ARTICLE IN PRESS
JID: JJBE [m5G;October 4, 2016;12:20]

Medical Engineering and Physics 000 (2016) 1–9

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Probabilistic finite element method for large tumor radiofrequency ablation simulation and planning

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ARTICLE INFO

Article history:
Received 14 October 2014
Revised 5 August 2016
Accepted 30 August 2016
Available online xxx

Keywords:
Radiofrequency ablation
Probabilistic finite element simulation
Mean-value first-order second-moment method
Radiofrequency ablation planning

ABSTRACT

A challenging problem of radiofrequency ablation (RFA) in liver surgery is to accurately estimate the shapes and sizes of RFA lesions whose formation depends on intrinsic variations of the thermal–electrical properties of soft tissue. Large tumors, which can be as long as 10 cm or more, further complicate the problem. In this paper, a probabilistic bio-heating finite element (FE) model is proposed and developed to predict RFA lesions. Uncertainties of RFA lesions are caused by the probabilistic nature of five thermal–electrical liver properties: thermal conductivity, liver tissue density, specific heat, blood perfusion rate and electrical conductivity. Confidence levels of shapes and sizes of lesions are generated by the FE model incorporated with the mean-value first-order second-moment (MVFOSM) method. Based on the probabilistic FE method, a workflow of RFA planning is introduced to enable clinicians to preoperatively view the predicted RFA lesions in three-dimension (3D) within a hepatic environment. Accurate planning of the RFA needle placements can then be achieved based on the interactive simulation and confidence level selection.

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1. Introduction

Radiofrequency ablation (RFA) is a minimally invasive procedure which applies high frequency alternating current to destroy tumor cells. It has been demonstrated to be an effective and safe alternative for patients who are not physically fit for surgical resection [1]. In a typical percutaneous RFA treatment, RFA needle insertions are usually navigated using medical imaging modalities such as ultrasonography, Magnetic resonance (MR) or computed tomography (CT) images. However, the therapeutic effect of RFA treatment is often challenged by the following problems.

Firstly, it is difficult to use present medical imaging technology to obtain an explicit picture of the abdomen in real-time to guide the RFA procedure. Real-time CT imaging exposes patients and clinicians to radiation hazard and thus is not suitable to be used for the RFA procedure, especially for large tumor treatment. Large tumor treatment requires multiple RFAs hence a longer treatment time, exposing more radiation threats to patients and clinicians. MR and ultrasound imaging may also be used to monitor the RFA process. However, since human tissue contains water, gas would occur in the heated tissue, causing numerous micro-bubbles in the MR and ultrasound images [2,3]. These micro-bubbles can blur the images, making it challenging for the clinician to insert the RFA needle to target points. Secondly, reliable RFA simulation for preoperative RFA planning is a challenging problem. RFA simulation significantly depends on thermal–electrical properties of tissue such as thermal conductivity, tissue density, specific heat, blood perfusion rate and electrical conductivity. However, thermal–electrical properties of soft tissue are often subjected to inherent variations due to anatomic microstructural differences and patient individual differences [4–9]. Hence, it is important to consider the variations of the thermal–electrical properties in RFA simulation. Thirdly, current RFA devices cannot create a very large volume of lesion from one needle insertion due to the limited working range of needle distal tips within the tissues [10]. For large tumors which can be as long as 10 cm or more, multiple ablations have to be conducted. In this case, a reliable ablation planning method is required to improve the accuracy and efficiency of RFA needle placement.

In this paper, we proposed and developed a generalized probabilistic bio-heating finite element (FE) model which incorporates the mean-value first-order second-moment (MVFOSM) method to determine the probabilistic distribution of the shapes and sizes of RFA lesions. In this FE model, we focused only on electrical and thermal properties of the liver and mechanical properties are not considered. Thermal conductivity, tissue density, blood perfusion rate, electrical conductivity and specific heat were assumed to be normally distributed in the bio-heating model. Three-dimension

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http://dx.doi.org/10.1016/j.medengphy.2016.08.007
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(3D) RFA lesions with corresponding confidence levels can be generated. Based on the 3D RFA lesions, an ablation planning strategy was proposed for large tumor treatment. Since liver tumor is one of the most common intra-abdominal malignancies in the world, we will use RFA of liver tumor to exemplify our probabilistic FE RFA simulation and planning method.

2. Related work

FE simulation for liver tumor RFA has been reported in existing literatures. Ahmed et al. [11] investigated the combined effects of varying perfusion, electrical and thermal conductivity on RFA heating using an established computer simulation model of RFA. Varying electrical and thermal conductivities were assigned to tissue, fats and saline injection to represent their different thermal–electrical properties. Haemmerich et al. [12] studied the differences between monopolar and bipolar RFA devices using a FE model. Their results showed that the bipolar RFA device could create larger lesions. Compared to monopolar RFA heating, bipolar RFA heating is more robust and less dependent on inhomogeneity of liver tissue thermal–electrical properties. Chang and Nguyen [13] used a two-dimensional (2D) FE model to simulate RFA process in soft tissue. The model was integrated with a self-updating structure which updates thermal conductivity and blood perfusion during simulation. Haemmerich et al. [14] conducted a FE study of RFA induced coagulation zones close to blood vessels. They concluded that the recurrence rates of tumor cell close to blood vessels could be reduced by bipolar RFA through increasing current density and heat deposition in the perivascular spaces. Tungjitkusolmun et al. [15] investigated effects of changing myocardial properties in cardiac RFA using FE modeling. Their results showed that changes of myocardial properties affect the results of the FE analysis of power-controlled RFA more than those of temperature-controlled RFA. Kröger et al. [16] presented a novel method to predict the vascular cooling effect in RFA simulation. A look up table was used to store the results of vascular cooling effect which depends on the radius of the blood vessel and the distance of RFA applicator from the vessel.

In order to completely destroy large tumors, Chen et al. [17] adopted mathematical protocol to optimize the process of RFA planning. Different overlapping modes were introduced for different sizes of tumors. The objective of this method was to achieve safety margin of 5 mm with adequate overlapping. One-ablation, six-ablation and 14-ablation models were proposed in Dodd et al. [18] for large tumor RFA planning. Ablation spheres were optimally overlapped in order to achieve maximum coverage volume with a 10 mm tumor free-margin. Nicolau et al. [19] proposed an augmented reality based planning method for liver ablation. Their system was evaluated in both phantom and clinical studies. The maximum errors for phantom and clinical studies are below 2 mm and 5 mm, respectively. These results are favorable based on radiologists' claim that an accuracy better than 5 mm can avoid destroying too many healthy cells. Khajanchee et al. [20] explored the relationship between tumor size and smallest number of ablations for complete tumor destruction. Assuming that the tumor and ablation lesions have a perfect spherical shape, they computed the required number of ablations for different tumor sizes and concluded that the minimum number of ablations for complete tumor destruction increases significantly as the tumor size increases. Baegert et al. [21] presented a trajectory planning for hepatic RFA. Some practical constraints were considered in this study. Their method could achieve a satisfactory result based on different constraints. Yang et al. [22] presented a robotic navigation system for large liver tumor ablation. Overlapping ablation technique was used for needle path planning. The ablation lesion was treated as a perfect sphere with constant size. The navigation system was tested through an animal experiment. Their results showed good ablation accuracy with an average 1.5 mm deviation between ablated zone and tumor. Altrogge and Preusser [23] presented an optimization of probe placement in RFA considering the uncertainty of biophysical tissue properties. Their results showed significant temperature sensitivity with varying tissue properties.

Probabilistic uncertainty analysis was mainly used to solve structural engineering problems [24,25] while it recently draws interests in the field of biomedical applications. Hu et al. [26] studied the behavior of human placenta tissue using stochastic FE analysis. Visco-hyperelastic material parameters with statistical nature were utilized. They showed agreement between simulated results and actual data. Delalleau et al. [27] applied stochastic method to determine elastic property of skin which was modeled by a classic single layer hyperelastic model and a double layer Neo-Hookean potential model. They concluded that the stochastic method had potential in solving optimization problems. In the study conducted by Santos et al. [28], they proposed a probabilistic FE method to model the variations of tissue thermal–electrical properties. The probabilistic model was based on a simple two-dimensional monopolar electrode model using unscented transform. Their results showed that blood perfusion rate and thermal conductivity account for more than 95% of the variability in coagulation zone volume. Huang and Chui [29] described a preliminary RFA planning system using stochastic FE method by which the inherent variations of physical properties of the liver tissue was discussed.

3. Overview of the probabilistic RFA simulation and planning method

In general, RFA is considered as a safe, well-tolerated and effective treatment only for small liver tumors which are less than 6.0 cm in diameter [30]. Reliable RFA simulation and planning are important for large liver tumor treatment. The objective of RFA simulation and planning is to assist clinicians to verify that the lesions produced by multiple RFAs can fully cover a large tumor with minimal damages to the surrounding healthy tissues. We proposed a probabilistic RFA simulation and planning method to predict the RFA lesions for treatment planning. This probabilistic method may improve the safety and effectiveness of RFA treatment for large tumor.

In our RFA planning procedure, the clinician should specify the positions of RFA needle. The probabilistic bio-heat FE simulation is then applied to predict the RFA lesions according to the specified RFA needle positions. Different shapes and sizes of RFA lesions, along with their probabilities, can be displayed. The results can provide clinicians an overview of ablation effect for potential risk evaluation, and help them to decide which specific RFA plan to adopt for the patient.

Fig. 1 shows the workflow of probabilistic bio-heat FE simulation based RFA planning. Geometric information including critical anatomic structures for FE model construction is acquired from preoperative medical images. After the position and geometric profile of tumor are identified from the medical images, the safety margin of tumor will be specified. A local coordination system is established at the center of the targeted tumor. This coordination system defines the RFA planning space. Tissue thermal–electrical properties, initial and boundary conditions, such as temperatures of the liver, are assigned to construct the bio-heat FE model. Multiple RFA needle placements are set within the bio-heat FE model. The probabilistic distribution of temperature can then be calculated using the MVFOSM method. The probabilistic simulation allows clinicians to choose different confidence levels and generates the corresponding 3D views of the RFA lesions. Clinicians can choose a specific confidence level according to patient-specific condition and their own experiences. They can try different needle

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