Improving SNR in small temperature change MR Thermometry to acquire SAR Maps of a pair of ASL Labelling Coils

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Introduction

Separate labelling coil continuous arterial spin labelling (CASL) [1] typically utilises a close fitting surface coil coupled with a low power RF amplifier to deliver continuous wave (CW) power to the neck. Despite the low total power (1-2W), local SAR close to the coils can be high, therefore it is desirable to obtain SAR maps to ensure that local SAR limits [2] are not exceeded. Full-wave electromagnetic simulations have become the prevailing method for producing SAR maps. However the software is complex, commercial packages are costly, and it can be difficult to capture the nuances/imperfections of 'home-built' coils. MR Thermal Imaging [3] (MRTI) using the proton resonance shift allows 3D temperature maps to be acquired by taking advantage of the temperature dependence of the magnetisation phase. Presented is an optimised method for acquiring an MRTI time series of heating from a pair of CASL labelling coils using a 3D EPI acquisition and an image processing technique for calculating high SNR SAR maps.

$$a_1 x e^{a_2 x} + a_3 x e^{a_4 x} \quad (1)$$

$$SAR = \frac{c\left(T_{fit}(2) - T_{fit}(1)\right)}{\Delta t} \quad (2)$$

$T_{fit}(1/2)$ temperature at 1st/2nd measurement.
c: voxel specific heat capacity
Δt: time between measurements

Theory: SAR Estimation

Previous studies have assumed that the only contribution to the temperature change within a voxel is from SAR [4, 5], valid only if thermal conduction is negligible between the two measurements (2 minutes [5]), and if the object is at thermal equilibrium when heating commences. The low power level used in separate coil CASL means that only a small temperature rise occurs over this short period, and consequently the measurements suffer from low SNR. To increase SNR it is proposed to make regular MRTI measurements over an extended period of heating, and to then fit the temperature change to equation 1 on a voxel-by-voxel basis. SAR maps can then be calculated from the initial temperature change in the fitted data using equation 2. The fitting function was empirically found to closely match MRTI data in voxels experiencing SAR heating and thermal conduction, and fibre optic thermometer probe data from the same locations.

Method

Imaging was performed on a 3T Siemens Tim Trio (Erlangen, Germany) whole-body scanner, interfaced to a two-channel in-house built transmitter system based around a re-cycled spectrometer (MR5000, Surrey Medical Imaging Systems, Guildford, UK), equipped with 1W nominal RF power amplifiers (ZHL-3A, Mini-Circuits Inc. Brooklyn, NY, USA). Each channel drove an element of an ASL labelling transmit array, comprising of two 45mm inner diameter circular surface coils tuned and matched to 123.2MHz. A whole-body birdcage coil was used to transmit the imaging RF pulses, and a 12 channel receive-only head coil for reception. A 12cm diameter, 20cm long cylindrical gel phantom (2% agar, 1.6% $CuSO_4$, 0.9% NaCl) was positioned within the head coil and three 32mm diameter, 30cm long 1.6% $CuSO_4$ doped distilled water cylindrical reference phantoms were placed equilaterally around the gel phantom. The three reference phantoms were used for first-order B_0 drift correction [6]. Coils were positioned at opposite sides of the phantom. The temperature of each phantom was logged during MRTI measurements using a fibre-optic thermometer (ProSens with PSP-62 Modules and OTP-A Sensors, OpSens, Quebec, Canada). 3D gradient echo EPI volumes of resolution 128×128×48 were acquired every 33.84s with FOV = 210 × 210mm, 2.5mm slice thickness, TE=32.86ms, TR=80ms, and GRAPPA 2× acceleration. The time to acquire one volume was 3840ms. Prior to MRTI measurements this sequence was run for 2.5 hours, establishing a dynamic thermal equilibrium to account for heating of the gradient coils. MRTI measurements consisted of an initial EPI volume acquisition, followed by 99 blocks of transmitting at full power for 30s on the ASL coil array and an EPI volume acquisition, yielding a time-series of 100 phase images. To avoid the saturation of spins, RF heating was applied at 100 kHz higher than the imaging frequency. Data was acquired in five separate scanning sessions: each ASL coil element pulsing individually, and both coil elements pulsing with phase shifts of 0° (Helmholtz), 90° (quadrature) and 180° (Maxwell). Two MRTI datasets were collected in each scan session. After MRTI measurements had been made a turbo spin echo sequence with identical voxel positions to the EPI volumes was run to facilitate precise location of the temperature probe.

Complex phase images were processed by dividing by the first image in the time series, to obtain phase increment images, $\Delta\varphi$. A first-order 2D linear fit generated from the temperature corrected phase of the reference phantoms was subtracted for B0 drift correction. ΔT maps were calculated according to $\Delta T = \Delta\varphi/\alpha\gamma B_0 TE$[3], with $\alpha = -0.0097$ppm, and the time series of each voxel was fit to the equation 1. SAR maps were calculated with the equation 1, where c = 4200J/kg, and divided by the RF duty cycle to obtain SAR maps at 100% duty cycle. In addition maps of the sum of squares residuals between the measured temperature data and the model fit were generated, providing a measure of confidence. Image processing was performed in Matlab (The Mathworks Inc., Natick, MA).

	SAR_{max} (W/kg)
Right Coil	5.51±0.19
Left Coil	7.79±0.69
Helmholtz	8.78±0.38
Quadrature	7.73±0.20
Maxwell	7.89±0.78

Table 1: Peak SAR

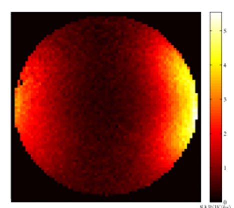

Fig 1: Quadrature SAR Map

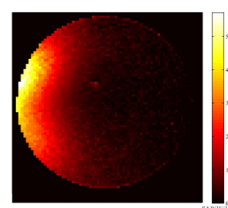

Fig 2: Left Coil SAR Map

Results

Figures 1 and 2 show SAR maps at the centre of the ASL coil array, obtained from the quadrature configuration and the left hand coil only, respectively. Figure 3 is a histogram of the SAR all of the voxels within the imaging volume with a sum of squares error less than 2. The y axis is logarithmic (base 10). Figure 4 is a plot of the temperature measured by the thermometer probe (blue) and in two regions of interest (ROI) positioned at the probe location (orange), and close to a transmitting coil (black). Thicker lines represent the fitted functions, thin lines the actual data. Figures 3 and 4 are from the quadrature configuration. Table 1 displays the peak SAR in each SAR histogram.

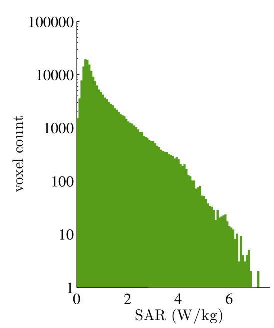

Fig 3: Quadrature SAR Histogram

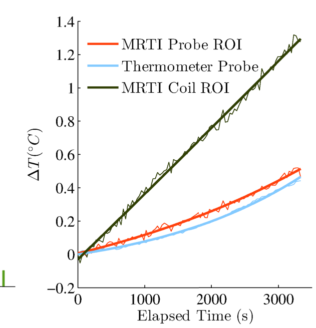

Fig 4: Quadrature ΔT Plot

Discussion and Conclusion

Thermometer probe and MRTI measurements show good agreement with each other, indicating that the temperature compensated B_0 correction produces accurate temperature measurements. The fitted functions closely match the data in both ROIs. SAR maps show a similar spatial distribution; high local SAR close to the coils. The quadrature, Maxwell and Helmholtz maps match well with superpositions of the individual coil SAR maps. Similar SAR distributions between all configurations are also seen in the SAR histograms. The peak SAR in table 1 show good agreement, and the highest measured SAR; 8.78±0.38W/kg for the Helmholtz configuration is within the 10W/kg local SAR limit set by the IEC[2]. To conclude, presented is a method for measuring the SAR of a transmitter RF coil, by acquiring a time series of EPI phase images and fitting the data to improve the SNR of the initial measurements, from which the SAR is calculated. MRTI measurements were validated against a fibre optic thermometer, and calculated SAR maps show consistency throughout a range of measurements. Further work will be to validate the SAR maps against full wave electromagnetic simulations.

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