.6%), reducing the effectiveness of the algorithm to 95.2%. The segmentation error between the two observers was 19.8%, and between the observers and this algorithm was 16.3%, demonstrating that inter-observer variability is similar for the algorithm and humans.

Conclusions: A novel and effective segmentation method has been developed for cine DENSE, where encoded motion in the myocardium is used to guide a set of contours through time. The total user interaction in cine DENSE analysis is thus reduced to the manual demarcation of the myocardium for a single frame. The method was successful in 95.2% of the images studied here. This may be improved by accommodating for through-plane motion with slice-followed (SF) cine-DENSE [3]. There are a number of unique advantages to this segmentation method: 1. the parameters used to discern between useful and noisy vectors are all based on practical physiological limits; 2. the method ensures that only "high quality" displacement data is used for analysis; 3. contours are calculated for the first few cardiac phases, where it is difficult to distinguish blood from myocardium; 4. whereas many segmentation methods are specific to a particular view of the heart, this motion-based segmentation with SF cine-DENSE is independent of the imaging plane; 5. the method is independent of the shape of the tissue delineated.



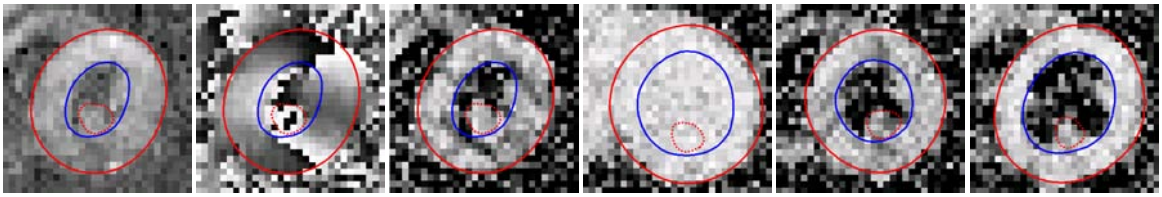
(a) (b)

Figure 1 (a) Un-contoured DENSE displacement field for a single frame. (b) The corresponding strain mask.



(a) (b) (c)

Figure 3. Frame-to-frame trajectories obtained (a) using the 3 closes vector tails, (b) using the strain mask, and (c) using both the strain mask and the vector magnitude and angle deviation criteria.



(a) (b) (c) (d) (e) (f)

Figure 2 (a) Magnitude, (b) phase, and (c) inverted phase quality map of a short axis view at end-systole depicting manually drawn contours. Corresponding motion-guided contours depicted on inverted phase quality maps for (d) end-diastole, (e) early-systole, and (f) mid-diastole. The dotted line depicts a papillary muscle that has been separately tracked and contoured using the same algorithm.

1. Kim D. *et al.* Radiology 2004; 230:862-871. 2. Spottiswoode B.S. *et al.* Proc. ISMRM 2005; #778. 3. Spottiswoode B.S. *et al.* Proc. SCMR 2006.

Acknowledgements: Supported in part by NIBIB grant RO1 EB 001763.