Fast adaptive control for MRI-guided ultrasound hyperthermia treatment for prostate disease: *in vitro* and *in vivo* results

L. Sun¹, C. M. Collins², M. B. Smith², N. B. Smith¹³

¹Bioengineering, The Pennsylvania State University, University Park, PA, United States, ²Radiology, The Pennsylvania State University College of Medicine, Hershey, PA, United States, ³Graduate Program in Acoustics, The Pennsylvania State University, University Park, PA, United States

**INTRODUCTION**

Previous researchers have successfully demonstrated the application of temperature feedback control for thermal treatment of disease using MR thermometry (1-4). Using the temperature-dependent proton resonance frequency (PRF) shift, ultrasound heating for hyperthermia to a target organ (such as the prostate) can be tightly controlled. However, the response of the target to ultrasound heating varies in type, size, location, shape, stage of growth, and proximity to other vulnerable organs. To adjust for clinical variables, a novel adaptive feedback control system has been designed utilizing real-time, on-line MR thermometry by adjusting the output power to an ultrasound array to quickly reach the hyperthermia target temperatures. The advantages of this fast adaptive control method are that there is no need of *a priori* knowledge of the initial tissue properties and it can quickly reach the steady state target temperature by adaptively changing the output power according to the dynamic tissue properties (e.g. thermal conductivity, blood perfusion). To rapidly achieve and manage therapeutic temperatures from an ultrasound array, this research was conducted to utilize closed loop MRI guided temperature control using a novel adaptive feedback system with *in vitro* and *in vivo* experiments.

**MATERIALS AND METHODS**

**Fast adaptive MRI control system:** To shorten hyperthermia treatment time, previous researchers have evaluated several control schemes (1, 4, 5). Although the controllers initially operated well, some controllers had undesirable overshoots and oscillations (1, 5). The rapid adaptive control approach used here was designed to track an exponential target temperature with a very fast time constant and to avoid overshoots and oscillations. This robust control system had an ordinary feedback loop composed of the hyperthermia process and a second feedback loop that adjusted the controller parameters (Fig. 1). The mechanism for adjusting the parameters in a model reference adaptive system can be obtained in gradient method by applying Lyapunov stability theory (6). Three dimensional finite difference time domain computer simulations based on Pennes’ bioheat transfer equation were conducted to determine the initial values of the control parameters.

**Ultrasonic hyperthermia system:** For treatment of prostate disease, the ultrasound hyperthermia system consisted of a transrectal intracavitary array with 16 elements operating at 1.5 MHz. To drive the array, a multi-channel programmable ultrasound phased array driving system operating between 1-2 MHz and capable of 60W per channel was used. Verification of the temperature change within the target used a multi-channel fiber optic (Luxtron®) thermometer probe to provide a reference for the MR temperature map results.

**RESULTS**

Robust adaptive MR temperature control has been demonstrated for both the *in vitro* and *in vivo* experiments. A temperature map (Fig. 2) using phase subtraction imaging from an *in vivo* rabbit experiment can be seen with a color bar indicating the temperature change within the selected heating ROI from the array below. Since the desired target temperature profile was 38°C for all *in vitro* experiments, Fig. 3(a) plots nine averaged MR temperature results (mean ± s.d.) which were consistent with the Luxtron® results (x-marks). Consistently starting with an initial phantom temperature of 28°C, the controller achieved the steady state temperature within 6 minutes and deviation from the target profile was no greater than ± 1.37°C. Similar to the *in vitro* results, *in vivo* temperature control can be seen in Fig. 3(b) where the rabbit thigh muscle was heated initially from about 36.5°C for 25 minutes. For this experiment, the target temperature was 44.5°C and was achieved in 8 minutes. From *other in vivo* experiments, the maximum variation from the desired temperature profile was -3.9°C; after reaching steady state, tissue temperature was maintained at 44.5°C ± 1.2°C.

**DISCUSSION AND CONCLUSION**

Dynamic MR temperature control for hyperthermia is necessary for fast effective thermal treatments while eliminating the risk of permanently damaging healthy tissue due to overheating. Integration of ultrasound hyperthermia and MR thermometry with robust adaptive control between the modalities has clinical applications. Considering that the accuracy of PFR technique is approximately ± 1°C, the adaptive control system works well to effectively track the reference by adjusting the transducer power according to dynamic tissue properties such as blood perfusion rate.

**REFERENCES**