

Impact of Electrode Size on Electrogram Voltage in Healthy and Diseased Tissue

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Abstract

Atrial fibrillation can be treated using low voltage (LV) (amplitude of intracardiac electrogram $< 0.5\text{mV}$) targeted ablation. However, catheter characteristics can alter the voltage leading to changes in identified LV areas. This study evaluates the impact electrode size has on the voltage in healthy and diseased tissue. A realistic setup was generated of tissue, bath and two high conductivity electrodes, with centre to centre spacing of 2mm, placed in contact to the tissue and perpendicular to the planar wavefront. Simulations were performed varying the dimensions of the cubic electrodes from 0.2 to 1.6 mm in healthy tissue and including fibrosis in different locations. An inverse relationship was found between the electrode size and the voltage. When including epicardial fibrosis, a voltage decrease of 1 mV was found in electrodes. When fibrosis was placed closer to the electrodes, a morphological signal change was seen and a 9 mV drop in voltage for small electrodes. Large electrodes deliver smaller voltages. A fibrotic area on the epicardial side has a small influence on the voltage, which was not amplified by increasing electrode size. Endocardial fibrosis delivers significantly smaller voltages than healthy tissue. Little difference in the voltage was seen between large electrodes ($>1\text{ mm}$) in diseased tissue. Electrode size needs to be accounted for when determining LV areas using different catheters.

1. Introduction

Atrial fibrillation is the most common cardiac arrhythmia, characterised by an irregular, rapid heart rate, which can lead to stroke, heart failure and other complications [1]. One technique used to treat the arrhythmia is performing electroanatomical mapping, specifically targeting areas of low voltage (LV) (amplitude of the bipolar intracardiac electrogram $< 0.5\text{ mV}$) for ablation [2, 3]. This is a commonly used and important technique, however, the method has limitations as characteristics of the catheter can alter the voltage and lead to changes in identified LV areas.

In order to further understand the effects the catheter

has on the voltage, previous studies have performed in-silico experiments evaluating the impact of the catheter angle, inter-electrode spacing and the thickness of the tissue [4, 5]. Anter et al. looked into the effect of two different sizes of electrodes (3.5 mm and 1 mm) and identified that areas of LV and scar were enhanced with small electrodes [6]. Additionally, the effect of the electrode size on the spatial resolution was examined and found that changes in the electrode height had the greatest impact [7]. From these studies, it can be seen that the electrode size can have a significant impact on the identification of LV areas. Therefore, it is important to quantify and study the effect further and assess if it is possible to account for the electrode size when identifying LV areas.

In this study, the relationship between the electrode size and the bipolar and unipolar voltage were assessed. The simulations were performed in healthy tissue and diseased tissues, which allowed for an extensive overview of the impact the electrode size has and what measures should be considered in the clinical practice to prevent false LV areas being identified due to characteristics of the catheter used.

2. Methods

In this study, meshes were generated to reproduce a realistic setup of tissue, bath and electrodes. The patch of atrial tissue was comprised of tetrahedral elements with a mean average length of 0.2 mm, and the human atrial cell model by Courtemanche et al. [8] was used. The tissue had dimensions 60x30x2 mm for all simulations, as shown in figure 1. Additionally, in figure 1, the bath can be seen, indicated by the black outline. The dimensions of the bath were chosen as 68x30x10 mm to exceed the tissue in the length and height and to be the same width as the tissue to reproduce the bath load effect on the propagation of the wave. Two highly conductive electrodes were added to the setup, both in contact to the tissue with a centre to centre distance of 2 mm from each other for all simulations (shown as grey cubes in figure 1).

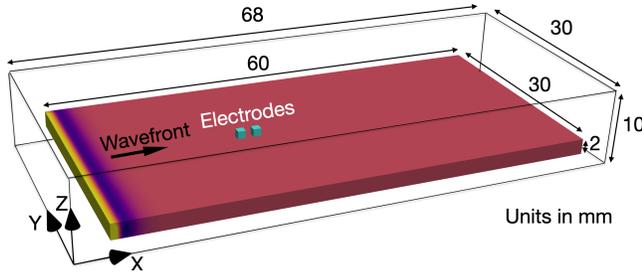


Figure 1: Diagram of the atrial tissue (in red) shown with the surrounding bath (black outline) and two cube electrodes (in grey) placed on the surface and in contact to the tissue. The wave direction within the tissue is from left to right (the yellow region indicates the start of the wavefront).

To allow for interactions between the intra and extracellular space and account for the effects of the electrodes, bidomain simulations were performed. An intracellular stimulus of 50 mA was applied for 2 ms to the left hand side of the tissue (yellow region in figure 1). The direction of the wavefront, additionally indicated in the figure, is defined as a planar wavefront perpendicular to the electrodes. The myocardial intracellular conductivity was set to 0.36 S/m and extracellular to 1.29 S/m to achieve a realistic conduction velocity of 0.71 m/s [9]. The bath was modelled with a conductivity of 0.63 S/m to represent human blood [10]. The conductivity of the electrodes was set as 700 S/m to simulate a highly conductive element.

The first batch of simulations were then performed changing the length, width and/or height of the electrode. The initial size of the electrodes were set to 1 mm³ and then one or more dimensions were increased or decreased in steps of 0.2 mm. The electrodes were changed from 0.2-1.6 mm in four ways: (1) changing all dimensions of the electrode (x,y,z), (2) changing the height (z), (3) changing the width and height (y,z) and (4) changing the length and width (x,y). The dimensions of the electrodes were chosen to represent a range of electrode sizes that are currently being used in the clinical practice [11].

In the next batch of simulations, the electrode size was again changed in all dimensions (x,y,z) from 0.2 mm³ to 1.6 mm³. However, in this case, a patch of fibrotic tissue was included in three locations on the z-axis: on the epicardial side of the tissue, in the middle of the tissue and on the endocardial side. The fibrotic patch was represented by non-conductive mesh elements, that represent collagen fibres, with a length of 0.3mm and a diameter of 0.1mm randomly placed inside an ellipsoid region located in the centre of the patch (x,y), which followed the fibre direction of the tissue.

3. Results

3.1. Electrode Size in Healthy Tissue

When changing the size of the electrode in all dimensions (x,y,z) in healthy tissue, it was found that the voltage decreases as the electrode size increases. In figure 2 the bipolar and unipolar signals are shown for each size of electrode. It can be seen that there is little change to the morphology of the signal, but the amplitude of the signal decreases as the size increases. Additionally, in figure 2, a closer look into the relationship between the voltage and changing all the electrode dimensions can be seen. For smaller electrodes (0.2-0.8 mm³), the line of best fit has a steeper gradient, voltage = -9.4*size+13.1 for bipolar compared to voltage = -4.4*size+9.1 for electrodes of size >= 0.8 mm³.

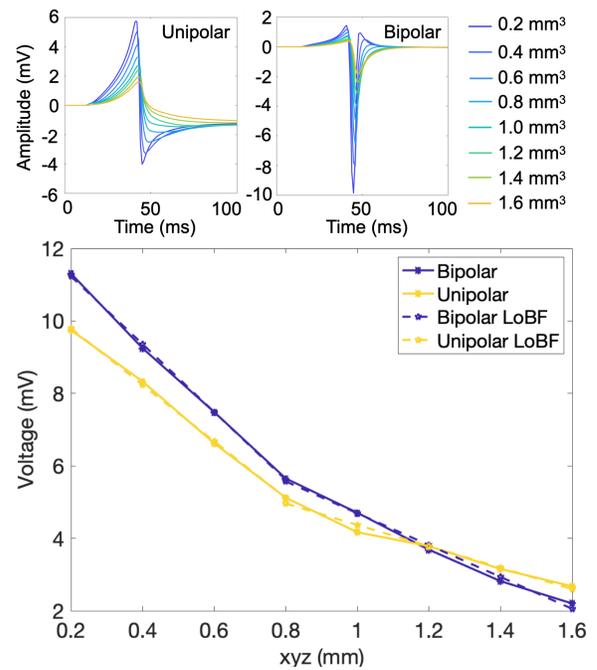


Figure 2: The top figure shows the unipolar electrograms from the electrode closest to the wavefront and the bipolar electrograms. Each colour represents one size of the electrode in mm³. The bottom row shows the voltage for different electrode sizes, bipolar (purple) and unipolar (yellow). Two lines of best fit (LoBF) were then calculated for each, from 0.2-0.8 mm³ and 0.8-1.6 mm³.

To further examine the effect the electrode size has on the voltage, the dimensions of the electrode were altered in four ways, as defined above. In figure 3 it can be seen that in all cases there is an inverse relationship between the electrode size and the voltage. When the dimensions of

the electrode are greater than 1 mm there is only a difference of 0.1 mV which is not significant ($p = 0.99$) between increasing the electrode in diameter, height or length and width. However, changing all the dimensions still shows a considerable decrease in the voltage (4.7 to 2.2 mV).

If the length of the electrode was kept constant at 1 mm but the width and height of the electrode was reduced, the voltage will increase (gradient = 6.6) but not as rapidly as reducing the the electrode in all directions (gradient = 8.3), as the volume of the electrode remains larger. Additionally, decreasing the height of the electrode will increase the voltage but not as drastically as changing all the dimensions or the diameter. For electrodes where the height is kept constant at 1 mm it can be seen that this gives lower voltage values (8.3 to 4.7 mV) between 0.2-1 mm compared to changing the dimensions of the electrode (10 to 4.7 mV) even though the volume of the electrode is the same as when the diameter is changed.

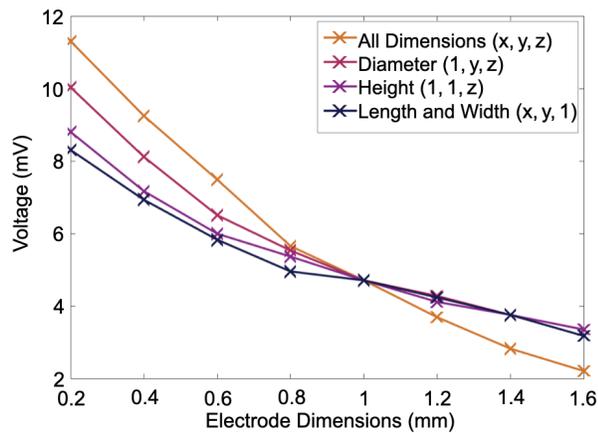


Figure 3: The figure shows a line graph comparing the bipolar voltage to changing the electrode size. The four lines each represent one or more variation in the dimensions of the electrode.

In figure 4, it can be seen that when fibrosis is included in the tissue, the amplitude of the electrogram reduces. When placed on the epicardium, there is little change in the morphology of the signal; however, the voltage is slightly reduced. This reduction in voltage remains approximately constant across the different cubic electrode sizes. When the fibrosis patch is moved into the middle of the tissue, the signal becomes more spread out and there is a time delay of 5 ms. Additionally, a substantial drop in the voltage is seen, specifically for small electrodes (11.3 to 4.9 mV for 0.2 mm^3 electrode) from healthy tissue to when fibrosis is placed in the middle of the tissue. For electrodes of size $>0.8 \text{ mm}^3$ little change in the voltage is seen between the different sizes.

When the fibrosis patch is moved to the endocardium it

can be seen that the changes are similar to when the fibrosis is located in the middle of the tissue with a slightly further reduction in the voltage. Furthermore, figure 4 shows that when the fibrosis is on the epicardial side, the bipolar voltage is greater than the unipolar. However, when the fibrotic patch is in the middle of the tissue or on the endocardial side, this is no longer the case.

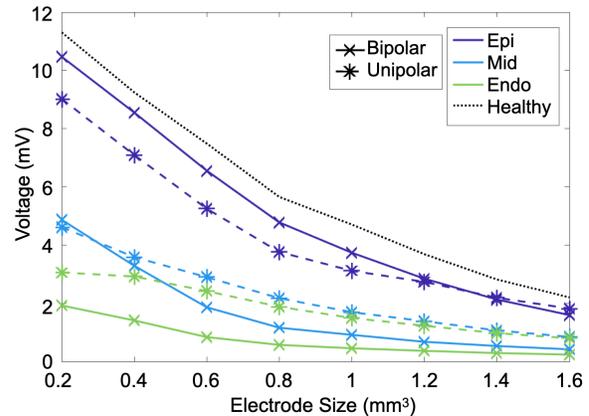
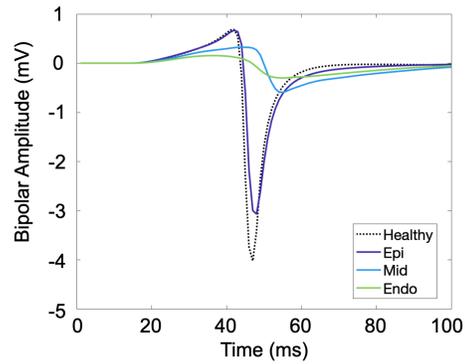


Figure 4: The figures shows the bipolar electrograms for the 1 mm^3 electrodes and the relationship between the voltage and the electrode size on the line graph when the fibrotic patch is placed at different positions in the tissue.

4. Discussion

From the results, it was observed that the electrode size can substantially affect the voltage. A big change occurs when the volume of the electrode is increased or decreased. A substantial decrease of at most 5.7 mV is seen in the voltage when one or more dimension is changed from 0.2 to 0.8 mm. The voltage continues to decrease when the dimensions are changed from 0.8 to 1.6 mm. However, the difference is not as vast, with a max change of 3.5mV. In the smaller electrodes, a much more localized signal is being obtained. Therefore, the voltage reflects the activation of the tissue just below the tissue. However, with larger

electrodes, a larger area of tissue is contributing to the signals, so when the tissue at the start of the electrode is being activated the end of the electrode is still obtaining signals far away from the activation point, which will reduce the overall voltage.

A batch of simulations changing only the width and height of the electrode were performed. Therefore, a comparison could be made between changing the width and height and changing the length and height where the volume is the same but the amount of contact the electrode has to the tissue is changed. It can be seen from the results that while keeping the volume the same, the voltage is lower when changing (x,y) for all the different electrode sizes compared to changing (y,z). This shows that not only the volume has an effect on the voltage, but the electrode having more of its area further away from the tissue (larger z) also plays a role.

A fibrotic area on the epicardial side has a small influence on the endocardial voltage. However, the difference remains constant regardless of the electrode size. Therefore, increasing the electrode's volume does not result in better detection of fibrosis placed on the epicardial side. When the fibrosis is placed closer to the electrodes, then significantly smaller voltages ($p < 0.01$) are obtained than in healthy tissue. With diseased tissue, the electrode size's impact on the voltage is explicitly reduced with dimensions greater than 0.8 mm.

5. Conclusion

Electrodes with a larger volume deliver smaller voltages. The impact is much more substantial in electrodes of smaller sizes 0.2 to 0.8 mm. When fibrotic tissue is placed on the epicardium, there is a small decrease in the voltage across all electrode sizes. Fibrotic tissue located closer to the electrodes has a greater impact on the voltage. However, after 1 mm electrodes, increasing the size of the electrode no longer impacts the voltage. Therefore, either a universal electrode size should be used, or the electrode size needs to be accounted for when determining LV areas. However, any adjustment factor will need to depend on which dimension of the electrode is changed.

6. Acknowledgements

The authors thank Giorgio Luongo for his valuable suggestions and gratefully acknowledge financial support by Deutsche Forschungsgemeinschaft (DFG) through DO637/22-3 and by the Ministerium für Wissenschaft, Forschung und Kunst Baden-Württemberg through the Research Seed Capital (RiSC) program.

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