Improving MR-guided RF hyperthermia with model-based control – a simulation study

Several hyperthermia treatment planning (HTP) strategies exist for radio frequency (RF) hyperthermia to increase the selectivity of heating tumors while limiting the healthy tissue temperature. HTP methods range from basic techniques that assume the patient is a homogeneous cylinder [1] to patient-specific methods that maximize the target hotspot SAR ratio (THQ) [2] by optimizing the SAR or directly maximizing the expected tumor temperature [3]. Nevertheless, in all these HTP strategies the real-world performance relies on the accuracy of the patient model, which is often imperfect [3].

To deal with imperfect models, we propose an offset-free Model Predictive Control (MPC) strategy [4] that uses both the patient model as well as MR-thermometry (MRT) to continuously optimize the signals applied to the RF antennas during the treatment. Loosely speaking, MPC maximizes the tumor temperature while enforcing temperature limits. Critically, MPC uses noisy MRT to adapt the patient model thereby counteracting model imperfections. As a result, MPC can be robust to model and MRT uncertainty.

To demonstrate the robustness of MPC with respect to imperfect patient models, we performed a Monte-Carlo simulation study. To assess performance, we compared the tumor temperature percentiles between MPC, THQ and temperature HTP. In this study, HTP and MPC use a nominal Virtual Family model (Ella) while the virtual patient has randomly generated thermal and electrical tissue parameters, like [3]. MRT inaccuracies were modeled by adding Gaussian noise with 1°C standard deviation to the virtual patient temperature and excluding regions like bone and fat. For all methods, we limit the tumor to 44°C and healthy tissue to 42°C.

Fig. 1 shows the 90^{th}, 50^{th}, and 10^{th} temperature percentile after the treatment for 500 randomly generated models. Comparing MPC to THQ shows mean improvements of 0.80°C, 0.96°C, and 1.34°C for T90, T50, and T10, respectively. Similar improvements are observed between MPC and temperature-based HTP. Recall that for all results, the healthy tissue is limited to 42°C.

This simulation study indicated that steering RF antennas using MPC can result in a clinically relevant tumor temperature increase, while simultaneously limiting healthy tissue temperatures. Critically, MPC allows uncertain MRT to improve the robustness with respect to imperfect patient models. These results motivate further research to exploit MPC for clinical use in hyperthermia.

Bibliography

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