Simultaneous PRF and T_1-mapping based MR thermometry for monitoring high-intensity focused ultrasound ablation of primary bone tumors

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Target Audience:
The target audience of this work includes researchers and clinicians interested in focused ultrasound therapy, magnetic resonance thermometry, and bone tumor therapy.

Purpose:
Conventional treatments for primary bone tumors suffer from side effects including the invasiveness of surgical removal with bone reconstruction, and the risk of developing secondary malignancy from radiation therapy. Computed tomography guided laser ablation offers a more localized, minimally-invasive treatment, but lacks direct temperature monitoring. Magnetic resonance guided high-intensity focused ultrasound (MR-HIFU) is an effective noninvasive thermotherapy for palliative management of bone metastasis pain. Localized temperature elevations in the muscle surrounding the bone are monitored in near real time using the proton resonance frequency (PRF) shift technique [1]. However, conventional PRF-based MR thermometry is limited to water-based soft tissues, such as muscle, and temperature is not measured in cortical bone and the fat-based yellow bone marrow, limiting the ability to quantify thermal dose in and around bone tumors. We hypothesize that marrow temperature can be measured accurately by quantifying the change in the longitudinal relaxation time (T_1) of the marrow during heating, and that the temperature distribution across the cortical bone can be calculated from the surrounding measured temperatures at the bone-muscle interface and in the bone marrow. This abstract introduces a MATLAB™-based research interface to simultaneously measure temperature in muscle and fat using an established, hybrid PRF-T_1 technique [2,3].

Methods:
A 2 cm thick cross-section of bovine femur (diaphysis region) was coupled with degassed water to the acoustic membrane of a Philips Sonalleve HIFU bed and imaged with a dual-channel FLEX coil in a Philips Achieva 3.0T TX scanner. A T-type thermocouple was placed in the bone marrow, close to the edge of the cortical bone. A custom MATLAB™-based research interface, developed using an open source toolkit for Philips MR scanners known as MatMRI [4], was used for remote acquisition and on-line processing of all thermometry data. The interface is also used to acquire a dual-angle based B_1^+ correction map, which is essential for correcting RF transmit field inhomogeneities when mapping T_1 using the variable flip angle (VFA) method [5]. In addition to dynamically displaying magnitude, phase, a PRF thermal map, a T_1 map and a T_1 thermal map, the interface also plots the standard deviation of both the PRF and T_1 thermal maps. This allows the flip angles to be adjusted during initial calibration to optimize the precision of both thermal maps. The HIFU beam was aimed on the thermocouple and a continuous wave sonication at a transmit frequency of 1.2 MHz was initiated for 20 s with an acoustic power of 120 W to induce coagulative necrosis in the marrow. A fast field echo sequence with two interleaved flip angles was used to acquire both magnitude and phase images of the femur during and after HIFU exposure (FA_1 = 10˚, FA_2 = 55˚, TE = 10 ms, TR = 75 ms, FOV = 200 mm, in-plane voxel size = 2.5 mm, slice thickness = 5 mm, dynamic frame rate = 4.6 s/frame). Since T_1 is determined from magnitude information and PRF is determined from phase information, both temperature maps in this sequence were acquired and processed simultaneously.

Results and Discussion:
PRF and T_1-based temperature maps were calculated and displayed (with an arbitrary temperature scale) with a dynamic scan time of 4.6 s/frame during both sonication and cooling using our custom research interface (Fig. 1). The standard deviation of the PRF and T_1-based thermal maps were approximately 0.5°C and 2°C, respectively. T_1 vs. time was recorded as a time series at a voxel approximately 0.5 cm away from the thermocouple in order to prevent susceptibility artifacts from the thermocouple from confounding T_1 measurement. Thermocouple temperature recording was also synchronized to T_1 measurement. T_1 and thermocouple temperature were plotted as a function of time (Fig. 2), and a positive T_1 temperature dependence in bone marrow of 10 ms/°C was observed during heating. This is higher than the T_1 temperature dependence observed in fatty breast tissue of 4.5 ms/°C [2,3], which could be an artifact of the 0.5 cm distance between the thermocouple and the T_1 measurement voxel. The cooling phase showed a temperature dependence of 4 ms/°C. Overall, the T_1 in the marrow changed from 300 ms before heating, to 400 ms after adequate cooling, indicating that the ablation process caused an irreversible changes in T_1 relaxation due to protein denaturation resulting from the high temperatures reached during treatment [3].

Conclusions:
We have demonstrated that PRF and T_1-mapping based thermometry can by acquired simultaneously and dynamically with frame rates adequate for intraoperative temperature monitoring during MR-HIFU ablation of bone. The positive T_1 temperature dependence in yellow bone marrow of 10 ms/°C during heating and 4 ms/°C during cooling highlights how T_1 can also provide a direct indication of thermal dose since magnetic relaxation time demonstrates a hysteresis effect once the tissue has undergone coagulative necrosis [3]. The simultaneous acquisition of temperature in both the bone marrow and at the bone-muscle interface should provide the necessary boundary conditions to dynamically calculate cortical bone temperature during treatment, improving the safety and efficacy of thermal ablation of primary bone tumors.

References:
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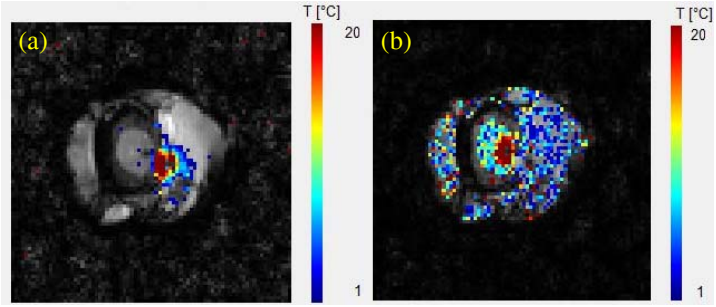

Fig. 1: (a) PRF change in muscle; (b) T_1 change in marrow (arbritary temp. scale)

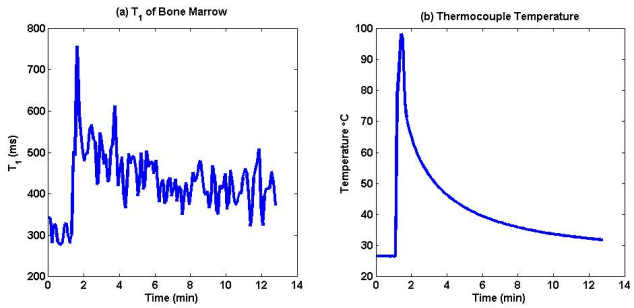

Fig. 2: (a) T_1 of marrow at thermocouple location; (b) Thermocouple temperature