Optimization of volumetric MR-guided high-intensity focused ulatrsound ablations in moving organs

S. Hey[1], B. D. de Senneville[1], G. Maclair[1], M. O. Köhler[2], B. Quesson[1], C. T. W. Moonen[1], and M. Ries[1]

[1]UMR 5231, CNRS/Université Bordeaux 2, Laboratory for Molecular and Functional Imaging, Bordeaux, France, [2]Philips Healthcare, Vantaa, Finland

Introduction

In this work, a method for the optimization of volumetric MR-guided high intensity focused ultrasound (HIFU) ablations is presented. While commonly MR-guidance of thermal therapies is based on temperature control the on-line assessment of the thermal dose has been suggested to determine the therapy endpoint [1]. Therefore, we propose to monitor the thermal dose [2] of the treated tissue to ensure a complete destruction of the tumor tissue. The short positioning time of modern ultrasound transducer systems as compared to the acquisition time of an MR-thermometry image enables the treatment of several points between successive images. Optimizing this trajectory of ablation points [3] in combination with a 3D motion correction technique [4,5] allows for an effective destruction of the target tissue with minimal energy, time and damage outside the target area. The feasibility of the proposed method was tested experimentally ex vivo under conditions simulating respiratory movement of abdominal organs.

Materials and Methods

$$\mathrm{TD} = \int_0^t R^{(43-T(\tau))}\mathrm{d}\tau \qquad (1)$$

$$R = \begin{cases} 0.25 & T(t) < 43°\mathrm{C} \\ 0.5 & T(t) > 43°\mathrm{C} \end{cases}$$

A widely used method to determine temperature-induced tissue damage is the thermal dose TD [6] (1), where $T(\tau)$ is the tissue temperature at instant τ and R was determined empirically. This quantity is normalized so that the value TD=1 represents the thermal dose acquired after 240min at 43°C. Temperature images are acquired using the PRF method yielding the relative temperature as compared to the start of the treatment. For each temperature map the integral thermal dose is calculated and compared to the target value $\mathrm{TD}_{\mathrm{target}}$. As a next step the corresponding required temperature change is calculated and translated into the necessary energy ΔE to be absorbed by the tissue. Given the restricted number of points to be treated between two successive temperature images only those points with a maximal ΔE are chosen. Finally, the acoustical power to be applied is calculated based on the treatment time for each trajectory point (which was fixed to the minimal update time of the used transducer). Furthermore, to avoid the destruction of surrounding tissue, for the same ΔE trajectory points in the center of the target area are preferred to those in the periphery. The obtained MR temperature images were directly transferred to an external work station were in-plane motion-compensation, phase corrections [7] and trajectory optimization were carried out.

All experiments were performed on a 1.5 T Achieva clinical scanner (Philips Healthcare, Best, the Netherlands). For real-time PRF-thermometry a 2D EPI single-shot gradient echo sequence (TE=41ms, TR=100ms, flip angle 35°, voxel size: 2.7x2.7x6mm^3, coronal) was applied. The Philips Healthcare clinical HIFU platform with a 256-channel transducer was integrated into the MR bed and equipped with a dedicated multi-channel coil for signal registration. A circular region of 1cm was targeted for 100s with a maximal acoustic power of 60W while a trajectory of 4 points was optimized. The gel was displaced periodically with a peak-to-peak amplitude of 1.6cm in the y-direction and approximately 2mm in the x direction with a frequency of 0.13Hz where the movement was controlled by a motor placed outside the scanner room.

Results and Discussion

The top image of Figure 1 shows the magnitude image of the used gel phantom with a color overlay of the logarithm of the thermal dose measured after the treatment. All voxels in the targeted circular area (9 voxels) show a value well above the target value of TD=1. Regarding the control zone extending 5mm around the target zone we find 4 voxels (36 voxels in total) with a thermal dose TD > 1 representing 11% of the control voxels (Fig. 1 bottom). Taking into account the displacement of approximately 6 pixels during the treatment a much higher percentage is to be expected if no motion correction is applied. The area with increased thermal dose below the target area is due to the secondary lobes of the ultrasound beam but still well below the threshold of TD=1. A total acoustic energy of 6kJ was applied where ~12% was absorbed in the target area and ~20% in the control area (which is four times as large as the target area). Note that thermometry was only applied in 2D which is why heating in the slice select direction could not be evaluated and might account for the relatively low apparent absorbed energy. Figure 2 shows the position of the heating points relative to the center of the target area during the treatment. The displacement of the trajectory points represents a superposition of the periodic movement of the phantom and the trajectory optimization. Both in the x- and the y-direction the amplitudes of the displacements due to the optimization algorithm (visible as parallel offsets between adjacent periodic trajectories) do not exceed the size of the target area marked by the dashed red lines.

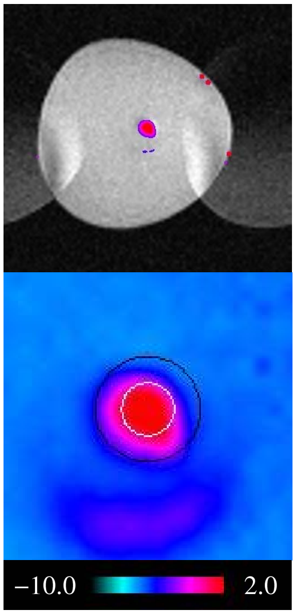

Figure 1: Top: Magnitude image with logarithm of the thermal dose (color overlay). The red regions received a lethal thermal dose. Bottom: The white and the black circles define the target area and the control area respectively.

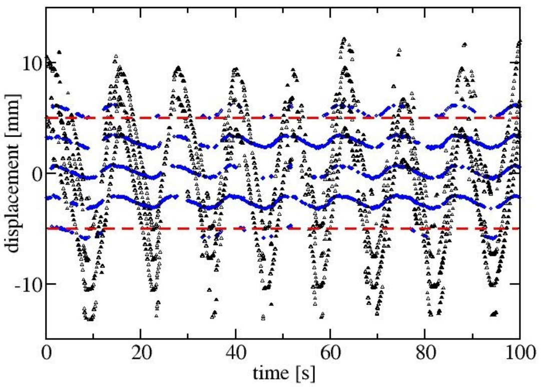

Figure 2: Displacement of the treatment points during the treatment relative to the center of the transducer (center of the target area). The displacement in the y-direction (black triangles) reflects clearly the movement of the phantom while the displacement in the x-direction (blue circles) remains mainly within the target area (red dashed lines).

Conclusions

The proposed method enables precise volume ablations even in the presence of motion with amplitudes similar to those due to respiratory motion. While all voxels within the target volume received a lethal thermal dose, only a small percentage of the adjacent voxels were heated to that extent. By optimizing the trajectory such that heating is always applied to the points with the largest difference to the target energy, the treatment time and overall energy deposited are minimized. Hence, the described method may allow for effective tumor ablations in the future inflicting minimal damage on the surrounding tissue.

References

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