

Volumetric HIFU Ablation under 3D Guidance of Rapid MRI Thermometry

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Introduction

The clinical therapeutic thermal ablations based on High Intensity Focused Ultrasound (HIFU) on abdominal organs are usually performed by iterative point-by-point sonications, interleaved with cool down periods, until the desired volume is treated [1]. However, this method remains rather slow due to suboptimal utilization of energy deposition and may lead to an inhomogeneous treatment by leaving pathological cells located between adjacent sonications untreated. We propose an alternative approach based on a volumetric sonication method that uses electrical beam-steering to take advantage of the intrinsic thermal diffusion of tissues to ensure a uniform thermal treatment. This strategy should also improve the efficiency of the treatment by exploiting the thermal diffusion of previously deposited thermal energy within the heated region during each sonication. However, volumetric sonication could induce excessive heating of surrounding tissues outside the target volume, in the near (e.g. on the skin) and far fields of the HIFU beam propagation pathway. To overcome this problem and to provide a fully controlled and secure ablation procedure, rapid volumetric thermometry is performed simultaneously. The applicability and usefulness of the volumetric sonication method under volumetric MRI thermometry is demonstrated in-vivo on a large animal model by comparing the resulting non-perfused volume of each sonication to the lethal thermal dose volume [2] calculated on-line from MRI temperature maps.

Materials and Methods

Seven pigs (50 kg body weight) were sedated and kept under general anesthesia by continuous intravenous infusion of ketamine (10ml/h), propofol (40ml/h) and curare (0.5ml/h), and ventilated (Respirator paraPac, ResMed SA, France) during the complete procedure. Monitoring of vital parameters included cardiac frequency and rectal temperature. This experimental protocol was approved by the Ethical committee (Agreement AP1/01/2007). The animals were positioned on a Philips Medical Systems clinical HIFU platform with a 256-channel transducer, which was integrated into a 1.5T Philips Achieva MRI scanner. Volumetric sonication was performed by electronically steering the focal-point along multiple outwards-moving concentric circles. Several ablations with different sizes were achieved by adding or removing outside circles. Volumetric temperature imaging was performed simultaneously to sonication using 3 slices perpendicular to the beam-axis centered on the focal-region and one sagittal slice aligned along the HIFU propagation direction. Two additional coronal slices were positioned near the skin and subcutaneous-fat to monitor potential excessive near-field tissue heating introduced by volumetric sonication. For each slice, a multi-shot FFE-EPI sequence was performed (TE=20ms, TR=37ms, Resolution= 2.5x2.5x7mm³, Flip angle=20°, EPI-factor=11, 121-binomial water sel. excitation pulse, 3-element dedicated coil, temp. resolution=2.9s). After completion of the ablations, T1-weighted contrast enhanced (CE) images were acquired before and after injection of gadodiamide (Omniscan, Amersham, 0.2ml/kg) and subtracted to highlight the treated region. The animal was then quickly sacrificed and the ablated thigh muscles extracted for histological analysis (HES staining). The dimensions of the apparent ablation zones observed on CE difference images were correlated to the resulting thermal dose (240 equivalent minutes at 43°C - 240EM) in coronal (diameter) and sagittal (length) planes.

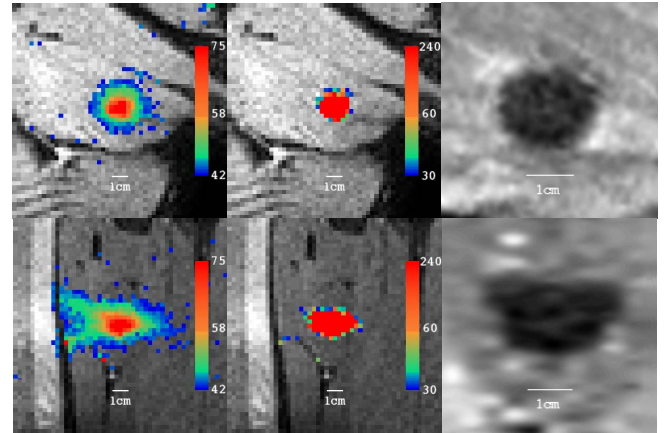


Figure 1. Maximum temperature (left), thermal dose (middle) and corresponding T1w-CE difference image (right) as seen in the coronal (top row) and sagittal plane (bottom row). In the sagittal view the transducer is at the left-hand side of the image. Temperatures are in Celsius and thermal dose in equivalent minutes at 43°C.

Results and Discussion

No technical failure was observed for the investigated animals and a total of 25 ablations were performed with trajectories of different diameters. Figure 1 shows typical results of volumetric imaging during a volumetric HIFU sonication of 16 mm diameter. The temperature map at the end of the sonication, the resulting 240EM thermal dose and the corresponding non-perfused volume obtained from the CE difference images in both the coronal and sagittal planes are displayed. The temperature standard deviation in the area of interest was 1.1°C in the absence of sonication and 1.3°C during sonication. Due to the optimized slice acquisition order, the partial magnetization saturation at the cross-section of perpendicular slices had a negligible effect on the temperature standard deviation in the region of interest. Correlation curves (for the diameters and lengths of all sonications) between 240EM thermal dose and CE difference images are presented in Figure 2. An excellent correlation was found for diameter (R=0.977) and length (R=0.988), respectively, demonstrating the precision of this volumetric monitoring method. Histological markers confirmed irreversible tissue damage in the treated region (data not shown), with a clear delineation at the interface between the ablation zone and the surrounding healthy tissue. The larger volumes required more energy than small volumes, however, the efficiency of the proposed approach was found better the larger the volume, since the ratio of ablated volume and required energy were approximately 0.04cc/kJ, 0.34cc/kJ and 0.56cc/kJ for the 4mm, 12mm and 16mm diameter trajectories, respectively.

Conclusions

The proposed volumetric ablation is shown to provide a significant improvement to both treatment speed and homogeneity as compared to the current point-by-point ablation methods. The volumetric temperature monitoring sequence required for a precise monitoring of these volumetric sonications is demonstrated to be of excellent quality (Figure 1). The 240EM thermal dose volume gives a fast and precise estimate of lesion size, both parallel and perpendicularly to the beam-path and thus provides the clinician a therapeutic end-point. The orthogonal temperature imaging also increases patient safety by monitoring the temperature along the beam-path, both in the near- and far-field and at the skin-fat-muscle interfaces. This rapid and volumetric thermometry enables accurate temporal and spatial control of heat deposition, which is mandatory to obtain a precise, reproducible and safe therapeutic procedure.

References

- [1] McDannold N. et al., Radiology, 2006, 240:263-272.
- [2] Chung A. H. et al., Med Phys, 1999, 26:2017-2026.

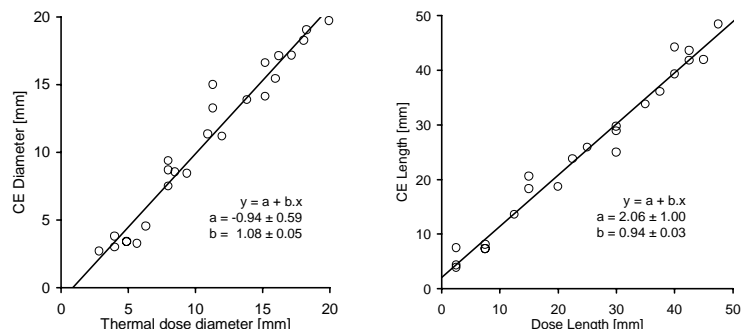


Figure 2. CE difference-image diameter (left) and length (right) versus the corresponding 240EM thermal dose dimensions. The solid line corresponds to the regression fit.