Estimation of the Ablated Area size based on Local Conduction Velocity Simulations and animal experiments

J Siles¹, J Salinet¹, S Pollnow², O. Dössel², I Uzelac³

¹ Biomedical Engineering, Engineering, Modelling and Applied Social Sciences Centre of the Federal University of ABC, São Paulo, Brazil
² Karlsruhe Institute of Technology (KIT) / Institute of Biomedical Engineering, Karlsruhe, Germany
³ Georgia Institute of Technology, School of Physics, Georgia, USA

Abstract

Estimation of the radiofrequency ablated (RFA) area size, local conduction velocity (CVL), and general electrophysiology at the ablation sites remains a challenge in clinical electrophysiology. This study proposes a circle method (CM) for estimation of local CV vector fields, applied to identify late activation zones, and for localization and characterization of ablated tissue. The method is based on automatic detection of the wavefront propagation direction calculated along directions in circular disposition. The method robustness is tested and validated to estimate the electrophysiological effects and lesion sites after RFA ablation. RFA was modeled in simulations and performed in isolated hearts. Local CV at the center of the ablation area showed a logarithmic curve increasing with larger radius, suitable for estimating the ablated area size. From the CVL maps, distinct regions of substantially lower CVLs showed the ablated area’s location. Maps of CVL directions around the ablated area show characteristic deviation symmetric regarding the propagating wavefront allowing for more accurate delineation of ablated area. The method is validated for different ablation geometries and sizes, wavefront curvatures and different animal experiments. Estimation of ablated area’s size and its location could be performed without prior knowledge of the wavefront propagation direction.

1. Introduction

Atrial fibrillation (AF) is the most common cardiac arrhythmia, affecting 1-2% of the worldwide population [1]. It is characterized by the collapse of the synchronized wavefront atria depolarization, a condition resulting from multiple causes, which can occur in young patients without demonstrable structural heart disease.

Previous studies have shown that areas with slowed atrial conduction velocity (CV) might be critical, favoring reentry formation and consequently maintaining AF [2–4]. CV is also slower in patients with AF recurrence compared with patients in which AF has been terminated after pulmonary vein isolation, being an essential predictor of AF recurrence [5]. Accurate CV measurements and its directional dependency of the propagation of the electrical waves across cardiac tissue can further enhance the characterization of the underlying myocardium’s properties.

The role of radiofrequency catheter ablation (RFA) to prevent AF has shown several benefits. However, AF recurrence occurs in 20-40% of patients when non-conductive cauterized tissue becomes conductive. Different parameters can influence the effectiveness of the RFA, including tissue thickness, electrode-tissue interface temperature, electrode size, electrode-tissue contact pressure, and time duration of RFA [6, 7].

Optical mapping with voltage-sensitive opens new avenues to map temporal and spatial action potential (AP) dynamics [8] after RFA, thus applicable only experimentally, not clinically. However, optical mapping is indispensable research to study wavefront propagation around the ablated area, where methods in clinical electrophysiology may fail consequently affecting CV estimation [9], and effectiveness of ablation treatment [10]. This study shows a robust method for local CV estimation in magnitude and direction, termed the circle method, and estimation of ablated area size validate in both simulation and experimental data.

2. Methods

2.1. Database and Pre-processing

The database is composed of six simulations of 2D wavefront propagation and from experimental measurements on four isolated hearts. Simulations were based on Fenton-Karma 3V model [11] on a 2D 256x256 grid domain (10 x 10 mm). For each simulation, a segment of
500 ms is obtained (sampling frequency 10 kHz), and simulations were done for two different wavefront curvatures, planar and convex, propagating from two different directions, horizontal and diagonal, of reference baseline CV magnitude of 0.55 cm/s in non-ablated areas. The effect of RFA was modeled by changing the conductivity parameter from 0.395 S/cm to 0.45 S/cm in the 2D domain, creating non-conductive islets of different sizes and geometries.

Animal experiments consisted of isolated right atria from two Fisher rats (10 x 10 mm) [12] and left ventricles of two guinea pigs. The atrial epicardium was stimulated at 6.7 Hz, followed by optical mapping to record Optical Action Potentials (OAPs). Atria were stained using Di-4-ANNEPS dye. The emitted fluorescence from the endocardium was acquired using an EMCCD camera (Evolve Delta 512, Photometrics) at resolution of 82 x 82 pixels, sample frequency of 868 Hz with a binning factor of 2, and a spatial resolution of 128 x 128 µm. RFA was performed in the center of the atrium for durations ranging from 0.5 s to 14.5 s with 2 minutes resting between ablations [12]. For ventricular analysis, isolated guinea pig hearts were perfused in a Langerdorff setup and stained with Di-4-ANBDQPQ dye. Left ventricles OAPs were also acquired using a fast-speed camera at 500 fps and a resolution of 128 x 128 (Evolve128, Photometrics). Similar time duration of ablation strategy was performed with a RFA power of 10 W [13].

The OAP pre-processing consisted of an adaptive Spatio-temporal Gaussian filter [14], followed by baseline drift removal with a low-pass Kaiser Window FIR filter. OAPs are stacked (ensemble-averaged) to reduce noise, leading to significantly higher accuracy in the estimated CV [15]. For better precision, OAPs were re-sampled from native 868 Hz to 10 kHz, followed with a light smoothing of the OAPs with a Gaussian spatial kernel filter of 3 x 3 and a temporal of 1 x 70 (7 ms) kernel sizes [13].

2.2. Conduction Velocity

The local activation time (LAT) maps were obtained using 50% criteria [16]. CV is obtained with a proposed method termed the circle method (CM), enabling CV estimation without any prior knowledge of the propagating wavefront direction (Fig. 1A). For each pixel, CVL’s magnitude and direction were calculated along direction in a circular disposition spanning from 0° to 180° outlining a circle of a specific radius. In this fashion, the maximal CVL corresponds to the direction parallel to the propagating wavefront, allowing estimation of the actual CV located at the angular distance of 90° (Fig. 1B). Maximum is a point which can be detected accurately along the direction parallel to the propagating wavefront due to minimal LAT difference resulting in the sharp increase of calculated CV values. The actual true CV value is located at a distance of 90° (Fig. 1A and B). Depending on the chosen radius, a local CV is obtained. In this study, CV maps were calculated for a fixed radius of 10 pixels in a selected area with RFA region inside (Fig. 1C).

![Figure 1](image1.png)

**Figure 1.** A. Circle method process. B. Angle parallel to the wavefront propagation and the real CV angle. C. the circle method to find the ablated area with the dotted square and the dotted circle that represents the ablated area.

Determine the suitable radius for investigating the ablated areas and their delimitation is the key factor for the proposed method. Two scenarios are considered: a point located far away from the RFA area and another in the middle of it. For the first case, radii vary from 1 to 40, avoiding reach the RFA area, and for the second case, radii vary from 1 to 100 to analyze the CV behavior far away from the ablated area.

3. Results

3.1. Simulation results

The CM accuracy was tested based on the selection of different circle radius, choosing points inside and outside of the ablated area (Fig. 2). The CM accuracy is only affected for radius of less than 10 pixels (Fig. 2A), and CV increase with radius shows characteristic logarithmic curve, useful to estimate the RFA area size based the curve knee point (Fig. 2B).

![Figure 2](image2.png)

**Figure 2.** A. The CV values for increasing radius from 1 to 40 at location outside the ablated area. B. The CV values for increasing radius from 1 to 100 with the circle’s center inside the ablated area. Both figures shown different wavefront propagation simulations.

Figure 2B presents CV’s results inside the ablated area for both cases named before. The radii increased from 1
to 100, showing a significant variation before the radius of 5 pixels. CV with a radius under 20 pixels, related to the ablated area, presents lower values and returns to a stable value according to radius increase.

Figure 3. A. LAT map with outlined square selected to calculate CVL, and outlined simulated RFA oval area at the center. A’. CV map and A”. Angle map for the square. B. LAT map, inside it the square selected to apply the CM with two circular RFA areas. B’. CV map and B”. Angle map for the square.

Figure 3 presents a LAT map with two different ablation simulated areas and their respective CV map and the wavefront propagation angle. On the left of Figs. 3A-B, two LAT maps are presented for an oblique wavefront. The dotted oval and the two dotted circles (30 and 20 pixels) represent the ablated area. The CM was applied for all pixels inside the dotted square. Figure 3A’ and B’ show blue areas in the middle with lower CV values. Both cases present an extended red site with higher values of CV. Figs. 3A’ and B’ show the change of wavefront direction due to the ablation areas, highlighting CV angles’ heterogeneity. When the vectors are coming to the ablated area, they turn more positive (light blue) or more negative (dark blue) symmetrically. After the ablated area, vectors before positive turn negative and positive turn negative. Finally, they have almost 90 degrees, turning them parallel to the wavefront propagation.

3.2. Atrial results

CV magnitudes and angles were calculated for different RFA time duration with the CM center selected to coincide with the center of the RFA area. For total RFA time longer than 1.5 s in duration there is prominent decrease of CV (Fig. 4A). The CM is applied using different radii ranging from 1 to 30 pixels. For radius of less than 15 pixels CV significantly decreases. Variations were also observed in in the angle map, especially for radii less than 10 pixels. The CM with selected radius of 10 pixels was applied to calculate CV magnitude and the angle maps for RFA of the total duration of 4s (Fig. 4B). The CV map shows distinct blue colored area of CV decrease showing the effect of RFA suitable to estimate the ablated area location, size and shape. Outside of the ablated area variation of CV values is attributed to tissue heterogeneity and oval shaped heart mapped as 2D projection. Due to these variations the angle map does not have a clear pattern as compared with simulations (Fig. 3).

3.3. Ventricular results

Fig. 5 shows LAT maps before (baseline) and after 14.5 s of RFA. The corresponding CV maps show the impact of the ablation. Finally, the relative change map was calculated as relative changes in local CV values before and after RFA. The location where the RFA was performed is marked with a black arrow. The actual photo of the heart shows ablation electrode and the location where the RFA was performed. Comparing the results of ventricular RFA with simulations and atrial RFA, the specific region of CV decrease due to RFA was not detected.

4. Conclusions

This study presents a method for accurate and precise local CV estimation as validated on both simulations and isolated heart experiments. The proposed circle method is suitable to obtain CV maps without any prior knowledge of the wavefront propagation direction, and suitable to estimate local CV magnitude in an area less than 1 mm in
The proposed method's potential is beyond studies related to catheter ablation assessment to estimate its location and size of the ablated area and is suitable for studies of CV spatial dispersion, characterisation of deceleration zones, identification of tissue heterogeneities or ischemic regions, and AF maintained by reentries among others.

Figure 5. LAT map from ventricular data in baseline and after 4 s of RFA, under them the CV map and the relative change map where the black needle represents the ablation electrode and the heart image with the ablation electrode.

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References


Address for correspondence:
Jimena Gabriela Siles Paredes
Biomedical Engineering - CECS
Federal University of ABC - UFABC
Street: Av.Anchieta, Sao Bernardo do Campo - SP, Brazil
E-mail: jimena.gabriela@ufabc.edu.br