New Blood Flow Model for Thermo-Simulations of RF-Ablation

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CO-ME PROJECT #02

INTRODUCTION

Thermal ablation is used to treat small tumors or cardiac arrhythmia. The treatment has the advantage of often being minimally invasive. It tries to improve the patient's condition by irreversibly changing some tissue characteristics locally using heat. In most cases the goal is to destroy unwanted tissue. We will focus on RF-ablation (alternatively, laser light or ultrasound can be used). RF-ablation is related to the hyperthermia treatment of cancer in which lower temperatures are used and larger regions are heated. During RF-ablation one or several antennas are placed interstitially and the resulting currents heat the surrounding tissue.

A simulation tool would strongly benefit RF-ablation treatments, as it could be used to:

- **Train staff**: the treatment is complex, and especially when multiple antennas are used and major blood vessels are present, the task can be challenging and the outcome hard to predict.
- **Perform treatment planning**: optimizing the treatment using simulations could improve treatment outcome.
- **Develop better treatment methods**: a good simulation environement could be used to improve treatment methodology and/or build better applicators.

Such a tool should be able to perform the following tasks:

- Create a patient model using segmentation
- Simulate the EM field distribution
- Determine the resulting temperature distribution
- (Optimize the treatment)
- (Optimize the antennas)

OBJECTIVES

This study aims at developing and implementing a **new model to calculate EM induced temperature distributions**. The temperature distribution in living tissue is strongly influenced by blood flow effects. Improving the modeling of the blood flow (by taking into account its directivity, discreetness and temperature dependence) will result in more reliable predictions.

CURRENT APPROACH AND DRAWBACKS

Many EM induced effects are caused by temperature elevation. Current tools that simulate this are usually based on the bioheat equation developed by Pennes in 1948 [1]. This equation takes into account blood flow by introducing a cooling effect proportional to the local temperature and a tissue specific perfusion. (Pennes' equation is based on the assumption of local equilibrium between the blood and the environmental temperature.) Furthermore, specific heat generation rates can be assigned to each tissue.

However Pennes' equation suffers from several drawbacks:

- It does not account for the directivity of blood flow.
- It neglects the discreetness of blood vessels. At best, the blood vessels are accounted for by introducing corresponding boundary conditions.
- Its standard formulation / implementation does not account for the temperature dependence of various (tissue) parameters.

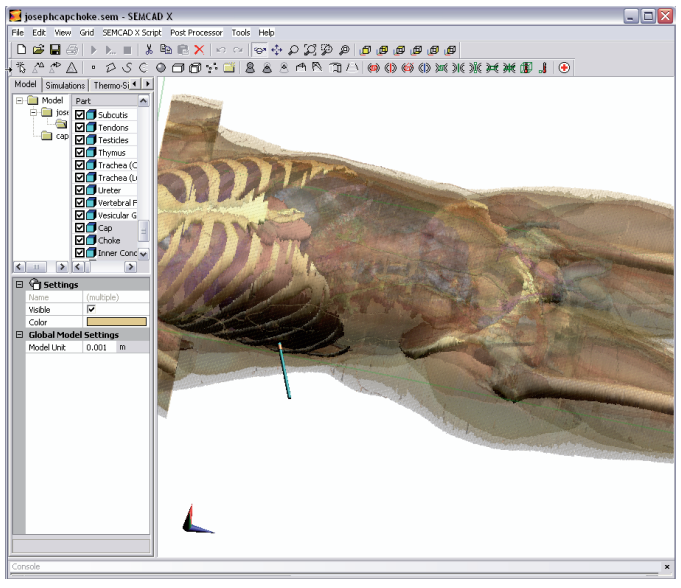
The work presented in this study therefore attempts to create a model that retains the simplicity of Pennes' approach while introducing the following improvements to overcome the above mentioned problems.

PROPOSED IMPROVEMENTS

Tensorial heat conductivity (k): This accounts for the directivity of blood flow. Having a tensorial k makes it possible to preferentially conduct heat along a blood vessel, perpendicular to it or in any given direction. This corresponds to real tissue, where the vasculature / microvasculature is often distributed in an anisotropic way.

Discrete vessel network: The 3D temperature simulation is coupled to a pseudo-1D simulation of the blood flow in the major vessels (cp. [2,3]). In the next step the vessel tree can be used to determine the local tensor character (orientation of main axis and degree of anisotropy) of the heat conductivity, resulting in a position dependent k instead of a k that is constant throughout the organ/solid.

Temperature dependent parameters: Perfusion, thermal conductivity and electrical conductivity (and therefore SAR) can be made temperature dependent. Currently only simple dependencies have been implemented, though work is underway to extend this. A model has been developed to permit fast simulations with complicated temperature dependences. The model allows complex temperature dependence for perfusion and simple perfusion dependences for other parameters.
Furthermore, the metabolic heat generation rate can be time dependent to account for metabolic changes due to prolonged heating.
The new model can largely work with tissue parameters that have already been determined for other thermo-models.



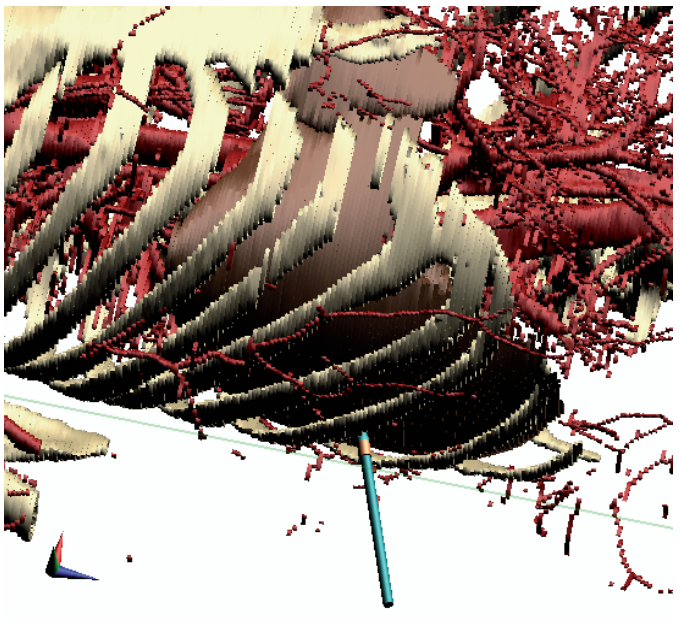


Figure 2: Segmented human trunk and a model of a cap-choke ablation catheter in the SEMCAD X simulation environment.

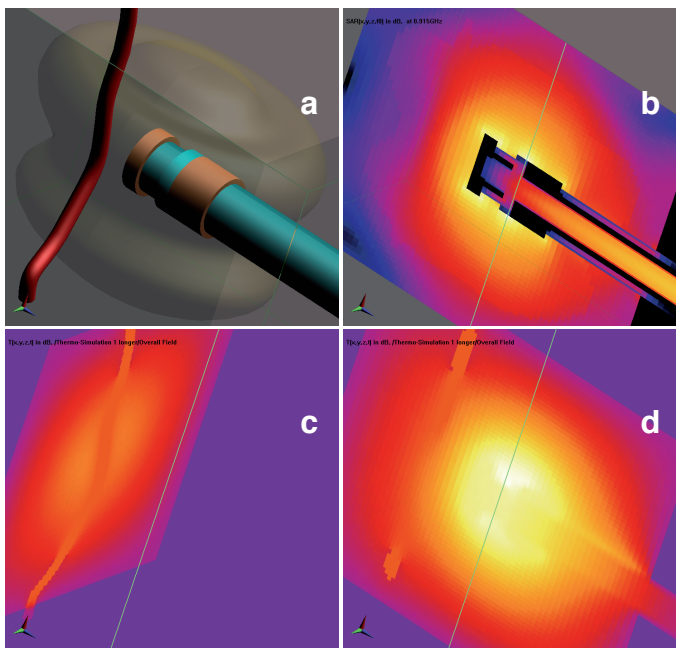


Figure 3 Simulation of a cap-choke ablation catheter inside a tumor: a) model, b) SAR distribution, c) and d) temperature distribution

IMPLEMENTATION

The new thermo-model has been implemented as part of our commercial EM simulation platform SEMCAD X [4]. This permits us to use SEMCAD X's gridder, voxeler, postprocessing and visualization features. Furthermore, embedding the thermo-solver in SEMCAD X provides the advantage of having a unified tool to perform both EM- and thermo-simulations within a single environement thereby improving interfacing. Like the EM-solver, the thermo-solver uses the FDTD method on a graded mesh. FDTD permits the simulation of highly detailed and nonhomogeneous models and offers information in both the time and the frequency domains. It is efficient and fast, permitting large models.
Results from various EM simulations can be individually scaled and coherently or incoherently added before they are used for heating. The scaling can be made time dependent, allowing for pulsed excitation. Various boundary conditions (fixed temperature, fixed flux, temperature dependent radiation and a mixture thereof) can be specified for all material interfaces separately. A conform subcell model is being developed to reduce staircasing errors at interfaces.
The implementation is tuned toward high speed and subsequently low memory usage. It permits simulations with sub-millimeter resolution in critical regions and millions of voxels to be performed within minutes.

CONCLUSIONS AND NEXT STEPS

- A new thermo-solver is being developed.
- The new solver is based on Pennes' Bioheat equation but includes numerous improvements, mainly in the area of blood-flow modeling.
- The first implementation is functional. It permits simulations of unprecedented detailedness and accuracy.
- The SEMCAD X front-end / gridder / voxeler has been adapted to host the new solver (*Fig. 2*).
- Some highly detailed EM simulations of a cap-choke ablation catheter in a tumor next to a blood vessel have been carried out using SEMCAD X and a hardware acceleration card (*Fig.s 3 and 4*). The results have been used in thermal simulations (*Fig.s 1 and 3*).

After finishing the implementation of the proposed model the following points should be addressed:

- Implementation of alternative numerical schemes (ADI)
- Developement of a model for necrosis / tissue changes
- Experimental validation of the model

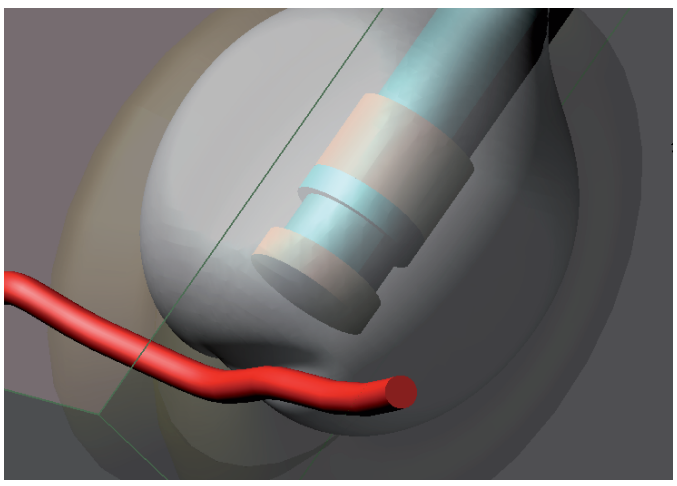


Figure 1: Isotemperature surface of the temperature distribution induced by a cap-choke ablation catheter in a nodular tumor next to a simple bloodvessel.

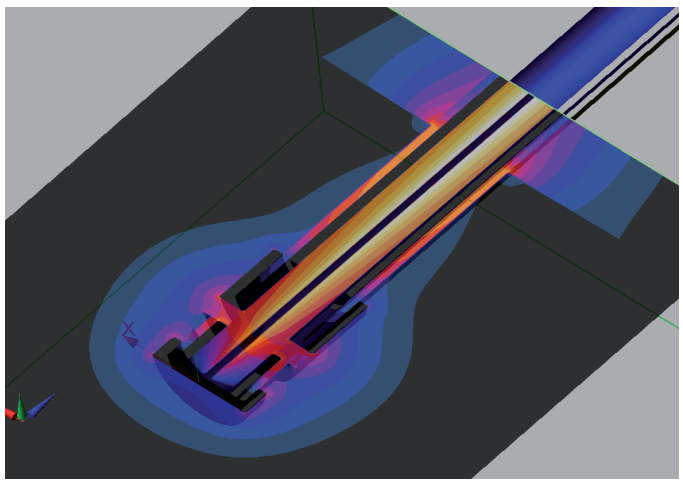


Figure 4: SAR for cap-choke antenna (s. Fig. 3).

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