How Does the Dispersive Patch Affect the Efficacy of Radiofrequency Ablation?

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Abstract

Radiofrequency ablation (RFA) is a minimally invasive procedure used to treat cardiac arrhythmia. Power plays an important role during the procedure as it generates the heat necessary to ablate the targeted tissue.

We developed a 3D in-silico model based on patient imaging data. A key aspect of our study is the placement of a dispersive patch at various positions on the torso, as the electrode's location can impact both the effectiveness and safety of the procedure. Proper placement is crucial to ensure optimal current distribution and to minimize any potential risks.

We examine the impact of the patch location on both tissue power dissipation and the overall power dissipation within the torso geometry.

Our results show significant variations in tissue power based on the patch position and orientation. By analyzing these variations, we aim to identify optimal patch placements that maximize therapeutic efficacy.

1. Introduction

RFA is a minimally invasive treatment of atrial fibrillation (AF), a common heart rhythm disorder. During RFA, radiofrequency (RF) current is delivered through a catheter to target and destroy abnormal electrical connections within the heart. A catheter is inserted into the patient's groin and guided through a blood vessel to reach the arrhythmogenic substrate of the heart. An electrode on the catheter tip delivers RF current, which induces resistive heating at the interface between the electrode and tissue. The heat then propagates through the myocardium and the rest of the body until it reaches a dispersive patch (DP), typically placed on the patient's back or thigh, completing the electrical circuit. Each DP location creates different impedance due to the varying properties of organs and the different distances from the tip electrode.

Different placements of the DP can play an important role in RFA. Proper positioning of the DP can help achieve optimal power dissipation within the targeted area, potentially minimizing collateral damage to sensitive tissues. The power dissipated inside the tissue generates heat, raising the temperature within. Too much power can cause collateral damage to surrounding healthy tissue, while too low power may lead to an insufficient and ineffective procedure. Thus, the identification of the power dissipation within different tissues is essential for the design of protocols in order to optimize the ablation efficacy and safety.

In this study, a 3D virtual human model is used to examine the impact of the location of the DP on the power distribution near the electrode, as well as on the amount of power dissipated in the cardiac tissue.

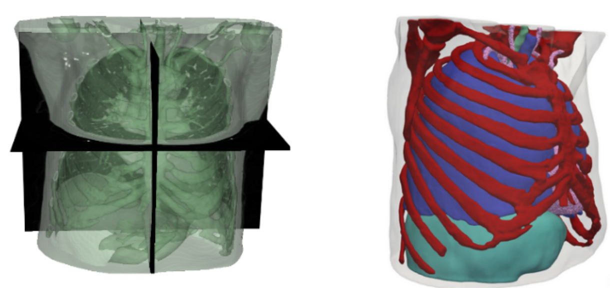

Figure 1. Left: Segmentation of the thoracic CT scan consisting of 35 distinct labels. Right: The tetrahedral mesh of the segmented scan.

2. Methods

2.1. Geometry

We developed a 3D torso model using a patient's thoracic CT scan. The segmentation consists of 35 distinctly labeled subdomains, including blood vessels, the four cardiac chambers, and surrounding organs (see Figure 1).

We discretized the multi-labeled torso segmentation using Studio software by NumeriCor GmbH, resulting in an unstructured tetrahedral mesh of $106,399,049$ elements. A catheter was embedded in the geometry, traversing the inferior vena cava and reaching the left atrial tissue by piercing the interatrial septum (as seen in Figure 2). A $7\,\mathrm{F}$ spherical tip electrode and length $3.5\,\mathrm{mm}$ [1] was placed perpendicular to the tissue at a depth of $0.5\,\mathrm{mm}$ into the tissue. The catheter design was created in Salome (https://www.salome-platform.org).

2.2. Mathematical model

A quasi-static electrical potential equation is solved in the torso geometry

$$-\nabla \cdot \sigma \nabla \Phi = 0, \tag{1}$$

where Φ is the electrical potential and σ the electrical conductivity. The total power of the system is calculated as

$$\int_{\Omega} \sigma \nabla \Phi \cdot \nabla \Phi = P. \tag{2}$$

where P is the total power dissipated in torso geometry Ω. To calculate the power distribution within the torso at different radial distances P^r_{torso}, we use the formula

$$\int_{B(c,r)} \sigma \nabla \Phi \cdot \nabla \Phi \mathrm{dx} = P^r_{torso},$$

where $B(C,r)$ is a ball centered at point C (center of the electrode) with a sphere radius r. When restricted within the left atrial tissue, the power distribution near to the electrode is obtained, given by

$$\int_{B(C,r)\cap\Omega_{LA}} \sigma \nabla \Phi \cdot \nabla \Phi \mathrm{dx} = P^r_{LA},$$

where Ω_{LA} is the left atrial tissue subdomain.

2.3. Boundary conditions

We apply a potential $\Phi = V_0$ at the upper boundary of the electrode, tuned to match the desired power setting as in [1]. We impose a zero potential ($\Phi = 0\,\mathrm{V}$) on the DP which completes the electric circuit, while electrical insulation boundary conditions are imposed on the remaining torso boundary $\left(-\sigma \frac{\partial \Phi}{\partial n} = 0\right)$, as in Figure 2.

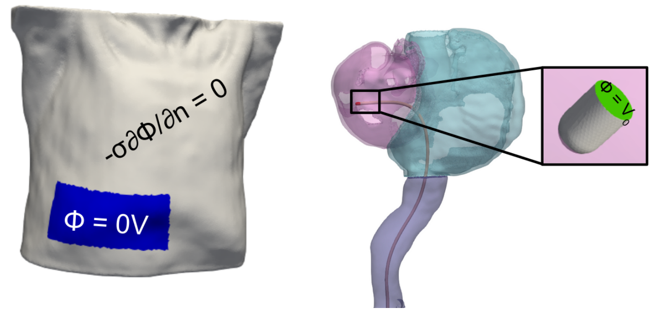

Figure 2. The dispersive patch has a homogeneous Dirichlet boundary condition (in blue), while the rest of the torso boundary has a homogeneous Neumann boundary condition (in white). A voltage tuned to match a given power setting is applied at the upper part of the electrode boundary (in green).

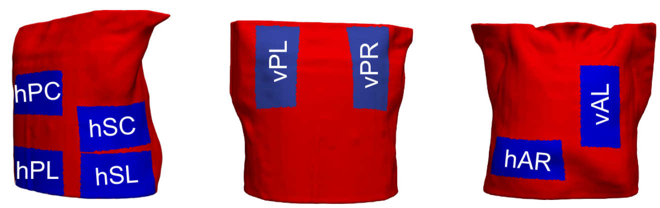

Figure 3. Eight different locations of DPes in the torso geometry are considered, including anterior, posterior, and side positions, with both horizontal and vertical orientations.

2.4. Dispersive patch

A DP of $8 \times 16.75\,\mathrm{cm}^2$ is placed in both horizontal and vertical orientations on the anterior, posterior, and right side surfaces of the torso thorax. The specific locations include: vertically on the posterior left (vPL) and right (vPR), and on the anterior left (vAL); horizontally on the lower side (hSL), center (hSC), lower back (hPL), posterior center (hPC), and anterior right (hAR) as shown in Figure 3.

2.5. Model parameters

Each subdomain exhibits a heterogeneous conductivity value, obtained from a publicly available database at a frequency of $500\,\mathrm{kHz}$ [2]. We assume the same conductivity value for all cardiac tissues, all blood partitions and all vessel walls subdomains (namely Cardiac Tissue, Blood and Blood Vessel Wall respectively in Table 1). For the lungs, we used the average electrical conductivity value of inflated and deflated states. In the torso, we assumed a composition of $30\,\%$ fat tissue and $70\,\%$ muscle tissue, typical values for a 60-year-old male [3]. The pericardium, composed of fibrous and serous tissues with potential fat infiltration, lacked specific conductivity data in the literature. Therefore, we adopted the conductivity value of fat to represent its insulating properties.

Parameters	**Conductivity (S/m)**
Bone	0.02
Lungs	0.12
Liver	0.14
Stomach	0.55
Esophagus (lumen)	10^{-5}
Esophagus	0.55
Spleen	0.14
Electrode	4.6×10^6
Cardiac Tissue	0.28
Pericardium	0.04
Blood	0.74
Blood Vessel Wall	0.32
Kidney	0.22
Pancreas	0.56
Torso	0.24

Table 1. The electrical conductivity of all the different subdomains of the virtual patient.

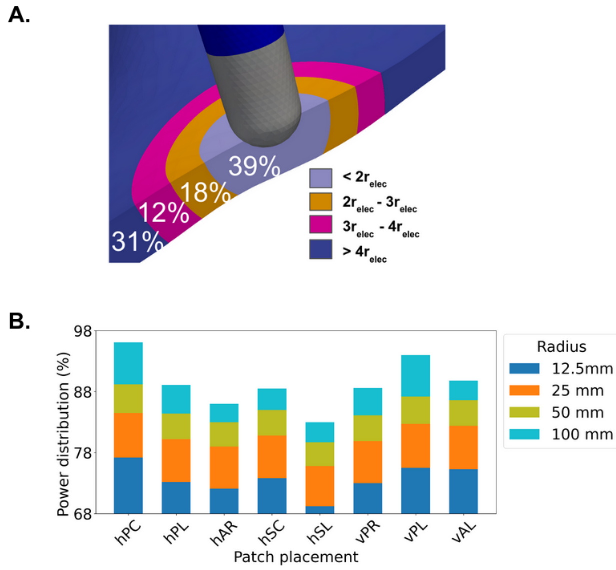

Figure 4. **A.** The percentage of power dissipated within the tissue at different radii. Different colors indicate varying distances from the electrode. **B.** Power distribution in the torso for different radii and different patch locations.

2.6. Ablation protocol

The electrode is positioned at the left atrial wall near the left inferior pulmonary vein (LIPV), a common position for pulmonary vein isolation (PVI) procedure. Eight different dispersive patch locations were considered, as detailed in Section 2.4. A standard power setting of 25 W was used, representing a typical clinical protocol for posterior wall ablation [4].

3. Results

We performed eight simulations considering various DP positions using the finite element method implemented in FEniCSx open-source software `(fenicsproject.org)`.

At first, we examine the percentage of power dissipated in the atrial tissue at various radii from the electrode. Approximately 38% of the power is dissipated within a distance of twice the radius of the electrode ($2r_{elec}$) from the center of the electrode as shown in Figure 4A. When the distance is increased to $3r_{elec}$, the power dissipation rises to 56%. Increasing the distance even further, up to $4r_{elec}$, results in 78% of the power being dissipated within the area. Notably, the majority of the power dissipation occurs within $4r_{elec}$, indicating that most of the energy is concentrated near the electrode. It is also important to note that the patch has no significant effect on the percentage of power distribution inside the atrial tissue.

Next, we explore the power distribution within the torso. We use four concentric spheres centered around the electrode with radius ranging from 12.5 mm to 100 mm. The analysis of power dissipation across various patch locations on the torso shows significant differences. The hPC position exhibits the highest power dissipation across all four radii compared to other patch locations. In contrast, the hSL position shows the lowest power dissipation. For instance, at a radius of 12.5 mm, the hSL position has a power dissipation decrease of 10.4% compared to the hPC position. At a radius of 100 mm, this decrease reaches 13.6%. Other patch locations, such as vAL, vPL, vPR, hSC, and hAR, show varying decreases in power dissipation when compared to the hPC position: the hPL, hAR, and vPR patches show an approximate 5% decrease, (vAL and vPL) each show a 2% decrease, and hSC has a 4.4% decrease, all at a radius of 12.5 mm, as shown in Figure 4B.

We further investigate the impact of the DP placement on the power dissipation within the atrial tissue. Various positions were compared relative to the baseline reference position hPC. In terms of the vertical patches, vPR exhibited the largest reduction in tissue power, with a decrease of 5.5% compared to the reference position. The other two positions (vPL and vAL) resulted in a moderate decrease of 2.1% in tissue. For the horizontal DP orientations, hSL position experienced the largest decline, with a 10.2% decrease in tissue power relative to the baseline position. The other locations (hPL, hSC and hAR) yielded a reduction in tissue power between 4.3 - 6.3% (as shown in Figure 5B).

Finally, we explore whether there is a correlation between impedance and tissue power dissipation. From Figure 5A, it is evident that there is a trend showing a consistent increase in power dissipation with a decrease in impedance. The hSL position has the lowest power dissipation at 1.97 W in tissue, yet it exhibits the highest impedance at 126.6 Ω. Conversely, the hPC position, which has one of the lowest impedance values at 113 Ω, shows the highest power dissipation in the tissue (namely 2.2 W). On the other hand, the power dissipation for the vPR position is 2 W with an impedance of 120 Ω, while the vPL and vAL positions have a slightly higher power dissipation at 2.1 W but a lower impedance of 116.5 Ω.

This pattern highlights an inverse relationship between impedance and tissue power, implying that for varying DP locations increasing impedance tends to decrease the amount of power effectively delivered to the tissue.

The hPC, vPL, and vAL positions are the most effective for power dissipation in the tissue, while the hSL, hSC, and hAR positions are the least effective. The other positions fall in between these extremes, with moderate performance.

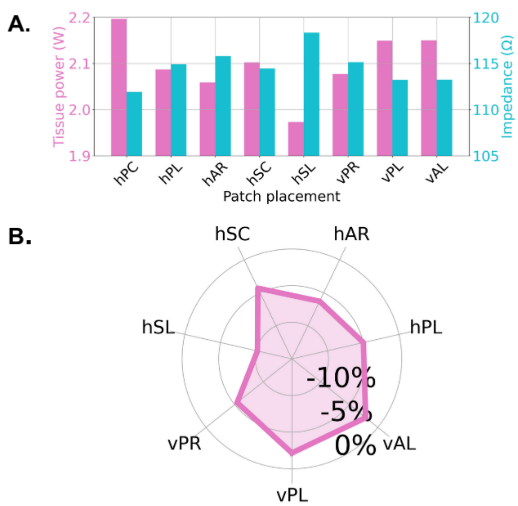

Figure 5. **A.** Tissue power (left y-axis) and total impedance (right y-axis) with respect to different patch orientations and locations. **B.** Tissue power variations of the various DP positions, using the standard thoracic back position (hPC) as the baseline.

4. Conclusions

Our study shows that the DP significantly influences the power dissipated within the atrial tissue and the power distribution within the torso, but has minimal impact on the distribution inside the tissue. An inverse relationship between tissue power and impedance is observed for varying DP positions. The hPC patch location provides the most effective placement for the specific electrode position near LIPV.

However, due to its high power delivery to cardiac tissues, the hPC position may pose a potential risk when the target ablation site features a thinner wall, such as in the case of the posterior left atrial wall. This aspect is the subject of our current investigation.

Acknowledgments

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References

[1] Petras A, Leoni M, Guerra JM, Jansson J, Gerardo-Giorda L. A computational model of open-irrigated radiofrequency catheter ablation accounting for mechanical properties of the cardiac tissue. International Journal for Numerical Methods in Biomedical Engineering 2019;35(11):e3232.

[2] Hasgall P, Di Gennaro F, Baumgartner C, Neufeld E, Lloyd B, Gosselin M, Payne D, Klingenböck A, Kuster N. IT'IS Database for thermal and electromagnetic parameters of biological tissues, 2022. URL itis.swiss/database.

[3] Borrud LG, Flegal KM, Looker AC, Everhart JE, Harris TB, Shepherd JA. Body composition data for individuals 8 years of age and older: Us population, 1999–2004. Vital and health statistics Series 11 Data from the national health survey 2010;(250):1.

[4] Leshem E, Zilberman I, Tschabrunn CM, Barkagan M, Contreras-Valdes FM, Govari A, Anter E. High-power and short-duration ablation for pulmonary vein isolation: biophysical characterization. JACC Clinical Electrophysiology 2018;4(4):467–479.

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