MODEL-PREDICTIVE CONTROLLER USING MR THERMOMETRY FOR DYNAMIC OPTIMIZATION OF HEATING/COOLING PULSES FOR HIFU THERAPIES

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Introduction Magnetic Resonance Temperature Imaging (MRTI) makes possible a completely non-invasive treatment modality, MR Guided Focused Ultrasound (MRgFUS), that can be computer controlled. Previous control strategies have concentrated on MRTI based feedback; however, significant unmet needs exist, especially in realizing fast, efficacious and safe treatments. To achieve these goals, it is essential that the controller be able to predict the effects of heating pulses and anticipate dose delivered during cooling periods. A new model-predictive controller has been implemented which reduces treatment time by optimizing individual pulse heating and cooling times while guaranteeing treatment safety[1,2]. The clinician retains full supervisory control while leveraging a computer's ability to rapidly monitor and adjust many parameters simultaneously.

Methods This controller leverages MRTI as a feedback mechanism to optimize heating and cooling pulse durations using model-prediction. Optionally, the controller's software allows safety constraints to be placed around any critical tissue providing clinicians the power to balance treatment speed and safety. Based on anatomical MR images of the patient, the clinician initializes the controller by identifying two types of regions:

1) Treatment volumes (tumor tissue)
2) Safety constraint volumes (tissue to be protected)

The clinician prescribes a target dose for each treatment volume and either a temperature or a thermal dose constraint for normal tissue volumes. A trajectory of successive focal zone locations covering all treatment volumes is determined during pre-treatment planning.

Before treatment, low-power heating pulses are used to identify the coefficients of the exponential heating and cooling model (SAR and thermal time constants) for each treatment volume. During treatment, this simple and computationally efficient model is used to reduce treatment time by predicting when the beam can be shut off such that the target thermal dose will be delivered to the treatment site after all cooling has occurred.

After each MR temperature measurement, safety constraint volumes are monitored for safety and treatment volume predictions are updated.

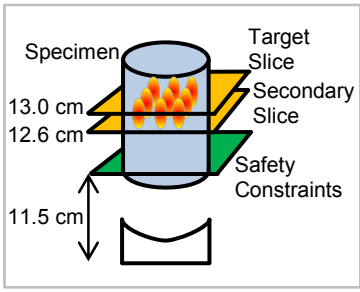

Figure 1: Experimental setup

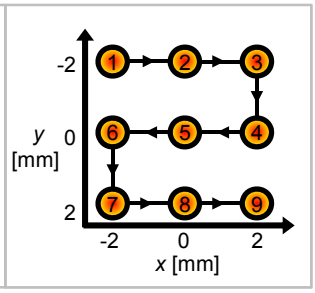

Figure 2: Top view of 3x3 US raster trajectory

Results The controller was tested in tissue mimicking phantoms, *ex vivo* pork samples, and *in vivo* rabbit thighs. In all tests the transducer was beneath the test specimen, and a 3x3x3 mm treatment volume was prescribed a target dose of 240 CEM (figure 1). Nine focal zone positions covered this volume using a 3x3 raster trajectory shown in figure 2. Proton Resonant Frequency MR temperature measurements were acquired every 3.8 sec using a 2D-GRE sequence. Each measurement consisted of three slices with a 2x2x3 mm spatial resolution. Two slices monitored the focal zone while one slice monitored the safety constraint locations.

Table 1 and the plots in figure 3 show the controller treating an *in vivo* rabbit thigh. The data demonstrates the controller successfully delivered the target thermal dose to all treatment sites, safeguarded normal tissue, and made predictions that reduced treatment time.

Tests in phantom and *ex vivo* samples were also successful. The fact that the thermal dose delivered to treatment positions 7-9 match the target value of 240 CEM closely demonstrates that the controller made accurate predictions. Overdosing at positions 1-6 is due to SAR overlap between focal zone locations as well as thermal diffusion. Neither of these "future dose" effects is currently accounted for in the controller's predictions. It is possible that these effects could be anticipated by the controller and heating times further reduced.

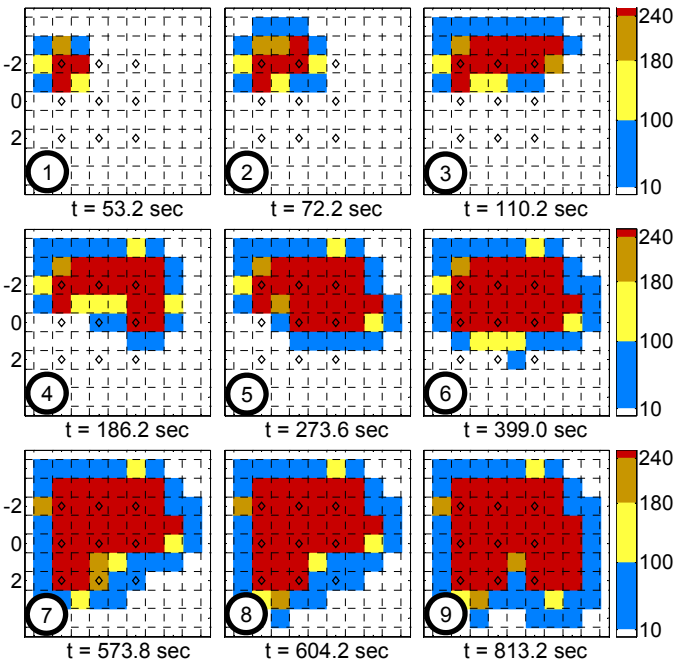

Figure 3: Thermal dose (CEM) snapshots throughout treatment. Diamonds indicate treatment volumes targeted by controller.

TV#	1	2	3	4	5	6	7	8	9	NT
Final TD [CEM]	1282	1171	1244	1085	998	1122	493	281	683	8.4
Max Temp [°C]	56.7	56.5	56.6	55.6	55.6	55.3	54.2	53.1	54.8	45.6

Table 1: Treatment volumes (TV) fully dosed, normal tissue protected.

Conclusion & Future Work A model-predictive controller was developed and successfully tested *in vivo*. The exponential model used proved sufficient in these scenarios and the controller was able to accurately predict the thermal dose delivered during individual heating and cooling pulses while safeguarding healthy tissue.

Future work includes reducing model identification time using a combination of a priori knowledge and online model adaptation to correct model mismatch. The exponential model may also facilitate multi-pulse predictions thus accounting for SAR overlap and further reducing treatment times. Initial results indicate that this control strategy is effective in reducing treatment times while ensuring patient safety.

Literature Cited

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