# RF shimming with regularization of maximum and mean RF power

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***Introduction***: RF shimming is a well-known technique, where amplitudes and phases of a transmit RF coil array are optimized to obtain a homogeneous B1 profile, i.e., compensating wave propagation effects at main fields of 3T or above (see, e.g., [1]). However, the targeted B1 homogeneity has to be counterbalanced by the corresponding RF power required. This trade-off can be described by "regularized" RF shimming (see, e.g., [2]) minimizing the mean forward RF power. This procedure frequently results in heterogeneous power distributions over the different transmit channels, which is disadvantageous for multi-channel RF amplifier design. To achieve comparable power requirements for all transmit (TX) channels, this study investigates "double-regularized" RF shimming, minimizing the mean as well as the maximum RF power. The approach was tested in abdominal applications for a whole-body, 8-channel TX/RX system operating at 3T [3,4].

***Theory***: The TX sensitivities $\underline{B}_{1n}$ of the $N$ TX channels ($n = 1...N$) are superposed to $\underline{B}_{1tot}$ using the complex shim coefficients $\underline{A}_n = a_n \exp(i\varphi_n)$, i.e., amplitudes $a_n$ and phases $\varphi_n$ (Eq. (1)). To determine the optimum $\underline{A}_n$, a cost function $\delta$ to be minimized was defined via Eq. (2). The first term of $\delta$ optimizes the homogeneity of $\underline{B}_{1tot}$ via minimizing its Coefficient of Variation (CoV). The second term of $\delta$ minimizes the average forward RF power $P_{mean}$, the third term the maximum forward RF power $P_{max}$ (average and maximum over TX channels). The second and third term are normalized to the mean of $\underline{B}_{1tot}$ and weighted with the (freely adjustable) regularization parameters $\alpha$ and $\beta$.

$$\underline{B}_{1tot}(\mathbf{x}) = \sum_{n\leq N} \underline{A}_n \underline{B}_{1n}(\mathbf{x}) \qquad (1)$$

$$\delta = \mathrm{CoV}^2 + \frac{\alpha}{N\overline{B}_{1tot}^2} \sum_{n\leq N} a_n^2 + \frac{\beta}{\overline{B}_{1tot}^2} \max_{n\leq N}\left(a_n^2\right) \qquad (2)$$

***Methods***: An Achieva 3T MR system (Philips Healthcare, The Netherlands) equipped with an $N = 8$ element TX/RX body coil and corresponding RF channels [3,4] was used. The TX sensitivities $\underline{B}_{1n}$ of 5 healthy volunteers were acquired in the pelvic area using an inverted version of "Actual Flip angle Imaging" [5,6] (TR1/TR2/TE=40/200/3.5 ms, $\alpha$ = 70°, voxel size 8.7×8.7×10 mm$^3$). The sensitivities have been smoothed using a Gaussian filter. Optimal shim coefficients $\underline{A}_n$ were determined by minimizing Eq. (2) iteratively via a combination of a global and local minimization algorithm [2] for all suitable values of $\alpha$ and $\beta$.

***Results***: Choosing $\alpha > 0$, $\beta = 0$ yields the well-known L-curve balancing $P_{mean}$ and CoV (Fig. 1). However, this method typically results in $P_{max} \approx 3\ P_{mean}$. On the other hand, using $\alpha = 0$, $\beta > 0$, the case $P_{max} \approx P_{mean}$ can be obtained without significant increase of CoV. Simultaneously, this reduction of $P_{max}$ leads to a small increase of $P_{mean}$ (Fig. 1). The resulting $P_{max}$ and $P_{mean}$ for $\alpha > 0$, $\beta > 0$ are located between the two cases discussed above. Example results for corresponding B1 maps are shown in Fig. 2. Similar results have been found for the other volunteers.

***Discussion & Conclusion***: Regularization of $P_{max}$ seems to be more effective than regularization of $P_{mean}$ due to the intrinsic limitation of $P_{mean}$ performed automatically while limiting $P_{max}$. On the other hand, a purely phase-based RF shimming via enforcing $P_{max} = P_{mean}$ (i.e., $a_n = a_m$ for all $n$, $m$) cannot be recommended due to significant residual B1 inhomogeneities observed for these cases. Thus, the regularization of $P_{max}$ appears to be advantageous for the specification of multi-channel RF amplifiers because it allows utilizing the available dynamic of all amplifiers more appropriately. This is cost effective for RF shimming as well as for other applications of parallel transmission.

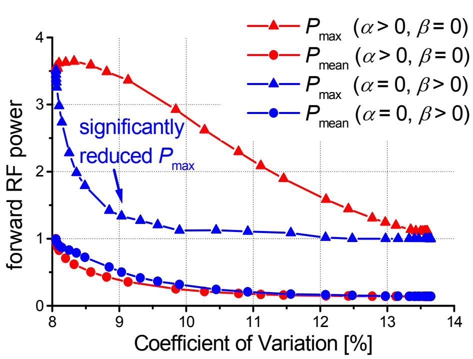


Fig. 1: Red data: $P_{max}$ (triangles) and $P_{mean}$ (circles) for standard regularization of $P_{mean}$. Blue data: $P_{max}$ (triangles) and $P_{mean}$ (circles) for suggested regularization of $P_{max}$. $P_{mean}$ is normalized to $\alpha = \beta = 0$ and $P_{max}$ to corresponding $P_{mean}$.

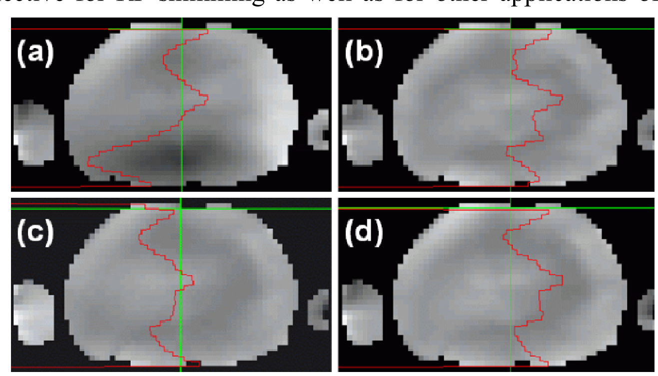


Fig. 2: Transverse abdominal B1 maps. (a) Quadrature excitation. (b) Optimal B1 homogeneity $\alpha = \beta = 0$ (CoV = 8%). (c) Regularizing $P_{mean}$ for CoV = 9% yields $P_{max}$ / $P_{mean}$ = 3.4. (d) Regularizing $P_{max}$ for CoV = 9% yields $P_{max}$ / $P_{mean}$ = 1.2, i.e., acceptable power scenario as well as sufficient B1 homogeneity.

***References:***

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