Accessory Pathway Localisation Optimisation: In Silico Heart Model Evaluation

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Abstract

Wolff-Parkinson-White (WPW) syndrome is a cardiovascular disease characterized by abnormal atrio-ventricular conduction facilitated by accessory pathways (APs). The primary treatment modality is invasive catheter ablation of the AP. Successful ablation outcomes depend on precise localization of the APs; however, current catheter diagnostic procedures often struggle with accurately determining AP locations. A cardiac model of electrophysiology that was specifically tailored to represent antegrade APs was utilised and an HD-Grid catheter model was developed with the aim of locating an AP by means of intracavitary signals. The retrieved signals were used to compute bipolar electrograms (EGMs), omnipolar electrograms (oEGMs) and wavefront propagation direction vector maps. The paremeters extracted from the HD-Grid are accurately computed and highlight the potential of this new tool as a foundation for further research over optimal ablation sites localisation and cardiac mapping in general. It will not only deepen our understanding of the underlying mechanisms of WPW syndrome but also potentially enhance the diagnostic accuracy of cardiac mapping procedures.

1. Introduction

WPW syndrome is a heart rhythm disorder that is characterised by the presence of at least one or more accessory pathways (APs) facilitating abnormal atrio-ventricular conduction. WPW affects between 0.68 and 1.7 in 1000 in the general population [1]. Without treatment, the condition can lead to paroxysmal palpitations and morbidity through supraventricular tachycardias or sudden cardiac arrest.

Treatment of WPW syndrome typically involves invasive catheter ablation in efforts to restore the normal heart rhythm. The position of the AP can be detected prior to the procedure using localisation algorithms that rely on the clinically standard 12-lead electrocardiogram (ECG). Prediction accuracy is fairly high at above 90% for most recent techniques [2]. However, such algorithms are known to be less sensitive in the septum, deep coronary sinus, and in close proximity to the His-bundle. The algorithms are also not applicable in the instance when the patient has a compounding condition.

When pre-procedural localisation fails, electro-antomical mapping of the endocardium of the heart is used to localise the AP during the procedure. High Density (HD) mapping catheters, like the HD-Grid from Abbott, offer enhanced local electrical conduction and depolarisation wavefront characterisation. Furthermore, they offer the possibility to calculate oEGMs, that unlike the widely used bipolar signals, they have the advantage of being independent of the catheter's orientation with respect to the direction of propagation of the electrical wave. Recently, multiple parameters derived from these oEGMs have been developed, such as local vector maps [3] or the vector field heterogeneity [4], that may help to locate APs.

Since obtaining on-demand signals in-vivo is not feasible, an exploration in-vitro is needed. Virtual models of cardiac electrophysiology (EP) that are capable of representing WPW syndrome can be of value in order to undersand how HD-grid mapping can be used to better localise the pathway. Therefore, in this study we aim to gain more knowledge about APs and provide new biomarkers for their detection through cardiac modeling and the development of a HD-Grid model. This will enable accurate ablation in future interventions.

2. Materials

Previous research involved constructing a detailed model of whole-heart electrophysiology from clinical magnetic resonance images. This model was customised for an individual subject according to clinically-recorded 12 lead ECGs in order to simulate a realistic normal sinus rhythm [5]. It includes a more physiologically-detailed representation of the His-Purkinje System (HPS) and a the

possibility to model WPW syndrome by introducing an AP.

In order to simulate the electrical activity of the heart once the AP has been introduced, the Reaction-Eikonal (R-E) model is used [6]. Repolarisation is dictated by gradients in action potential duration. Within this study, the Mitchell-Schaeffer ionic model [7] was used. The simulation framework is implemented within CARP*entry* and the *open*CARP simulation environment [8].

3. Methods

3.1. Accessory Pathway Representation

The method developed in [9] was used to insert a short atrio-ventricular bypass tract within the isolation layer of the heart allowing antegrade conduction and facilitating pre-ventricular excitation. A realistic conduction velocity of $2.0ms^{-1}$ was set to replicate His-Purkinje fibers in accordance with reported conduction velocities in Mahaim Accessory Pathways [10].

3.2. HD-Grid Model

In order to retrieve the signals generated by the simulation as a real HD-Grid would do, a modeled HD-Grid is needed. The method performs a series of steps in order to build the catheter:

1. Run a simulation of the heart activation taking into consideration the AP. For each node in the mesh, a signal of the potential variation over time is obtained.
2. Extract the endocardial surface of the ventricle in study.
3. The exact localisation of the first point of the electrode (A1 on Figure 1) into an existing node in the mesh is facilitated through open-source meshtool [11].
4. Calculate the exact distances from that point to the rest of the nodes in the mesh.
5. Thus with the initialised direction vector, the element of the mesh that is at $\sqrt{12^2+12^2}$mm from A1 and contains D4 is selected (see Figure 1). It would not be accurate to select another node of the mesh, because the HD-Grid would be deformed, so D4 will be located inside the element. This element is formed by nodes n_0, n_1 and n_2, which have associated their cartesian coordinates (v_0, v_1 and v_2) and the value of their distance from A1 (e_0, e_1 and e_2).

$$v_{p1} = v_0 + t_{p1}(v_2 - v_0) \tag{1}$$

$$v_{p2} = v_1 + t_{p2}(v_2 - v_1) \tag{2}$$

$$t_{p1} = \frac{e_d - e_0}{e_2 - e_0} \tag{3}$$

$$t_{p2} = \frac{e_d - e_1}{e_2 - e_1} \tag{4}$$

Where e_d is the exact distance from A1 to D4 and v_{p1} and v_{p2} are the exact coordinates of the points p_1 and p_2. The intersection point (D4) between the line that joints the points and the direction vector is computed.

6. The exact distances from D4 to every node in the mesh are calculated.
7. Points A4 and D1 (see Figure 1) are obtained from the data of the distances from A1 and D4. To obtain the exact coordinates of A4 and D1, the formulas described in step 5 are again used.
8. The exact distances from A4 and D1 to every node in the mesh are calculated.
9. The rest of the points of the HD-Grid can be obtained. For instance, to obtain A2, a vector within A1 and A4 is calculated and the point that is at 4mm from A1 is selected.

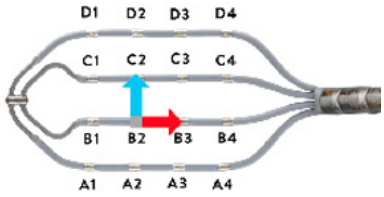

Figure 1. Advisor HD Grid.

3.3. Unipolar EGMs Retrieval

The signal in point A1, which corresponds to a node in the mesh, is straightforward to retrieve. However, for the rest of the points that are inside of a mesh element, an interpolation within the nodes of each element needs to be made. Therefore, the triangle element selected is transformed into an arbitrary one, using the matrix $B \in R^{3x3}$. Each node of the triangle has associated its cartesian coordinates (v_0, v_1 and v_2) and the value of its EGM (φ_0, φ_1 and φ_2). The coordinates of D4 (named now p) are transformed into the coordidates of $\hat{p}$, which is the same point but on an arbitrary triangle. We now that:

$$p = B\hat{p} + v_0 \tag{5}$$

So

$$\hat{p} = B^{-1}(p - v_0) \tag{6}$$

With $B = (v_1 - v_0, v_2 - v_0, (v_1 - v_0) \times (v_2 - v_0))$. Therefore, it is possible to obtain $\hat{p} = (\hat{p}_x, \hat{p}_y, \hat{p}_z)$. In the arbitrary triangle we have the following shape functions: $\hat{\Psi}_0 = 1 - \hat{x} - \hat{y}$, $\hat{\Psi}_1 = \hat{x}$ and $\hat{\Psi}_2 = \hat{y}$. It is possible now to calculate $\varphi(p)$ as follows.

$$\varphi(p) = \varphi_0\hat{\Psi}_0(\hat{p}_x, \hat{p}_y, \hat{p}_z) + \varphi_1\hat{\Psi}_1(\hat{p}_x, \hat{p}_y, \hat{p}_z) + \varphi_2\hat{\Psi}_2(\hat{p}_x, \hat{p}_y, \hat{p}_z) \tag{7}$$

Taking the shape functions into consideration, and also the fact that the element is a 2D element and therefore has

no component z, the Eq. 7 can be recasted into:

$$\varphi(p) = \varphi_0 + (\varphi_1 - \varphi_0)\hat{p}_x + (\varphi_2 - \varphi_0)\hat{p}_y \qquad (8)$$

3.4. Parameter Computation

The retrieved surface signals using the method of the previous section are then analysed by computing bipolar EGMs, oEGMs and the propagation direction using vector maps. They were computed to study their validity, to show that they can be successfully extracted from the model and for a first approximation to the use of vector maps for AP localisation. For the oEGMs computation, the cross-configuration was used, as it is more robust to the direction of propagation of the wavefront [12]. To calculate them, the bipoles obtained within a clique of the HD-Grid are rotated by an angle equal to the propagation angle. The cardiac surface can be interpreted as a vector field generated by a traveling wave, allowing the direction of propagation to be determined from the oEGM within each clique [13].

4. Results

The proposed methodology for modeling the HD-Grid enabled the acquisition of unipolar signals at multiple catheter locations with the appropriate interelectrode distance, similar to what would be done in conventional cardiac mapping. Unipolar EGMs were obtained as Figure 2A shows. Bipolar EGMs were calculated from the subtraction from two unipolars (Figure 2B) and then compared with real signals (Figure 2C). After positioning the modeled catheter at multiple points on the surface, direction of propagation maps of the model's endocardium were obtained (Figure 3).

5. Discussion

5.1. HD-Gid Model

The extracted unipolar EGMs are employed to accurately compute bipolar EGMs, oEGMs, and vector maps. First, the quality of the signal obtained with the model was evaluated by qualitatively comparing real and synthetic signals. Bipolar signals were chosen for evaluation because real unipolar signals can have significant sources of interference, which are canceled out in bipolar signals. The evaluation primarily focused on the morphology and the order of magnitude of the signal amplitude, demonstrating a strong resemblance, suggesting that the model is effectively fulfilling its intended purpose. The amplitude difference observed between the real bipolar EGM and the one extracted from the heart model is due to the fact that in real cases the contact between the heart's surface and the electrodes is not perfect, decreasing the signal's amplitude. On the model, the contact is ideal, retrieving the highest possible amplitude of the signal.

5.2. WPW Characterisation

The AP behaves as a distinct electrical activation focus, different from the AV node. The farther away from the AP ending point, the more homogeneous the propagation becomes (as it would in a normal situation); however, as the catheter is positioned closer to the AP, focal propagation is observed.

An analysis of the vector maps obtained from random locations with the same AP shows that the propagation direction is more chaotic and shows a focus in the location near the AP and more organised far from the AP. However, it can be difficult to locate the AP by only looking at the vector maps. During cardiac simulations, it was observed that the AP depolarised tissue led to retrograde conduction through the HPS, causing depolarisation in other regions of the heart. This phenomenon influences the activation times within the model, as areas distant from the AP may activate simultaneously with regions in close proximity. Metrics such as divergence or Vector Field Heterogeneity can quantitatively measure this effect, providing more precise insights for AP localisation.

5.3. Future Work

The procedures employed in constructing the HD-Grid model represent the first instance of extracting EGMs from a cardiac model utilising a catheter model. Furthermore, this methodology is versatile and can be applied to other high-density mapping catheters. Thus, this virtual tool has the potential to be a basis for further research not only in locating optimal ablation sites in patients with WPW syndrome, but also but also in enhancing the understanding of signals obtained during catheter mapping for other conditions, such as arrhythmias. Preliminary results suggest that the obtained signals are of high quality. However, future work involves a more extensive comparison with empirical data to validate the reliability and applicability of the computed signals. It will also entail more trials to achieve the goal for which the HD-Grid framework has been developed: finding a parameter that can be obtained during ablation procedures to guide cardiologists in accurately determining the ablation site in future interventions.

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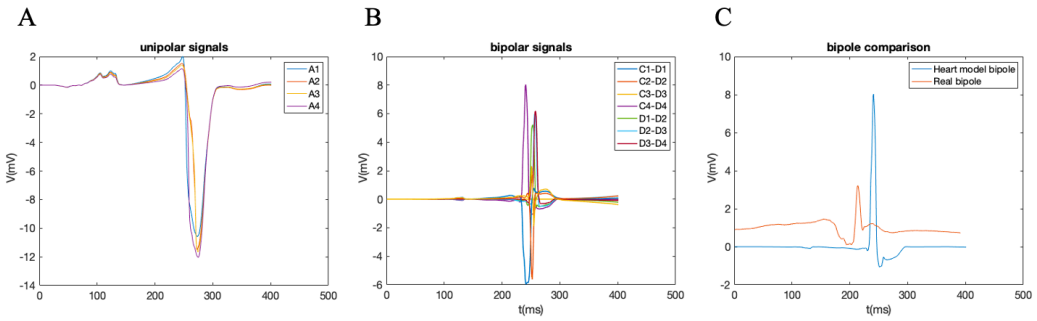

Figure 2. A shows the unipolar EGMs obtained from a random location of the modeled HD-Grid. B shows some of the bipolar EGMs calculated from the unipolars in A. C compares a real bipolar EGM (in orange) with one obtained in the model (in blue).

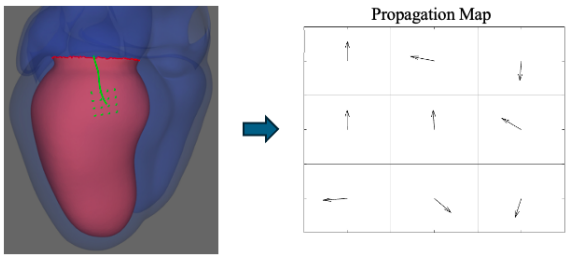

Figure 3. Complete heart model with the HD-Grid placed near the ending point of the pathway. The red structure in both images is the endocardial surface of the heart, the long thread in green is how an AP is modeled and the green points are the exact locations where the EGMs are retrieved.

References

[1] Lu C, Wu M, Chen H, Kao F, Huang S. Epidemiological profile of wolff–parkinson–white syndrome in a general population younger than 50 years of age in an era of radiofrequency catheter ablation. International journal of cardiology Jul 2014;174(3):530–534.

[2] Wren C, Vogel M, Lord S, et al. Accuracy of algorithms to predict accessory pathway location in children with wolff–parkinson–white syndrome. Heart Feb 2012; 98(3):202–206.

[3] Deno D, Balachandran R, Morgan D, Ahmad F, Massé S, Nanthakumar K. Orientation-independent catheter-based characterization of myocardial activation. IEEE Transactions on Biomedical Engineering May 2017;64(5):1067–1077.

[4] Ruiperez-Campillo S, Pancorbo L, Ramirez E, Chorro F, Merino J, Casado-Arroyo R, Castells F, Millet J. Quantifying local cardiac substrate heterogeneity from high density recordings: an experimental study. Europace May 2024;26.

[5] Gillette K, Gsell M, Prassl A, Karabelas E, Reiter U, Reiter G, Grandits T, Payer C, Stern D, Urschler M, Bayer J, Augustin C, Neic A, Pock T, Vigmond E, Plank G. A framework for the generation of digital twins of cardiac electrophysiology from clinical 12-leads ecgs. Medical Image Analysis 2021;71:102080.

[6] Neic A, Campos F, Prassl A, Niederer S, Bishop M, Vigmond E, Plank G. Efficient computation of electro- grams and ecgs in human whole heart simulations using a reaction-eikonal model. Journal of computational physics Oct 2017; 346:191–211.

[7] Mitchell C, Schaeffer D. A two-current model for the dynamics of cardiac membrane. Bulletin of mathematical biology Sep 2003;65(5):767–793.

[8] Plank G, Loewe A, Neic A, Augustin C, Huang Y, Gsell M, Karabelas E, Nothstein M, Prassl A, Seemann GSJ, Vigmond E. The opencarp simulation environment for cardiac electrophysiology. Computer Methods and Programs in Biomedicine Sep 2021;208:106223.

[9] Gillette K, Gsell M, Kurath-Koller S, Prassl A, Plank G. Exploring role of accessory pathway location in wolff-parkinson-white syndrome in a model of whole heart electrophysiology. 2022 Computing in Cardiology CinC 2022; 1–4.

[10] Sternick E, Sanchez-Quintana D, Wellens H, Anderson R. Mahaim revisited. Arrhythmia Electrophysiology Review Apr 2022;11:e14.

[11] Neic A, Gsell M, Karabelas E, Prassl A, Plank G. Automating image-based mesh generation and manipulation tasks in cardiac modeling workflows using meshtool. SoftwareX 2020;11:100454.

[12] Ruiperez-Campillo S, Castells F, Segarra I, Merino J, Casado-Arroyo R, Milltet J. Novel reconstruction technique of omnipolar signals in high density electrode arrays. EP Europace June 2023;25.

[13] Deno D, Balachandran R, Morgan D, et al. High-resolution, live, directional mapping. Heart Rythm Sep 2020;17(9):1621–1628.

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