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Authors
Ozhinsky, Eugene
Han, Misung
Krug, Roland
et al.

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T2-Based Temperature Monitoring in Trabecular Bone Marrow for MRgHIFU

Eugene Ozhinsky[1, a)], Misung Han[1], Roland Krug[1], and Viola Rieke[1]

[1]*Department of Radiology and Biomedical Imaging University of California, San Francisco, 185 Berry Street, Suite 350, Box 0946, San Francisco CA 94107*

[a)]Corresponding author: eugene.ozhinsky@ucsf.edu

Abstract. Current clinical protocols for HIFU treatment of painful bone metastases rely on measurement of temperature change of adjacent muscle to estimate the temperature of the bone. In this study, we investigated if T2-based temperature mapping could be used to determine the temperature within ex vivo trabecular bone during HIFU ablation. We have shown that T2-based ablation monitoring in the red marrow in trabecular bone is feasible. The linear relationship between T2 change and temperature could be used to quantify the temperature during heating of up to 60°C.

OBJECTIVE

MR-guided high-intensity focused ultrasound (HIFU) is a noninvasive technique for the treatment of painful bone metastases. Recent studies have shown that aggressive treatment (increased temperature and duration) is promising for local tumor control (1).

Proton resonant frequency shift (PRF) thermometry is commonly used for temperature monitoring in water-based tissues, but fails to detect temperature changes in tissues with high lipid content, such as bone marrow. Current clinical protocols rely on measurement of temperature change of adjacent muscle to estimate the temperature of the bone. This can lead to poor temperature accuracy in the treated area and sub-optimal ablation. Heijman at al. has previously demonstrated the feasibility of T2-based MR thermometry in extracted samples of yellow and red bone marrow (2).

In this study, we investigated if T2-based temperature mapping could be used to determine the temperature within ex vivo trabecular bone during HIFU ablation. We also examined if T2-changes caused by the ablation were reversible and measured the patterns of heating and tissue damage in the red marrow in trabecular bone.

METHODS

T2-Based Thermometry in Ex-vivo Subcutaneous Fat

To evaluate the feasibility of T2-based thermometry in fatty tissues during HIFU ablation, T2 maps were acquired from samples of porcine subcutaneous fat. Heating was performed with Uterine Fibroid HIFU system ExAblate 2100 (InSightec, Israel) in a 3T MRI scanner (GE Healthcare, Waukesha, WI).

During heating, double-echo Fast Spin-Echo images were acquired (TE = 34.5/179.5, TR = 563 ms, echo train length = 40, FOV = 16 cm, 128 x 128 matrix size, 10mm slice thickness), sampling every 10 s. These images were used to calculate T2 maps and maps of T2 difference from baseline (3).

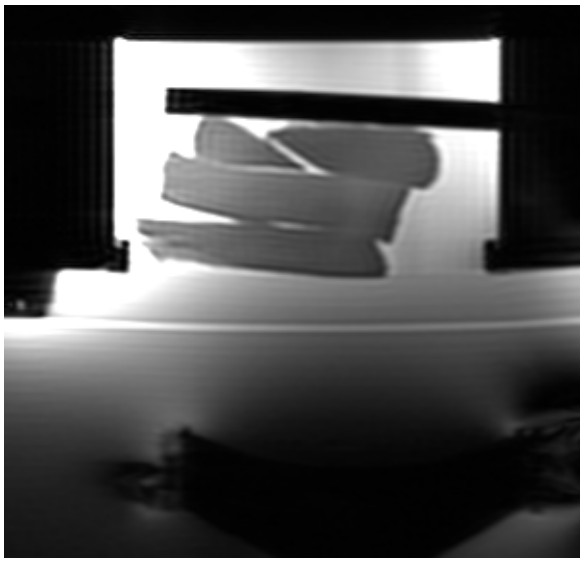

FIGURE 1. T2-based thermometry of ex-vivo subcutaneous fat during focused ultrasound sonications; (a) fat samples in water with the HIFU transducer below.

T2-Based Thermometry in Trabecular Bone Marrow

Two ex-vivo experiments were performed on epiphysis segments of bovine femur with the birdcage head coil on a 3T MRI scanner (GE Healthcare, Waukesha, WI). Three fiber optic sensors (Luxtron, LumaSense Technologies, Santa Clara, CA) were placed into drilled holes within the red marrow (fig. 2). The femur segments were sonicated with the ExAblate 2100 conformal bone system (InSightec, Israel) with acoustic power of 17.6 W, sonication time of 60 secs, repeated 8 times.

Bone marrow T2 was quantified by using a double-echo fast spin-echo sequence with water suppression (TE = 35/181 ms, TR = 723 ms, echo train length = 40, FOV = 24 cm, 128 x 128 matrix size, 10mm slice thickness, 15 sec/slice). Images were acquired during heating and cooling, and after the sample reached room temperature.

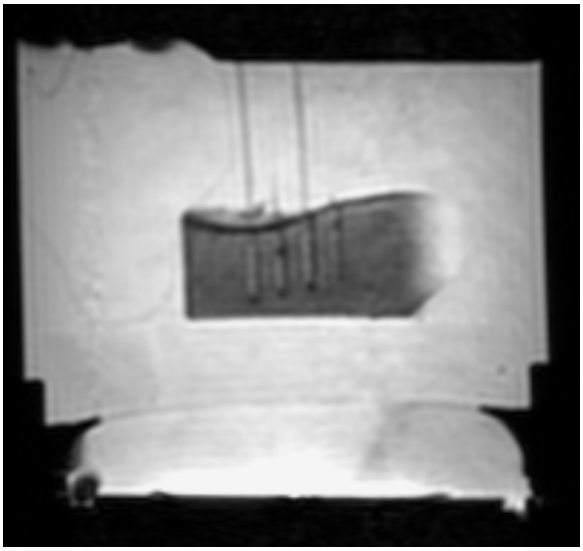

FIGURE 2. Setup for T2-based thermometry of ex-vivo subcutaneous fat during focused ultrasound sonications showing the fiber optic probes.

RESULTS AND DISCUSSION

T2-Based Thermometry in Ex-vivo Subcutaneous Fat

Figures 3 (a,b) show the acquired double-echo FSE images during the sonication of porcine subcutaneous fat samples. T2 maps (fig. 3c) show elevated T2 values in the area being heated, as well as at the locations of previous sonications. This indicates irreversible changes in the tissue properties due to heating. ΔT2 maps (fig. 3d) show sharp increase in T2 in the ablation hotspot.

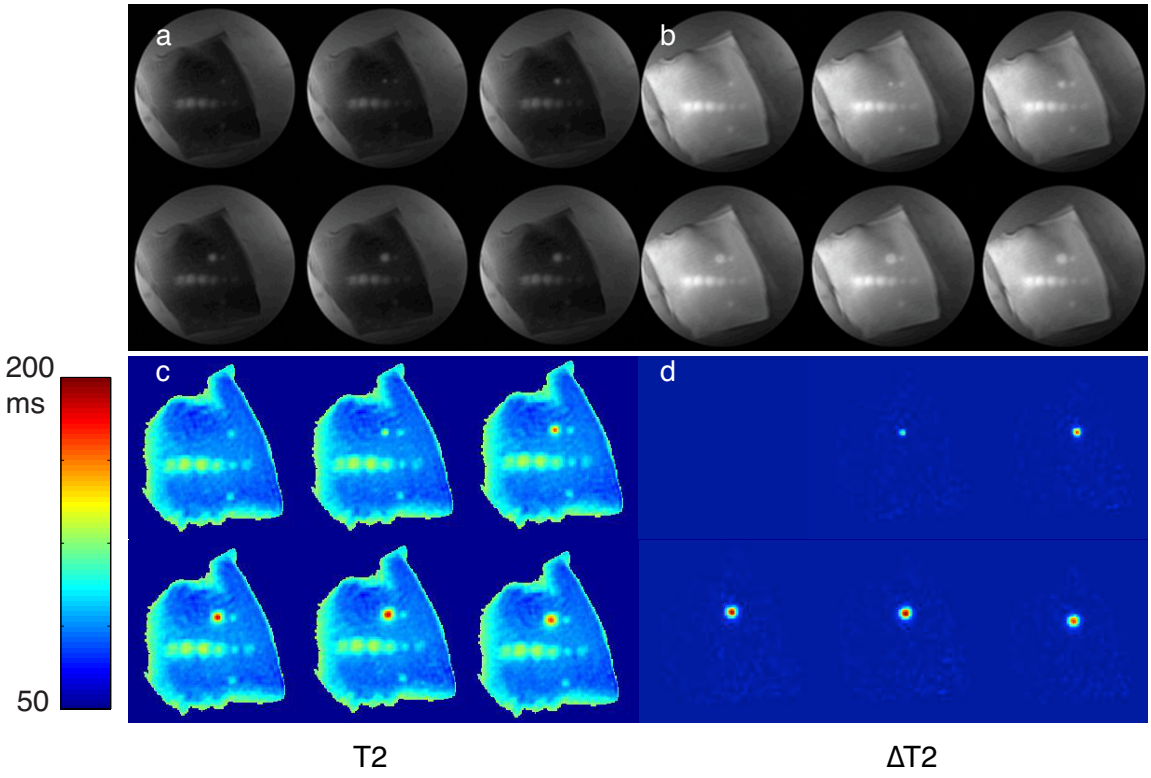

FIGURE 3. T2-based thermometry of ex-vivo subcutaneous fat during focused ultrasound sonications: (a,b) images, acquired by double-echo fast spin-echo sequence with water suppression; (c) calculated T2 map (c) map of T2 difference from baseline.

T2-Based Thermometry in Trabecular Bone Marrow

Figure 4 shows the T2 change during heating and cooling of a sample of trabecular bone marrow. The acoustic energy was transferred to heat at the edge of the sample and then radiated into the sample.

Figure 5 shows the T2-change of another bone segment during heating (a) and after it returned to room temperature (b). The calibrated thermometry data showed propagation of thermal energy within the trabecular bone. The profiles through the heated region (fig. 5 c,d) show residual elevated T2 of about 35 ms in the ablated area suggesting irreversible changes. The area of residual T2 elevation after cool-down matched the area of the heating. Elevated T2 values in the areas of thermal damage could allow for evaluation of treatment effects during bone MRgHIFU therapy.

Figure 6 shows a plot of T2 change versus the temperatures, measured by the three fiber optic probes. We can see a linear relationship (5.7 ms per °C) during the heating stage of the experiment (red points). The T2-change during cooling (fig. 6, blue) showed a reduction with temperature, but did not follow the same linearity as during heating. This is likely the result of the irreversible changes in the tissue, caused by the heating.

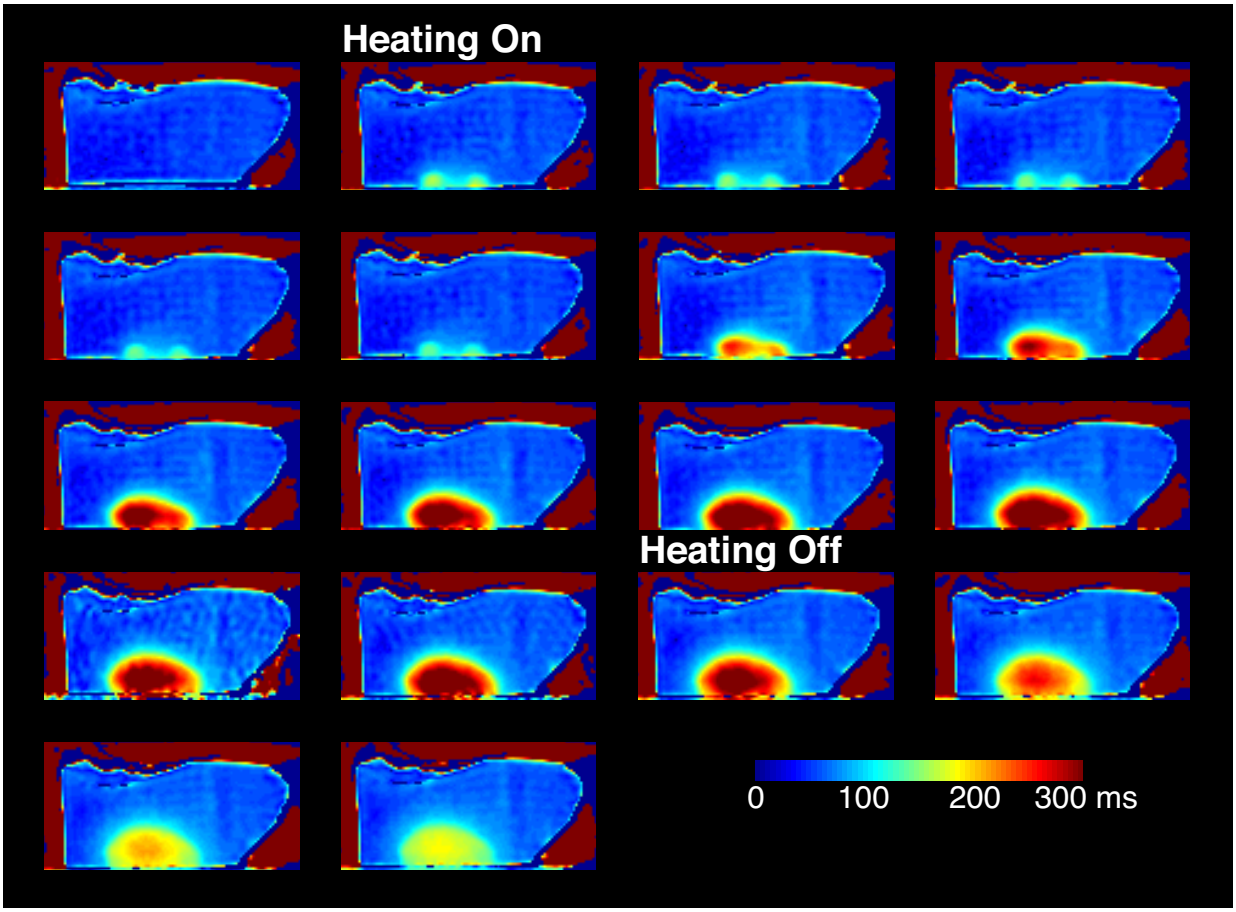

FIGURE 4. T2 maps of sample 1 during heating and cool-down

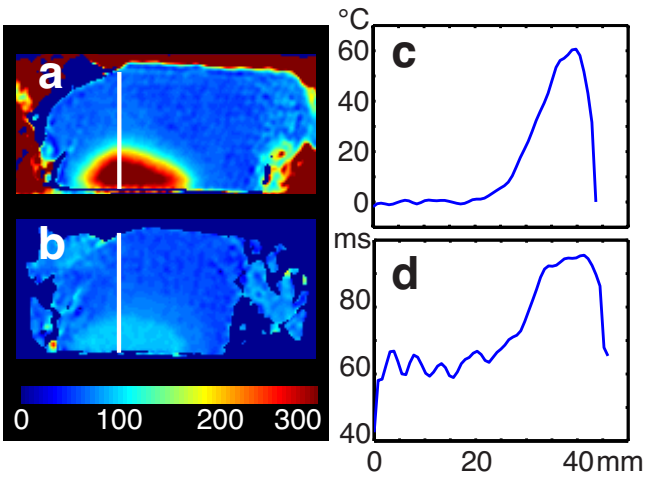

FIGURE 5. T2 maps of sample 2: (a) during heating; (b) after reaching room temperature;
(c) thermal profile of the sample along the line, shown on (a);
(d) T2 profile after reaching room temperature.

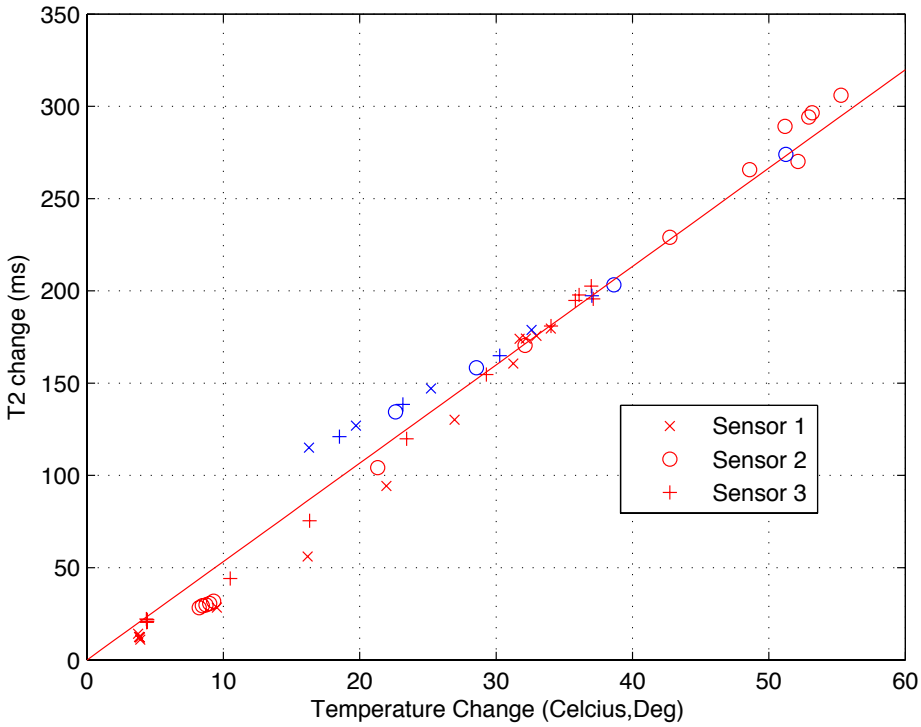

FIGURE 6. Temperature change, measured by 3 probes and T2 change at the same locations during heating (red) and cooling (blue)

CONCLUSIONS

We have shown that T2-based ablation monitoring in the red marrow in trabecular bone is feasible. Our results were consistent with previously published data in marrow and subcutaneous fat. The linear relationship between T2 change and temperature could be used to quantify the temperature during heating of up to 60°C. This would allow to reliably and accurately monitor the temperature inside the trabecular bone during treatment of patients with bone tumors.

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