URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

MRI Shimming via Field Intensity Shaping

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Abstract

The high frequency of the radiofrequency (RF) fields used in high field magnetic resonance imaging (MRI) causes electromagnetic field variations which increase the specific absorption rate (SAR) local level and also imaging artifacts degrading the quality of MRI images. For this reason, different approaches have been proposed in literature, which aim at simultaneously improving the B_1^+ homogeneity and reduce the SAR level in the body. However, most of them do not involve the determination of the complex excitation currents pertaining to the RF coil of MRI systems. In this contribution, starting from a recently introduced field intensity shaping technique, we propose a novel procedure for B_1^+ shimming which is also able to control the purity of polarization of the total RF field as well as to limit the SAR level within the biological tissues. This procedure is based on convex optimization and is assessed in the following in case of brain imaging.

1 Introduction

The main need of diagnostic imaging systems is to obtain high resolution and excellent quality images. This optimal result can be achieved in different ways, depending on the imaging technique at hand [1]. Clinical magnetic resonance imaging (MRI) at medium and high field strength is widely used today because of it has several advantages over the old 1.5T MRI, such as increasing SNR, which implies qualitatively improved images. On the other hand, the most worrying consequence is that the high intensity of the static field B_0 also causes undesired electromagnetic RF field variations and, hence, increases the levels and occurrence of imaging artifacts [2].

Thus, an essential parameter that influences the quality and resolution of MRI images is the homogeneity of the amplitude of the RF Field B_1^+. Because of the non-homogeneity of the scenario and of the several constraints at hand, the field usually obtained is far from the being homogeneous. This is especially the case for high and ultra-high static fields (B_0 >7T), with the consequent increase of the Larmor frequency [3].

In this scenario, the issue of levelling or *shimming* the B_1 field has received considerable importance [3],[4]-[8]. There are two macro categories of shimming techniques: passive shimming and active shimming. The first one commonly uses additional materials as shims, such as iron pieces or high-permittivity, low-conductivity materials. Indeed, High-permittivity materials (HPMs) placed between RF coils and the subject have been proposed as a method to vary the spatial distribution of the B1 field, improve field homogeneity and, also, enhance SNR in targeted regions [4],[7],[8]. The use of HPMs in combination with RF coils has also been shown to reduce overall required input RF power in transmission and improve coil sensitivity at a variety of field strengths in reception, both in experiments and numerical simulations [4].

On the other side, the active shimming uses small coils, also known as shim-coils. However, many shim-coils are necessary to obtain an accurate shimming with an increased magnet cost. In the active shimming techniques, the B_1^+ inhomogeneity can be addressed by using transmit arrays and applying RF shimming or parallel transmission techniques [2],[5]. These techniques can be optimized to also reduce global Specific Absorption Rate (SAR), since constructive interferences between the electric fields from multiple transmit coils can result in amplifications of local SAR difficult to predict., and also and polarization purity [3].

In this contribution, a new active shimming procedure is introduced by relying on a completely different perspective. In particular, the proposed procedure hinges on field intensity shaping paradigm, so far exploited in several applications, such as microwaves hyperthermia treatment [9]. More in details, by tacking advantage from the procedures in [3],[10],[11], a new approach to field intensity shaping is set up for B_1^+ shimming, which exploits different control points located in the region of interest (ROI) and is able to take contemporaneously into account all constraints regarding polarization, strength of the B_1 Field and SAR levels. The convexity of the proposed procedure ensures to achieve the global minimum of the problem and, hence, an accurate, repeatable, and optimal solution of the shimming problem.

2 The proposed method

Let us assume known the electromagnetic properties ε, σ, i.e. the relative permittivity and conductivity, respectively, and the geometrical characteristics of the under testing scenario. Moreover, let us consider a given birdcage coil composed of N conductors each excited with different currents I_n (with $n = 1,...,N$).

In such a context, the overall electromagnetic fields, $\underline{B}_1(\underline{r})$ and $\underline{E}(\underline{r})$, induced in the biological scenario under investigation and evaluated in a generic point can be expressed as:

$$\underline{B}_1(\underline{r}, I_n) = \sum_1^N I_n \, \underline{b}_n(\underline{r})$$

(1)

$$\underline{E}(\underline{r}, I_n) = \sum_1^N I_n \, \underline{e}_n(\underline{r})$$

(2)

where $\underline{B}_1(\underline{r}) = B_1^{\ +}(\underline{r})\hat{p}_1^+ + B_1^{\ -}(\underline{r})\hat{p}_1^-$, $\hat{p}_1^+$ and $\hat{p}_1^-$ are the unit polarization vectors, $B_1^{\ +}$ and $B_1^{\ -}$ are its left-hand (LH) and right-hand (RH) circular polarizations. Finally, $\underline{b}_n(\underline{r})$ e $\underline{e}_n(\underline{r})$ are the total fields induced in $\underline{r} \in$ ROI by each unitary excited n-th conductor composing the coil.

During transmission the LH circular polarization of the RF field, $B_1^{\ +}(\underline{r})$ is of interest. Then, the goal of the problem at hand is to *"determine the optimal set of complex excitations coefficients I_n such to produce the desired homogeneous $B_1^{\ +}$ field, while ensuring polarization purity and SAR limits".* From a mathematical point of view, by exploiting the rationale in [3],[10],[11], the proposed shimming procedure formulates the problem as follows:

$$\max_{I_n} \left|B_1^{\ +}(\underline{r}_{t_0})\right|^2$$

(3)

subject to:

$$\left|B_1^{\ +}(\underline{r}_{t_0})\right| = \left|B_1^{\ +}(\underline{r}_{t_i})\right| \quad with\ i = 1, \dots, L$$

(4.a)

$$SAR \leq 3.2\ W/kg$$

(4.b)

$$\left|B_1^{\ -}(\underline{r})\right|^2 \leq \frac{1}{2}\left|B_1^{\ +i}(\underline{r})\right|^2$$

(4.c)

$$B_1^{\ +}(\underline{r}_{t_0}) \geq B_{1\,des}^{\ +}$$

(4.d)

wherein $\underline{r}_{t_0}$ is a given point in the ROI which is assumed as reference point, while r_{t_i}(i = 1,…,L) are a number of controls points belonging to the ROI, $B_1^{\ +i}(\underline{r})$ is the initial spatial distribution of $B_1^{\ +}(\underline{r})$. Eq. (4.a) aims at enforcing the homogeneity in the ROI, while (4.b) limits the SAR levels everywhere, according to the guideline dictated by ICNIRP [3]. Eq. (4.c) regards the field polarization, which is constrained to remain close enough to the desired RH one. Finally, by means of Eq. (4.d), the amplitude of the desired polarization of $B_1^{\ +}$ is above a specific target value $B_{1\,des}^{\ +}$, which is set according to [3]. For simplicity, in the following, the case of L = 1 is considered.

Unfortunately, the constraints (4.a) are non-convex and the objective function (3) is a quadratic form. However, the field $B_1^{\ +}$ in the target point $\underline{r}_{t_0}$ can be assumed to be real and this assumption simply corresponds to a change of the overall phase reference [10],[11]. Moreover, an additional parameter, denoted by φ, represented by the phase shift between the fields in the reference point $\underline{r}_{t_o}$ and the control point $\underline{r}_{t_1}$ can be exploited [10],[11]. Thus, the problem (3)-(4) can be turned into:

$$\max_{I_n} Re\{B_1^{\ +}(\underline{r}_{t_o})\}$$

(5)

subject to

$$Im\{B_1^{\ +}(\underline{r}_{t_0})\} = 0$$

(6.a)

$$Re\{B_1^{\ +}(\underline{r}_{t_1})\} = Re\{B_1^{\ +}(\underline{r}_{t_0})\} * cos(\varphi)$$

(6.b)

$$Im\{B_1^{\ +}(\underline{r}_{t_1})\} = Re\{B_1^{\ +}(\underline{r}_{t_0})\} * sin(\varphi)$$

(6.c)

$$SAR \leq 3.2\ W/kg$$

(6.d)

$$\left|B_1^{\ -}(\underline{r})\right|^2 \leq \tfrac{1}{2}\left|B_1^{\ +i}(\underline{r})\right|^2$$

(6.e)

$$B_1^{\ +}(\underline{r}_{t_0}) \geq B_{1\,des}^{\ +}$$

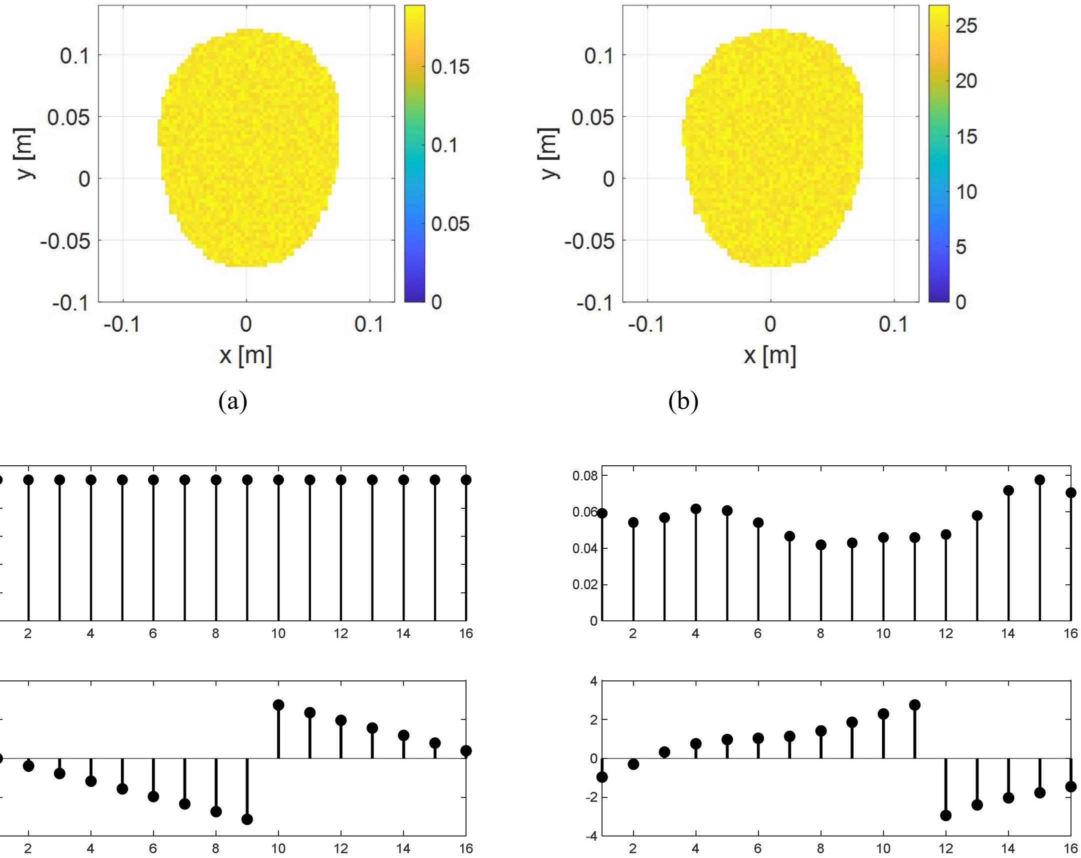
(6.f)

wherein $\varphi \in [-\pi, \pi]$. For any fixed value of φ, the problem (5)-(6) is convex and the shimming problem is now recast as the maximization of a linear function in a convex set, which corresponds to a convex programming (CP) problem. Then, the globally optimal solution of overall optimization problem can be directly determined by solving different CP problems corresponding to the different values of φ belonging to $[-\pi, \pi]$ and by selecting the solution that allows to obtain a better homogeneity of the $B_1^{\ +}$ field. In order to estimate the 'degree' of homogeneity of the field, a synthetic parameter related to the relative standard deviation of the amplitude of the field $B_1^{\ +}$, denote by RSD and defined as in [3], has been considered in the following.

3 Numerical tests

The scenario used to evaluate the proposed shimming approach is a simplified 2D scenario, mimicking a human head, embedded in the air, and discretized with 100x100 number of cells, see Fig.s 1(a)-1(b). The head has been modeled as a homogenous medium with electrical properties set equal to the average value of the ones of the brain tissues [3], respectively, $\sigma \approx 0.15 \frac{S}{m}$ and $\varepsilon \approx 25$.

The birdcage structure is schematized as a circular antenna array located around the head, with radius $r = 0.25\ m$, in accordance with the realistic size of common birdcage coil adopted in clinic [3]. The number of antennas N is set equal to 16. The coefficients $[I_n]$ at the starting point have been



(a) (b)

(c) (d)

Figure 1. Simplified 2D head model: (a) electrical conductivity [S/m] and (b) dielectric permittivity profiles. Amplitudes (upper box) and phases (lower box) [rad] of the initial (c) and the optimal excitations $\boldsymbol{I_n}$ (d).

selected according to [3] (se Fig. 1(c)), which corresponds to a ‘standard’ design of the birdcage coil. The considered Larmor frequency is 128 MHz, which stands for a standing field B_0 of 3 T.

The results have been obtained by means of the proposed shimming approach by considering two control points (including the reference point) spaced $\lambda_m/4$ and located as in Fig 2(c), being λ_m the wavelength of the brain medium. Figs. 1(c)-(d) gives the initial and the optimal amplitudes and phase of the complex excitations *In* of the N conductors.

Fig. 2(a) reports the initial spatial distribution of the amplitude of ${B_1}^+$ in all the head obtained by considering the initial excitations in Fig. 1(c). The picture shows that the initial RF field is not homogeneous. Conversely, Fig. 2(c) shows the spatial distribution of the amplitude of ${B_1}^+$ obtained by means of the convex procedure described in Section 2 and the optimal excitations in Fig. 1(d). As can be seen, the proposed procedure is able to design the antenna system in such a way to ensure a better homogeneity of the RF field.

To compare the results and evaluate the effectiveness of the method with respect to the standard design of the birdcage coil, the RSD has been calculated. In particular, the initial RSD is 0.4, while, by means of the proposed procedure, its value is as low as 0.15. This means that the field ${B_1}^+$ is now more homogeneous.

Finally, one of the most important constraints at hand for human safety is the limit on the SAR levels. Fig 1(d) shows the initial SAR distribution, while Fig. 2(b) the final one. As can be seen, this procedure also allows a better control of the SAR levels into the head.

More details about the proposed approach, as well as some numerical examples against realistic biological scenario, will be given at the conference.

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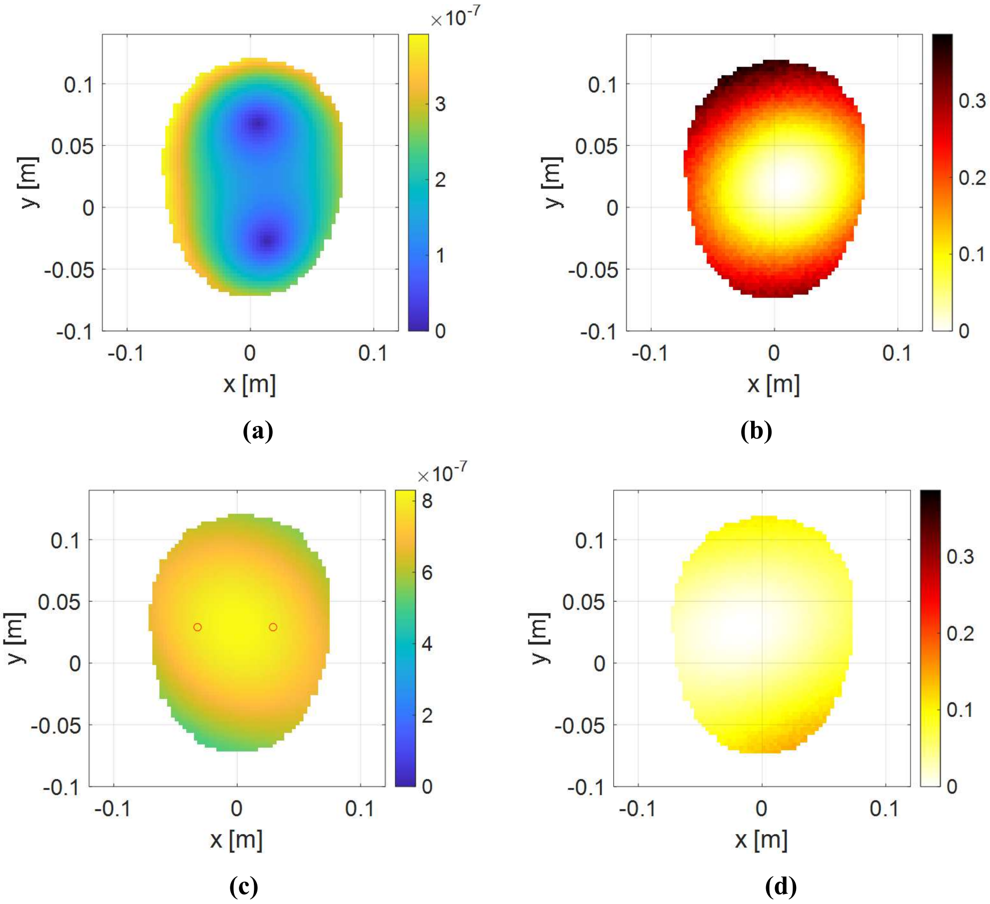

Figure 2. Initial distribution of the $\boldsymbol{B_1}^+$field intensity [T] (a) and the initial SAR distribution [W/kg] (b). Optimal distribution of $\boldsymbol{B_1}^+$field intensity [T] (c) and the corresponding SAR distribution [W/kg] (d).

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