Adaptive Volumetric MR-guided High-Intensity Focused Ultrasound Ablations

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Introduction

Recent technological advances in the field of clinical high intensity focused ultrasound (HIFU) transducer systems and real time MR thermometry using PRF thermometry [1] lead to an increasing trend towards real time feedback control for the MR-guidance of thermal therapies with HIFU. In particular phased array HIFU systems with short beam repositioning times and large aperture/focal length ratios can benefit from this approach, since they allow to ablate larger tumor volumes in each ablation cycle. However, real time feedback control of the HIFU beam position and the beam power requires continuously updated volumetric information of the thermal dose [2] and temperature over the entire target area. Furthermore, usage on abdominal targets requires the possibility to extract target location in real time from the MRI data to allow the compensation of physiological motion [3].

Here, we present a dynamic volume sweep for volumetric and motion compensated MR-thermometry and dosimetry in combination with a real time adaptation of the ablation trajectory for this purpose. The feedback control algorithm is based on the target temperature, as it is required for the use of HIFU in local drug delivery applications, or directly on thermal dose estimates as is preferable for the direct thermal destruction of tumors.

Materials and Methods

Volume sweep: Two slices are acquired for each dynamic scan (Figure 1a). One remains static and is placed in the center of the target area. The purpose of this slice is twofold: It provides thermometric information and updates of the current target location with a high temporal resolution. The second slice is dynamically repositioned for each dynamic scan to perform a volumetric sweep. This allows to sample the entire extend of the target volume, albeit at a lower temporal resolution. All slices are corrected for 2D motion and motion induced phase variations [4]

Volume Control: The algorithm similar to [5] was implemented to allow volumetric control of the HIFU heating based on either temperature or thermal dose maps. This was achieved by continuously calculating the required acoustic energy for each voxel in the target area and adjusting the sonication trajectory following the local maxima. In order to meet the specific requirements of each control method and their applications, an additional spatial weighting was introduced. As a result, for temperature control (i.e. creating and maintaining an isothermal volume), inverse radial weighting was implemented in order to homogeneously heat a pre-defined target area. For thermal ablations using thermal dose control, radial weighting was used to reduce energy deposition outside the target area. The ablation trajectory (5 points of 25ms duration each) was dynamically recalculated after the arrival of every new dynamic scan (i.e. 8Hz update rate).

Experimental setup: MR-imaging was performed on a 1.5 T Philips Achieva MR scanner (Philips Healthcare, The Netherlands) using the circular coil integrated in the Philips Sonalleve breast MR-HIFU platform. A single-shot EPI sequence (TR/TE = 125/30 ms, bandwidth = 1560 Hz, matrix 128x54x2, voxel = 2.5x2.5x3mm³, flip angle = 25°) was used for image acquisition for sustained imaging over a duration of 9min. The slice position was shifted by 3 mm for each dynamic acquisition covering a total volume of 2.1 cm along z. Heating was performed for 500s on a breast phantom with a maximal electric power of 60 W. The control algorithm was programed to either achieve a thermal dose of TD_T=24 EM, or a temperature elevation of ΔT=6°C in a spherical target area of 2 cm diameter.

Results and Discussion

The results of the heating experiments are shown in Figure 2. The feedback control based on temperature achieved an isothermal area in the designated target after 80s. All target voxels showed at this point temperatures equal or higher than 6°C with maximal overshoots of 1.6°C. The control algorithm maintained a stable temperature (±0.1°C) over 7 min. Outside the target area, 74 voxels were heated above 6°C. Control based on the thermal dose delivered the pre-defined thermal dose to all targeted voxels after 80s. Energy deposition outside the target area was unavoidable as a result of the focal point shape and lead to thermal doses higher than the target value in 172 adjacent voxels.

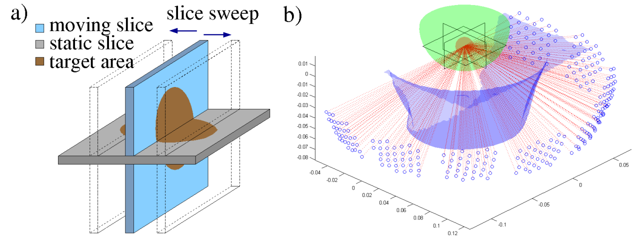

Figure 1: Left: Principle of the slice sweep. One slice remains static, while the second slice is translated continuously to cover a pre-defined volume containing the target area. Right: Experimental setup showing breast phantom (green), target area (red), ultrasound transducer elements (blue circles), breast cup of the Sonalleve breast platform (blue).

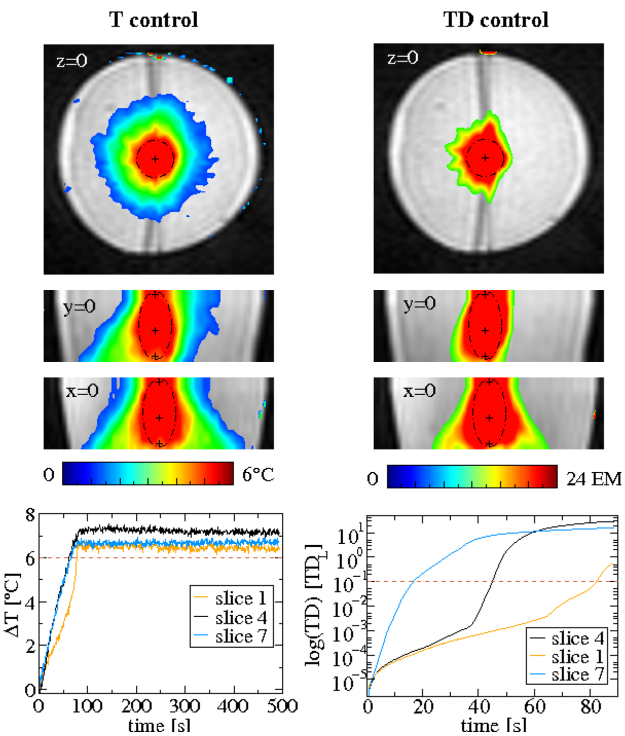

Figure 2: Top: Temperature and thermal dose maps after 80s of treatment are shown for z=0, y=0, and x=0. The target area is depicted by the black dashed line. Bottom: The temporal evolution of the temperature and thermal dose in the voxels depicted by the black crosses is shown in comparison to the target value (red dashed line). Left: Temperature control. Right: Thermal dose control.

Conclusions

The proposed strategy allows precise volumetric heating in the designated target area while remaining compatible with previously suggested motion compensation schemes. The approach accommodates feedback control based on both the temperature or the thermal dose depending on the particular application scenario. Hence, the described method is an interesting candidate for effective tumor ablations inflicting minimal damage on the healthy surrounding tissue.

References

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