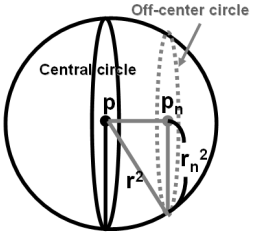
Three-slice MR pre-treatment temperature mapping and spherical model estimation for accurate localization of the heating focus before high-intensity focused ultrasound treatment

H-H. Peng[1], T-Y. Huang[2], H-W. Chung[3], P-C. Chen[4], Y-H. Ding[4], S-Y. Ju[2], Y-H. Yang[2], W-Y. I. Tseng[5,6], and W-S. Chen[4,7]

[1]Department of Biomedical Engineering and Environmental Sciences, National Tsing Hua University, Hsinchu, Taiwan, [2]Department of Electrical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan, [3]Department of Electrical 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, [6]Department of Medical Imaging, National Taiwan University Hospital, Taipei, Taiwan, [7]Division of Medical Engineering Research, National Health Research Institutes, Miaoli, Taiwan

Introduction: Recent development of high intensity focused ultrasound (HIFU) technology has offered a potentially noninvasive approach for local deposition of thermal energy deep inside the body [1]. During the past few years, temperature measurement procedure using MR phase mapping was developed based on the temperature dependence of the water proton chemical shift [2]. This is called the proton resonance frequency (PRF) shift method. During HIFU treatment, the focus of ultrasound (US) beams is arranged to the targeting region determined in advance. In practical treatments, however, the focus might be deviated due to the complex path (tissue-bone interface or tissue-air interface) of US beams. For safety considerations, accurate localization of heating focus is particularly important before performing HIFU pulses with high power. In this study, a spherical model is proposed to estimate the real position of the focus of US beams from images obtained in low power pre-treatment experiments [3] performed on *ex vivo* porcine muscle. The estimated focus position was verified via magnetization transfer (MT) images in response to tissue damaged zone after a high power HIFU transmission.

Theory: The ablated spot and the temperature distribution in HIFU treatment is usually in a spindle-like shape. To simplify matters, a spherical model of heated region is proposed for determination of the position of focal point. As shown in Fig.1, the area of central circle represents the temperature increasing region at central focal plane during HIFU transmission, and the center of the circle (p) is the position of the plane. If the imaging slice located at position p_n, the distance between the two points, p_n and p, can be written as Eq.(1) (shown within Fig.1) where r_n is the radius of the off-center circle and can be derived from the area of temperature increasing region (A_n) of the circle. The focal position of p can be derived if three slices were acquired. To objectively and quantitatively evaluate the values of A_n, a temporal sliding-window step function was used to calculate the correlation coefficient map (C.C. map) with the ΔT map in a pixel-by pixel manner.



$$(p - p_n)^2 + r_n^2 = r^2, n = 1,2,3 \quad (1)$$

$$\pi \cdot r_n^2 = A_n, n = 1,2,3 \quad (2)$$

Fig.1. A sphere model represents the heated region for determination of the position (p) of central focal slice. The distance between other centers of circles of off-centered slice (p_n) and p can be related as Eq. (1). In Eq.(2), the radius of off-center circle (r_n) can be derived from the area of heated region (A_n).

Methods and Materials: A single-element focused piezoelectric transducer (central frequency 1.85 MHz, 10 cm diameter, 12.5 cm curvature, Imasonic, Besancon, France) was immersed in 37 ºC degassed water and was used as the source of sonication. Continuous wave HIFU pulses with a low power of 8 Watt were first performed on porcine muscle tissue. MR images were acquired continually at pre-heating (t=0~47 sec), heating (t=48~94 sec) and post-heating time (t=95~110 sec). All MR images were acquired on a 3T clinical imager (Siemens Trio, Erlangen, Germany) with a flexible receiving surface coil on the top of porcine muscle. The pulse sequence used a gradient-echo sequence whose phase was used to estimate PRF shift in response to temperature change (ΔT). Imaging parameters were TR=81 ms, TE=7.86 ms, flip angle=20º, FOV=240x240 mm², matrix size=128x96, slice thickness=3 mm. Three slices were acquired for each trial. After the first 8 Watt transmission, the phase images were exported out to a stand-alone computer and the ΔT map was calculated by Matlab code. The temperature increasing region was determined by the C.C. map. The position of focal point was estimated according to the spherical model described above. In the second trial, the position of the middle of the three slices was shifted to the focus determined in the first trial. The same calculating procedure was repeated until the desired focus was found, followed by 40 Watt high-power HIFU ablation for 41 sec. To verify the position of focus, the ablated region after high-power HIFU sonication was examined using MT imaging. MT imaging was done using a 3D gradient echo sequence with and without MT pulse performed consecutively (TR/TE=35/4.15 ms; slice thickness=1.5mm; offset frequency = –1200 Hz). The MT ratio (MTR) was calculated using the formula: 1-(M_{MT}/M_0), where M_{MT} and M_0 are the signal intensity of magnitude images with and without off-resonant MT pulse, respectively.

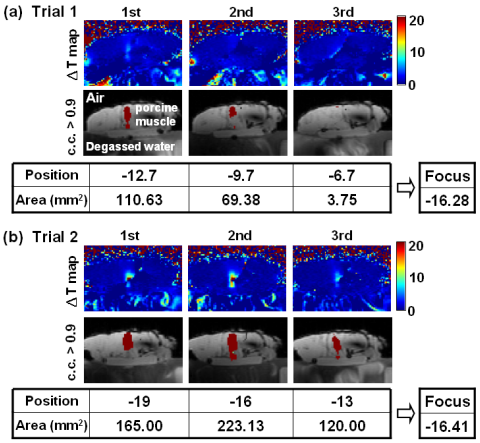


Fig.2. ΔT maps and C.C. maps overlapped on magnitude images (t=94sec) of two trials. In these maps, the HIFU pulses were applied from the bottom upward. (a) The asymmetry of the areas of the 1st and 3rd slices indicates that the focal point might have deviated to the direction of the 1st slice. The focal point was estimated as -16.28. (b) The areas of the 1st and 3rd slices were relatively symmetric suggesting that the focal point is around the position of -16 (estimated as -16.41).

Results: Fig.2 shows ΔT maps and C.C. maps overlapped on magnitude images (t=94sec) of two trials. In these maps, the HIFU pulses were applied from the bottom upward. The tables in Fig.2 showed the slice positions and areas of the temperature increasing regions, chosen automatically with C.C. > 0.9. In the first trial (Fig.2(a)), the temperature increased slightly (ΔT ~ 8 ºC) at the 1st slice only, with smaller temperature changes shown at the 2nd and 3rd slices. The area in C.C. maps (C.C. > 0.9) were 110.63, 69.38, and 3.75 mm² for the three slices, respectively. The asymmetry of the areas of the 1st and 3rd slices suggests that the focal point might deviate to the direction of the 1st slice. The spherical model estimated the focal point to be at -16.28 (negative sign: off-centered toward the foot direction in the patient's coordinate). The second trial shifted to slice positions at -19, -16, and -13 (Fig.2(b)), showed that the heated areas of the 1st and 3rd slices (165 and 120 mm²) are relatively more symmetric than in the trial 1 (110.63 and 3.75 mm²), suggesting that the focal point should be around the position of the 2nd slice (-16), highly consistent with the estimate from the first trial (-16.28). Fig.3 shows the magnitude images with and without MT pulse, as well as the calculated MTR maps after transmitting a continuous wave 40 Watt sonication for 41 sec. The symmetry of the ablated regions shown in position = -18.25 and -15.25 plus the largest area of ablation at slice = -16.75 were in very good agreement with the spherical model estimation.

Discussion and Conclusions: HIFU treatment provides local energy deposition within a targeting region during a short exposure of US beams. For safety considerations, accurate localization of the true focal point is important before a high power sonication. In this study, a spherical model used on pre-treatment experiments was applied to estimate the position of heating focus with slight elevation in temperature, using two three-slice trials at 8 Watt sonication. The estimated focal point was verified by the MTR map after a continuous wave 40 Watt ablation. In our experience on porcine muscle experiments, 2~5 trials usually suffice in finding out the focus with satisfactory accuracy. In summary, performing pre-treatment experiments before high power HIFU treatment is able to provide the information of real US focal position using the simple spherical model. The proposed method has potential avoiding erroneous ablation of healthy tissues in high-power HIFU treatments.

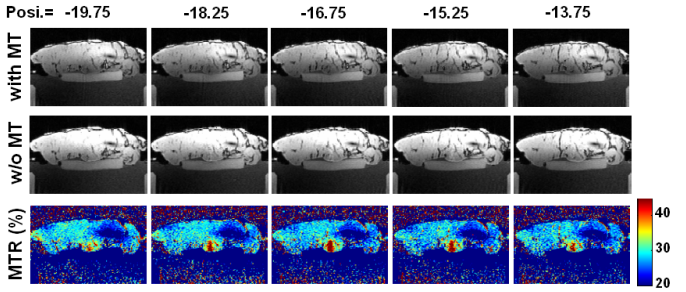


Fig.3. The magnitude images with and without off-resonant MT pulse as well as the calculated MTR maps after transmitting a continuous wave 40 Watt sonication for 41 sec. The symmetry of the ablated regions shown in position = -18.25 and -15.25 indicates that the focal point might locate around -16.75 which is close to the estimated focus in trial 2 (position = -16.41).

References:

[1] de Senneville BD et al. MRM 2007; 57(2): 319-310. [2] Ishihara et. al, MRM 1995; 34: 814-823. [3] Hynynen K et al. Radiology 1997;204(1):247-253.