Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2018 February ; 10576: . doi:10.1117/12.2322523.

Technical Note: On Cardiac Ablation Lesion Visualization for Image-guided Therapy Monitoring

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Abstract

The delivery of insufficient thermal dose is a significant contributor to incomplete tissue ablation and leads to arrhythmia recurrence and a large number of patients requiring repeat procedures. In concert with ongoing research efforts aimed at better characterizing the RF energy delivery, here we propose a method that entails modeling and visualization of the lesions in real time. The described image-based ablation model relies on classical heat transfer principles to estimate tissue temperature in response to the ablation parameters, tissue properties, and duration. The ablation lesion quality, geometry, and overall progression is quantified on a voxel-by-voxel basis according to each voxel's cumulative temperature and time exposure. The model was evaluated both numerically under different parameter conditions, as well as experimentally, using *ex vivo* bovine tissue samples. This study suggests that the proposed technique provides reasonably accurate and sufficiently fast visualizations of the delivered ablation lesions.

Keywords

image-guided cardiac catheter ablation; radiofrequency ablation; ablation lesion modeling and monitoring; model evaluation and validation; lesion visualization

1. INTRODUCTION

Although ablation therapy has received extensive attention for the treatment of arrhythmic conditions, and, in particular, atrial fibrillation, reported ventures into the treatment of some arrhythmias have been somewhat discouraging. Successful treatment is not only accompanied by lengthy procedures and prolonged exposure to ionizing radiation,¹ but

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studies have also shown that 30–50% of patients undergoing ablation treatment require repeat procedures, while others experience complications, such as cardiac perforation and tamponade, and atrioesophageal fistula formation when ablating in the posterior wall of the left atrium.^{2,3}

The success of cardiac catheter ablation therapy has been hampered by sub-optimal visualization and navigation inside the beating heart, and lack of adequate monitoring of the thermal damage induced during ablation. Often, the tissue is only temporarily inflamed as a result of the ablation, and, in time, it regains its viability, raising the need for a repeat procedure. Catheter-tissue contact also plays a major role in the delivery of fully developed, irreversible lesions toward achieving contiguous, transmural ablation patterns. Since electrode-tissue contact directly impacts the heat flux into the tissue, but contact area is difficult to measure, contact force has been used as a contact surrogate. Regardless of how improved contact may be achieved and measured, the success of the ablation depends on the delivery of irreversible lesions, which is impacted by the electrode-tissue contact. Here we consider the effects of the electrode-tissue contact together with lesion and tissue injury characterization.

Extensive research has been conducted on improving visualization and guidance to facilitate catheter navigation inside the heart. One example is the advanced prototype platform for image-guided cardiac ablation therapy described by Rettmann *et al.* (Fig. 1) that incorporates dynamic, pre-operative, subject-specific anatomical cardiac models, tracked electro-physiology data, and tracked real-time ultrasound (US) imaging registered to the patient.^{4–6}

Electro-anatomical mapping (EAM) systems are routinely employed in the clinic (CARTO — Biosense-Webster Inc., Diamond Bar, CA; EnSite NavX — St. Jude Medical, St. Paul, MN; and Rhythmia — Boston Scientific, Marlborough, MA), and complement fluoroscopy imaging with electro-anatomic models intra-operatively generated using the tracked catheter. Nevertheless, these models are somewhat coarse, as not all endocardial sites can be reached and not all recorded locations truly belong to the endocardial wall.

Traditional EAM systems depict the delivered ablation lesions by marking the locations visited by the tracked catheter with spherical glyphs. However, neither the size nor the color of these generic markers correlates with the size or quality of the lesion,⁷ hence providing no information on the lesion quality. In addition to the glyphs that mark the “ablated” locations, extensions of the traditional EAM systems, such as the VisiTag technology,⁸ show the user a “gauge” whose color changes according to the Ablation Index estimated at a specific location based on power, contact force, and ablation time.⁹ Although this technology represents an improvement over traditional EAM systems, as it leverages the knowledge that enhanced contact and ablation duration improve lesion transmural, the force-time gauge display is based on force and time thresholds empirically defined by the user according to their experience, instead of validated thresholds that confirm irreversible ablation.

This work builds on 1) the need for thermal injury assessment / monitoring and lesion characterization to ensure complete ablation, 2) the limitations associated with current

standard of care platforms as far as addressing these needs, 3) the inadequacy of existing direct sensing method to provide feedback on lesion size, geometry, and extent of induced tissue damage during the ablation procedure, and 4) the potential of non-direct sensing-based techniques, such as ablation lesion models for lesion characterization and visualization, to provide a means to monitor ablation lesion delivery.

The full, extended version of this manuscript¹⁰ describes an image-based ablation lesion model that 1) quantifies tissue temperature based on heat transfer principles and available input data and tissue parameters, 2) characterizes tissue injury and provides representations of lesion geometry and quality based on the estimated temperature and ablation duration (which are the factors that play into the thermal dose calculation, along with tissue properties), and 3) renders ablation lesions in a timely fashion for use during procedures. The methods are accompanied by both numerical verification against previously developed and disseminated ablation models, and also by validation experiments conducted in animal myocardial tissue samples in a convective saline bath at body temperature using direct temperature sensing probes for real-time temperature measurements and post-ablation assessment of the lesion.

This work does not describe the development of a thermal ablation model intended to substitute or compete with previously disseminated approaches that employ finite element methods to model the tissue and heat transfer phenomena in their full complexity.^{11–13} Rather, we describe a surrogate method that follows a fast, image-based implementation, leverages intra-operative information to characterizes the induced thermal injury,^{14,15} and generates visual representations of the created lesions. We envision that this lesion characterization and visualization tool could be potentially leveraged clinically by integrating it into existing platforms, such as VisiTag. This approach could represent an upgraded version of what VisiTag currently offers and provide simultaneous guidance on lesion delivery and characterization / monitoring during ablation.^{16,17}

2. METHODOLOGY

2.1. Governing Principles:

Tissue response to RF energy can be approximated with sufficient accuracy by a coupled resistive - conductive heat transfer process.¹⁸ Our proposed surrogate ablation model incorporates a resistive component occurring at the electrode-tissue interface, and a conductive component responsible for energy diffusion into the tissue (Fig. 2). The heat transfer equilibrium in the tissue during ablation is governed by the bioheat equation.¹⁹

2.2. Model Formulation and Image-based Implementation:

As opposed to solving the heat transfer equation on a discretized geometry using a traditional finite element mesh, the proposed ablation model was solved and implemented using an image-based approach, where the computational elements were the image voxels themselves: multiple *image volumes*, described in detail in,¹⁰ are used to predict tissue temperature, extent of tissue damage, and lesion progression on a voxel-by-voxel basis during the ablation.

In short, following temperature initialization at 37 °C, the following *image volumes* are used to evaluate tissue temperature, exposure (i.e., measure of tissue damage), and lesion progression during the ablation. The *conductivity volume* is defined by assigning all voxels in each image compartment — tissue and blood — their corresponding thermal conductivity values. An image volume of identical size is defined as the *temperature volume* by assigning each voxel its corresponding temperature value, first initialized at 37 °C. The tissue *exposure volume* is a volume of the same size as the temperature volume in which each voxel is assigned its corresponding cumulative exposure. Cumulative exposure is defined as the area under the temperature-time curve or the cumulative sum of the temperature-time product during the ablation duration.

The cumulative exposure is computed as the cumulative sum of the temperature - time product for each individual voxel in the *temperature volume* throughout the duration of the ablation. Cumulative exposure can be essentially interpreted as the area under the temperature - time curve for each voxel accumulated during the ablation cycle. This new parameter quantifies and characterizes lesion irreversibility in a similar fashion to the Arrhenius-based tissue damage coefficient, however with a much higher computational efficiency, which is critical for the intended time sensitive intra-procedural monitoring application.

In summary, our image-based model implementation stores tissue temperature distribution in the time-variant tissue *temperature volume*, which constitutes the basis for estimating the tissue injury that is stored in the time-variant tissue *exposure volume*. Corresponding voxels in the tissue *exposure volume* are digitally marked in the tissue *lesion volume* according to their cumulative exposure relative to the cell-death threshold (55 °C or higher for 5 s or longer) as either irreversible lesion or reversible lesion penumbra.

3. NUMERICAL MODEL EVALUATION AND EXPERIMENTAL VALIDATION

We conducted numerical simulations to assess the sensitivity of the model to several parameters, including tissue thermal conductivity, tissue damage criteria, and electrode-tissue contact. Moreover, we also conducted numerical simulations aimed at comparing the size and geometry of the irreversible lesion core predicted by each of the three tissue injury criteria: the Arrhenius-based tissue damage coefficient, the volume enclosed by the 50 °C isothermal surface, and the computationally-efficient cumulative exposure proposed here. Lastly, we also simulated a cooled vs. dry electrode ablation, as described in detail in.¹⁰

In addition, we conducted a series of ablation experiments using *ex vivo* bovine tissue samples To validate our model against physical measurements. The 1-cm thick muscle samples were submerged in a convective 0.9% saline bath. Direct tissue temperature measurements, considered as ground truth, were recorded using focal 0.8 mm diameter fiberoptic temperature probes (OpSens Inc., Quebec City, Canada) inserted in the samples at prescribed locations relative to the ablation electrode.

Fig. 3 compares the model-predicted and experimentally recorded temperature profiles at both the proximal and distal sampled locations during the ablation cycles at 90 °C ablation, showing agreement between the model and direct temperature measurements.

The model-predicted ablation lesions were also characterized according to lesion volume — estimated as the volume occupied by all voxels that reached the exposure threshold; maximum lesion diameter — estimated as the diameter of the lesion where voxel exposure exceeded the required lesion exposure threshold) at its widest location; surface lesion diameter — estimated as the width of the lesion at tissue surface (provided the lesion exposure threshold was reached); and surface exposure diameter. Lesion geometry was defined according to the cumulative exposure tissue injury criterion: voxels exposed to temperatures above 55 °C for at least 5 s were classified as irreversible lesion, and reversible lesion penumbra, otherwise.

While force may serve as an acceptable surrogate for contact, it does not provide an objective measure of the extent of the contact. For example, same applied force deflects stiffer tissue less than softer tissue, yielding a smaller contact area. Contact area, on the other hand, is a more direct measure, as it directly impacts heat flux into the tissue and lesion size. We have conducted several experiments aimed at establishing the correlation between electrode penetration depth, contact area, contact force, and approach angle.²⁰

The intended clinical application requires that the model provide lesion visualization and monitoring with minimal latency, in the real time of the procedure. The computational speed of the image-based implementation presents a significant advantage over computationally prohibitive finite element approaches. The proposed model was implemented on a standard desktop PC (Intel Core2 Quad 2.5 GHz processor with a 8 GB DDR2 RAM) and yielded updates of the tissue temperature distribution and rendered a model-predicted ablation lesion during a 60 s ablation cycle in ~1 minute. The computational efficiency can be further improved via parallel multi-thread computing and GPU implementation, enabling lesion monitoring with no workflow latency.

4. CONCLUDING REMARKS

This work describes the implementation, numerical verification and *ex vivo* experimental validation of a fast and accurate method to model, predict, characterize, and visualize ablation lesions. These studies demonstrated less than 5 °C difference between the model-predicted and experimentally measured end-ablation temperatures. The predicted and observed lesion patterns were also in agreement, suggesting sufficiently accurate modeling of the ablation lesions. Lastly, our proposed method enables therapy delivery feedback with minimal latency.

Given the support provided by new methodologies of planning, simulation, and training, this work demonstrates an effective and fast extension of a theoretical model into a practical tool. Following further development and validation, including *in vivo* evaluation in animal models and integration into an existing electro-anatomical mapping platform, this technology has the potential to allow for quantitative monitoring of ablation therapy with integrated guidance.^{17,21}

This lesion characterization and visualization tool could be leveraged clinically by integrating it into existing platforms, such as VisiTag. As such, this could be an upgraded

version of what VisiTag currently offers. Once integrated with an image guidance platform for left atrial ablation therapy, the proposed model has the potential to provide the cardiologist with online characterization, visualization, and monitoring of the delivered RF lesions. In concert with the catheter position provided by the tracking system, the model-predicted lesions will be displayed as superimposed on the electro-anatomical model used for guidance. Clinicians will have access to dynamically updated lesion maps during therapy that indicate the location and size of the lesions that need to be delivered to avoid the presence of gaps in the ablation pattern.

Acknowledgment

We thank Jason Robey for help with data acquisition, Ron Karwoski, Al Larson, and Bruce Cameron for software development, Dr. Matthew Swale for his clinical expertise, and Mark Korinek, Roger Mahon, and Randy Kinnick for engineering support. We also acknowledge funding support from National Institutes of Health (NIBIB R01-EB002834), Natural Sciences and Engineering Research Council, and Heart & Stroke Foundation of Canada.

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Figure 1.

Advanced platform for image guidance and visualization for cardiac ablation therapy. a) Left atrial model integrated with real-time magnetic catheter tracking and b) real-time 2D US imaging; c) Ablation lesion map generated using the proposed surrogate ablation model described in this paper and used to visualize and monitor therapy progression.

Figure 2.

Schematic diagram of the heat transfer processes during cardiac RF ablation. RF electrode is in contact with tissue resulting in resistive (Joule) heating at the electrode-tissue interface, and conductive heating further within the tissue. A fresh blood supply inside the cardiac chamber convectively cools the electrode-tissue interface. Moreover, provided large blood vessels are present in the vicinity, internal tissue perfusion might also contribute to heat dissipation from the ablation site. Adapted from.¹⁸

Figure 3. Temperature plots of the electrode model, as well as model-predicted and experimentally-measured (mean $\pm$ standard deviation) temperatures at the proximal and distal locations for the 90 °C target electrode temperature ablation.