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Image-based Modeling and Characterization of RF Ablation Lesions in Cardiac Arrhythmia Therapy

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Abstract

In spite of significant efforts to enhance guidance for catheter navigation, limited research has been conducted to consider the changes that occur in the tissue during ablation as means to provide useful feedback on the progression of therapy delivery. We propose a technique to visualize lesion progression and monitor the effects of the RF energy delivery using a surrogate thermal ablation model. The model incorporates both physical and physiological tissue parameters, and uses heat transfer principles to estimate temperature distribution in the tissue and geometry of the generated lesion in near real time. The ablation model has been calibrated and evaluated using *ex vivo* beef muscle tissue in a clinically relevant ablation protocol. To validate the model, the predicted temperature distribution was assessed against that measured directly using fiberoptic temperature probes inserted in the tissue. Moreover, the model-predicted lesions were compared to the lesions observed in the post-ablation digital images. Results showed an agreement within 5°C between the model-predicted and experimentally measured tissue temperatures, as well as comparable predicted and observed lesion characteristics and geometry. These results suggest that the proposed technique is capable of providing reasonably accurate and sufficiently fast representations of the created RF ablation lesions, to generate lesion maps in near real time. These maps can be used to guide the placement of successive lesions to ensure continuous and enduring suppression of the arrhythmic pathway.

Keywords

Image-Guided Cardiac Procedures; Data Integration for the Clinic/OR; Image-guided Cardiac Ablation; Intra-operative Modeling and Monitoring; Evaluation and Validation; Intra-procedure Visualization

1. INTRODUCTION

Radio-frequency (RF) ablation therapy aims to locally destroy unwanted biological tissue via thermal energy delivery, typically using an electrode that is inserted intra-vascularly and guided to the target region using medical imaging. The technique was first introduced in the

1980s and a treatment approach for cardiac arrhythmias, then found utility in a number of conditions in the 1990s, and now is the therapy method of choice for certain cardiac arrhythmic conditions.

We have identified two significant factors that have hampered the success of catheter ablation therapy: (1) inadequate visualization and guidance of the ablation catheter inside the beating heart for accurate targeting of the arrhythmic sites; and (2) lack of sufficient feedback information with respect to the changes occurring in the tissue in response to the radio-frequency energy delivery (i.e., is the induced “tissue damage” sufficient to ensure irreversible electrical isolation of the arrhythmic pathway?)

Extensive research has focused on developing efficient, rapid, robust and intuitive real-time solutions for intra-operative catheter navigation.^{1, 2} In our previous work,³ we reported on the development of a robust guidance environment as part of a prototype system for advanced visualization and navigation for image-guided left atrial ablation therapy. Our platform permits ready addition and integration of multiple imaging modalities, tracking of interventional devices, and electrophysiology data, enabling subject-specific procedure planning and guidance using 3D dynamic cardiac models obtained from routinely-acquired pre-operative CT images. This platform allows dynamic update, animation, synchronization, and visualization of the multi-modality data in direct spatial and temporal relationship with the intra-operative patient.

While positioning of the therapy catheter on target is important, intra-procedure feedback on the characterization of the ablation lesions is also a major contributor to therapy success. Very little research has been conducted to provide feedback on therapy delivery by showing the changes that occur in the tissue in response to the RF energy delivery. If available in near real time, such information could significantly enhance the cardiologist's ability to achieve successful treatment. Several groups have explored mathematical and physiological modeling of radio-frequency ablation⁴ to investigate the temperature distribution and lesion development in response to RF energy delivery.^{5, 6} However, these approaches have not focused on fast implementations of the ablation models for use in conjunction with interventional platforms for intra-operative applications.

This paper describes work which complements our previous efforts toward enhancing catheter guidance by providing a means for estimating and visualizing the RF lesions generated during the ablation protocol. Unlike other previous approaches that have employed commercially available finite element analysis packages to model the tissue^{7, 8} in its full complexity at a high computational expense, our solution is based on an image-based implementation and can provide near real-time visualization and monitoring of therapy delivery.

2. METHODOLOGY

2.1. Governing Principles

The response of the tissue to the delivery of RF energy can be approximated with sufficient accuracy by a coupled resistive - conductive heat transfer process. The proposed ablation

model incorporates a resistive component occurring at the catheter tip-tissue interface, coupled with a purely conductive component responsible for the diffusion of thermal energy into the tissue (Fig. 1).

In the proposed model, the ablation electrode is represented by a virtual construct based on the physical properties of the catheter. During clinical ablation procedures, the RF generator is typically operated in the temperature-controlled mode. The temperature-controlled mode is incorporated in the model by reducing the output power as the electrode-tissue interface temperature approaches the preset target electrode temperature.

The time-varying tissue conductivity is also considered in the model, along with its changes due to dehydration (i.e. with dehydration, tissue becomes more insulative, resulting in reduced conductivity). Internal tissue temperature is estimated by updating its thermal conductivity according to the “ablation exposure” (i.e., integral of temperature over time) on a voxel-by-voxel basis for the duration of the ablation.

2.2. Image-based Implementation

As opposed to implementing the heat transfer equations using a classical finite element discretized mesh of the tissue geometry, the model is implemented using an image-based formulation. Multiple image volumes, outlined below, are manipulated to update tissue temperature, thermal conductivity, tissue damage and lesion progression, on a voxel-by-voxel basis throughout the duration of the ablation. The electrode is defined by means of voxel occupancy in the “temperature volume”: tissue voxels at the electrode tip-tissue interface undergo resistive heating, while tissue voxels remote from the interface experience heating by conduction, implemented via a flow-based anisotropic diffusion on the “temperature volume”.

- an initial “conductivity volume” is established by replacing each labeled image region with representative heat conductivity values specific to tissue and blood;
- an image volume of identical size is initialized to the ambient body temperature of 37°C, labeled as the initial “temperature volume”;
- the “tissue exposure volume” is generated based on the cumulative temperature and exposure times of each voxel (i.e. area under the temperature-time curve);
- the “tissue ablation volume” is generated based on the voxels of the “tissue exposure volume” that have been exposed to temperatures above the cell-death threshold (55°C) for at least 5 seconds.⁹

Note that the conductivity of the voxels that constitute the “ablation volume”, and hence the lesion (classified as irreversible tissue damage as a result of exposure to temperatures above the cell-death threshold for 5 seconds or longer) is recorded by updating the intensity of the associated voxels in the “tissue conductivity volume”, which is, in turn, used to update the “tissue temperature volume” in the next computational cycle.

2.3. Experimental Evaluation

To evaluate the feasibility of the proposed model, we conducted experimental assessments using *ex vivo* thin (0.5 cm thick) beef muscle samples submerged in a 0.9% saline waterbath maintained at 37°C by a convective heat pump. Fiberoptic temperature probes (0.1°C precision and 50Hz sampling rate) were inserted within the tissue at specified locations to record direct tissue temperature measurements during the ablation. Digital photographs of the samples were acquired post-ablation for lesion evaluation (Fig. 2).

3. RESULTS

We present the results achieved during a temperature-controlled 60 second ablation protocol conducted at 90°C target electrode temperature using a temperature-feedback 9F catheter. Catheter-tissue contact was achieved by displacing the catheter vertically to slightly deflect the tissue surface, resulting in a hemispherical contact area of the same radius as the catheter tip (~ 1.5 mm). Four fiberoptic temperature probes were inserted symmetrically with respect to the ablation catheter at 2.5 mm radial distance and 3 mm depth (proximal) location, and 5 mm radial distance and 3 mm depth (distal) location. The model was interrogated for the tissue temperature within a search area of 1.0 mm × 1.0 mm around each location. Table 1 summarizes the model-predicted and experimentally measured temperatures.

Fig. 3 summarizes the model-predicted and experimentally measured temperatures. Given the 0.5 mm spatial resolution (i.e., precision of the model) and the potential uncertainty (on the order of 0.5 mm) in positioning temperature probes at the exact locations. Multiple model measurements were recorded for comparison to the experimental measurements.

The tissue damage predicted by the thermal model was characterized according to the following physical parameters:

- lesion volume was estimated as the volume occupied by all voxels that reached the exposure threshold;
- maximum lesion diameter was estimated as the diameter of the lesion ((where voxel exposure exceeded the required lesion exposure threshold) at its widest location;
- surface lesion diameter was estimated as the width of the lesion at tissue surface, again provided the lesion exposure threshold was reached;
- surface exposure diameter was estimated as the width of the extent of tissue damage (width of the exposure volume, regardless of the magnitude of the voxel exposure threshold) at tissue surface.

Fig. 4a shows the transient trends of the lesion characterization parameters (lesion volume, maximum lesion diameter, surface lesion diameter and surface exposure diameter) during the 90°C target electrode temperature ablation protocol. As noted, the lesion volume reached ~ 100 mm³, the achieved maximum lesion diameter at end-ablation was ~ 6 mm and occurred at 2 mm depth below the tissue surface, the lesion diameter at the surface was on the order of 5 mm, and the surface exposure diameter was approximately 9 mm. The lesion

characterization measurements predicted by the model are consistent with those observed in the digital images of the tissue samples (surface and section views) acquired post-ablation (Fig. 5a).

Fig. 4b presents two-dimensional cross-sectional renderings of the model-generated tissue damage at six stages during the ablation: 0, 5, 10, 30, 60, and 90 seconds. The non-viable lesion region (irreversibly ablated tissue) is labeled as bright, while the lesion penumbra (stunned tissue) is also displayed less prominently.

4. DISCUSSION

We present the development and initial evaluation of a thermal modeling approach for characterizing tissue temperature distribution and extent of tissue damage during RF ablation procedures.

The results presented here are promising toward confirming that the proposed model does provide feasible estimates of the temperature distribution and lesion characterization. Nevertheless, there are potential limitations of the current work in the context of its long-term intended application to the intra-operative guidance of left atrial ablation therapy.

To avoid the limitations imposed by a closed, beating heart environment, with temperature probes inserted invasively in the live myocardium of animal subjects, and since the primary objective of this study was to disseminate on the image-based implementation of the ablation model and to demonstrate its capabilities in providing tissue temperature and lesion development, the experiments were conducted in a well-controlled environment using thin beef muscle samples, where all physiological parameters were modeled according to the literature. Nevertheless, we plan to conduct *in vivo* investigations as part of our future evaluation studies.

One limitation to the clinical implementation arises due to the motion of the beating heart and its effect on the contact between the catheter and left atrial wall. It was suggested by Shah *et al.*¹⁰ that the area under the real-time contact force curve predicts the size of the created RF lesion, and also by Yokoyama *et al.*¹¹ that the contact force estimated by a sensor integrated in the ablation catheter is also an indicator of the lesion size. As such, a suboptimal contact force may lead to inadequately developed lesions, and hence gaps in the ablation line, requiring the repetition of the entire procedure.¹² We propose to employ real-time 2D or 3D ultrasound imaging, currently in the process of being integrated into our prototype image guidance system, to visualize the electrode-tissue contact and include this information in the ablation model formulation as a function of the resistive heat flux at the electrode-tissue interface.

A primary requirement of the clinical application is the feasibility of the model to output the thermal maps with minimal latency, in the real time of the procedure. The computational speed achieved via the image-based implementation presents a significant advantage over other traditional computationally prohibitive commercially available FEA packages. The proposed model was implemented on a standard desktop PC (Intel Core2 Quad 2.5 GHz processor with a 8 GB DDR2 RAM) and provided updates of the tissue temperature

distribution and lesion progression every 0.7 seconds, resulting in the rendering of a full ablation cycle in less than a minute. As such, the model can provide online (rather than real-time) lesion monitoring with minimal workflow latency. The computational speed can be further improved via parallel multi-thread computing and GPU implementation.

Once integrated within the prototype guidance and navigation platform for cardiac ablation therapy, the thermal model will provide the cardiologist with online visualization and monitoring of the changes induced in the tissue during RF energy delivery. In addition to information related to the position and orientation of the catheter, available from the integrated tracking system, the physiological changes occurring in the tissue will be displayed by means of temperature colour maps superimposed on the pre-operative anatomical model, thereby enhancing therapy guidance.

5. CONCLUSIONS AND FUTURE WORK

This paper describes initial development of a near real-time 3D image-based ablation model that enables specific site monitoring of tissue response during ablation exposure, including tissue temperature distribution, exposure, and geometric progression of the lesion. Studies conducted in *ex vivo* beef muscle samples have demonstrated less than 5°C difference between the model-predicted and experimentally measured temperature profiles. The predicted and observed lesion patterns were also in agreement, confirming a sufficiently accurate and realistic modeling of the ablation process. Unlike other commercially available packages which focus on modeling the tissue in its full complexity at a high computational expense, our solution is based on an image-based implementation that provides both visualization of tissue temperature distribution and lesion progression in near real time during the procedure, with no significant workflow latency.

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Figure 1.

Schematic diagram of the thermodynamic processes occurring during RF ablation - adapted from Haemmerich *et al.*⁴ The RF electrode is in contact with the tissue resulting in resistive (Joule) heating at the electrode-tissue interface, and conductive heating further into the tissue. A fresh blood supply circulating through the left atrium convectively cools the electrode-tissue interface and the electrode itself, shifting the created lesion deeper into the tissue (note the geometry of a typical ablation lesion). Similarly, internal tissue perfusion may also contribute to heat dissipation from the ablation lesion if large blood vessels are present nearby, otherwise this process can be neglected.

Figure 2.

a) Schematic diagram of the experimental setup for model validation and temperature measurements during the RF ablation of *ex vivo* beef muscle samples, where fiberoptic probes are inserted at various radial distances and depths (x , y , z , w); b) Experimental apparatus showing a muscle sample submerged in a convective saline bath at 37°C. The ablation electrode tip was in hemispherical contact with the tissue surface and fiberoptic temperature probes were inserted in each sample. A grid template is used to position the ablation electrode and fiberoptic probes at desired spatial locations.

Figure 3. 90°C Target Electrode Temperature: Time-varying temperature plots of the electrode model (Model Electrode), as well as model-predicted (Model $R \times D$) and measured temperatures (Fiberoptic Probe 1 & 2) at the proximal and distal locations. Two symmetrically placed fiberoptic temperature probes (Fiberoptic Probe 1 & 2) were inserted at each location. Model-predicted temperatures were estimated at nine voxels (0.5 mm in each direction) in the vicinity of each probe location.

Figure 4.

Model-predicted characterization of tissue damage created during ablation at 90°C target electrode temperature: lesion volume (right axis), maximum lesion diameter, surface lesion diameter and surface exposure diameter are shown over a 90 second ablation cycle (left); cross-section and surface rendering of the model-predicted ablation lesion and penumbra shown at six time points throughout the 90°C ablation. Note the lesion appearing bright at the core of the display, surrounded by the lesion penumbra effect near the periphery (right).

Figure 5.

Analysis of post-ablation digital images of muscle samples following 90°C ablation: A surface exposure diameter of ~ 9 mm and a maximum lesion diameter of ~ 6 mm shown are in the section.

Table 1

Model predicted vs. experimentally measured tissue temperature at the proximal and distal lesion location during a 60 second temperature-controlled ablation procedure at 90°C.

Time Stamp	Proximal Lesion Location (2.5 mm R × 3.0 mm D)		Distal Lesion Location (5.0 mm R × 3.0 mm D)	
(sec)	Predicted Temp. (°C)	Measured Temp. (°C)	Predicted Temp. (°C)	Measured Temp. (°C)
11.2	57.5	61.6	37.3	37.1
19.6	65.8	70.7	37.4	38.8
30.8	69.6	74.9	38.8	39.7
39.2	72.1	77.2	40.3	40.4
50.4	72.9	78.5	41.6	40.8
58.8	74.2	78.9	44.2	41.4

Note: Measured temperature values were averaged between two symmetrically placed sensors. The model-predicted temperature values were recorded at the second nearest to measurement time.