COST EMF - MED (Action BM1309):
European network for innovative uses of EMFs in biomedical applications

STSM Report:

Implementation of patient-specific discrete vasculature model to improve temperature predictions in the H&N region under radio frequency exposure

Researcher: Kemal Sümser. email: k.sumser@erasmusmc.nl

Home Institution: Erasmus MC (Rotterdam, Netherlands). Contact: Maarten Paulides. email: m.paulides@erasmusmc.nl

Host Institution: Foundation for Research on Information Technologies in Society (IT'IS) (Zürich, Switzerland). Contact: Prof. Dr. Niels Kuster

STSM Reference: ECOST-STSM-BM1309-38399

STSM dates: FROM 18th September 2017 TO 27th October 2017

Abstract:

Vessels that are running through the neck towards head contribute to the cooling and causes reshaping of the heating patterns when patients are treated with Hyperthermia. Classical Pennes' Bioheat thermal model assumes continuous, homogenous tissue perfusion cooling. Objective of this STSM was to implement discrete vasculature (DIVA) thermal solver into simulation program Sim4Life. Previously developed DIVA solver from SEMCAD X is successfully ported and interfaced with Python scripting. The simulation results showed agreement with the theoretical values. Lastly, a pipeline for patient specific vasculature modelling was prepared for the further studies.

A. Purpose of the STSM

During radio frequency (RF) hyperthermia, tumor cells are heated to 40-44°C, affording selective sensitization for ionizing radiation. Blood vessels and perfusion in the volume of interests are the main responsible for tissue cooling, affecting treatment safety and potentially limiting treatment efficacy. Only the effect of microvasculature is modelled by the classic Pennes' Bioheat thermal model (as a continuum model). At the Erasmus MC Cancer Institute (Hyperthermia Unit) hyperthermia treatment planning is done using the simulation platform Sim4Life. The purpose of the STSM is to implement and validate a discrete vasculature (DIVA) thermal model in Sim4Life, and to assess the prediction differences between DIVA and the standard Pennes' Bioheat model in simulations of Head and Neck (H&N) hyperthermia treatments.

B. Work Description

The main work conducted during the stay was to establish a full workflow allowing previously segmented patient and vasculature information to be transformed into patient-specific treatment planning simulations. For that, a previously developed DIVA solver (from the SEMCAD X software) was ported to Sim4Life and interfaced on a Python scripting and I/O file level (no GUI integration). A basic DIVA model consists of following settings: Points defining the vessel trajectory and/or vessel tree, radii, initial temperature, thermal conductivity, specific heat capacity, and flow rates of the individual vessels, as well as temperature and flow rates of the inflows. These settings need to be merged with the other settings of a thermal simulation such as tissue properties, grid and voxel information etc. In order to keep the structure of the simulation settings the

same, DIVA settings are included by editing the simulation input file. The solver I/O-related C++ functions had to be rewritten.

After the interface for DIVA simulations had been established, the solver was verified for different model parameters against a vessel model with known analytical solution. A straight vessel inside a coaxial tissue cylinder was used to verify the model (see Figure 1). The investigated DIVA model parameters included bucket density (a bucket is the smallest discretization unit of a vessel, it can be thought as vessel's local grid), tilted and shifted vessel positions relative to the simulation grid, and branching in a multistraight model. The basic parameter set is listed in Table 1. And finally a patient model under RF excitation was simulated using Pennes and DIVA models to assess the ability of handling complex models and the impact of considering discrete vasculature. Selected results for these tests are given in the next section. All verification tests were successful and it is concluded that the DIVA simulation basis for future exploration has been established.

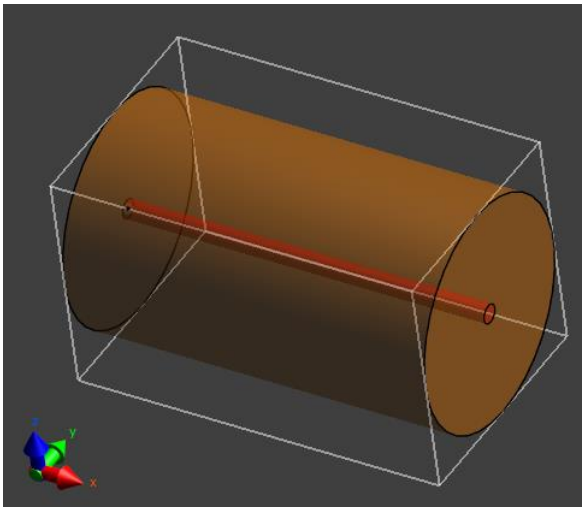

Figure 1. Model used for validation: A coaxial setup involving a straight vessel inside a tissue cylinder

Table 1. Basic Model Parameters

Tissue Conductivity	0.6 $W \cdot m^{-1} \cdot K^{-1}$
Tissue Specific Heat	4000 $J \cdot kg^{-1} \cdot K^{-1}$
Tissue Density	1000 $kg \cdot m^{-3}$
Tissue Radius	0.003 m
Tissue Length	0.01 m
Vessel Radius	0.00025 m
Vessel Length	0.01 m
Blood Velocity	0.025 $m \cdot s^{-1}$
Tissue Initial Temperature	1 °C
Inflow Blood Temperature	0 °C
Bucket Density	5000
Number of Grid Voxels	31x31x50

C. Results

Thermal equilibrium length (L_{eq}) is defined as the length that the temperature difference between the blood and the constant tissue temperature at distance R from the center of the vessel has diminished by a factor Euler's number (e) [1]. A theoretical formulate to compute L_{eq} given as:

$$L_{eq} = \frac{\rho_b c_b \langle v \rangle r_{ves}^2}{2} \left\{ \frac{2}{Nuk_b} + \frac{1}{k} \ln\left(\frac{R}{r_{ves}}\right) \right\}.$$

The theoretically calculated L_{eq} results are compared with the results obtained from Sim4Life simulations. Simulation results show very good agreement with the theoretical value (see Figure 2).

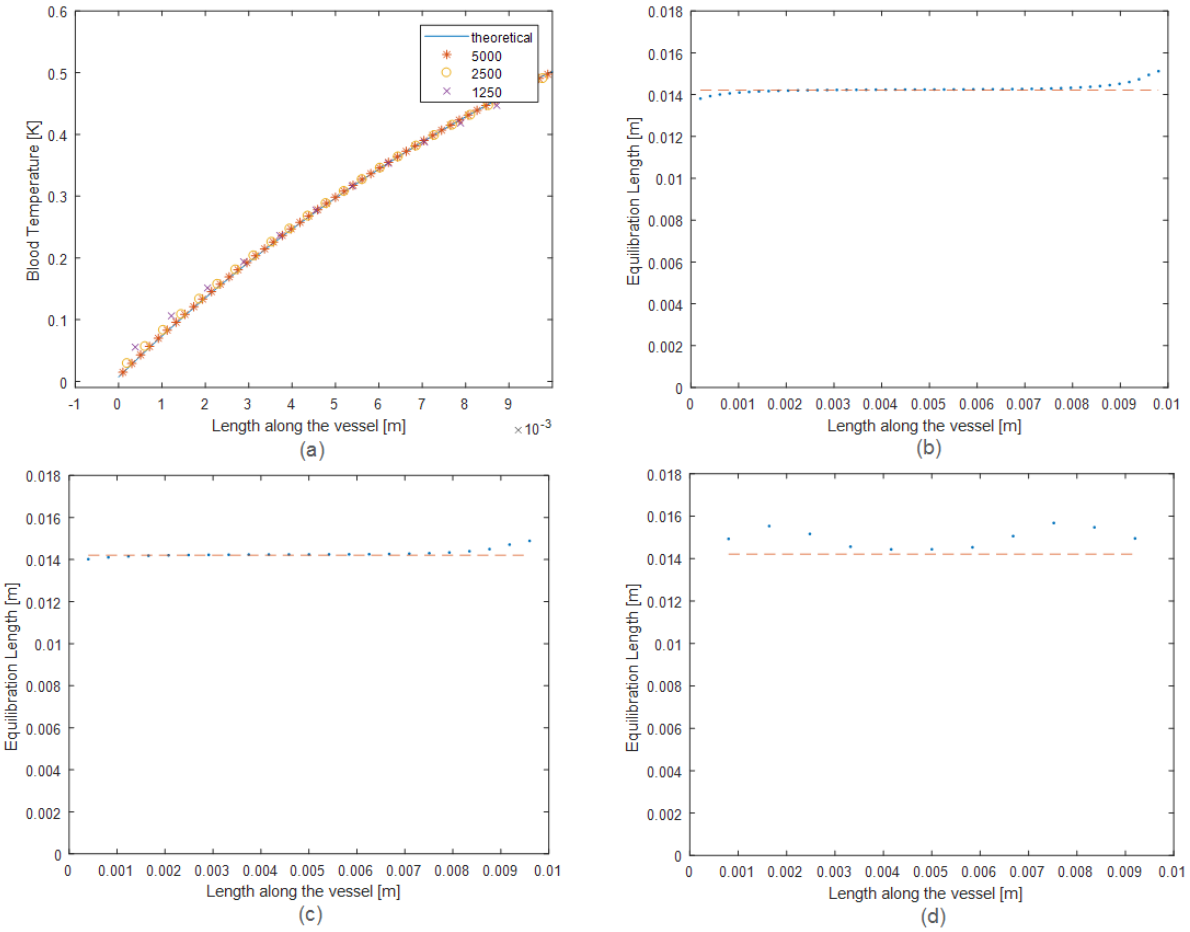

Figure 2. Theoretical and simulated Leq for different DIVA parameters. (a) Temperature along the vessel, (b) Leq when the bucket density is 5000, (c) L_{eq} when the bucket density is 2500, (d) Leq when the bucket density is 1250

As expected, the agreement was better for simulation with a higher bucket density. Theoretical and simulated values also showed good agreement on L_{eq} for different vessel radius (Figure 3). Dependency of vessel location is tested by shifting the location of the vessel center line. The original centerline of the vessel is shifted by quarter of the grid step size to ensure vessel spans partly in some voxels. Simulated values of vessel temperature showed small deviation (<1%) when the vessel is tilted relative to the grid axis (Figure 4). Lastly, the branching test only showed small deviations at the connection points of the vessel branches (Figure 5).

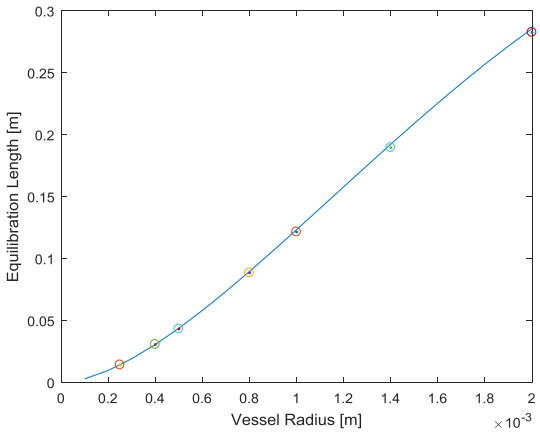

Figure 3. Comparison of the theoretical and experimental dependencies of L_{eq} on the vessel radius. Blue line theoretical value.

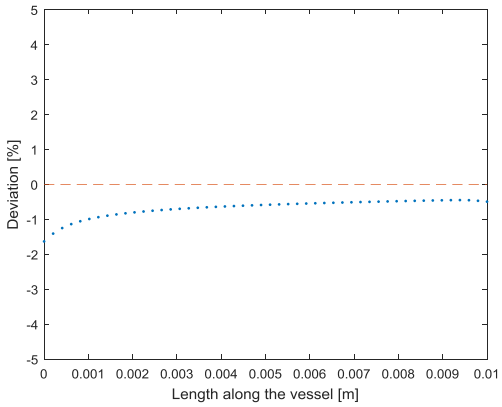

Figure 4. Basic simulation with the vessel shifted relative to the grid axis showing the deviation of the vessel temperature of simulation from the theoretical value.

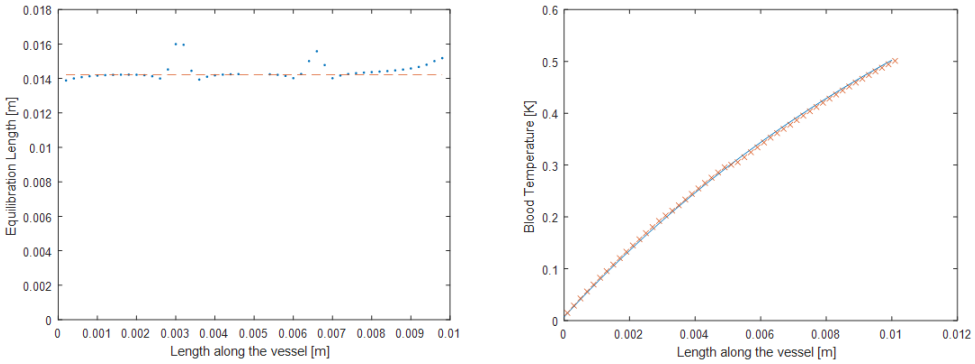

Figure 5. L_{eq} and temperature profile of three connected vessel segments

After the DIVA model had been successfully verified, a patient model with detailed vessel information was simulated using both, the Pennes and the DIVA models, to assess the temperature differences under RF exposure. The same 1 mm uniform square grid was used in both Pennes and DIVA simulations. In Figure 6a, patient model with the vessel information is shown, in Figure 6b, an isosurface of the temperature difference map ($T_{pennes} - T_{diva}$) is shown. The DIVA model introduces the expected extra cooling (up to 3°C) around the vessels.

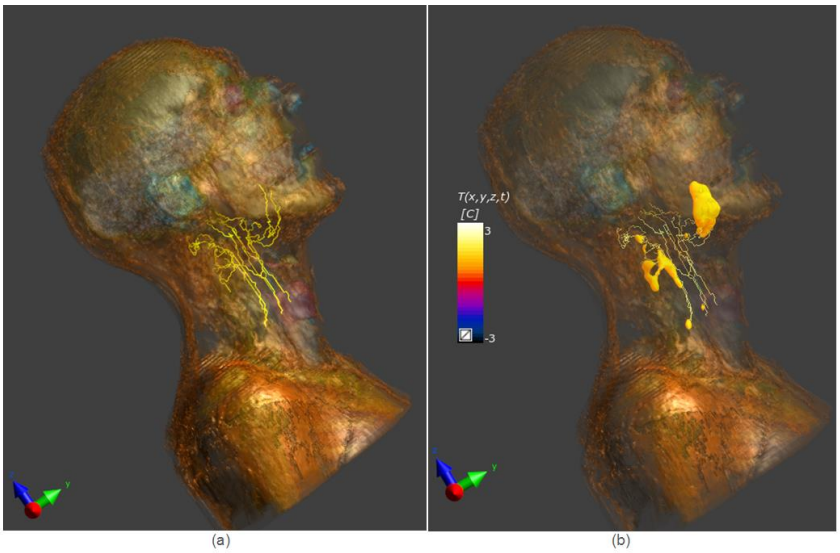

Figure 6. (a) Patient model with vessel trees (b) Isosurface temperature map of difference in Pennes and DIVA model

In this STSM, the full pipeline to do patient-specific DIVA simulations and treatment planning in Sim4Life was created. Further studies to assess if the DIVA model improves thermal predictions for hyperthermia treatment modeling and supports improved treatment quality will be performed in Rotterdam.

D. Future collaboration with host institution

We aim to continue collaboration existing between host and home institution in the future by joint paper publications. Additionally, in the future we aim to study 1) the impact of vessels on the heating caused by MRI exposure and 2) to include (MRI) perfusion maps complementing the discrete vessel models into the thermal modelling to capture inhomogeneous perfusion by micro-vessels.

E. Expected Publications

A journal paper titled 'Effect of patient-specific discrete vascular modelling on temperature predictions in head and neck hyperthermia treatment planning' is in preparation.

F. References

[1] Kotte, A., van Leeuwen, G., de Bree, J., van der Koijk, J., Crezee, H., & Lagendijk, J. (1996). A description of discrete vessel segments in thermal modelling of tissues. Physics in Medicine and Biology, 41(5), 865.

Confirmation by the host institution of the successful execution of the STSM:

We confirm that Kemal Sümser has performed the research work as described above.

Contact Person of Host Institution	Name of researcher
Prof. Dr. Niels Kuster	Kemal Sümser