

Effect of Scar Interpolation Methods on Simulated Ventricular Tachycardia in Infarcted Heart Models

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Abstract

Patient-specific computational cardiac models show promise in identifying ablation targets for myocardial infarction (MI) related ventricular tachycardia (VT). However, these models typically rely on low interslice resolution late gadolinium enhanced cardiac MRI (LGE-CMR), necessitating accurate three-dimensional (3D) interpolation of infarct geometry. We proposed a novel methodology using anisotropic Eikonal diffusion of low-resolution scar along apex-base orientations to reconstruct 3D infarct geometry. Moreover, we extensively evaluated its efficacy against high-resolution manual scar reconstructions and the current baseline scar interpolation method, using metrics of both geometrical and electrophysiological similarity. In a porcine cohort of 7 infarcted left ventricle (LV) models, our method demonstrated superior geometrical accuracy compared to the current baseline, achieving an average Dice similarity coefficient (DSC) of $71.5\% \pm 7.0\%$. However, outcomes of electrophysiology simulations revealed greater deviations in VT induction using the proposed methodology compared to gold-standard scar. This study highlights the importance of precise infarct representation in patient-specific models to enhance their functional accuracy for predicting VT inducibility.

While this resolution is sufficient for generating 3D reconstructions of larger ventricular anatomy, accurately representing complex scar morphology and narrow conducting isthmuses (< 8 mm) [1], which are critical substrates for sustaining VTs, remains challenging.

Several interpolation methods have been employed to reconstruct scar from low interslice resolution 2D LGE-CMR slices [2–4]. Most notably, a shape reconstruction method, based on the logarithm of odds (LogOdds) function [5], has been shown to outperform these techniques [6]. Nonetheless, the LogOdds method has shown limited accuracy in reconstructing narrow isthmuses [1], underscoring the need for more robust interpolation methods.

The main contribution of this paper is threefold. Firstly, we proposed a novel interpolation methodology that uses Eikonal-based diffusion to obtain a 3D reconstruction of the infarct geometry from a multi-slice LGE-CMR image sequence. Secondly, we evaluated the accuracy of the proposed interpolation method using high-resolution LGE-CMR of porcine subjects and compared it to the baseline LogOdds method, assessing the sensitivity of both methods to their parameters. Finally, we aimed to quantify the functional electrophysiological implications of scar interpolation methods used during CMR-based model construction on VT inducibility.

1. Introduction

Patient-specific computational cardiac models demonstrate potential in guiding the identification of ablation targets for myocardial infarction (MI) related ventricular tachycardia (VT). These models are typically constructed using late gadolinium enhanced cardiac MRI (LGE-CMR), which often has a low interslice resolution (6–20 mm) [1].

2. Methods

2.1. Mesh Generation

LGE-CMR data with a 1 mm isotropic spatial resolution were acquired using 1.5T scanners for a cohort of seven porcine hearts [7]. Manual segmentation of the left ventricle (LV) myocardium and blood pool was performed by a single observer in Seg3D [8]. A full-width at half max-

imum intensity threshold technique was used to segment the infarct zone [9]. Three-dimensional (3D) computational models of the LV and scar tissue were subsequently generated for the porcine cohort based on tetrahedral finite element meshes using Meshtool [10]. Myocardial fibre orientations were incorporated into the model using the Laplace-Dirichlet rule-based approach by Bayer et al [11].

2.2. Scar Reconstruction

Gold-standard scar tissue (1 mm isotropic resolution) was downsampled to a short-axis interslice resolution of 10 mm, representing typical clinical LGE-CMR acquisitions. Two further computational models were generated for each porcine subject with reconstructed scar using different interpolation strategies (Figure 1). Firstly, we used statistical shape reconstruction based on the LogOdds function [5]. Briefly, this method involved the application of Gaussian smoothing and 3D cubic interpolation, followed by logistic filtering to segment the interpolated infarct shape. Secondly, we implemented anisotropic Eikonal diffusion of scar tissue along the apex-base (long-axis) orientation to reconstruct the downsampled scar. This proposed methodology involved mapping downsampled gold-standard scar points into the 3D LV mesh. A Laplace solve was then performed to compute the apex-base orientation, which subsequently defined the anisotropy in the Eikonal solve, along which scar points were diffused and thresholded to obtain the reconstructed scar.

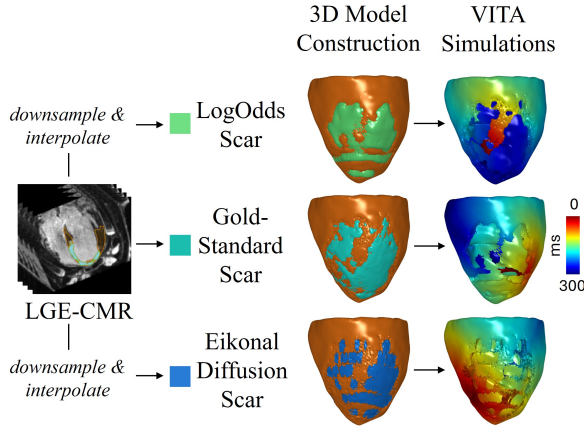


Figure 1. Overview of the methods, including 3D model construction and VITA simulations for the three ‘equivalent’ LV models with gold-standard scar and reconstructed scar via LogOdds and Eikonal diffusion interpolation.

2.3. Parameter Sensitivity Analysis

To determine the sensitivity of each method to its parameters, a sensitivity analysis was performed. The LogOdds

scar interpolation method was parameterised by the size of the Gaussian filter kernel (σ) in the smoothing step of the LogOdds method and a binary threshold (t_1) applied to segment the infarct shape. These parameters were varied individually in the interval $[0, 3.5]$ and $[0, 1]$, respectively. The Eikonal diffusion method was parameterised by the anisotropic ratio (AR), which determined the rate of diffusion along the apex-base orientation, and a binary threshold (t_2) which was applied following the anisotropic Eikonal solve to segment the reconstructed scar. Similarly, these parameters were varied individually in the interval $[1, 10]$ and $[0, 60]$, respectively. Appropriate parameter pairs were selected based on optimising the Dice similarity coefficient (DSC) and volumetric difference (ΔV) between the gold-standard and reconstructed scar.

2.4. Electrophysiology Simulations

The Virtual Induction and Treatment of Arrhythmias (VITA) framework [12] was applied to the virtual cohort of infarcted porcine hearts at five different pacing locations to probe the viability of the reconstructed scar substrates in sustaining re-entrant VTs. Briefly, VITA is a fully-automatic algorithm that leverages reaction-Eikonal models to induce VTs and assess the vulnerability of isolated isthmuses of conduction within scar to sustain re-entrant circuits based on their round trip time. The algorithm generated a set of activation maps for unique VTs which were assessed qualitatively. Additionally, for each porcine subject, quantitative VITA simulation metrics, including the total number of induced VTs and unique VTs, following filtering of equivalent VTs identified from different pacing sites, were compared for the three ‘equivalent’ models.

3. Results

3.1. Geometrical Accuracy of Scar Reconstructions

Table 1 quantitatively evaluates the similarity between the reconstructed scar and the gold-standard scar for each subject. The LogOdds and Eikonal diffusion interpolation methods achieved a similar geometrical accuracy, with a mean DSC of $70.1\% \pm 4.6\%$ and $71.5\% \pm 7.0\%$ and a median DSC of 71.9 and 68.1, respectively. However, the mean ΔV was greater for the Eikonal diffusion scar than the LogOdds scar, at $8.49\% \pm 4.04\%$ versus $5.19\% \pm 3.30\%$, respectively. For both methods, the volume of reconstructed scar was greater than the gold-standard scar in most subjects. Overall, the LogOdds method generated relatively smooth and anatomically realistic scar geometries. In contrast, the distribution of reconstructed scar generated by Eikonal diffusion interpolation appeared more fragmented than the gold-standard scar.

Table 1. Geometrical similarity metrics between reconstructed and gold-standard scar for all porcine subjects.

Subject	LogOdds		Eikonal Diffusion	
	<i>DSC</i> (%)	ΔV (%)	<i>DSC</i> (%)	ΔV (%)
1	72.5	(-) 5.39	72.9	(-) 10.3
2	69.3	(+) 6.50	64.7	(+) 13.6
3	70.5	(+) 0.04	79.0	(+) 10.3
4	73.8	(-) 3.98	67.7	(+) 11.0
5	71.9	(-) 6.47	64.2	(+) 2.72
6	59.5	(+) 2.59	68.1	(+) 2.09
7	73.4	(+) 11.4	84.1	(+) 9.32
Mean	70.1	5.19	71.5	8.49
Median	71.9	5.39	68.1	10.3

3.2. Parameter Sensitivity Analysis

For the LogOdds method, the *DSC* remained relatively consistent as σ was varied for each subject, although occasional abrupt variations in the *DSC* were observed within a narrow σ interval, as depicted in Figure 2. Across subjects, the range of optimal σ that maximised the *DSC* varied greatly between 0.70-2.60. In contrast, the *DSC* demonstrated greater sensitivity to changes in t_1 for each subject, with a general decreasing trend as t_1 increases. However, the optimal t_1 was more consistent across subjects, ranging between 0.2-0.4. Comparatively, the Eikonal diffusion method demonstrated a sharp drop in the *DSC* as *AR* and t_2 were varied around the optimum. Notably, the optimum *AR* and t_2 were consistent across subjects.

3.3. Electrophysiological Accuracy of Scar Reconstructions

Figure 3 summarises the results for the VITA simulations performed with the three ‘equivalent’ models for each subject. Overall, total and unique induced VTs were greater in Eikonal diffusion scar models (17.9 ± 14.2 ; 4.3 ± 1.9), compared to LogOdds (11.1 ± 8.3 ; 1.9 ± 1.5) and gold-standard (12.1 ± 12.7 ; 2.0 ± 2.1) scar models. Application of VITA to the LogOdds scar models induced VTs in 2 out of 3 non-arrhythmogenic subjects, despite no VTs induced in the gold-standard scar models. This was additionally observed with the Eikonal diffusion models in all 3 subjects. Conversely, in subject 4, no VTs were induced in the LogOdds model, despite being arrhythmogenic. Moreover, in the arrhythmogenic porcine subjects, the LogOdds models consistently induced fewer total and unique VTs compared to the gold-standard scar model. In contrast, the Eikonal diffusion models demonstrated greater variability, with significantly more induced unique VTs in 4 out of 7 subjects than the gold-standard scar model.

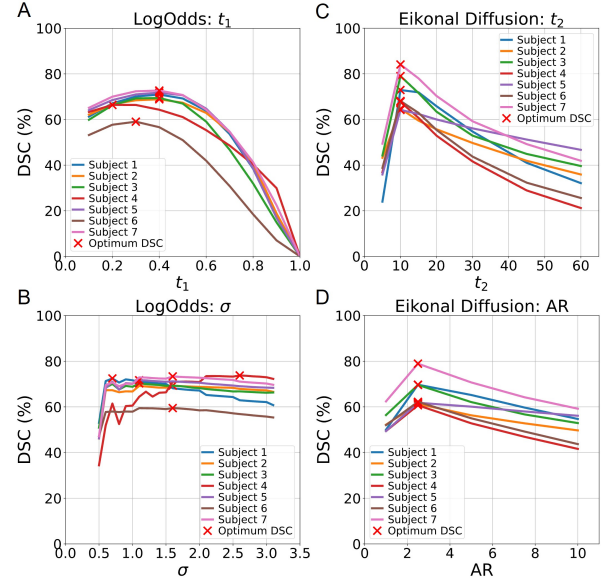


Figure 2. Parameter sensitivity analysis optimising the Dice similarity coefficient (*DSC*) for (A-B) LogOdds and (C-D) Eikonal diffusion interpolation.

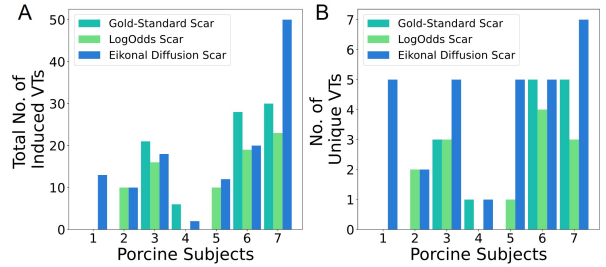


Figure 3. Comparison of VITA metrics, including (A) total induced VTs and (B) unique VTs for all subjects.

4. Discussion

Patient-specific computational cardiac models have shown promise in guiding ablation procedures and predicting treatment outcomes for MI-related VT. Nevertheless, the typically low interslice resolution of clinical LGE-CMR images poses significant challenges in precisely incorporating intricate scar morphology in these models. The availability of high-resolution porcine LGE-CMR data to serve as a gold-standard has enabled the development and evaluation of interpolation strategies. In this study, we proposed a novel 3D reconstruction methodology based on Eikonal diffusion of scar from 2D multislice LGE-CMR data and comprehensively evaluated its efficacy, using both anatomical and functional measures of similarity.

We demonstrated that our proposed Eikonal diffusion interpolation method achieved a marginally greater

mean *DSC* compared to the current baseline LogOdds method. However, LogOdds interpolation outperformed the Eikonal diffusion method based on outcomes of electrophysiology simulations. VITA induced VT circuits in the LogOdds models that were matched most closely to the gold-standard scar models. However, a consistently greater number of unique VTs were induced in non-arrhythmogenic porcine subjects in the Eikonal diffusion scar models. This discrepancy is likely due to the introduction of unrealistic artificial conduction pathways in the Eikonal diffusion reconstructed scar. Thus, while both methods adequately captured the overall infarct geometry from reconstructed low resolution LGE-CMR, precise anatomical detail within the infarct zone is critical for constructing functionally accurate models to simulate VT.

Nonetheless, the LogOdds method demonstrated a strong dependency on the precise tuning of σ , the optimal value of which varied greatly across subjects. Moreover, LogOdds interpolation created marked stripes through the scar, exhibiting a staircase effect, which was particularly prominent when suboptimal parameters were employed. Our proposed methodology demonstrated consistent optimal parameters across all porcine subjects. This lack of parameter sensitivity is particularly important when constructing patient-specific models given the vast inter-patient variability observed in scar morphologies.

In this study, we used data from a limited cohort size of only 7 post-MI porcine subjects. It would be valuable to extend this investigation to include a larger cohort with greater diversity in infarct size, topology and geometry. While the *DSC* and ΔV are widely used metrics to evaluate segmentation performance, it is possible that alternative metrics, such as surface area, might offer deeper insights into the comparative efficacy of our proposed method. Given the crucial role of border zone tissue in cardiac arrhythmogenesis, further evaluation of the interpolation methods for reconstruction of border zone is warranted. Additionally, evaluating the outcomes of the electrophysiology simulations against clinical electroanatomical mapping data would be important future work.

5. Conclusion

We presented a novel Eikonal diffusion method to reconstruct low interslice resolution LGE-CMR scar data. Our method achieved a comparable anatomical accuracy to the LogOdds approach and demonstrated less sensitivity to parameter tuning, though application of VITA revealed that LogOdds interpolation was functionally superior. Importantly, our findings emphasise the critical role of the interpolation strategy used to incorporate precise anatomical scar representations in functionally accurate models. Furthermore, this study highlights the need for routine clinical acquisition of high resolution LGE-CMR data to expand

the clinical utility of personalised computational models.

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