Feasibility of ECGI Endocardial Solutions in Localizing the VT Reentrant Circuit

Maryam Toloubidokhti[1], Omar A Gharbia[2], Natalia Trayanova[3], John Sapp[4], Linwei Wang[1]

[1] Rochester Institute of Technology, Rochester, NY,
[2] Cardiovascular Research and Training Institute, University of Utah,
[3] Department of Biomedical Engineering, Johns Hopkins University, Baltimore, MD, USA,
[4] Department of Medicine, Dalhousie University, Halifax, Nova Scotia, Canada

Abstract

Electrocardiographic imaging (ECGI) effectively reconstructs the epicardial surface's activation pattern, aiding in arrhythmia detection like Ventricular Tachycardia (VT). Yet, the feasibility of ECGI endocardial solutions for VT mapping remains unclear due to lost local activation details. Our goal is to assess the reliability and feasibility of endocardial ECGI solutions in categorizing reentrant circuits as either 2D epicardial, endocardial, or 3D circuits. We utilize Laplacian eigenmaps (LE) for dimensionality reduction and visualization. The LE of ECGI solutions on the left ventricle revealed a pattern for capturing endocardial breakthrough time. Considering activation order, we defined two VT circuit categories: closer to or on the epicardial or endocardial surface. Additionally, we used isochronal activation time maps to identify regions of reentrant circuit rotational activities. By analyzing activation percentage within the VT cycle on each surface, we categorize VT circuits as either 2D on endocardium or epicardium (full circuit on one surface) or 3D (involving the mid-myocardial wall). We validated our method on 23 simulation data sets from eight chronically infarcted porcine hearts. 21/23 cases were accurately classified as closer to the Epicardium or Endocardium, and 82% were correctly categorized as either 2D, 3D, or mid-myocardial.

1. Introduction

Episodes of ventricular tachycardia (VT) typically feature reentrant circuits that are enabled by thin strips of living tissue located in regions of irregular scars or at scar borders [1,2]. About 350,000 cases of out-of-hospital sudden deaths that occur annually in the United States are caused by the VT [3]. Presently, the primary method for analyzing the shape and structure of these reentrant circuits is through catheter mapping [4]. However, catheter mapping comes with a few limitations, notably:

1. It is performed only on one surface of the ventricles, either epicardium or endocardium, that offers a simplified, two-dimensional (2D) perspective that presumes all crucial components of the reentrant circuit are contained within a single surface even though the circuit is naturally 3D.
2. Catheter mapping is not available before the ablation procedure, leading to long and high risk operations.
3. Catheter mapping is not beneficial when dealing with non-sustainable VT where, in reality, up to 90% of the inducible VTs are non-sustainable [2].

These limitations call for an alternative approach to understanding the 3D nature of the VT circuit. Noninvasive electrocardiographic imaging (ECGI) is a computational method to derive cardiac electrical sources from body-surface electrocardiograms (ECGs) and heart-torso geometry with the potential to address the above-mentioned vital limitations [5]. However, while ECGI has been extensively used for studying ventricular reentrant circuits, its epicardial imaging is predominantly used, leaving endocardial ECGI solutions less explored [6, 7] with only a few examining simultaneous epi-endocardial ECGI for mapping reentrant VT [8, 9]. However, these studies have remained qualitative, without exploring how epicardial and endocardial ECGI might be combined to reveal the 3D structure of VT reentrant circuits.

In this study, we explore the feasibility of the ECGI endocardial solutions for providing information about the structure and location of the reentrant circuit when considered jointly with the epicardial breakthrough. Specifically;

1. we show that, with the use of laplacian eigenmaps, the timing of the endocardial breakthrough can be identified, and the order of the breakthroughs on the two surfaces can inform us about the surface to which the VT reentrant circuit is closer.
2. Inspired by a recent study done by Tung et al.[10], we use the 2D isochronal analysis of the activation map on combined epicardium and endocardium to understand the 3D structure of VT and categorize the reentrant circuits

into two groups of 2D circuit living on one surface or 3D circuit also involving the myocardium wall.

Given the inherent complexities in obtaining experimental data on the transmural architecture of the reentrant circuits, we conducted this study on previously documented high-fidelity simulations of three-dimensional reentrant circuits derived from post-infarction porcine models as the basis for our proof of concept study [11] and showed that laplacian eigenmap is an effective approach for inferring the time of the endocardial breaktrough.

2. Methodology

2.1. Electrocardiographic Imaging (ECGI): We employ ECGI to reconstruct the temporal sequence of extracellular potential, specifically unipolar electrograms, across the epicardial and endocardial surfaces [8]. This correlation between the heart-surface electrogram and the body-surface ECG is defined by Laplace's equation as per the principles of quasi-static electromagnetism [12].

Numerically solving this equation on discrete surface biventricular and torso meshes yields a forward matrix $\mathbf{H}$, which relates the unipolar potential ϕ_v(t) at the ventricular surface to the body-surface potential ϕ_b(t), such that ϕ_b(t) = $\mathbf{H}\phi_v$(t) for each time instant.

Given a sequence of ϕ_b(t), we can independently compute ϕ_v(t) for each time instant by resolving the second-order Tikhonov regularization [13] as shown in equation 1:

$$\mathbf{u} = \arg\min ||\mathbf{\Phi} - \mathbf{Hu}|| + \lambda||\mathbf{Lu}|| \quad (1)$$

2.2. Using Laplacian Eigenmaps for identifying the Endocardial breakthrough timing: Upon examining the endocardial ECGI solutions, it becomes evident that although the amplitude of the ECGI solutions is inaccurately reconstructed at each time step, a distinctive pattern of slow and then rapid progression is consistently detected in each VT cycle. In this study, we utilized Laplacian Eigenmaps (LE) [14,15], to identify the exact time of the endocardial breaktrough. LE is a non-linear dimensionality reduction technique that helps simplify the complex, multi-dimensional nature of ECGI solutions obtained from the endocardium. The goal was to uncover and understand the patterns in the spatiotemporal activation sequences over time while preserving the temporal characteristics of the ECGI solutions.

The LE method creates a graph that represents the distances between data points using a heatmap kernel, which helps to highlight the relationships between neighboring nodes. This is followed by computing the graph Laplacian matrix and applying Singular Value Decomposition (SVD). The SVD process is crucial as it helps identify and rank the importance of the manifold's coordinates. We then used the two largest eigenvalues to encapsulate the key features of the original signals, while significantly reducing the dimensionality of the space. As a result, we obtained new coordinates that define what is termed the "LE space". This space represents a manifold or trajectory that maps out the ECGI solution pattern over time. Each data point from the set of electrodes is then assigned a unique position on this manifold revealing the underlying patterns in the data.

Figure 2 is an example of four laplacian eigenmaps computed from the ECGI solutions on the left ventricle's endocardium surface.

2.3. 3D Categorization of the Reentrant Circuits To derive activation isochronal maps, we applied the Hilbert transform to the ground-truth heart-surface EGMs and the ECGI solutions to obtain the instantaneous phase signal at each spatial location, following the method in [16]. The activation wavefront at any time instant is identified as the location with phase = π/2 suggested by [8].

Through the isochronal maps, we locate regions of rotational activation and quantify the visible portion of rotation on each surface [10]. The activation gap is then defined as the time period when rotation is not visible on a surface and is marked by black color in the isochronal color bar as shown in figure 1. If a rotation is not partially visible on a surface, the activation is considered focal on that surface.

Finally, we categorize the 3D characteristics of reentrant circuits based on the definition in [10]:
1) 2D circuits: A complete rotation with no activation gap is observed on one surface (Fig 1.A).
2) 3D circuits (Fig 1.B): Partial rotations with activation gaps are observed on one or both surfaces, or partial rotation with activation gaps on one surface and focal activation on the other.
3) Mid-myocardial circuit (Fig 1.C): Focal activation is observed on both surfaces.

3. Results

3.1. ECGI solutions ECGI effectively reconstructed epicardial electrograms, with spatial and temporal correlation coefficients of 0.89 and 0.90, respectively, and a relative mean squared error of 0.31. In all 23 cases, the earliest activation site was clearly visible on the epicardium, pinpointing the epicardial breakthrough location. This resulted in good accuracy in localizing these breakthrough sites, with errors of 12.58 mm in space and 8.6 ms in timing for sub-epicardial cases, and 9.50 mm in space and 10 ms in timing for sub-endocardial cases.

ECGI solutions on the endocardium were generally poorer, yielding a spatial correlation coefficient of 0.30 ± 0.11, temporal correlation coefficients of 0.46 ± 0.14, and a relative mean squared error (RMSE) of 0.31±0.13 with unclear location of the breakthrough sites.

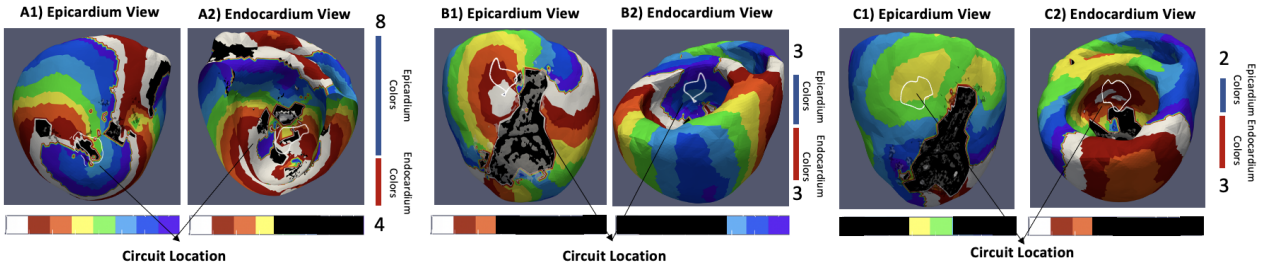

Figure 1. Examples of epi-endo isochrone maps of activation, and their corresponding 3D circuit categorization. A: 2D circuits: a complete rotation without any activation gap is seen on one surface, and focal activation on the other surface. B: 3D circuits: partial rotations with activation gaps are observed on both surfaces. C: Mid-myocardial circuit: focal activation is observed on both surfaces.

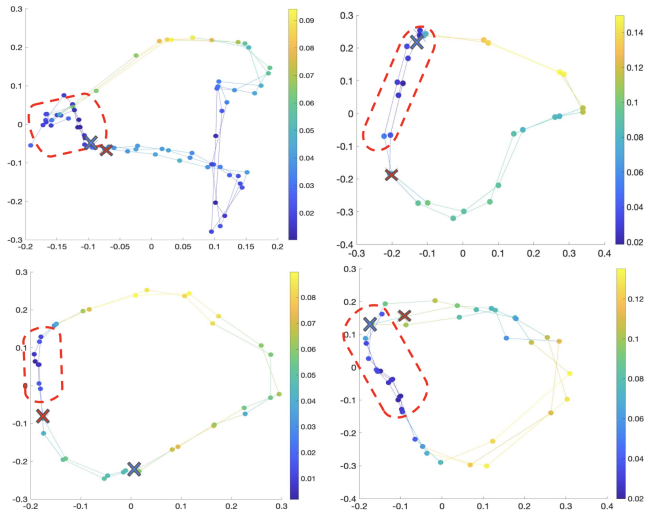

Figure 2. The laplacian eigenmap of ECGI solutions. The red dashed area is the densest part of the map, the red cross and the blue cross are the ground-truth endocaridal and epicardial breaktrough time respectively. The time of exiting the densest area is ECGI's endocardial breaktrough time.

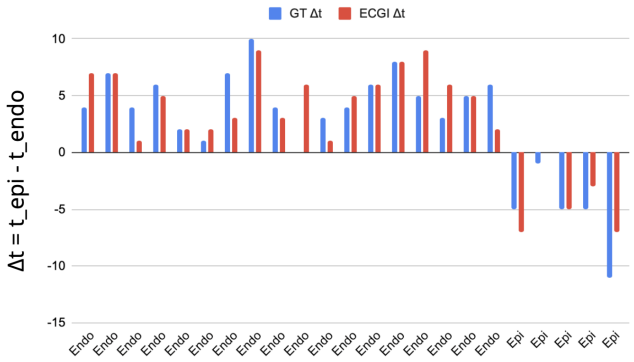

Figure 3. categorizing the re-entrant circuits using ECGI solutions as either closer to epicardium or endocardium.

3.1. Identifying Endocardial Breaktrough Time: Figure 1 shows an example of the laplacian eigenmaps of 4 cases in our dataset. After analyzing all 22 samples in the dataset, we detected a pattern for identifying the endocardial breakthrough, suggesting the time of exiting the densest part of the LE map. Since on the simulation dataset we have access to the ground truth values of the endocardial breakthrough, we were able to quantify the mean squared error of the timings. The absolute error of the endocardial breakthrough is 14.3 ± 13.2ms with average length of the beats being around 230ms.

3.2. Use of Breaktrough Time in Understanding the 3D construct of VT The order of the breaktrough on the surfaces indicates to which of the epicardium or endocardium surface, the reentrant circuit trajectory is closer to. The time of the epicardium breakthrough is identified by analyzing the magnitude of the ECGI solutions. Specifically by eye-balling, we search for the maximum negative derivative of the ECGI solutions, and the endocardial breakthrough timing is identified as explained in section 2. Finally if $(t_{Epi} - t_{Endo}) < 0$ the VT circuit is closer to the epicardium and if $(t_{Epi} - t_{Endo}) < 0$ the circuit is closer to the endocardium. Figure 3 summarizes the classification results given the above analysis indicating that 22/23 cases were correctly classified as either closer to the epicardium or endocardium.

4. 3D categorization of the VT reentrant circuit from the activation maps

As described in section 2, we analyzed the activation map of the 23 cases in our dataset and categorized them according to the percentage of the VT cycle observed on each surface. In the ground truth data, out of the 23 circuits, 2D circuits were observed in 26% of the cases (n=6) on the endocardium, whereas 3D circuits were found in

74% of the cases (n=17). 23% (n=4) of these 3D circuits were partially observed on only one surface, and one of the circuits was mid-myocardial. Analyzing ECGI solutions, 82% of the cases were correctly classified. In the four incorrectly reconstructed cases, one mid-myocardial circuit was reconstructed to be 2D endocardial, one endocardial circuit was reconstructed to be mid-myocardial and one reconstructed to be 3D, and one 3D circuit was reconstructed to be mid-myocardial.

5. Conclusion

In this study we showed that noninvasive ECGI can provide vital insights into the hidden aspects of 3D reentrant circuits, which is currently unachievable, opening the door for further studies and guiding new strategies for ablation treatment. Specifically, we showed that phase information on endocardium can reveal clinical information related to VT cycle (timing and location of the endocardial breakthrough) and laplacian eigenmaps can be used to detect the endocardial breakthrough time. Moreover, the order of the breaktrough time on the surfaces and the activation pattern on epicardium and endocardium, can reveal critical information regarding the location and the 3D structure of the reentrant circuit.

Acknowledgments

This study was supported by grants from the National Institutes of Health under R01HL145590 and the Cardiac Arrhythmia Network of Canada.

References

[1] de Chillou C, Lacroix D, Klug D, Magnin-Poull I, Marquié C, Messier M, Andronache M, Kouakam C, Sadoul N, Chen J, et al. Isthmus Characteristics of Reentrant Ventricular Tachycardia After Myocardial Infarction. Circulation 2002; 105(6):726–731.

[2] Wissner E, Stevenson WG, Kuck KH. Catheter Ablation of Ventricular Tachycardia in Ischaemic and Non-ischaemic Cardiomyopathy: Where Are We Today? a Clinical Review. European Heart Journal 2012;33(12):1440–1450.

[3] Stevenson WG. Current Treatment of Ventricular Arrhythmias: State of the Art. Heart Rhythm 2013;10(12):1919–1926.

[4] Stevenson WG, Soejima K. Catheter Ablation for Ventricular Tachycardia. Circulation 2007;115(21):2750–2760.

[5] Burnes JE, Taccardi B, Rudy Y. A Noninvasive Imaging Modality for Cardiac Arrhythmias. Circulation 2000; 102(17):2152–2158.

[6] Robinson CG, Samson PP, Moore KM, Hugo GD, Knutson N, Mutic S, Goddu SM, Lang A, Cooper DH, Faddis M, et al. Phase i/ii Trial of Electrophysiology-Guided Noninvasive Cardiac Radioablation for Ventricular Tachycardia. Circulation 2019;139(3):313–321.

[7] Cuculich PS, Schill MR, Kashani R, Mutic S, Lang A, Cooper D, Faddis M, Gleva M, Noheria A, Smith TW, et al. Noninvasive Dardiac Radiation for Ablation of Ventricular Tachycardia. New England Journal of Medicine 2017; 377(24):2325–2336.

[8] Wang L, Gharbia OA, Horáček BM, Sapp JL. Noninvasive Epicardial and Endocardial Electrocardiographic Imaging of Scar-related Ventricular Tachycardia. Journal of Electrocardiology 2016;49(6):887–893.

[9] Tsyganov A, Wissner E, Metzner A, Mironovich S, Chaykovskaya M, Kalinin V, Chmelevsky M, Lemes C, Kuck KH. Mapping of Ventricular Arrhythmias Using a Novel Noninvasive Epicardial and Endocardial Electrophysiology System. Journal of Electrocardiology 2018; 51(1):92–98.

[10] Tung R, Raiman M, Liao H, Zhan X, Chung FP, Nagel R, Hu H, Jian J, Shatz DY, Besser SA, et al. Simultaneous Endocardial and Epicardial Delineation of 3d Reentrant Ventricular Tachycardia. Journal of the American College of Cardiology 2020;75(8):884–897.

[11] Pashakhanloo F, Herzka DA, Halperin H, McVeigh ER, Trayanova NA. Role of 3-dimensional Architecture of Scar and Surviving Tissue in Ventricular Tachycardia: Insights from High-Resolution Ex Vivo Porcine Models. Circulation Arrhythmia and Electrophysiology 2018;11(6):e006131.

[12] Plonsey R. Bioelectric Phenomena. Wiley Encyclopedia of Electrical and Electronics Engineering 2001;.

[13] Gockenbach MS. Linear Inverse Problems and Tikhonov Regularization, volume 32. American Mathematical Soc., 2016.

[14] Belkin M, Niyogi P. Laplacian Eigenmaps for Dimensionality Reduction and Data Representation. Neural Computation 2003;15(6):1373–1396.

[15] Good WW, Erem B, Zenger B, Coll-Font J, Bergquist JA, Brooks DH, MacLeod RS. Characterizing the Transient Electrocardiographic Signature of Ischemic Stress Using Laplacian Eigenmaps for Dimensionality Reduction. Computers in Biology and Medicine 2020;127:104059.

[16] Umapathy K, Nair K, Masse S, Krishnan S, Rogers J, Nash MP, Nanthakumar K. Phase Mapping of Cardiac Fibrillation. Circulation Arrhythmia and Electrophysiology 2010; 3(1):105–114.

Address for correspondence:

Maryam Toloubidokhti
1 Lomb Memorial Dr, Rochester, NY 14623
mt6129@rit.edu