Monitoring of HIFU Treatment Effectiveness by MR Imaging: Advantage of the Magnetization Transfer Ratio over the Thermal Dose as Evidenced by Overheating Experiments

H-H. Peng[1], T-Y. Huang[2], H-W. Chung[1], C-C. Wu[3], W-S. Chen[4], and W-Y. I. Tseng[5]

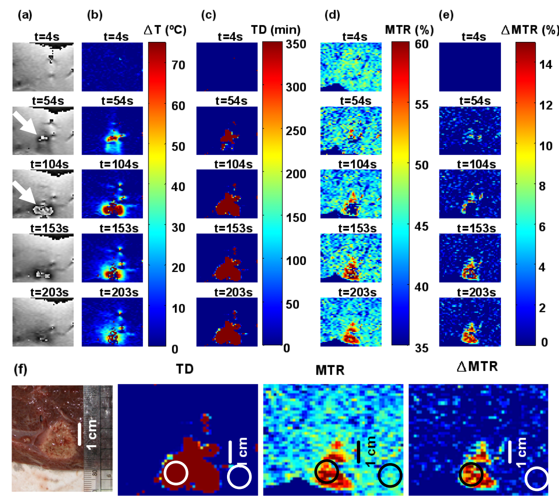
[1]Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, [2]Department of Electrical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan, [3]Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan, [4]Department of Physical Medicine and Rehabilitation, National Taiwan University Hospital, Taipei, Taiwan, [5]Center for Optoelectronic Biomedicine, Medical College of National Taiwan University, Taipei, Taiwan

Introduction

The utilization of MRI for guiding high-intensity focused ultrasound (HIFU) beams not only increases the localization accuracy during HIFU procedures but also allows evaluation of HIFU-induced lesions after treatment [1]. During the past few years, temperature monitoring using phase mapping was developed based on the temperature dependence of the water proton chemical shift [2], so-called proton resonance frequency (PRF) shift method. The degree of cell damage is usually evaluated by the thermal dose (TD), which is derived from an integration of the incremental temperature changes throughout the treatment procedure [3]. Alternatively, the magnetization transfer (MT) contrast of tissues altered after heating treatment was also investigated as an index for cell damage [4]. In our previous studies [5, 6], we have investigated the accuracy and the feasibility of simultaneously monitoring for temperature changes and MT contrast on phantoms and *ex vivo* experiments. In this study, we further applied our technique on a deliberately designed overheating HIFU experiment, to demonstrate the advantages of the MT method over the TD method in the evaluation of cell damage.

Materials and Methods

Continuous-wave HIFU pulses with power of 83 Watt were transmitted to a porcine liver tissue immersed in 25^{o} C degassed water. Serial MR images were acquired at pre-heating (t=0~19 sec), heating (t=20~122 sec) and post-heating time (t=123~223 sec). Thus the HIFU pulses were transmitted for a continuous period of 102 seconds, sufficient to boil tissue water. All MR images were acquired on a 3T clinical imager (Siemens Trio, Erlangen, Germany). The pulse sequence used a dual gradient-echo design, with ON and OFF of the MT pulse interleaved [5], such that the phase images from the two gradient echoes could be used to estimate PRF shift in response to temperature change, and the first echoes from two consecutive measurements could be used to derive the MT ratio (MTR) on a pixel-by-pixel basis. Imaging parameters were TR=29 ms, TE=3.61/7.57 ms, flip angle=20^{o} , FOV=160x120 mm^2, matrix size=128x85, slice thickness=3 mm, off-resonance frequency of MT pulse=−450 Hz. Temporal resolution of about 1.85 sec for monitoring temperature and MTR changes was achieved simultaneously. To characterize the time course of temperature and MTR with respect to the heating time, several ROIs were selected in the heated and non-heated areas (2 cm from the heated area) from the phase and the magnitude (with MT pulses) images.



Results

The serial changes of the MR phase images, temperature increase, thermal dose, MTR, and ΔMTR at five selected time points were put together in Fig.1(a-e). As shown in Fig.1a, manifest susceptibility artifact (white arrows) was shown in the phase images, with the pattern consistent with the presence of air bubbles generated from the boiling effects of tissue water due to long-duration overheating. The interference of air bubbles led to erroneous estimations of the PRF shifts and hence unreliable temperature estimations (Fig.1b), both within the bubbles (due to signal loss) and in their surrounding areas (due to susceptibility-induced off-resonance). Due to its integration nature from incremental temperature changes, the thermal dose became incorrectly estimated as well (Fig.1c). Although the overheating effect affected both the magnitude and phase MR images during heating procedure, MTR and ΔMTR measured after turning off HIFU transmission still outlined the heated spot (Figs.1d and 1e) successfully, with contour in close agreement with the optical picture taken from the cut face of the heated tissue (Fig.1f). The comparison of optical picture, thermal dose, MTR, and ΔMTR maps (Fig.1f) further showed that the spot size estimated from the TD map was substantially overestimated, whereas the spot areas shown in MTR and ΔMTR maps were comparable with that in the optical picture. Fig.2 showed the temporal changes in temperature and MTR as measured from the MR images. Because the susceptibility artifact occurred at around the 70th sec, the signal void invalidated measurements of both temperature and MTR. Nevertheless, after turning off the HIFU pulses, the increased MTR from 45% to 55% still provided clearly distinguishable information to evaluate the effectiveness and spatial extent of the heated spot.

Fig.1. Comparing the serial changes of MR phase images (a), temperature rise (b), thermal dose (c), MTR (d) and ΔMTR(e) maps at five selected time points. Manifest susceptibility artifact was shown in the phase images (white arrows). (f) A comparison of the cut face of the heated tissue, thermal dose, MTR, and ΔMTR maps (t=203 sec). The spot size evaluated in the thermal dose map was obviously overestimated, whereas the spot sizes shown in MTR and ΔMTR maps were comparable with that in the optical picture.

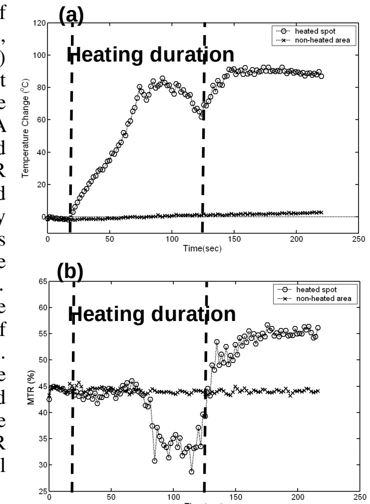


Fig.2. The time courses of temperature change (a) and MTR values (b) in ROIs of the heated spot and non-heated region. Both temperature change and MTR in the heated areas after the 70th sec showed incorrect estimations. Nonetheless, the clearly distinguishable change in MTR from 45% to 55% still provided useful information to evaluate the heated extent.

Discussion and Conclusions

The monitoring of temperature changes and degree of cell damage of a tissue under HIFU treatment is crucial to the evaluation of treatment efficiency. During the overheating process of HIFU treatment to temperatures close to or over 100^{0}C, however, temperature evaluation based on PRF shift was erroneous due to both the signal void and the susceptibility effects. In this study, we have verified the feasibility of monitoring cell damage extent after overheating treatments by evaluating MTR after termination of the HIFU procedures. Geometrical consistency between MTR maps and optical images of the treated tissues suggests that MTR offers some advantages over the thermal dose in the situation of overheating for defining the extent of cell damage (Fig.1f). Results from our experiments suggest that it is important to monitor heating efficiency not only by temperature changes but also by other independent measures such as the MT contrast. In conclusion, MRI with simultaneous temperature and MTR mapping is an effective technique to monitor local heating conditions and the degree of cell damage during HIFU treatment.

References

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