MRI-based Temperature and SAR Mapping With a New Dual-Coil Solenoid/Birdcage Heating/Measurement System

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Introduction: MRI-based temperature mapping techniques have been applied to detect the temperature changes for a variety of applications, including during the thermoablation of tumors, and in verifying minimal temperature increment induced by EEG electrodes and/or its wires during MRI. Temperature changes can be mapped through changes in the MR signal with a variety of methods [1]. The most widely used method is proton resonance frequency shift (PRF) technique [2], which utilizes the proportionality between temperature of the sample and phase of the received signal. Special chemicals, which have very high temperature-dependent chemical shift coefficient (up to 60 times higher than water), can be dissolved in a phantom to improve the sensitivity of phase change to the temperature change [3,4]. Another way to improve the quality of the temperature maps is to heat the sample with higher RF power. Here, we describe the SAR/temperature mapping using a new dual coil solenoid/birdcage heating system with MR thermometry at 3 T. The solenoid heating coil makes easy to control of the RF power. It certainly helps at the development of accurate temperature mapping methods, for assessment of SAR in phantoms and in vivo. It also could allow for SAR evaluations for field strength other than that of the given imaging magnet. To validate the experimental results, we also performed numerical calculations of the dual coil heating system.

Methods: The solenoid coil built for sample heating is shown in Fig. 1a. The diameter, length, and winding distance of the solenoid coil were 130, 140, and 45 mm, respectively. The coil was tuned and matched to 163.5 MHz. The volume and the density of the agar-gel phantom were 0.8 L and 1054 kg/m^3, respectively. The conductivity (σ) and the relative permittivity (ε_r) of the phantom were 1.886 S/m and 77.52, respectively (measured with Agilent 85070D Dielectric Probe Kit connected to an Agilent E4991A RF Impedance/Material Analyzer). Four thermo-optic probes (AccuSens; opSens, Canada) were placed near the surface and around the center of the phantom to measure the temperature changes (Fig. 2a) by applying 50 W of RF power. The RF heating system was consisted of a 200 W RF amplifier (LA200UELP Kalmus; Bothell, WA) and frequency synthesizer (PTS 200; Littleton, MA). The solenoid coil was placed in the center of a transmit/receive head-sized quadrature birdcage coil. The birdcage coil was tuned matched at 125.44 MHz for imaging in a Bruker 3T whole body system. The dual solenoid and the birdcage coils were used for RF-induced heating and MR imaging, respectively. PRF method was used to monitor the temperature change. The first phase map was acquired with a gradient-echo pulse sequence (repetition time = 100 ms, echo time = 10 ms, matrix size = 128×128, field of view = 120×120 mm^2, 10 mm slice thickness, four averages, an axial-slice at the center of the phantom). The scan time for the first phase map was 51 sec. Then 50 W of RF power was delivered to the solenoid coil for 2 min to heat the phantom using the RF heating system. Just after heating, the second phase map was acquired with the same imaging parameters as the first, but with no averages. The scan time was 12 sec for the second phase mapping. By design, the experiment was performed during a brief period of intense heating so that effects of thermal conduction were negligible [5]. After the temperature change map was calculated, the SAR map was estimated using the equation of SAR=$c \times \Delta T / \Delta t$, where c is the heat capacity of the phantom (≈4200 J/kg/°C [6]) and Δt is the period of sample heating (2 min in this case). We modeled the dual solenoid/birdcage coil system using the FDTD method (xFDTD; Remcom, State College, PA) for electromagnetic field calculation (Fig. 1c). The cell size in simulation was 2×2×2 mm^3. The solenoid coil was driven with one current source. SAR map was calculated at the same frequency with the temperature measurements (163.5 MHz). The net input power of this numerical simulation was scaled to 50 W in order to match the experimental condition.

Results and Conclusion: The measured temperature changes for the first 2 min were 0.59, 0.85, 0.71, and 1.63 °C at the positions of thermo-optic probes 1~4, respectively. The corresponding temperature changes, from the MR experimentally acquired temperature map, were 0.47, 0.92, 0.78, and 1.71 °C (see Table 1 and Fig. 2c). The numerically calculated and experimentally estimated SAR maps are compared in Fig. 2b and Fig. 2c. The distribution of each SAR map matched quite well. There was no significant coupling issue or any other interaction between the solenoid and the birdcage coil because of using different resonance frequencies (163.5 and 125.44 MHz). We separately used the solenoid coil for heating and the conventional birdcage coil for imaging of the sample. By using this new dual coil heating system, we can easily control the RF power to heat the phantom, and could possible explore SAR distributions at frequencies other than that of our system. This feature enhanced the accuracy of SAR/temperature mapping due to the improved sensitivity of the phase change to the temperature change. We could match the temperature measurements using thermo-optic sensors and the MR experimentally acquired temperature map with reliable accuracy. The numerical calculation and the MR experiments of SAR have almost identical distributions.

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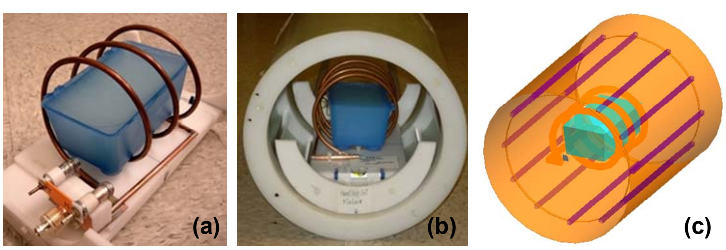

Figure 1. (a) The solenoid coil for heating with the conductive agar-gel phantom loading (b) The solenoid coil and the phantom were placed in the birdcage coil

	P1	P2	P3	P4
Thermo-optic (°C)	0.59	0.85	0.71	1.63
PRF (°C)	0.47	0.92	0.78	1.71

Table 1. Comparisons of temperature measurements using the thermo-optic sensors and PRF method.

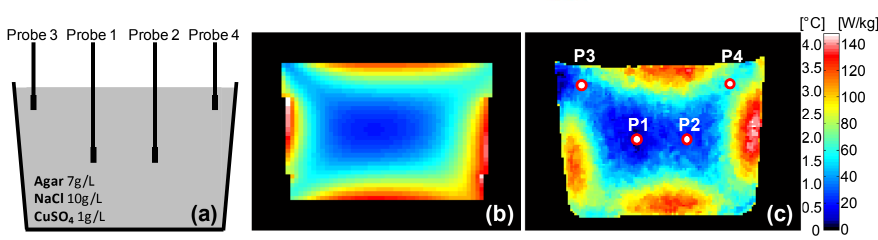

Figure 2. (a) Positions of four thermo-optic sensors (b) SAR map from FDTD calculation at the center slice (b) experimentally acquired temperature map and its corresponding SAR map. The four positions of the thermo-optic sensors were overlaid on the map.