Robust binary feedback control of MR guided volumetric HIFU ablation

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Introduction

Volumetric High Intensity Focused Ultrasound (HIFU) ablation has several advantages as compared to the traditional point-by-point ablation, such as improved energy efficiency and homogeneous thermal lesions with sharp borders [1]. However, there is an increased risk of excessive off-focus heating, especially in the near-field [2], and the thermal lesions can also vary in shape and size due to local differences in thermal tissue parameters as is the case for any predefined sonication procedure. Near-field heating can be monitored by multiplane volumetric MR thermometry that visualizes the heat development in the target region as well as along the beam-path and in sensitive near- and/or far-field regions. To overcome the problem of variability in size and shape of the thermal lesions, MRI thermometry can be used to dynamically adjust the local acoustic power deposition. This study presents a simple and robust binary feedback control algorithm specifically designed for the volumetric ablation method based on trajectories of concentric outwards-moving circles [1]. The proposed feedback control acts on the time while keeping the sonication power high and constant, in contrast to already published feedback methods that control the power [3]. The main benefit of this approach is that the treatment time is kept as short as possible The efficacy of the binary feedback controlled volumetric ablation is proven *in-vivo* by comparing the resulting thermal lesion size and the variability of the temperature of volumetric ablations with and without the proposed control method.

Materials and Methods

Eleven male pigs (50-80kg) were used for this study. The animals were kept under general anesthesia during the complete procedure by a continuous intravenous infusion of ketamine (1g/h), propofol (0.8g/h) and hourly intravenous bolus injections of curare (0.5mg). Vital parameters including rectal temperature and heart rate were monitored continuously. This animal protocol was approved by the local Ethical committee (Agreement AP1/01/2007). After preparation, the animals were placed on a Philips Healthcare clinical HIFU platform with a 256-channel phased-array HIFU transducer, which was integrated into a 1.5 T Philips Achieva MR scanner. The principle of volumetric ablation remained unmodified from [1], i.e. the focal point was electronically steered along multiple concentric outwards-moving circles. Based on the online analysis of temperature images acquired during sonications, the binary feedback control algorithm automatically decided when to switch from one circle to the next, and also when to stop the sonication, instead of these times being predetermined as for the normal volumetric ablation. This was achieved by online comparing several quantitative thermal attributes (e.g. min, mean, max temperature and thermal dose) to pre-calculated limits that were based on simulations of the non-feedback volumetric sonication trajectories. Volumetric thermometry was performed simultaneously to sonication using the proton resonance frequency (PRF) shift method with three coronal slices centered on the target region and perpendicular to the beam-axis, and one sagittal slice positioned along the beam-axis. Two additional freely positionable off-focus slices were placed at sensitive tissue interfaces in order to monitor for any excessive heating. The images for each slice were acquired with a multi-shot spoiled gradient recalled EPI sequence (TE=20ms, TR=37ms, Resolution=2.5x2.5x7mm^3, Flip angle=20°, EPI-factor=11, 121-binomial water sel. excitation pulse, multi-element dedicated coil, temp. resolution=2.9s). The three coronal slices centered on the targeted region were used for the binary feedback control of this study, meaning that the required thermal attributes were calculated for each of these slices and evaluated against the pre-calculated limits for the circle being sonicated. The thermal lesion size was determined by the area in which the thermal dose was above 240 equivalent minutes at 43˚C (240EM).

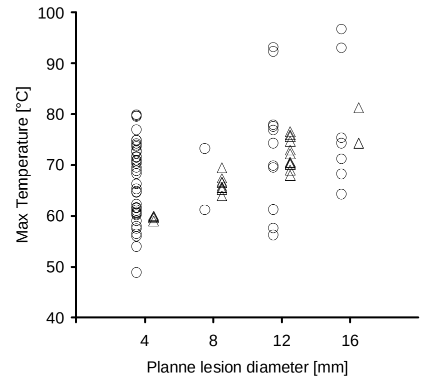

Figure 1. Maximum temperature for feedback controlled (triangles) ablations and non-feedback (circles) ablations of different sizes.

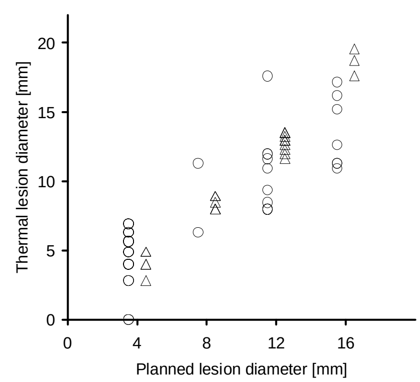

Figure 2. 240EM thermal dose diameter for the feedback controlled (triangles) and non-feedback (circles) ablations of different sizes.

Results and Discussion

60 non-feedback ablations and 30 feedback controlled ablations were performed in the thigh of the pigs with trajectories of different diameters, without any failure of the feedback algorithm. The maximum temperature for the differently sized feedback and non-feedback sonications can be seen in Figure 1. The variability in maximum temperature is clearly decreased for all of the different trajectory sizes when using feedback. Similarly, the reproducibility of the resulting thermal dose diameter (Figure 2) is improved for feedback controlled ablations. Moreover, with the proposed control algorithm the induced thermal lesion diameter correlates much better to the planned lesion diameter. Figure 3 shows a typical example of the maximum temperature and resulting thermal dose for a 12 mm binary feedback controlled sonication and the corresponding simulation from which the pre-calculated limits of the feedback controlled ablation were determined. Because the binary feedback does not alter the trajectory design of the volumetric ablation but only controls the sonication timing, the advantages associated with the concentric circle volumetric ablation still remain. In addition, since this approach ensures minimum sonication duration for a given acoustic power, the energy spread by thermal diffusion remains limited, which not only improves the control of the size of the resulting thermal lesion but also reduces the near-field heating.

Conclusions

The proposed binary feedback control was proven to be robust and its addition to the basic volumetric ablation strategy was shown to significantly improve both the reproducibility and the reliability of the sonication outcome. The variation in both the resulting thermal lesion size and maximum temperature was reduced, and the induced thermal lesion was closer to the intended size using a minimal energy. This was achieved without reducing the advantages associated with volumetric ablation. The addition of the binary feedback control to the volumetric ablation does therefore not only provide a more precise and reproducible treatment, but also improves patient safety due to a reduced near-field heating that can be monitored by volumetric thermometry.

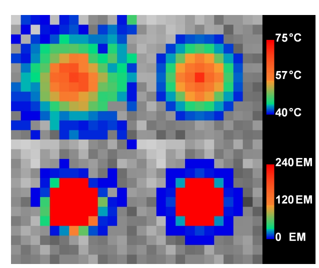

Figure 3. Maximum voxel temperature (top) and thermal dose (bottom) for a 12 mm binary feedback ablation (left) and for the simulated non-feedback 12 mm trajectory (right). The 12 mm feedback trajectory is designed to reproduce the same thermal dose as the simulated 12 mm trajectory shown. The FOV shown is 32.5 x 32.5 mm^2.

References

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