Clinical Validation of a Thermophysical Bladder Model to Improve Hyperthermia Treatment Planning in the Pelvic Region

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INTRODUCTION

Hyperthermia is a (neo)adjuvant treatment modality that increases the effectiveness of radiotherapy or chemotherapy by heating the tumour area to 41–43 °C. Loco-regional hyperthermia is delivered using radiofrequency phased array systems with individually controlled antennae operating at 70–120 MHz. Hyperthermia treatment planning is necessary to determine the phase and amplitude settings for the individual antennae that result in the optimal temperature distribution for a given patient anatomy. This consists of first simulating the electromagnetic (EM) field inside the patient and then determining the resulting temperature distribution. Both steps suffer from inaccuracies due to uncertainties in the relevant tissue properties.

Nevertheless, current treatment planning systems are fairly accurate for solid tissues, but they ignore the specific properties of the urinary bladder and its contents: both the dielectric properties, resulting in a large uncertainty in the computed EM field [1], and the thermophysical properties, resulting in a large uncertainty in the temperature distribution. This limits simulation accuracy in the pelvic region and may have clinical implications for such treatment sites as the rectum, the cervix uteri, and —most of all— the bladder itself.

We have therefore expanded our (finite difference) in-house developed treatment planning system, based on Pennes’ bio-heat equation, with a special module for the bladder in order to incorporate a physically correct description of the properties of the bladder contents—a higher electric conductivity, absence of perfusion, and presence of convection. The first two adjustments could be made using our current system, but for the fluid dynamics we needed additional software. We created a convective thermophysical fluid model, based on the Boussinesq approximation to the Navier-Stokes equations; this means we assumed all parameters to be temperature independent except for the mass density in the gravitational term. This was implemented using the (finite element) OpenFOAM tool-kit.

We verified the bladder module using a multi-step validation process. Previously, we have shown that our fluid algorithm works in a phantom study, comparing temperature measurements in- and outside a bladder in a phantom with the temperature predictions by both the current system with muscle- or tumour-like bladder contents and the improved system with bladder contents featuring fluid dynamics [2]. Currently, we are presenting step two in this process: clinical validation by means of retrospective patient data analysis. We assessed the differences between the new and the conventional model, and compared both to temperature measurements made during treatment.

MATERIALS AND METHODS

A CT scan with thermometry catheters in situ was obtained from a bladder cancer patient and a clinician delineated the bladder as part of the standard clinical work-flow. Using the antenna settings (phase and amplitude) used during treatment, we computed the resulting EM
field twice, with different conductivity values $\sigma$ for the bladder contents: once with $\sigma = 0.74$ S/m as is currently used, and once with $\sigma = 1.15$ S/m, using literature values obtained from [1] for the other tissue types. For each resulting EM field, we performed the temperature calculation thrice: once with the conventional treatment planning system with a solid, perfused (‘tumour-like’) bladder, once with an unperfused solid bladder, and once with the expanded system with a fluid-filled bladder. We subsequently calculated the differences between the resulting temperature distributions.

Reference temperature measurements were done as part of the normal clinical routine using copper-constantan thermocouples with 14 temperature sensors located at 0.5 cm intervals. Temperatures were obtained from the treatment planning system at positions reconstructed from the CT scan.

RESULTS

The temperature in and around the bladder as computed using the new module with realistic fluid modelling (higher conductivity, no perfusion, and with convection) is very different from that using the currently used treatment planning system, as is shown in Figure 1. Temperature differences ranged from –1.8 to +1.6 °C; clinically relevant tissue temperature differences of more than ±0.5 °C extended over 5 cm around the bladder. The differences are caused by a combination of an increased power absorption in the bladder due to the higher conductivity, lower heat loss due to the absence of perfusion, and the homogenizing effect and nett heat transport in the upward direction caused by the convection inside the bladder.

Only changing the conductivity of the bladder contents resulted in simulated temperatures that were about 1.5–2 °C lower than measured; and removing the heatsink term that models perfusion, resulted in temperatures that were around 3 °C too high. Realistic modelling of the bladder reduced the errors to 0.2–0.8 °C.

CONCLUSIONS

The addition of the new convective model to the hyperthermia treatment planning system leads to highly clinically relevant temperature changes compared to the current treatment planning system. These computed temperatures are in much better agreement with measurements during treatment than simulations with a ‘tumour-like’ conductivity or with a perfusion-mimicking heatsink in the bladder. Explicit modelling of fluids is particularly important when the bladder or its direct surroundings are part of the treatment target area.

REFERENCES