Effect of Contact Force on Local Electrical Impedance in Atrial Tissue - an In Silico Evaluation

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Abstract

Regions with pathologically altered substrate have been identified as potential drivers for atrial fibrillation (AF) maintenance. Recently, local impedance (LI) measurements have gained attention as surrogate for atrial substrate assessment as it does not rely on electrical activity of the heart. However, an appropriate electrode-tissue contact force (CF) is needed and its effect on the LI measurements has not yet been characterized in depth. In this study, we applied several CF to a catheter in contact with a tissue patch modeled as healthy and scar atrial myocardium whose thickness was varied in anatomical ranges to study the impact of the mechanical deformation the LI measurements. When applying CF between 0 and 6 g, in silico LI ranged from 160 Ω to 175 Ω in healthy myocardium, whereas 148 Ω and 151 Ω for scar tissue. Increasing CF in scar tissue up to 25 g, increased LI up to 156 Ω. The model was validated against clinically measured LI at different CF from AF patients. Simulation results applying identical CF in both tissues yielded lower LI values in scar. Moreover, LI increased in healthy and scar tissue when the thickness and CF were increased. Given the results of our study, we conclude that in silico experiments can not only distinguish between healthy and scar tissue by combining CF and LI, but also that our simulation environment represents clinical LI measurements with and without mechanical deformation in a tissue model.

1. Introduction

Atrial fibrillation (AF) is the most common cardiac arrhythmia and it is characterized by a remodeling of the cardiac substrate. A standard treatment for patients with AF is ablation. Applying controlled pressure to the tissue with the catheter can assure good electrode-tissue contact, which is important to perform effective lesions during ablation procedures.

In persistent AF patients, ablation lesions can be placed in areas of scar tissue in addition to usual pulmonary veins isolation (PVI). Currently, the characterization of the substrate is supported by voltage mapping to locate these scar tissue areas. Recently, local impedance (LI) has been gaining attention due to its independence on the electrical activity to better differentiate healthy tissue from scar [1]. Therefore, it may improve the current understanding of underlying substrate.

The new generation of ablation catheters, as the IntellaNav Stablepoint™ (Boston Scientific, Malborough, MA, USA), can assure good electrode-tissue contact by measuring it as contact force (CF) at the tip, and also record LI, including both as a novel combined technique to characterize the process of lesion formation.

Some studies have recently investigated the effect of CF in ablation assessment [2]. However, the effect of CF on the LI measurements to characterize the substrate needs to be further explored. In silico experiments are helpful to better understand tissue behavior in a controlled environment without noise sources and measurements uncertainties. Validation of the model is needed to show the clinically utility by comparison to LI clinical data acquired at manually controlled CF values to show the relevance.

In this work, we study the effect of mechanical deformation of the atrial tissue on LI measurements for several thicknesses and CFs using in silico experiments. We aim to explore the possibility to characterize healthy tissue and scar tissue by means of LI taking into account the effect of tissue thickness and CF.

2. Methods

An in silico framework (Figure 1) that models the IntellaNav Stablepoint™ in a similar way as in Pollnow et al. [3] was used embedded in a 140 mm × 140 mm ×

140 mm box that represents the surrounding blood. Centered below the tip of the catheter and in direct contact with it, a squared patch of tissue of dimensions 110 mm $\times$ 110 mm $\times$ t_{th} was placed, with t_{th} being the tissue thickness within the anatomical range from 2.5 mm to 7.5 mm [4] in steps of 1 mm.

Geometry representation and tetrahedral meshing was performed in Gmsh [5]. A total of 1,577,670 million tetrahedral elements comprised the mesh. Mesh resolution of blood and tissue elements was adapted to be the highest surrounding the tip and close to the tissue surface, while it decreased for larger distances to the catheter. The minimum, average, and maximum length of the elements were 0.0008 mm, 1.9668 mm, and 11.13771 mm, respectively.

2.1. Atrial tissue deformation model

Mechanical deformation was modeled with Ansys (Ansys®Academic Research Mechanical, Release 18.1). To model the tissue's mechanical behavior, we adopted an elastic model with Young's modulus reported by Bellini et al. [6] for human cardiac tissue. In the case of scar tissue, the healthy Young's modulus was increased five-fold as described in the work of Villemain et al. [7]. Thus, the Young's modulus for healthy and scar atrial tissue was set to 19.19 kPa and 88.73 kPa, respectively. A perpendicular CF between 1 and 6 g in steps of 1 g for both healthy and scar tissue, was applied in the model. Furthermore, the range between 10 and 25 g in steps of 5 g was also simulated for the scar tissue.

2.2. Local electrical impedance simulation

After the mechanical simulations, the electrical properties were assigned to each tetrahedral element of the setup mesh. Conductivity values for the metallic electrodes, insulator, blood, healthy tissue, and scar tissue in the mesh at 14.5 kHz were chosen as 400,000 S/m , 10^{-7} S/m, 0.7 S/m, 0.164 S/m, and 0.387 S/m, [8] respectively. To simulate the electrical field created by the Rhythmia HDx electroanatomical mapping system (Boston Scientific, Malborough, MA, USA) used in the clinics, an alternating current of 5 mA peak-to-peak amplitude at 14.5 kHz was modeled using the software EIDORS [9] in MATLAB (The MathWorks, Inc., Natick, MA, USA, version 2021a). Stimulation and measurement circuits were defined according to the catheter system and the resulting voltage amplitude was divided by the amplitude of the injected current to obtain the LI.

2.3. Clinical cohort

Patients undergoing left atrium (LA) ablation therapy with the IntellaNav Stablepoint™ catheter and the Rhythmia HDx electroanatomical mapping system (Boston Scientific, Malborough, MA, USA) in the Städtisches Klinikum Karlsruhe (Karlsruhe, Germany) were included in this analysis. The study was approved by the local ethics committee and all patients provided written informed consent.

For ten patients, CF and LI data were acquired after bipolar voltage electroanatomical mapping in healthy tissue areas on the anterior wall. At least one point in low voltage regions of the LA was also recorded for eight patients as scar tissue. Each LI measurement was correlated with its corresponding CF value, which was increased from 0 g to the saturation point ($\sim$70 g).

Due to the susceptibility to oscillations of raw LI recordings, a moving average approach was applied to the raw recordings. All LI measurements from each patient recorded at every applied CF were collected. Therefore, outliers determined as smaller than $median \pm 1.5 \times IQR$ were removed and median and interquartile range were selected to represent each CF.

3. Results

As shown in Figure 2, combined simulations with mechanical deformation and LI measurements yielded lower LI values in scar than in healthy tissue when applying the same CF. Increasing the thickness of the tissue led to higher LI values when applying a distinct CF. Increasing the CF for fixed tissue thickness entailed an increment of the LI.

In healthy myocardium, in silico LI values ranged from 160 Ω to 175 Ω for CF between 0 and 6 g, whereas values between 148 Ω and 151 Ω were obtained for scar tissue. When applying higher CF to the scar, i.e. between 10 and 25 g, LI values increased up to 156 Ω. There was no overlap between values obtained for healthy tissue and scar tissue for any of the given tissue thicknesses and CF.

Figure 3 shows trends for both healthy and scar tissue when increasing CF. Simulated values laid in the range of clinical data for scar and healthy tissue. Healthy and scar clinical data did not follow the trend of in silico values from 0 to 6 g as well as scar tissue did for from 6 to 25 g.

4. Discussion

In silico mechanical and LI experiments were performed to evaluate the effect of CF on LI measurements in atrial tissue. For CF values between 1 and 6 g, first mechanical deformation and subsequently electrical impedance measurement was simulated.

In silico results showed in Figure 2 that healthy and scar tissue can be distinguished even when increasing the contact force and varying tissue thickness. Moreover, in silico

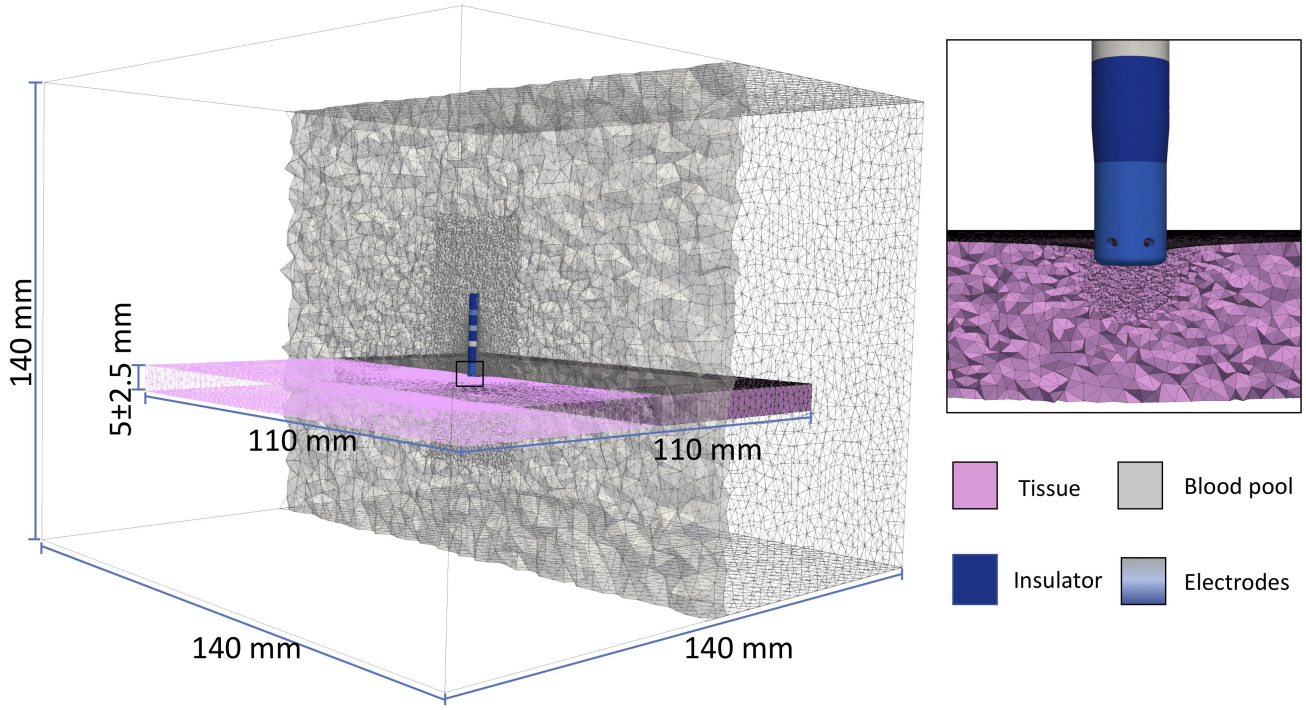

Figure 1. In silico experiment setup that contains the IntellaNav Stablepoint™catheter with its different conductive (light blue) and isolator (dark blue) parts, tissue patch (pink) with different thicknesses, and bloodpool (grey).

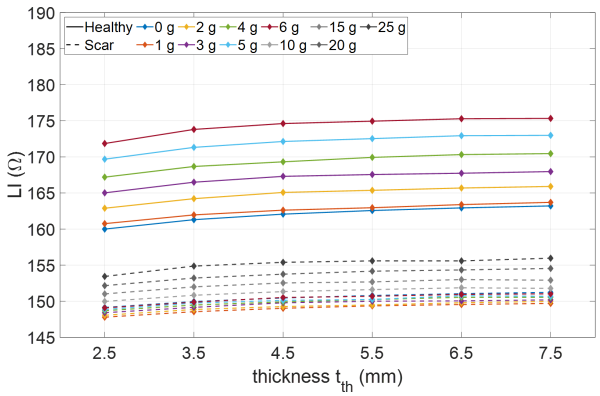

Figure 2. LI values for in silico experiments at CF between 0 and 6 g in healthy myocardium and scar tissue for t_{th} between 2.5 and 7.5 mm. In scar tissue also LI values for in silico experiments at 10 g, 15 g, 20 g, and 25 g are shown. Healthy tissue is represented by solid lines while scar tissue is represented by dashed lines.

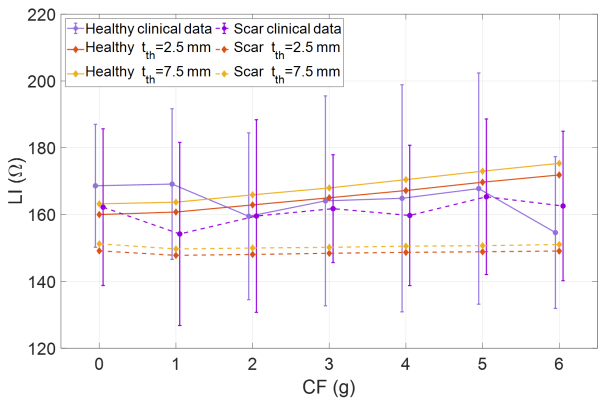

Figure 3. LI values for in silico (diamond) at CF between 0 and 6 g in tissues of 2.5 mm (red) and 7.5 mm (yellow) and clinical data (circles). Healthy tissue is represented by solid lines while scar tissue is represented by dashed lines.

results laid in the range of clinical data, as shown in Figure 3, for healthy and scar tissue. However, healthy clinical data shows a drop at 3 g and 5 g, which was not observed in silico but could be explained due to the extremely difficulty getting exact CF values below 10 g measured by human. However, trends of clinical data followed the expected behavior as scar tissue usually presents lower LI values than healthy tissue [10]. In silico healthy values showed more similar results when comparing with clinical data than scar tissue.

In this study, the whole tissue patch was simply changed to scar properties when simulating scar. In a more realistic way, diffuse patches of fibrosis and healthy tissue should be interspersed to better model the mechanical and elec-

trical interaction. Moreover, and due to the lack of more specific literature, left atrial tissue was model as an elastic tissue with ventricular parameters, which could have led to mismatches in the results. The introduction of an hyperelastic model in future studies will allow us to model broader ranges of CF as used in the clinics.

Nonetheless, using our in silico setup helped to better understand the link between CF and LI when distinguishing between healthy and scar tissue. It represents what is usually seen in both the in vitro and in human environment [2, 11, 12]. LI values are expected to distinguish between healthy and scar tissue independent from the atrial rhythm, which can improve the understanding of underlying substrate, even more, when corrected for an eventual lack of contact by combining it with CF. Understanding how this CF affects the LI will allow to move slowly towards an intracavitary impedance electroanatomical mapping system.

5. Conclusions

We were able to identify the effect of the CF and tissue thickness on LI measurements for healthy and scar tissue. Simulated LI values increased when CF, as well as with tissue thickness, grow. Healthy and scar tissue can still be distinguished by means of LI. Comparing to clinical data, our simulations laid within the range of clinical measurements for both healthy and scar tissue. A larger dataset with higher variability should be acquired for more detailed analyses in future work.

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