An MRI-based Automated Myocardium Boundary Detection Technique using Displacement Encoding with Stimulated Echoes (DENSE) Images

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Purpose: Displacement Encoding with Stimulated Echoes (DENSE) is a Magnetic Resonance (MR) elastography technique developed to encode phase information from myocardial tissue displacement, which occur during the mixing period of the sequence and is stored in the longitudinal magnetization direction for prolonged periods. While there exists a number of semi-automated algorithms for processing phase data in complex DENSE images, with displacements retrieved for Left Ventricular (LV) strain analysis, there remains a need for fast, sophisticated techniques that address myocardial segmentation in DENSE images. This study proposes a novel, automated technique for detecting myocardial boundaries, using the DENSE phase data and image quantization via thresholding, which can significantly expedite the strain computation process.

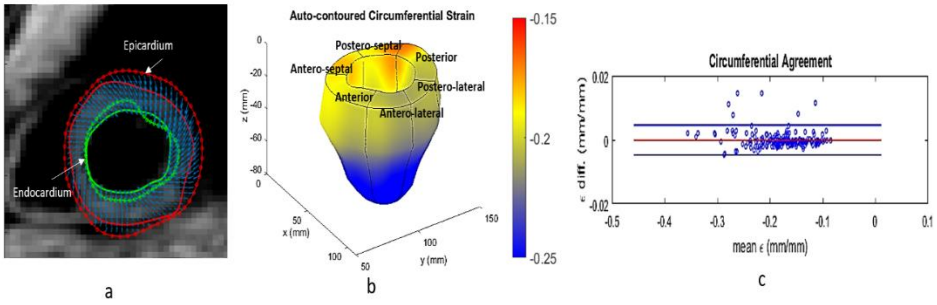

Figure 1. **(a)** Automated boundary detection in 2D slices assisted by temporal displacement analysis. **(b)** Circumferential strain map on 3D LV geometry reconstructed from automated contouring. **(c)** Bland-Altman agreement between circumferential strains from automated and manually contoured LV geometries.

Method: This detection algorithm has been primarily architected for auto-contouring the myocardial boundaries in short axis images (Figure 1a), based on both spatial and temporal increments, such that full 3D LV geometries can be reconstructed at discrete time-frames (points of image acquisition) during the cardiac cycle. Initially, a reference quantized image of the myocardium at end-diastole is created using an optimized threshold evaluation algorithm called multi-level Otsu's Method. With this approach, discrete points on a bounding ellipse, initially formed to enclose the basilar (largest) myocardium, radially search for pixel-based image gradients (intensity differences) in the quantized image, essentially forming an edge detection scheme that distinguishes the myocardium from surrounding tissue or chest cavity. The formation of the reference boundary is followed by spatio-temporal searches for boundaries in subsequent time-frames, guided by each boundary point's nearest-neighbor pixel displacements as obtained by unwrapping the phase images, and also updated image quantization that detect changes in myocardial shape (Figure 1a). In this way, the morphology of myocardial boundaries can be tracked between end-diastole and end-systole in each 2D short-axis slice and full 3D LV geometries reconstructed [1]. The accuracy of the algorithm was tested by performing DENSE scans on N=12 healthy subjects, conducting myocardial boundary detection using the automated method and a manual contouring scheme for control data, reconstructing 3D LV geometries from both contouring types, and followed by LV chamber quantifications (myocardial wall thickness, Ejection Fraction (EF), LV mass and others), and computation of 3D myocardial strains (Figure 1b) using the Radial Point Interpolation Method (RPIM) [1]-[2]. Statistical analysis was then conducted, using Student's t-test to compare the results of chamber quantifications and Bland-Altman analysis to establish regional strain agreements between the two contouring methods.

Results: Significant differences were not found between results of chamber quantifications, including wall thickness, which were 7.7 ± 1.3 mm and 7.8 ± 1.4 mm ($p = 0.71$), EF, which were 0.54 ± 0.05 and 0.54 ± 0.05 ($p = 0.79$), and LV mass, which were 40.9 ± 14.0 grams and 41.5 ± 13.8 grams ($p = 0.86$), for automated and manual contouring types, respectively. Neither were significant differences found from comparisons in global circumferential strains, which were -0.18 ± 0.05 and -0.18 ± 0.05 ($p = 0.98$), global longitudinal strains, which were -0.20 ± 0.09 and -0.20 ± 0.09 ($p = 0.99$), or global radial strains, which were 0.31 ± 0.11 and 0.30 ± 0.11 ($p = 0.81$), for the automated and manual contours, respectively. Figure 1c shows the Bland Altman agreement between regional (N=16 in each subject)

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circumferential strains, obtained with the two contouring methods, and similar biases were obtained for regional longitudinal and radial strains, both of which were 0.00 ± 0.05.

Discussion and Conclusion: The similar results for LV chamber quantifications and 3D strains obtained from automated and manual contouring techniques, as well as the small biases from the Bland Altman analysis on the two methods, indicate that the proposed automated contouring scheme can be reliably applied towards rapid and accurate computation of LV parameters. An additional conclusion is that this fast, less manually intensive myocardial boundary detection technique can become clinically significant once its accuracy is demonstrated in studies on cardiac dysfunction.

References:

[1] J. Kar *et al*., "Three-dimensional regional strain computation method with displacement encoding with stimulated echoes (DENSE) in non-ischemic, non-valvular dilated cardiomyopathy patients and healthy subjects validated by tagged MRI," *J. Magnetic Resonance Imaging*, vol. 41, no. 2, pp. 386-396, Feb. 2015.

[2] J. Kar *et al*., "A validation of two-dimensional in vivo regional strain computed from displacement encoding with stimulated echoes (DENSE), in reference to tagged magnetic resonance imaging and studies in repeatability," *Ann. Biomed. Eng*., vol. 42, no. 3, pp. 541-554, Mar. 2014.

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Introduction

This study presents a rapid and automated methodology for tracking left-ventricular boundary motion during the cardiac cycle. This approach is significantly unique due to the application of position encoded data for tracking the precise location of the left-ventricular (LV) myocardium (and its boundary) through cardiac systole. The advantages to automated boundary detection include significantly less interaction from the operator, significantly reduced post-processing time, and the ability to be standardized to provide clinically important evaluations i.e. estimates of ejection fraction (EF).

Boundary detection itself is broken up into three components: image segmentation using a threshold method based on quantization of grayscale pixels, feature identification using probability distribution of pixel intensities from the histogram of the quantized image, and motion analysis using high resolution phase information encoded in the complex images obtained with DENSE. Displacement Encoding with Simulated Echoes (DENSE) is a pulse sequence that encodes displacement in the phases of readout due to underlying tissue motion[4]. DENSE tracks boundary deformations identified with quantization and locates new points[5].

Image quantization is a lossy (irreversible) compression technique that compresses a range of pixel colors to a single quantum value.

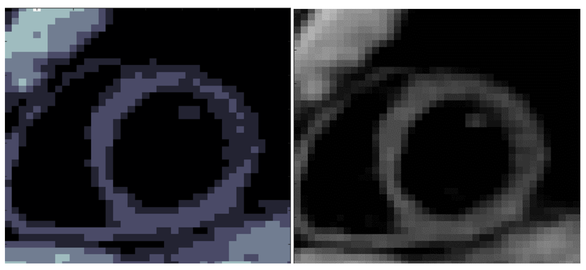

Figure 1: Original image quantized to 8 classes of pixels and 7 thresholds using the non-uniform, histogram-based Otsu's Method.

Methods

Image Quantization - Otsu's Method:

Otsu's Method[2] divides the original image into M classes and M-1 thresholds.

(1) $\sigma_b^2 = \sum_{i=1}^{M} w_k\,(\mu\_k - \mu\_T)^2$ minimizes an interclass variance.

(2) $\mu_k = \sum_{i\varepsilon C_k} i\,\frac{p_i}{w_k}$ forms the class mean.

w_k is the class probability, p_i is the probability of intensity, i, in the entire image.

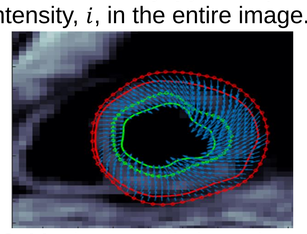

Figure 3: Moving systolic boundary due to quantization and displacement encoding

Phase Unwrapping:

Phase $\mathrm{unwrapping}$[1] occurs by integrating the difference, $\Delta\phi$, between locally wrapped phases,

(3) $\phi(r) = \int_C \nabla\phi(\mathrm{r}) \cdot \mathrm{dr} + \phi(r_0)$

where the "true" unwrapped phase for a pixel, $\phi(i,j)$:

(4) $\phi_{ij} = \phi_{ij} + 2\pi k_{ij}$

Therefore the pixels within the myocardial boundary can be considered a discrete collection of material points.

Strain Analysis with Meshfree Radial Point Interpolation Method (RPIM):

Define a continuous displacement field function, $u(x)$, passing through a cluster of nodes

(5) $u(x) = \sum_{i=1}^{n} B_i(x)a_i + \sum_{k=1}^{m} p_k(x)b_k = B^T(x)a + P^T(x)b$

where $P(x)$ is the matrix of monomial bases, $B(x)$ is the radial basis functions, b and a are coefficient $\mathrm{vectors}$[3].

Assemble a generalized basis function, G, by adding a constraint to the previous equation.

(6) $\begin{bmatrix} \mathrm{B} & \mathrm{P} \\ \mathrm{P^T} & 0 \end{bmatrix}\begin{bmatrix} \mathrm{a} \\ \mathrm{b} \end{bmatrix} = \mathrm{G}\begin{bmatrix} \mathrm{a} \\ \mathrm{b} \end{bmatrix} = \begin{bmatrix} \mathrm{u^e} \\ 0 \end{bmatrix}$

where (7) $\mathrm{u^e} = [\mathrm{u_1}, \mathrm{u_2}, \ldots, \mathrm{u_n}]^{\mathrm{T}}$ is the vector for displacements.

Compute the deformation gradient tensor,

(8) $\mathrm{F} = \frac{\partial \mathrm{u(x)}}{\partial \mathrm{a}} = \frac{\partial [\mathrm{B}(x), P(x)]}{\partial x}[a, b]^T$.

Results

Subject Details:

The average age of the subjects was 30.5 ± 7.8 years and body weight was 145.0 ± 21.1 lbs. Monitored mean heart rate (HR) from all studies was 66.6 ± 8.0 bpm while mean blood pressure (BP) was 120.0 ± 16.7/77.3 ± 15.1 mmHg.

Region	Myocardial Wall Thickness (cm)		Myocardial Diameter (diastolic) (cm)		Myocardial Diameter (systolic) (cm)		Diastolic Volume (ml)		Systolic Volume (ml)		Ejection Fraction (%)		Mass (g)	
	Automated	Manual	Automated	Manual	Automated	Manual	Automated	Manual	Automated	Manual	Automated	Manual	Automated	Manual
Apical	0.8 ± 0.2*	0.8 ± 0.2	3.8 ± 0.5**	3.8 ± 0.5	2.6 ± 0.5**	2.7 ± 0.5	34.9 ± 8.0**	35.2 ± 7.9	16.9 ± 5.4**	17.1 ± 5.4	0.53 ± 0.06**	0.52 ± 0.06	51.9± 10.7*	52.3 ± 10.5
Mid-wall	0.8 ± 0.1	0.8 ± 0.1	3.5 ± 0.4	3.6 ± 0.3	2.4 ± 0.4	2.4 ± 0.3	29.8 ± 5.4	30.2 ± 5.4	13.4 ± 3.5	13.6 ± 3.5	0.56 ± 0.05	0.56 ± 0.05	45.5 ± 8.3	46.0 ± 8.4
Basal	0.8 ± 0.1	0.8 ± 0.2	3.2 ± 0.3	3.2 ± 0.3	2.1 ± 0.3	2.2 ± 0.3	23.9 ± 4.8	24.4 ± 4.6	11.0 ± 3.3	11.3 ± 3.2	0.55 ± 0.04	0.54 ± 0.04	25.3 ± 4.0	26.2 ± 4.1

Table 1: Comparison of LV chamber parameters estimated with automated and manual contouring in N=14 normal subjects. All p-values ≥ 0.9 except *p=0.6,**p=0.8.

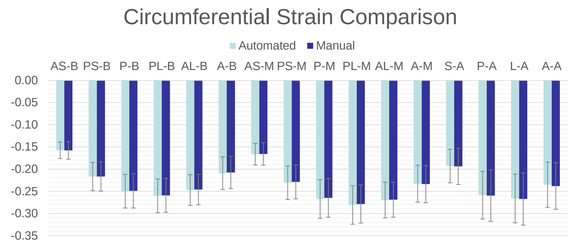

Table 2:Radial Point Interpolation Method (RPIM) was used to compute 3D circumferential strains within both automated and manually contoured boundaries. N=14 normal subjects.

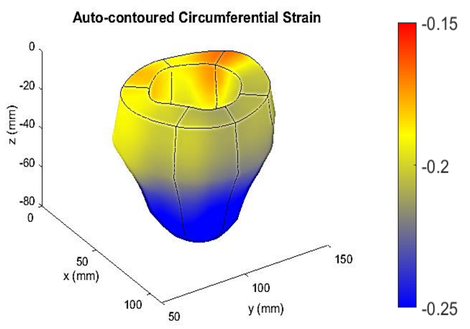

Figure 4: Circumferential surface strain map with automated contouring of myocardial boundaries.

Conclusions

1. The current study was conducted to demonstrate the feasibility of a novel process automation technique for rapid and accurate detection of myocardial boundaries.
2. Important dimensions and functional parameters related to cardiac output and its mechanism were computed,
3. Similarities with manual contouring results validate the automated processing.
4. Standardized automated boundary detection techniques based on true tissue displacement can provide clinicians with essential ground-truth information similar to most tissue contrast based techniques.
5. The encouraging results in healthy volunteers imply that the present technique should be tested in patient populations.

Bibliography

1. Kim et al., Myocardial. Radiology, 2004.
2. Otsu N. A Threshold. Cybernetics, 1979.
3. Liu GR. Meshfree. CRC Press, 2009.
4. Kar et al., Ann. Biomed. Eng., 2015.
5. Kar et al., Ann. Biomed. Eng., 2014.

Acknowledgments

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