Volumetric Local SAR Mapping for Parallel Transmission

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Introduction: In this study, a custom pulse sequence was implemented to streamline volumetric local SAR mapping in parallel transmit systems. This sequence combines MR thermometry and RF heating to determine the local electric field covariance matrix \( \Lambda_r \) as well as allowing the prediction of true local SAR for any transmit pulse weighting. The developed pulse sequence integrated the following processes required for local SAR mapping: 1) pre-heating GRE phase map acquisition, 2) RF heating period, 3) post-heating GRE phase map acquisition, 4) delay time to allow cooling. The sequence reduces manual intervention required to assess local SAR, which can be especially tedious for many-element transmit arrays since the number of required measurements is equal to the square of the number of coils.

Theory and Methods: In this work, local SAR induced by a three-channel transmit coil was mapped in an agar gel phantom (Figure 1) using an automated pulse sequence and post-processing. All measurements were performed on a 7T scanner (Siemens Medical Solutions, Erlangen, Germany) equipped with an 8-channel parallel transmit system. The local RF power deposition following a parallel excitation with multiple transmit coils is given by (1,2)

\[
\text{SAR}(r) = \left[ \mathbf{w}_1 \ldots \mathbf{w}_3 \right] \left[ \mathbf{H} \mathbf{e}_r \mathbf{H}^T \right]^{-1} \left[ \mathbf{H} \mathbf{e}_r \mathbf{H}^T \right]^{-1} \mathbf{w}_i \mathbf{A}_r \mathbf{w}^T
\]

where \( \Lambda_r \) is the electric field covariance matrix, \( \sigma \) is the conductivity of the sample, \( p \) is the density of the sample, \( e_i \) is the unit electric field generated by the \( i \)-th coil, \( w_i \) is the complex transmit current weight, \( r \) is position, and \( H \) represents the complex-conjugate transpose. To map local SAR for the three-element transmit array, \( \Lambda_r \) must be determined using 3 calibration steps, wherein a high duty cycle RF heating pulse is applied with various weightings as shown in table 2. Three additional steps with random transmit weightings were included to test the predictive capability of the model. The weightings were defined in an external file and incorporated into the sequence before runtime. To produce measurable RF heating for this gel phantom, a high amplitude 4 ms rectangular RF pulse was applied at 25% duty cycle for 480 seconds. Gradient pulses were not applied during this period to eliminate possible gradient-induced phase drift. Before and after each RF heating cycle, temperature difference maps were acquired using the proton resonance frequency shift (PRF) method (4). Assuming that heating occurs over a short period, heat diffusion is insignificant (4) and thus \( \Delta \Phi(r) = \text{constant} \times \text{SAR}(r) \). The temperature maps were calculated using (4)

\[
\Delta \Phi(r) = \frac{\Delta \Phi(r)}{\alpha \cdot T \cdot E \cdot \omega}
\]

difference in unwrapped phase between 2D spoiled GRE images acquired before and after the RF heating period, \( \alpha = 0.01 \text{ppm/°C} \) is the PRF change coefficient, \( T = 7 \text{ ms} \), and \( \omega \) is the larmor frequency. One transverse slice was acquired with the following parameters: TR = 60 ms, slice thickness = 8 mm, and matrix size = 128x128. Between any two experiments no imaging or RF was played out for 9.6 minutes, to allow the phantom and coils to cool off.

In summary, the developed pulse sequence integrated GRE phase mapping and RF heating to map local SAR. For the three-element transmit coil array investigated here, phase difference mapping and RF heating were repeated 9 times with predefined transmit weightings to measure \( \Lambda_r \) plus three additional cycles with random transmit weightings to compare the expected temperature change to that measured using PRF.

Results: Temperature difference maps for each calibration step for one slice location are shown in Figure 2. The three randomly weighted experimental results are presented in figure 3. For each of the random experiments, 3 slices of measured and predicted temperature-difference maps are presented.

Conclusion: A streamlined pulse sequence for parallel transmit local SAR mapping in a non-perfused phantom was presented. Based on this automated calibration process, we are able to predict temperature maps that are proportional to local SAR. After the \( \Lambda_r \) matrices are defined for a specific configuration, local SAR maps for any pulse shape can be obtained. Future work will include increasing calibration speed, and utilization of the sequence for parallel transmit coil efficiency evaluation.