Reduction of worst-case local SAR with constraints on RF shimming parameters based on principal component analysis

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Target Audience: Researchers and engineers who have interest in RF transmit technology and SAR safety in high field MRI.

Introduction The inhomogeneity of transmitted RF field (B_1) and high local SAR are major problems in high field MRI. To improve the homogeneity of B_1, RF shimming is used in clinical scanners[1, 2]. The parameters of RF shimming also affect the local SAR as well as the homogeneity of B_1. Although some methods to experimentally estimate the local SAR have been proposed[3, 4], numerical simulation to check the local SAR in all possible combinations of RF shimming parameters is important because the estimation does not have enough accuracy yet. As the number of RF transmission channels increases to obtain better homogeneity of B_1, the number of all possible combinations of RF shimming parameters increases, and thus, the peak local SAR may increase if an inappropriate combination of RF shimming parameters is chosen. Therefore it is worth excluding the combinations of RF shimming parameters with high local SAR by applying some constraints on the possible combination of RF shimming parameters. In this study, we applied principal component analysis to determine constraints on relation between RF shimming parameters based on volunteer study. Exclusion of high local SAR combinations of RF shimming parameters without degrading the homogeneity of B_1 was demonstrated by applying the determined constraints to numerical simulation.

Materials and Methods

Derivation of Constraints A 3T whole body MRI scanner equipped 4-channel RF transmit/receive coil[5] was used to measure B_1 maps of 20 healthy adult volunteers' head. B_1 maps for each transmission channel were acquired by multi Td method[6, 7]. The value of B_1 inhomogeneity (U_{sd}) was defined as $U_{sd} \equiv \sigma/\overline{B_1}$, where σ is the standard deviation of B_1 map and $\overline{B_1}$ is mean value of B_1 map. RF shimming parameters were calculated as minimizing the object function *f* described in equation (1).

$$f = \sqrt{(\mathrm{Usd/Usd\_QD})^2 + (\mathrm{WBSAR/WBSAR\_QD})^2} \quad (1)$$

Where WBSAR means whole body SAR and QD means quadrature drive mode.

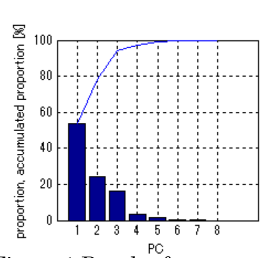

Figure 1 Result of principal component analysis

Principal component analysis was applied to these 20 combinations of RF shimming parameters (amplitude and phase of RF output for each channel, and each parameter was represented by a complex number C_i i=1 to 4). Principal components (PC_i i=1 to 8) were represented as linear combination of RF shimming parameters as equation (2), and the new constraint was derived as equation (3)

$$PC_i = \left[\left(\mathrm{Re}(C_1),\ \mathrm{Im}(C_1),\ \mathrm{Re}(C_2),\ \mathrm{Im}(C_2),\ \mathrm{Re}(C_3),\ \mathrm{Im}(C_3),\ \mathrm{Re}(C_4),\ \mathrm{Im}(C_4)\right) - \overline{x}\right]_k A_{ki} \quad i, k = 1,2,\ldots 8 \quad (2)$$

Where $\overline{x}$ represents average of 20 volunteers' RF shimming parameters, and A_{ki} is mixing matrix that diagonalize the covariance matrix.

$$\text{constraint}: -5\sigma_i \le PC_i \le 5\sigma_i \quad \text{where } \sigma_i: \text{standard deviation of } PC_i \quad (3)$$

Too severe constraint will cause degradation of effect of RF shimming, ±5σ was used as constraints and sufficient degree of freedom of RF shimming parameters was kept.

Local SAR evaluation 10 g averaged local SARs in four human models were calculated by using an electromagnetic field simulator (CST MicroWaveStudio ™), and the peak local SAR in the human model was evaluated. Height and weight of the four human models are as below, Fats: 182 cm, 120 kg, Hugo: 180 cm, 90.3 kg, Hanako[8]: 160 cm, 53 kg, and Roberta: 109 cm, 17.8 kg. The landmark position was set at the head of the human models. The calculated ranges of RF shimming parameters were -4 to 4 dB and -40° to 40° shifted from the RF shimming parameter of QD mode, respectively. The calculation steps of the amplitude and phase were 2 dB and 20° for all channels, respectively. The $\overline{B_1}$ in axial planes at z=0 and ±100 mm, where z=0 correspond the center of magnet, in QD mode was normalized to 1 μT. And maximum local SAR and U_{sd} were compared with and without the constraint (3).

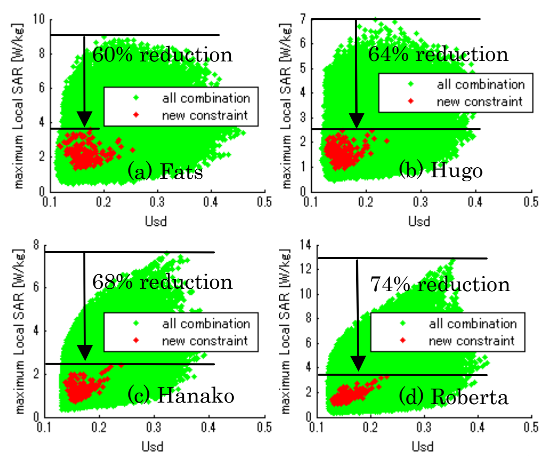

Figure 2 Relation between Usd and max (local SAR)

Results and Discussions The result of principal component analysis for 20 volunteers was shown in Figure 1. In Figure 1, Proportion and accumulated proportion of PCs are shown. The accumulated proportion of PC_3 was 94.3%, and almost all variance of 20 volunteers' RF shimming parameters were accounted by PC_1, PC_2, and PC_3. Figure 2 shows the relationship between U_{sd} and peak local SAR for all possible RF shimming parameters in the four human models. The red points representing the case with new constraints exhibited smaller U_{sd} and lower peak local SAR for all human models. These results suggest that the new constraints eliminate combinations of RF shimming parameters showing higher peak local SAR. The maximum peak local SAR was decreased 60 % or more for all models. The maximum peak local SAR means the worst-case value of local SAR in the all possible RF shimming parameters. Table 1 shows the maximum peak local SAR and the minimum U_{sd} in the all possible region of the RF shimming parameters without and with new constraints. The difference of the minimum U_{sd} between with and without constraints was small. So the effect of improving B_1 homogeneity by RF shimming can be achieved by using new constraints and the value of the local SAR in the worst-case combination of RF shimming parameters can be limited simultaneously.

Table 1 Maximum peak local SAR and minimum value of U_{sd}

	Fats		Hugo		Hanako		Roberta	
	Max. peak local SAR (W/kg)	Min. U_{sd}	Max. peak local SAR (W/kg)	Min. U_{sd}	Max. peak local SAR (W/kg)	Min. U_{sd}	Max. peak local SAR(W/kg)	Min. U_{sd}
w/o constraint	8.9	0.112	7.0	0.120	7.6	0.132	12.7	0.121
w/ constraint	3.6	0.118	2.5	0.127	2.4	0.139	3.3	0.130

Conclusions It was shown that the new constraint on RF shimming parameters based on principal component analysis can eliminate RF shimming parameters showing high local SAR without degradation of B_1 homogeneity.

References [1] Nistler J et al, ISMRM 2007; 15: 1063. [2] Hajnal JV et al, ISMRM 2008; 16 : 496. [3] Katscher, U. et al, IEEE TMI 2009, 28(9): 1365-1374. [4] Zhang et al, ISMRM 2013; 21: 288. [5] Soutome Y et al, ISMRM 2013; 21: 2750. [6, 7] Ito K et al. ISMRM 2013; 21: 2598, 2599, [8] Nagaoka T. et al. Phys Med BIol, 2004, 49: 1-15.