Simultaneous thermometry and T2 mapping, to detect tissue damage during thermal therapies

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Target audience: Clinical researchers involved in MR-guided thermal ablation work.

Purpose: Focused Ultrasound (FUS) Surgery has proved to be an efficient tool in treating a variety of deep-seated tumors(1), and procedures may be performed under MR guidance for improved results. However, there is currently no completely-satisfactory way of detecting tissue damage as it occurs, during treatment, under MR-guidance. The most widely-accepted strategy involves calculating the temperature dose (TD) and selecting a threshold beyond which damage is assumed to have occurred. Although very useful, TD measurements have notable drawbacks: 1) damage is inferred indirectly rather than seen directly in the images, and 2) the entire thermal history of each volume of tissue is needed toward TD calculations. Especially in abdominal organs, capturing the thermal history of any given piece of moving tissue can be a challenge, and errors readily propagate to all future TD measurements. In contrast, tissue damage is believed to be associated with changes in T_2(2) and might prove visible on a frame-by-frame basis if real-time T_2 maps were available. It is shown here that a recently-proposed thermometry sequence with advantageous temperature-to-noise characteristics(3) also has, as a great bonus, the ability to capture T_2 maps in real-time. Our goal is to supplement TD calculations with temporally-resolved T_2 maps to better detect damage as it occurs, especially when motion may make thermal histories and TD unreliable.

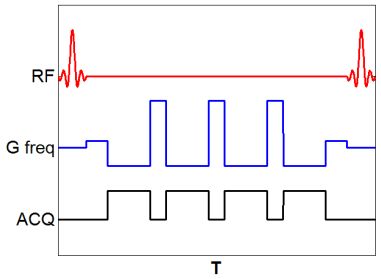

Fig. 1: The present sequence acquires four separate pairs of FISP (S^+) and PSIF (S^-) signals during a TR of about 21 ms. As usual in a DESS-like sequence, the G_{freq} pre-phaser is 1/4th the area of the readout.

Theory: A Siemens FLASH sequence was modified to allow pairs of FISP (S^+) and PSIF (S^-) signals to be acquired every TR(4). Unlike the 'Dual Echo Steady State' (DESS) sequence where only one pair of FISP-PSIF is acquired, the present sequence acquires two or more pairs (see Fig. 1). Four pairs were acquired here, allowing four different TE_{FISP} and TE_{PSIF} values to be sampled. The magnitude of the S^+ and S^- signals is described as:

$$|S^+| \propto \exp\{-TE_{FISP}\times(R_2+R_2')\},$$
$$|S^-| \propto \exp\{-TE_{PSIF}\times(R_2-R_2')\} \times \exp\{-TR\times(R_2+R_2')\},$$

where R_2' and R_2 represent reversible and irreversible decay, respectively, such that $T_2 \equiv 1/R_2$ and $T_2^* \equiv 1/(R_2+R_2')$. Because S^- is evolving toward an echo, reversible decay is in the process of being reversed, and R_2' has a minus sign in $-TE_{PSIF}\times(R_2-R_2')$. In contrast, S^+ is dephasing and R_2' adds to R_2 in $-TE_{FISP}\times(R_2+R_2')$. Because R_2' appears with different signs, it can be discriminated from R_2. The four S^+ and S^- sampled signals lead to six linear equations involving R_2' and R_2, which are quickly solved through matrix algebra.

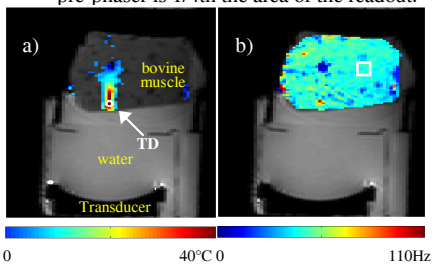

Fig. 2: Temperature (a) and R_2 (b) map for the time frame with peak temperature. See text for details.

Methods: FUS heating experiments were performed on *ex vivo* bovine muscle while running the proposed MRI sequence (Siemens Trio, never-frozen meat sample, 35W for 30s, sagittal plane, 4-channel head coil, 2.6 s per frame, TR=20.6 ms, flip angle=25°, FOV=20×20 cm^2, 64×128, resolution=3.1×1.6×5.0 mm^3, bandwidth=399 Hz/pixel, TE_{FISP}=[3.4; 7.6; 11.8; 15.9] ms, TE_{PSIF}=[4.7; 8.8; 13.0; 17.1] ms). Despite degassing the meat for 3 hours in saline, air bubbles were nevertheless observed in the phantom, and heating targets were carefully selected to avoid blood vessels, fat, and bubbles. While the phase of the acquired S^+ and S^- signals proves very-well suited for PRF temperature measurements(3,5), the magnitude of these signals were utilized to create R_2 maps, as described above. TD calculations were performed, and a TD threshold of 240 CEM43 (cumulative equivalent minutes at 43°C) was used to detect damage. The experiment did not include motion, so that temperature, TD and R_2 data could be compared.

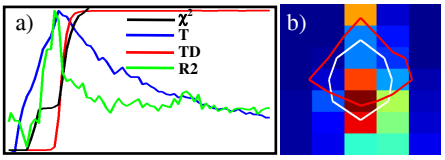

Fig. 3: a) Normalized temperature, TD, R_2 and χ^2 for focus region. b) See text for details.

Results: Temperature and R_2 maps are shown overlaid on a magnitude image in Fig. 2, for the time frame that featured maximum heating. The white circle in Fig. 2a marks the region where TD exceeded the 240 CEM43 damage threshold. The mean R_2 value over the square region in Fig. 2b was 22.8±1.1Hz, for a T_2 value of 44.4±2.5 ms, which is consistent with the 47 ms value expected for muscle. R_2 varied as the FUS beam heated the tissues, and Fig. 3a gives a plot of (normalized) temperature, TD, R_2 and χ^2 for the white-circle region from Fig. 2a, where χ^2 is the chi-square error obtained when trying to linearly map R_2 onto temperature. Figure 3b shows the white-circle damage region from Fig. 2a overlaid onto a map of χ^2, for the same time frame is in Fig. 2, along with a red contour that marks the region where R_2 varied by 75% or more.

Disussion: The main goal of this work is to find R_2-derived parameters that may closely correlate with the 240 CEM43 damage threshold, but which unlike TD would be available on a frame-by-frame basis. Especially in the presence of motion, when accurate thermal histories are difficult to obtain, a frame-by-frame approach would have a clear advantage. For example, one such possible candidate, a threshold set at 75%-change on R_2 compared to its expected value, was shown in Fig. 3b using a red contour. Whether correlations obtained in *ex vivo* tissues would hold *in vivo* remains, of course, an open question. About the χ^2 measurements in Fig. 3, their main value lies in how well they appeared to correlate with dose (Fig. 3a). But the χ^2 measure depends on temperature, and thus is presumably no more motion-robust than TD. It might however prove an interesting supplement to TD, possibly more attuned to heat-related biological changes. The current scan time of 2.6 s per frame could be brought down in various ways, such as implementing a segmented-EPI version of this sequence and/or including parallel imaging.

Conclusion: A dual-pathway steady-state sequence was proposed to simultaneously perform thermometry and T_2 mapping, to better detect tissue damage during thermal ablations procedures.

References: [1] Jolesz et al, JMRI 27:391(2008). [2] Anzai et al, JMRI 1:553(1991). [3] Madore et al, MRM 66:658(2011). [4] Cheng et al. ISMRM 2012:2371. [5] Ishihara et al, MRM 34:814(1995). Support from grants R01CA149342, P41EB015898 and R01EB010195 is acknowledged.