B1-based local SAR estimation for a parallel transmit system at 3T: A simulation study

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INTRODUCTION: To ensure patient safety during multi-transmission experiments, special attention must be paid to proper determination of the specific absorption rate, SAR. The standard approach, electromagnetic field simulations, requires accurate information about the transmit array and the patient. Another approach for SAR estimation is the post-processing of measured B1maps that has been demonstrated for the application of circular polarized fields during the transmit and receive process for birdcage-type coils [1,2] and for a multi-transmit array in combination with RF-shimming [3]. The major challenge of the latter method is the estimation of unknown magnetic field components and an additional phase distribution that results from the receive process and is inherent to every measurement. This work extends the method to make it applicable for a parallel transmit system at 3T. In particular, it addresses the correction for the influence of the receive phase, φ_{RX}.

THEORY & METHODS: The coupling of time-harmonic electric and magnetic fields produced by the transmit coil is described by Maxwell's equations. With known magnetic field H, conductivity σ and permittivity ε, the electric field E can be calculated via Ampere's law (Eq.1). In a rotating frame reference system with the static magnetic field B_0 pointing in positive z direction H consists of the components $H^+=0.5(H_x-iH_y)$, $H^-=0.5(H_x+iH_y)$ and H_z where only H^+ can directly be measured by MRI with currently available methods. However, for transmit arrays fulfilling the conditions $\partial H_z/\partial i\approx 0$ for all spatial directions $i=x,y,z$ and $E_z>>E_x,E_y$ for SAR relevant regions Eq.1 can be solved for E by replacing $H_x=2H^+$ and $H_y=2iH^+$. These expressions can be derived by separating the impact of H^+ and H^- on E_z in Eq.1. The modulation of H^+ by φ_{RX} (Eq.5, Eq.6) results in a spatially dependent error in the estimation of E that can be corrected for if a good estimation for the spatial variation of φ_{RX}, $\partial\varphi_{RX}/\partial i$ can be found (Eq.4).

$$\underline{\vec{E}} = \frac{\vec{\nabla}\times\underline{\vec{H}}}{\sigma+i\omega\varepsilon\varepsilon_0} \quad (1) \qquad \mathrm{SAR} = \frac{\sigma}{2\rho}\left|\underline{\vec{E}}\right|^2 \quad (2)$$

$$\underline{\tilde{H}}_x = 2\underline{\tilde{H}}^+ \;(3a) \qquad \underline{\tilde{H}}_y = 2i\underline{\tilde{H}}^+ \;(3b) \qquad \partial_i \underline{\tilde{H}}_z \approx 0 \;(3c)$$

"~" indicates φ_{RX} modulated quanitities or quantities derived from those

$$\underline{\vec{E}}\cdot e^{i\varphi_{RX}} = \begin{pmatrix}\underline{\tilde{E}}_x\\ \underline{\tilde{E}}_y\\ \underline{\tilde{E}}_z\end{pmatrix} - \mathrm{const}\cdot\begin{pmatrix}2\underline{\tilde{H}}^+\partial_z\varphi_{RX}\\ 2i\underline{\tilde{H}}^+\partial_z\varphi_{RX}\\ 2\underline{\tilde{H}}^+(\partial_x\varphi_{RX}+i\partial_y\varphi_{RX})\end{pmatrix} \quad (4)$$

$$\underline{\tilde{H}}^+(n) = \left|\underline{H}^+(n)\right|\exp\left(i\cdot\left(\varphi_{TX}(n)+\varphi_{RX}\right)\right) \quad (5)$$

$$\varphi_{RX} = \sphericalangle\left(\sum_{n=1}^{8}\underline{w}_n\cdot\underline{H}^-(n)\right) \quad (6)$$

For optimum symmetry conditions:

$$\frac{\partial}{\partial i}\left[\sphericalangle\left(\sum_{n=1}^{8}\underline{w}_n\cdot\underline{H}^-\right)\right]\approx\frac{\partial\langle\varphi_{RX}(n)\rangle}{\partial i}\approx\frac{\partial\langle\varphi_{TX}(n)\rangle}{\partial i} \quad (7a)$$

$$\frac{\partial\langle\varphi\rangle}{\partial i} = \frac{\partial\left(\frac{1}{8}\sum_{n=1}^{8}\varphi_{TX}^n+\varphi_{RX}\right)}{\partial i}\approx 2\cdot\frac{\partial\varphi_{RX}}{\partial i} \quad (7b)$$

Each of the n B1maps measurable with the n channel transmit system contains a channel-dependent transmit phase $\varphi_{TX}(n)$ and an unknown but fixed receive phase φ_{RX}. Averaging the phases of the n maps leads to the expression given in brackets in the numerator of Eq.7b. Assuming that the system consisting of transmit and receive array and the object exhibits $n/2$ symmetry axes within the transversal plane regarding the different sources of excitation and the produced fields, and that the same applies to the receive field defined by the weighted complex sum in Eq.6, then φ_{RX} at each point located on one of the symmetry axes matches the average phase of the n individual receive channels, $\langle\varphi_{RX}(n)\rangle$, and the latter one again matches the average of the n individual transmit channels, $\langle\varphi_{TX}(n)\rangle$ (Eq.7a). Potential global phase differences cancel out during the differentiation process in the next step. For this symmetric case $\partial\varphi_{RX}/\partial i$ can be determined by dividing $\partial\langle\varphi\rangle/\partial i$ by a factor of 2 (Eq.7b), which is of the same origin as the findings in [1] and [2]. The assumptions on symmetry, however, in general do not hold true for realistic coil-object configurations.

Therefore the sensitivity of this method regarding reduced object symmetry was investigated. For this purpose two electromagnetic field simulations were performed: 1. Simulation [4] of an 8-channel transmit array loaded with a cylindrical phantom (diameter: 20cm, σ=0.5S/m, ε=60) and 2. Simulation [5] of the same array loaded with a human whole body phantom [6].

H^+ and H^- were calculated from simulated magnetic field data and H^+ was modulated by φ_{RX}. For reception the 8 receive fields $H^-(n)$ were combined in quadrature mode.

For local SAR estimation from modulated H^+ a homogeneous tissue was assumed (cylinder: σ=0.5S/m, ε=60, human: σ=0.7S/m, ε=60).

Concerning the correction for φ_{RX} in Eq.4 the following situations were considered: i) disregarding the modulation by φ_{RX}, ii) correcting for it by the actual distribution $\partial\varphi_{RX}/\partial i$, iii) assuming optimum object symmetry and applying $\partial\varphi_{RX}/\partial i\approx(\partial\langle\varphi\rangle/\partial i)/2$ according to Eq.7b and iv) applying $\partial\varphi_{RX}/\partial i\approx(\partial\langle\varphi\rangle/\partial i)/k$ with k between 1 and 3 but $k\neq 2$.

RESULTS & DISCUSSION: Knowing the exact spatial phase variation $\partial\varphi_{RX}/\partial i$ yields a good correlation of the SAR distribution and good agreement in slice averaged SAR for both the human and the cylindrical phantom (Tab.1). Instead ii) disregarding the modulation by φ_{RX} results in a very strong increase in slice averaged SAR whereas the correlation still remains relatively good. The results of the correction iii) and iv) via $\partial\varphi_{RX}/\partial i\approx(\partial\langle\varphi\rangle/\partial i)/k$ are depicted in Fig.1 and 2. For the cylindrical phantom, which approximately fulfils the described symmetry conditions, the best correlation and the best averaged SAR is found for $k=1.8$. Correlation of local SAR and slice averaged SAR almost perfectly match the results obtained by i) knowing the exact $\partial\varphi_{RX}/\partial i$. For the human whole body phantom the estimations yield less good results. In addition to the reduced object symmetry, the SAR estimation is further affected by the assumption of a homogeneous tissue distribution leading to limited tissue dependent over- or underestimation of the local SAR as explained in [7]. No clearly defined optimum for k can be found, however, chosing $k=2$ is expected to yield still sufficiently good results to be considered for SAR management in parallel transmission experiments.

Tab.1		Cylinder	Human
exact $\partial\varphi_{RX}/\partial i$	Correlation	0.86±0.06	0.87±0.04
	Av.SAR (rel.)	0.99±0.02	1.11±0.04
negl. φ_{RX}	Correlation	0.67±0.02	0.81±0.06
	Av.SAR (rel.)	2.47±0.02	3.31±0.57

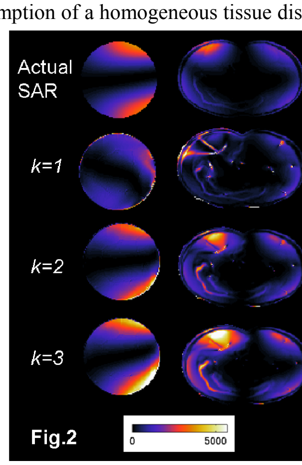

Fig.2
SAR distribution reconstructed from modulated H^+ via averaging of phase distributions for different settings of k.

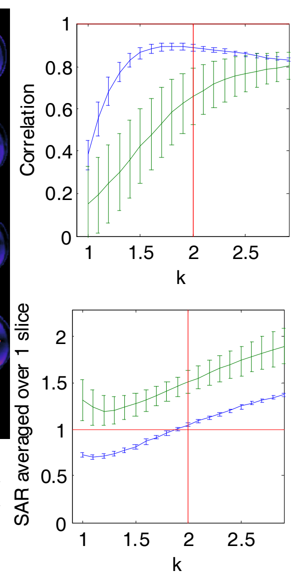

Fig.1
top: Spatial correlation of actual and estimated local SAR as a function of k.
bottom: ratio of actual and estimated local SAR each averaged over one slice as a function of k.

Blue: cylindrical phantom; green: human whole body phantom; red: expected results for optimal symmetry conditions.

From the results of the 8 different transmit channels mean and standard deviation were determined.

CONCLUSION&OUTLOOK: It has been demonstrated that using the described method the local SAR can be well estimated if certain conditions on the multi-transmit array and the object are fulfilled. This finding has to be validated in experiments.

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