The Effects of Electrode Configuration on Omnipolar Electrograms: An In-Silico Approach

MK Jothi Letchumy[1], Joseph Brook[1], Konstantinos Ntagiantas[1], Dimitrios Panagopoulos[1], Danya Agha-Jaffar[1], Nicholas S Peters[1], Norman Qureshi[1], Rasheda A Chowdhury[1,#], Chris D Cantwell[1,#]

[1] Imperial College London, London, United Kingdom
# These authors contributed equally

Abstract

Atrial Fibrillation (AF) is the most common cardiac arrhythmia, involving pathological triggers and substrate in the atria. In the clinical catheter laboratory, contact electrograms are an essential tool to characterise AF. Omnipolar electrograms (OE), derived from three or more neighbouring electrodes, are thought to be superior compared to traditional unipolar and bipolar electrograms by eliminating far-field effects and correcting for wavefront incidence angle. We sought to understand the changes in OE morphology under different electrode configurations using 2D simulations of healthy tissue and scarred tissue. Virtual unipolar electrograms (UE) were generated from single electrodes which were used to predict the local electric field and subsequently calculate OEs in cliques of 3, 4, and 6 electrodes at different inter-electrode spacings. Five features were identified on each OE to measure changes in OE morphology under different clique configurations. Additionally, the morphology of the OE signals in the presence of fibrosis was examined. OE signals obtained from scarred tissue are more fractionated compared to healthy tissue. The most appropriate inter-electrode distance for interpreting the OE signals was found to be 2-3mm, using either three or four electrodes.

1. Introduction

Atrial Fibrillation (AF) is the most prevalent chronic cardiac arrhythmia and it affects more than 1.4 million people in the UK [1]. It results in poor atrial function, erratic ventricular activation and reduced function efficiency of the heart. The probability of having AF increases with age and approximately 7 in every 100 people over 65 years are diagnosed with AF [2]. With an increasing global elderly population, this disease is leading to an exponential growth in the expense of treating atrial arrhythmia [2].

Fibrosis has been shown to increase susceptibility to AF and may serve as a critical substrate in the formation and stability of the arrhythmia. Additionally, atrial fibrosis is difficult to reverse and has therefore been considered as a major contributor in the progression from paroxysmal to persistent or permanent AF [3]. The correlation of the degree of atrial fibrosis with the persistence of AF in patients has been demonstrated. Mechanistically, fibrosis causes a decrease in the propagation velocity and leads to increased heterogeneity of electrical conduction [4]. Collagen fibres represent electrical barriers, which can cause asynchronous propagation of electrical activation [5].

The contact electrogram is the primary tool used by the electrophysiologist to diagnose AF. It represents the cumulative electrical activity measured from an electrode in direct contact with the myocardium. It is thought that catheter ablation can be enhanced through utilising recorded EGMs to infer the characteristics of the local myocardium. However, in clinical practice, EGM guided catheter ablation has not shown any improvement to date in preventing AF recurrence over conventional pulmonary vein insolation (PVI) [6]. Currently, EGM guided catheter ablation procedures use electrodes to record unipolar electrograms (UE) and/or bipolar electrograms (BE). UEs are obtained from a single electrode in contact with the myocardium, relative to distant electrode. BEs are obtained through the subtraction of two adjacent UEs [7]. BEs eliminate far-field electrical activation, but are more challenging to interpret as their signal depends on the relative orientation of the inter-electrode axis to the incident electrical wavefront [8]. A recently developed technique combines multiple unipolar electrograms to compute an *omnipolar electrogram* (OE), which overcomes these limitations. OEs effectively provide the optimal BEs from a clique of three or more electrodes by correcting for both the far-field effect and wavefront propagation direction [9].

Many aspects of the signal acquisition influence the morphology of the contact electrograms [10]. This *in silico* study focuses on characterising the influence on OE morphology of inter-electrode distance and the number of electrodes in the clique.

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2. Methodology

A structured finite element mesh was used to solve the monodomain equation on a 100 x 100 mm square of human atrial myocardium. The 2D rectangular domains, shown in Figure 1, represent healthy and non-healthy tissue. The colour indicate the conductivity of the tissue, applied through the diffusivity tensor of the monodomain equation. The conductivity used a physiological range from 0.03 mS/mm (scar) to 0.13 mS/mm (healthy).

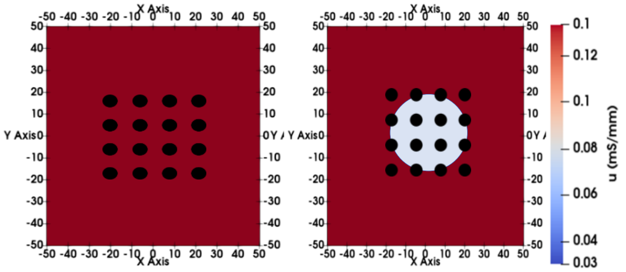


Figure 1. Conductivity of the two-dimensional domain representing human atrial myocardial tissue (A) Healthy tissue (B) Tissue with region of discrete scar.

Action potential (AP) simulations were carried out using the *CardiacEPSolver* built on Nektar++, which uses a high-order spectral/hp element method to solve the monodomain model [11], coupled to the Courtemanche model for the human atrial action potential [12]. The resting potential used was -81.0 mV. A semi-implicit time-integration method was used for time-marching the PDE, while the forward Euler method was used for numerical integration of ion concentrations and Rush-Larson [13] was used for integrating the gating variables. The tissue was stimulated along the left edge, producing a planar wavefront which propagated from left to right.

The main aim of this study is to understand how changes in the electrode configuration affects the OE morphology. We considered variations in inter-electrode distance and the number of electrodes in a clique. To investigate the effect of inter-electrode distances a clique of 4x4 electrodes was considered at with inter-electrode spacings of 1, 2, 3, 4, 5 and 6mm.

UEs were obtained by calculating the extracellular potential at the electrode locations during the simulation. These were used to calculate OEs by estimating the local electric field [9] using the E-field equation,

$$E(t) = E_a(t).a + E_w(t).w \tag{1}$$

For the purpose of calculating OEs, the electrodes and the respective UEs need to be in coplanar. Cliques were selected to derive the local electric fields (E-Field) such as to fully utilise the electrode group. The wavefront propagation within a clique can be calculated from the E-field equation by calculating the wavefront orientation which maximises the cross-correlation of the time and spatial derivatives.

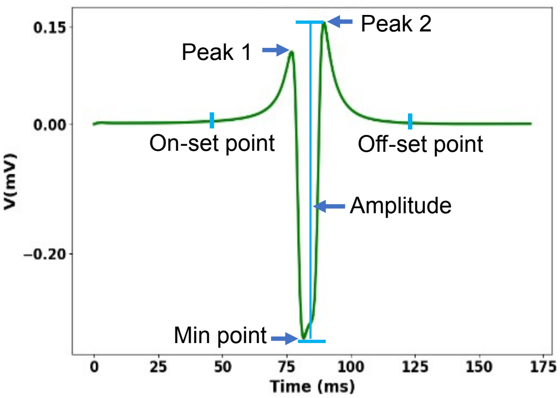


Figure 2. Calculated features of the Omnipolar electrogram

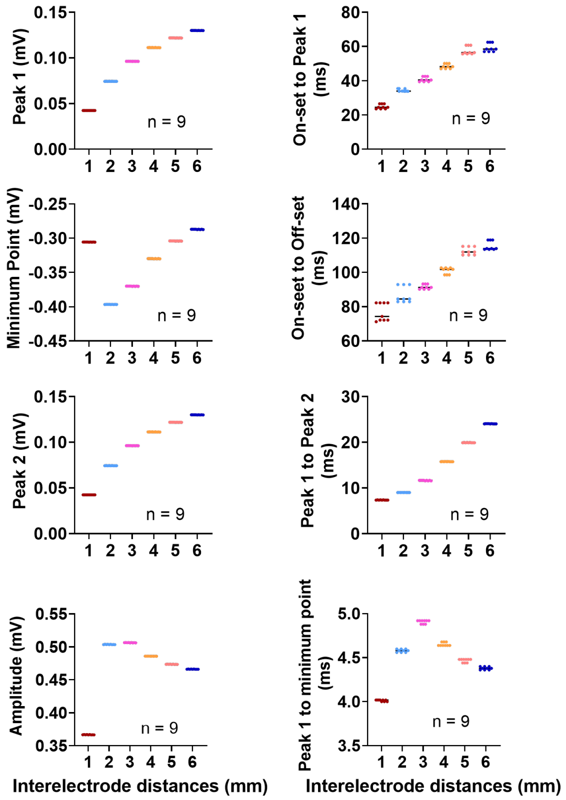
Time-domain features were extracted from the OEs that were calculated under different electrode configurations. Eleven features were calculated through a feature extraction algorithm written in Python 3.8. The time-domain features that were considered for this study are shown in Figure 2.

3. Results

We initially consider only the healthy domain. Changes in the voltage-based time-domain features of the OEs with inter-electrode distance are shown in Figure 3(A). The potential at peak 1 and peak 2 increases as the inter-electrode distance increases monotonically. The voltage at the minimum point initially decreases, but then increases with electrode distance. The OE amplitude consequently follows the reverse. The reason for the reduction of the amplitude is likely due to the separation of contributions of different electrodes, leading to a lower cumulative effect at greater distances. For an inter-electrode distance of less than 4mm, the clique of electrodes are all in the active depolarisation stage at the same time leading to a greater cancellation effect between the UEs.

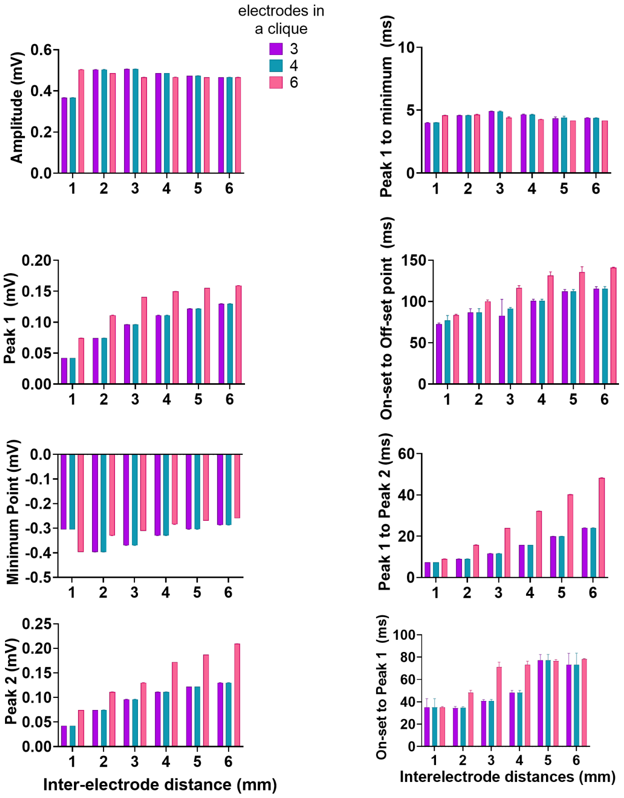
Figure 3(B) illustrates the effects of the inter-electrode distance on the time intervals between labelled points on the OEs. These gradually increase as the inter-electrode distance increases, except for the interval between Peak 1 and the minimum point. This feature is relatively constant across different electrode spacings, with the variation being an order of magnitude smaller than other time-interval features.

Figure 4(A) shows the effect of the number of electrodes in a clique on the voltage features of the OE, for each inter-electrode distance. The voltage of Peak 1 and



(A) (B)

Figure 3. The effect of inter-electrode distance on (A) voltage and (B) time-interval features of the OEs.



(A) (B)

Figure 4. The effect of number of electrodes in a clique on (A) voltage (B) time-interval.

Peak 2 increases monotonically as the spacing increases, for all clique sizes. The voltage at the minimum point increases as the inter-electrode distance increases across all clique sizes. As observed earlier, the amplitude voltage initially increases slightly but soon decreases as the inter-electrode increased, with only 6mm spacing leading to a monotonically decreasing behaviour. For time-interval features shown in Figure 4(B) we observe that the duration between the feature points increases as the inter-electrode distance increases, except for the duration of Peak 1 to Minimum point, for each clique size.

In Figure 5, the morphology of OEs has clear changes as the wavefront passes over the scar region; activation is delayed, amplitude is reduced and the OE complex is elongated in time, with multiple deflections observed in Clique 6. This is due to the slower conductivity of the scar region which reduces the velocity of the wavefront propagation compared with the healthy region.

4. Discussion

This study examined how the clique electrode configuration and spacing impacts the morphology of OEs. The characteristics of the tissue beneath the electrodes was determined through features extracted from the signals. The results suggest the most appropriate inter-electrode distance that can be used to acquire OEs from a myocardial tissue is 2mm or 3mm, as this provides the best compromise between cancellation effects at small spacings and localisation of activation. Electrode arrangements with more than 4mm spacing were less effective at characterising the underlying domain as the OEs had multiple minima which could reduce the ability to distinguish healthy from scar domain. Inter-electrode spacing less than 2mm led to low-amplitude signals which may be more susceptible to noise and therefore do not depict the characteristics of the tissue underneath the electrodes as clearly. Cliques with three or four electrodes were found to best capture local behaviour; the use of 6 electrodes incorporated information from a larger spatial region which reduced spatial localisation of the signal.

The OEs of the scar domain have a longer repolarisation time compared to the healthy domain due to the lower effective conductivity of fibrosis slowing wavefront propagation. As well as increasing the overall duration of the electrogram complex, the increased delay between activation

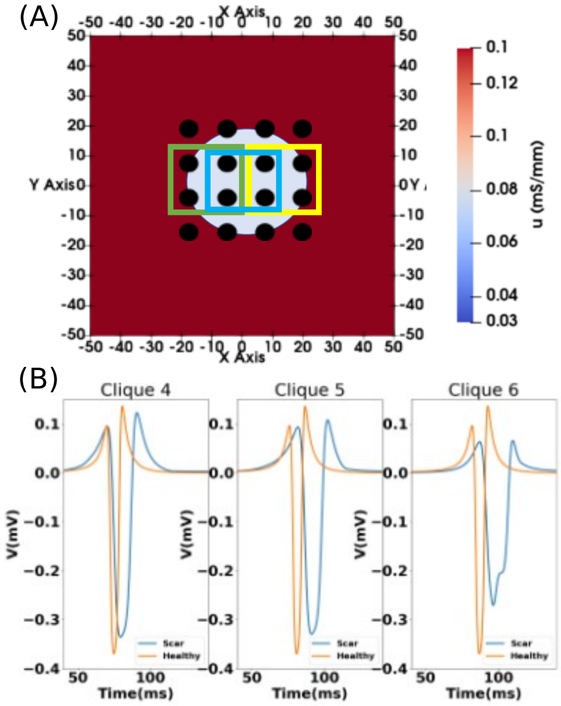


Figure 5. OEs calculated from healthy and scar domains. (A) The scar domain with electrodes, indicating clique 4 (green), clique 5 (blue), clique 6 (yellow). (B) The OEs from the original healthy (orange) and scar (blue) tissue.

at the different clique electrodes leads to increased fractionation which provides a mechanism to quantify scar, but also reduces the effectiveness of the signal for identifying activation times.

5. Conclusion

The most effective distance between the electrodes in the grid was found to be less then 4mm and greater than 2mm. The optimal number of electrodes in a clique was identified as 3 or 4. Further validation in a clinical setting is necessary to ensure translation.

Acknowledgements

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Address for correspondence:

Name: Chris D. Cantwell
Full postal address: Room 219, Department of Aeronautics, City and Guilds Building, South Kensington Campus
E-mail address (optional):c.cantwell@imperial.ac.uk