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Model-Based Multilayer Registration of the Left Ventricle Using CT Imaging

Enhancing LV Regional Longitudinal Strain Estimation and Arrhythmogenic Substrate Localization

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Abstract: Accurate localization of arrhythmogenic substrates is crucial for effective stereotactic arrhythmia radioablation (STAR) in ventricular tachycardia (VT) patients. Conventional CT registration methods for left ventricular (LV) strain estimation face challenges due to image quality limitations and motion coupling. We propose a novel model-based CT registration algorithm that incorporates anatomical constraints to enhance LV strain estimation. Our approach segments the LV myocardium using 3D Slicer's TotalSegmentator extension, models it as a harmonic scalar field, and discretizes it into multiple layers to preserve layer-specific motion. A non-rigid registration technique then aligns end-diastolic and end-systolic volumes to compute regional longitudinal strain (RLS). Evaluation on CT data from ten VT patients demonstrates superior alignment and anatomical accuracy compared to conventional methods, potentially improving LV strain estimation for targeted therapy.

Keywords: Ventricular Tachycardia, Cardiac CT, Image Registration, Regional Longitudinal Strain, Multilayer Myocardial Mode, Electroanatomic Mapping

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1 Introduction

Accurate localization of arrhythmogenic substrates is crucial for effective stereotactic arrhythmia radioablation (STAR) in patients with ventricular tachycardia (VT). While electroanatomic mapping (EAM) remains the gold standard for characterizing these substrates, its invasive nature and procedural complexity have spurred interest in non-invasive alternatives for scar detection. Although multilayer regional longitudinal strain (RLS) derived from speckle-tracking echocardiography (STE) can localize scar tissue and quantify low-voltage regions [1-2], its effectiveness is limited by image quality, which renders nearly 10% of studies unsuitable for analysis [3]. Similarly, while 4D cardiac computed tomography (CT) has been used to assess global longitudinal strain (GLS) [4–5], its utility for RLS is constrained either by time-consuming manual landmark registration or conventional automatic methods that fail to capture layer-specific motion, Artifacts from implantable cardioverter defibrillators (ICDs) and low myocardial contrast also compound constraints.
To address these limitations, we propose a novel model-based CT image registration algorithm that integrates anatomical constraints with a multilayer myocardial model. By leveraging prior knowledge of myocardial structure, our approach aims to enhance the precision of left ventricular (LV) strain estimation. This advancement has the potential to expand technical modalities for delineating arrhythmogenic substrates and holds promise for refining STAR treatment planning.

2 Model-based image registration

Our framework for LV strain estimation consists of four steps as shown in Figure 1. The process begins with the segmentation of the LV myocardium. Typically, LV strain is quantified as the mean of measurements derived from a series

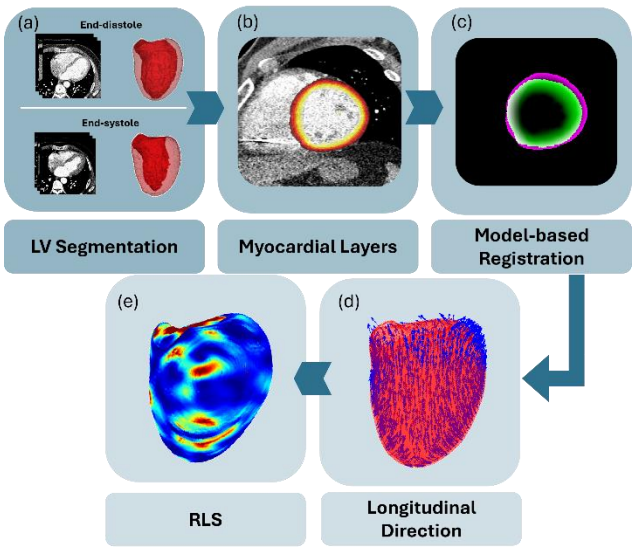

Figure 1 Pipeline for regional longitudinal strain estimation. (a) The left ventricular myocardium is segmented in both end-diastolic and end-systolic phases. (b) The segmented myocardium is discretized into distinct layers for each state. (c) The end-diastolic and end-systolic multilayer models are aligned using a npTV registration method. (d) The longitudinal direction is extracted. (e) Tensor strain is computed and projected onto longitudinal direction to derive the RLS.

of frames [4–5]. However, given that LV segmentation imposes significant computational and memory demands, our analysis was restricted to the end-systolic and end-diastolic phases for the generation of a single strain map. This is accomplished using TotalSegmentator [6], an open-sourced automatic segmentation toolbox.

To capture the structure of the myocardial layer, the LV is modeled as occupying a spatial region R^{LV} bounded by two simply connected surfaces: the endocardial surface $\partial_0 R^{LV}$ and the epicardial surface $\partial_1 R^{LV}$. A unique harmonic function u is computed over LV domain by solving Laplace's equation:

$$\boldsymbol{\nabla^2 u} = \frac{\partial^2 \boldsymbol{u}}{\partial \boldsymbol{x}^2} + \frac{\partial^2 \boldsymbol{u}}{\partial \boldsymbol{y}^2} + \frac{\partial^2 \boldsymbol{u}}{\partial \boldsymbol{z}^2} = \boldsymbol{0} \qquad (1)$$

For $(x, y, z) \in R^{LV}$. $\nabla^2 u$ represents local curvature of u, with boundary condition $u = 0$ on $\partial_0 R^{LV}$ and $u = 1$ on $\partial_1 R^{LV}$. Solving equation (1) enforces a monotonic increase from 0 to 1, ensuring smooth transitions and producing a continuous scalar field that gradually varies from the endocardium to the epicardium, effectively capturing the spatial structure of the myocardial wall.

To maintain the distinctiveness of various myocardial layers, the continuous gradient is discretized by partitioning the LV wall into several distinct layers. For every pair of adjacent layers, the amplitude is assigned as the average value within that segment, thereby ensuring a clear, measurable difference between neighboring layers (see Figure 1(b)). This approach preserves the inherent movement of each layer, ensuring that the displacement captured during registration remains confined to its corresponding layer.

The next step involves aligning the end-diastolic and end-systolic multilayer volumes (Figure 1(c)) using a non-rigid parametric Total Variation (npTV) registration method [8] from MATLAB's Image Processing Toolbox™, which computes a displacement field. Simultaneously, longitudinal direction vectors are extracted as those perpendicular to the LV surface and oriented from the apex to the mitral valve as shown in Figure 1(d). Finally, by projecting the computed tensor strain onto these vectors, an estimation of RLS is achieved (Figure 1(e)).

3 Results

Case data from 10 VT patients who underwent STAR therapy within the RAVENTA trial (NCT03867747) [9] were

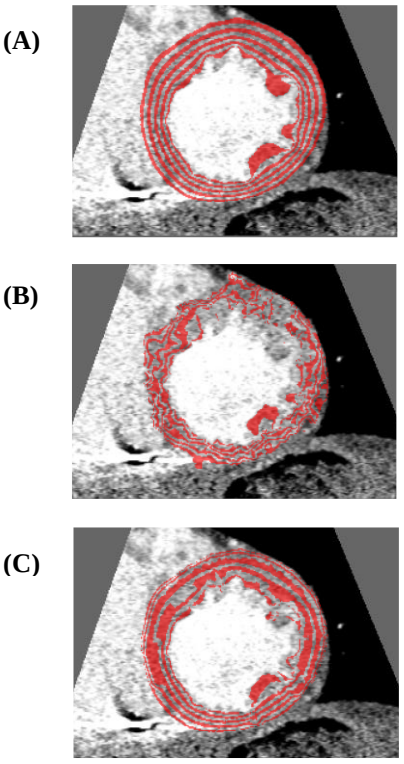

Figure 2 Comparison of image registration methods for left ventricular strain analysis. (A) CT image of the left ventricle in the systolic state, with the red-labeled multiple myocardial layers clearly highlighted. (B) Image-based npTV registration from diastole to systole, which introduces noticeable distortions in myocardial structures. (C) Proposed model-based npTV registration, resulting in significantly improved alignment and preservation of myocardial layers.

analyzed. Among these patients, seven had dilated cardiomyopathy (DCM) and three had ischemic cardiomyopathy (ICM). The myocardium was partitioned into five distinct layers to ensure that at least three non-adjacent layers (e.g., endocardial, mid-myocardial, and epicardial) exhibit independent motion, thereby minimizing motion coupling and reducing RLS measurement errors.

Through two experiments the registration algorithm was evaluated. Firstly, CT data from all 10 patients were used to assess registration accuracy by comparing our algorithm with a conventional CT image-based method using quantitative metrics. Secondly, clinical relevance was examined by comparing the spatial distribution of the RLS in five patients with high-quality EAM data to their corresponding EAM maps.

3.1 Registration accuracy evaluation

Figure 2 shows representative registered images with overlaid myocardial boundaries. The proposed method produces a more consistent and anatomically coherent alignment, with improved delineation of myocardial layers compared to the image-based method.

Table 1 compares both approaches using the Dice Similarity Coefficient (DICE) and Hausdorff Distance (HD) for overall LV segmentation and myocardium layer by layer (layer-specific). For the whole LV segmentation, our method achieves a higher DICE score (0.98 vs. 0.82) and a lower HD (11.0 mm vs. 20.2 mm). More notably, in layer-wise comparison, the proposed approach outperformed the image-based method (DICE: 0.57 vs. 0.28; HD: 10.5 mm vs. 20.6 mm). These results demonstrate that our method better preserves the distinctiveness of myocardial layers. Statistical analyses (paired t-tests) confirmed that the improvements in registration accuracy with the proposed algorithm were statistically significant ($p < 0.01$).

Table 1: Quantitative evaluation of left ventricular registration performance comparing the image-based method (IB) to the proposed model-based approach (MB) for overall LV segmentation and multiple layers. Metrics include DICE and HD, where increased DICE and decreased HD indicate improved accuracy.

	Overall LV		**Layer-specific**	
	IB	MB	IB	MB
DICE	0.82 ± 0.10	**0.95 ± 0.01**	0.28 ± 0.11	**0.57 ± 0.14**
HD (mm)	20.2 ± 6.8	**11.0 ± 4.1**	20.6 ± 5.9	**10.5 ± 4.5**

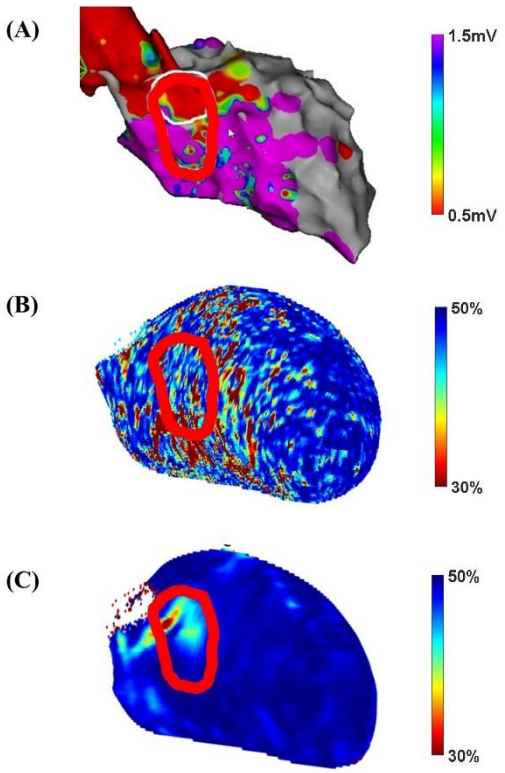

Figure 3 Visual comparison between EAM and RLS map for one representative case. (A) shows the EAM map with the designated STAR ablation target highlighted in red. (B) depicts the RLS distribution derived from a conventional image-based approach, again displaying the target in red. (C) presents the RLS distribution obtained from our proposed model-based approach, with the same target region outlined in red for reference.

3.2 Relationship between low RLS and EAM abnormal region

To assess the advantages of our proposed algorithm for computing RLS distributions, RLS maps were generated from data of five patients using both the model-based approach and a conventional image-based method, and subsequently compared with EAM data. As shown in Figure 3, the boundary of RLS regions around 30% closely corresponds with the transition between low and high voltage in the EAM maps. The narrow isthmus of low RLS in Figure 3(C) aligns with elevated activity in Figure 3(A). In contrast, the image-based RLS (Figure 3(B)) shows elevated noise and lacks clear correspondence, likely due to its chaotic displacement field without considering anatomical features.

4 Discussion

This study presents a novel model-based CT registration algorithm that enhances LV strain estimation by incorporating anatomical constraints and a multilayer myocardial model. By leveraging robust segmentation and discretizing the myocardium into multiple layers, our approach reduces motion coupling and improves strain measurement accuracy. Quantitative evaluation across ten VT patients revealed significantly improved registration accuracy, with higher DICE and lower HD compared to conventional image-based methods. Importantly, the qualitative comparison of RLS distributions with EAM data suggests that our method more accurately captures myocardial deformation patterns.

These findings highlight the potential of integrating prior anatomical information into image registration to improve both global and layer-specific assessments. Although no formal statistical correlation was performed, the visual observations suggest that our model-based RLS measure effectively captures myocardial deformation in line with underlying electrophysiological properties. This advancement is particularly relevant for optimizing STAR treatment, as precise localization of arrhythmogenic substrates is critical for effective ablation therapy.

However, some limitations must be considered. The small sample size may limit the generalizability of our findings, and a larger cohort is needed for further validation. Additionally, while our qualitative analysis suggests a strong correlation between low RLS regions and EAM abnormalities, a formal statistical correlation analysis is warranted. Future work should also explore extending the approach to full-cycle or dynamic imaging to capture myocardial motion more comprehensively.

Overall, our method represents a significant step forward in cardiac CT image registration, with promising implications for improving VT treatment planning and myocardial strain analysis. Future studies with quantitative correlation analyses and larger patient cohorts are warranted to further validate these findings.

5 Conclusion

Our novel registration approach improves LV deformation analysis by explicitly preserving layer-specific myocardial motion patterns. These results, validated through both quantitative metrics and EAM comparisons, suggest that our method may enhance arrhythmia substrate localization for VT patients undergoing STAR. Future work will expand on these findings with larger cohorts and quantitative EAM correlation analyses.

Author Statement

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