Method for evaluation of predictive models of microwave ablation via post-procedural clinical imaging

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ABSTRACT

Development of a clinically accurate predictive model of microwave ablation (MWA) procedures would represent a significant advancement and facilitate an implementation of patient-specific treatment planning to achieve optimal probe placement and ablation outcomes. While studies have been performed to evaluate predictive models of MWA, the ability to quantify the performance of predictive models via clinical data has been limited to comparing geometric measurements of the predicted and actual ablation zones. The accuracy of placement, as determined by the degree of spatial overlap between ablation zones, has not been achieved. In order to overcome this limitation, a method of evaluation is proposed where the actual location of the MWA antenna is tracked and recorded during the procedure via a surgical navigation system. Predictive models of the MWA are then computed using the known position of the antenna within the preoperative image space. Two different predictive MWA models were used for the preliminary evaluation of the proposed method: (1) a geometric model based on the labeling associated with the ablation antenna and (2) a 3-D finite element method based computational model of MWA using COMSOL. Given the follow-up tomographic images that are acquired at approximately 30 days after the procedure, a 3-D surface model of the necrotic zone was generated to represent the true ablation zone. A quantification of the overlap between the predicted ablation zones and the true ablation zone was performed after a rigid registration was computed between the pre- and post-procedural tomograms. While both model show significant overlap with the true ablation zone, these preliminary results suggest a slightly higher degree of overlap with the geometric model.

Keywords: hepatic, microwave, ablation, predictive, modeling

INTRODUCTION

The management and treatment of primary and metastatic liver cancer is a major US healthcare concern. Resection is the primary source of treatment for hepatic tumors due to a record of long-term patient survival, however many patients present with non-resectable tumors due to number or location. Localized tumor ablation techniques have emerged as a viable approach for the treatment of anatomically non-resectable tumors. While radiofrequency ablation (RFA) is the most commonly used ablative therapy for treating hepatic tumors, it has presented a high recurrence rate in larger tumors and difficulties in heating near vessels [1]. As RFA elevates tissue temperatures to therapeutic levels, it also increases tissue electrical impedance. Microwave ablation (MWA) has presented a promising improvement in relation to RFA. As MWA produces larger electric fields resulting in a more spatially distributed power deposition, it retains many of the thermal characteristics of RFA, but has the added benefit of larger thermal delivery, improved lesion development near blood vessels, and is an order of magnitude quicker [2]. It is clear that the efficiency of RFA to cover large lesions is compromised due to its self-limiting nature. These limitations have been overcome to some degree through probe design, however, it seems equally clear that a field-based method, as is provided by MWA, is likely to be a better direction for large lesion coverage [3]. This is not to say that RFA has no clinical role but rather that its preferential therapeutic application may be better suited for more focal disease.

While the ablative technique is important, understanding the factors that influence delivery of treatment are equally influential to procedural outcome. Various studies have identified that error in device placement may accrue from imaging artifacts, image misregistration, target motion, antenna deflection, tissue deformation, unexpected subsurface constrains, procedural experience, and human error [4,5]. These errors are cumulative and may have large effects on procedural outcome, especially when considering a target with a diameter on the scale of millimeters as can be seen in tumor ablation. Tool tracking and intraoperative imaging can increase procedural performance by minimizing misplacement but are unable to account for all sources of error [6,7]. Ablative therapies are generally guided via ultrasound (US) and/or intra-operative computed tomography (CT). Upon localization of the target in pre-operative images, an approach for delivery is determined by the physician. In order for a successful ablation to occur, the entire volume of the tumor, as well as a safety margin, must be contained within the lesion. Although the extent of the thermal lesion differs between the various methods of ablation, the accuracy of the ablation is highly dependent upon the placement of the probe with respect to the tumor – which is largely reliant upon the experience and intuition of the physician [8].

Development of a clinically accurate predictive model of MWA procedures would represent a significant advancement and facilitate an implementation of patient-specific treatment planning to achieve optimal probe placement and thermal delivery. Various iterations of 2-D axisymmetric models have been presented in the literature [9,10]. Currently, MWA device manufacturers provide specifications for generating a geometric model of the predicted ablation zone. Such a model is driven by system input parameters rather than patient-specific anatomy. The performance of these geometric predictive models has been limited to comparing measurements of the geometric overlap without accounting for the accuracy of placement, i.e. direct spatial overlap. In order to overcome this limitation, this research proposes a method of evaluation where the actual location of the MWA antenna is tracked and recorded during the procedure via a surgical navigation system. Various predictive models of the MWA lesion may be computed using the known position of the antenna within the preoperative image space. A quantification of the direct spatial overlap between predicted ablation zones and the true ablation zone may then be performed after registering the pre- and post-procedural tomograms. A validated predictive model of MWA could then be incorporated into a planning suite which (1) allows for the implementation of predictive MWA models that are more inclusive of the impacts of patient-specific anatomy, (2) optimizes the trajectory and placement of the MWA antenna, and (3) increases the accuracy of MWA delivery through surgical tracking of the antenna.

Clinical validation of predictive models of MWA procedures is a necessary step in the development of patient-specific treatment planning. The ability to determine optimal probe positioning given the patient-specific anatomy should facilitate more complete tumor ablations while minimizing collateral damage to healthy tissue and adjacent structures. The purpose of this work is to define and perform a preliminary evaluation of a method to validate predictive models of MWA using clinical datasets obtained in open hepatic ablation procedures. While previous work in the validation of predictive MWA models has been performed using bench experiments with *ex vivo* tissue samples, *in vivo* animal studies, and clinical data, the validation results have largely been qualitative and the quantitative aspects have not allowed for a direct, spatial comparison between the model prediction and the true ablation. The method presented in this research uses optical tracking within a surgical navigation system in concert with image registration techniques to directly compare predicted and true ablation zones.

METHODS

To summarize, the proposed method for evaluation of predictive MWA models using clinical data involves three general steps: (1) collection of ablation probe tracking data during the clinical procedure, (2) generation of the predictive MWA models based on the intraoperative probe location, and (3) retrospective analysis of the direct spatial overlap of the predicted ablation zone with the true ablation zone highlighted in the post-procedural tomographic images.

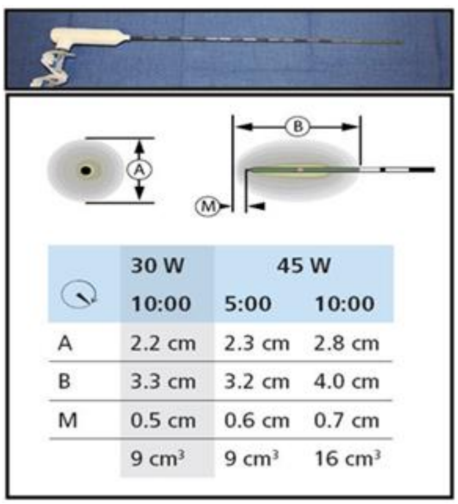
Intraoperative Data Collection

Prior to the surgical procedure, anatomical models of the liver, target lesion(s), and relevant anatomical structures were generated from the preoperative tomograms using surgical planning software (Scout™ Liver, Analogic Corporation, Peabody MA USA). The preoperative image data and associated models were then imported into a surgical navigation system (Explorer™ Liver, Analogic Corporation, Peabody MA USA) used during the ablation procedure. A Covidien Evident™ MWA antenna (Covidien Plc., Dublin, Ireland) was tracked within the Explorer™ Liver guidance system during the ablation procedure in order to record the location of the antenna within the patient anatomy. Immediately prior to the placement of the ablation instrumentation, intraoperative surface data was acquired using an optically tracked stylus for the purpose of computing physical-to-image space registration within the guidance system. After the ablation instrumentation was placed under ultrasound guidance and immediately prior to initiating the ablation process, the locations of the tip and trajectory of the tracked ablation instrument were recorded using the Explorer™ Liver device.

A series of clinical data is presented for two patients undergoing open liver ablation at Memorial Sloan-Kettering Cancer Center. The patients provided written consent and were enrolled in a study that was approved by the Memorial Sloan-Kettering Institutional Review Board. Case 1 consisted of three ablation probes being placed and simultaneously stimulated at 45 W for 15 minutes. Tracking data was only collected for the first of the three probes. Therefore, only one ablation may be simulated for this set of data. Case 2 consisted of three ablation probes being placed and simultaneously stimulated at 45W for 10 minutes. Following this ablation, the three probes were removed. A single probe was redeployed to a more lateral position and stimulated at 45W for a seven minute cycle. For the purposes of this research, only the first ablation will be reported for case 2.

Preliminary Microwave Ablation Modeling

For the purposes of evaluating the proposed validation routine, two different predictive models were utilized. First, the manufacturer specification of the Covidien Evident™ system was used to generate a geometric model of the predicted ablation zone (Figure 1). Given the information about the theoretical ablation zones obtained from the device labeling and the tracked location of the ablation probe recorded with the Explorer™ Liver device, the predicted ablation zone at the recorded position was calculated. Generating a model of the predicted ablation zone facilitates the retrospective comparison with the true ablation zone as indicated by the necrotic zone in the post-operative tomograms collected as part of standard patient follow up.



	30 W	45 W	
	10:00	5:00	10:00
A	2.2 cm	2.3 cm	2.8 cm
B	3.3 cm	3.2 cm	4.0 cm
M	0.5 cm	0.6 cm	0.7 cm
	9 cm³	9 cm³	16 cm³

Figure 1. Covidien Evident™ system manufacturer specifications for predicted ablation zone geometric model.

In addition to the simple geometric model, a 3-D finite element model (FEM) of a single MWA antenna placed within the patient pre-operative liver volume was created using COMSOL Multiphysics (COMSOL Inc., Burlington, MA USA) and Creo Parametric (PTC, Needham, MA USA). The 3-D liver surface model generated from the preoperative tomograms was imported into COMSOL and a CAD assembly of the antenna was placed using the tip and trajectory data recorded by the guidance system. Tetrahedral meshing was performed with increased refinement near the antenna-tissue interface. The model consisted of four material domains with associated relative permittivity, electrical conductivity, and thermal conductivity: (1) liver tissue [11], (2) catheter casing, (3) central catheter dielectric material, and (4) air. The distal end of the probe was simulated to have an input of 45W at 2.45GHz and the length of the ablation procedure was specified by the recorded case notes (10 – 15 minutes). All external faces of the model were set to have an absorption boundary condition in order to inhibit energy reflection at the model boundaries. Solutions were determined for a temporal step size of 15 seconds. At each time step, a solution was sequentially calculated for (1) Maxwell's equations in the frequency domain giving electric and magnetic field development and (2) Pennes bioheat equation and the Arrhenius equation to determine time-dependent variables such as temperature and tissue damage. Upon computation of the FEM solution, a 3-D surface of the region of predicted cell necrosis was generated. Due to an incomplete set of tracking data, one of three probes was simulated for case 1 and three of four probes were independently simulated for case 2.

Retrospective Analysis

As part of the standard patient follow up, tomographic imaging was acquired at approximately 30 days after the ablation procedure. Anatomical models of the necrotic zones were generated for use in the comparison with the predicted regions and a model of the liver was generated for the purposes of registering the post-operative images to the pre-operative data via a rigid surface-based registration. Once the registration between the pre-operative and post-operative image sets was computed, the overlap between the predicted ablation zone, using the intraoperative recordings from the Explorer™ Liver device, with the true ablation region indicated by the necrotic zone in the post-operative tomograms was computed.

Figure 2. Visualization of the process of computing the positive predictive value (PPV) metric used to quantify the overlap of the predicted ablation zone with the true region as indicated by the necrotic zone on the post-operative image set. The regions shown indicate the predicted ablation (green) contour from the MWA models and the true zone of ablation (black) segmented from the post-operative image set and overlaid on the pre-operative image set. The PPV is calculated via counting the number of true positive voxels (N_{TP}), highlighted in blue, and the number of false positive voxels (N_{FP}) highlighted in red.

$$PPV = \frac{N_{TP}}{N_{TP} + N_{FP}} \times 100\%$$

Figure 2 depicts the method used to quantify the degree of overlap, specified as positive predictive value (PPV). The first step in computing the PPV metric is to generate binary mask images that represent the true ablation zone generated from the necrotic zone model in the post-operative images and the predicted ablation zone given the data acquired from the Explorer™ Liver device. Given these mask images, the number of voxels in the predicted ablation zone that overlap with the true zone indicated by the region of necrosis (N_{TP}) as well as the number of voxels in the predicted zone that do not overlap with the necrotic zone were computed (N_{FP}).

RESULTS and DISCUSSIONS

Model Simulations

Simulation of the 3-D patient-specific geometry COMSOL model for individual probes required <30 minutes on a 2.4GHz Intel® Core™ i7 processor with 8 GB RAM. Model elements resulting in 50% or greater cell death were considered to be the resulting ablation zone. An example visualization of the overlap between the two MWA models and the necrotic zone in the post-procedural tomograms for one of the clinical cases are shown in Figure 3. Based on qualitative inspection, there is significant overlap between the predicted ablation zones computed from both the geometric model the FEM-based computational model from COMSOL. While conserving patient-specific geometries, the computational model simplified tissue to a homogenous medium. Therefore the significant overlap between the geometric and computational models is not unexpected.

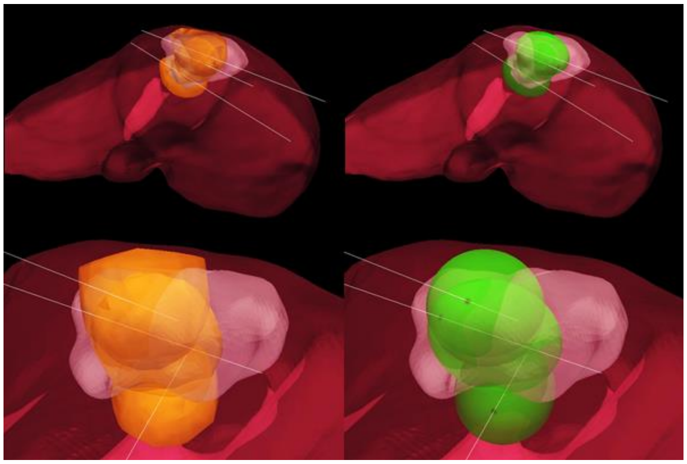


Figure 3. Overlay visualization of the necrotic zone model (grey) and the predictive MWA models generated via the intraoperative tracking data. The predicted ablation zone generated from the COMSOL solution (orange) is shown in the left column and the predicted ablation zone generated via the geometric model (green) is shown in the right column. Also, the trajectories (white line) of the Covidien Evident^{TM} recorded by the Explorer^{TM} Liver device are rendered for reference.

Positive Predictive Value Study

A summary of the PPV measurements computed for two clinical data sets is shown in Table 1. The results indicate a slightly higher degree of spatial overlap for the simple geometric model specified by Covidien with the true ablation zone. It should be noted that the PPV measure does not penalize for true ablation regions that are not contained within the predicted ablation zone, given the fact that limited tracking data was collected for each set of case data.

Table 1. Summary of the PPV measurements computed for a single Covidien Evident™ probe placement in two different clinical procedures. The preliminary results indicate a higher degree of overlap between the geometric model and the true ablation zone segmented in the post-procedural image volume.

Patient	Probe	Geometric Model PPV (%)	COMSOL Model PPV (%)
1	1	93.2	84.7
2	1	23.5	25.1
2	2	91.1	97.4
2	3	75.6	71.1

Limitations

There are multiple limitations present in the presented research. The major limiting factor to the current study is that the MWA procedure tracked data sets are incomplete. In other words, for a particular case, not all ablations are accompanied with tracked probe data. This limits the degree to which we can compare simulated ablation zones to true ablation zones. A complete set of data that includes tracking information for all performed ablations would facilitate a more thorough evaluation of the predictive models. Such a data set could be acquired in phantom, animal, or clinic and still satisfy the goals of this research. The computational model used for simulation is limited by its simplicity. While the model is novel in that it accounts for 3-D patient specific geometries, it does not include tissue heterogeneity, subsurface features, temperature-dependent electrical properties, or other features that have been developed in the literature for 2-D axisymmetric models. For future work, these modeling considerations could be accounted for and initially validated using the proposed method.

Conclusions

This study demonstrated the potential for validating models of hepatic microwave ablation by using clinical data sets. Pre- and post-operative CT images were used to create a patient-specific liver model and post-operative ablation zone geometry. Recorded tracking information of probe tip location and trajectory were used to simulate ablations within the CT-derived liver model. Overlay of the simulated models with the post-operative ablation zone were used to measure a positive predictive value which quantifies the direct spatial overlap between model solution and true ablation. Qualitative results show significant overlap between the manufacturer-specified geometric ablation model and the 3-D COMSOL computational model. The PPV measurement does not quantify a significant difference between the simple geometric models and the COMSOL computational models. This new method may help to facilitate the further development and validation of MWA computational models.

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