Fundamental physical constraints on minimum energy deposition in parallel radiofrequency excitation for MRI

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Background

The principles underlying parallel MRI [1, 2] have been recently applied in radiofrequency (RF) transmission to accelerate multidimensional excitation pulses [3, 4], widening the range of clinical applications for which they can be employed. By transmitting tailored RF waveforms with the independently driven elements of an array of transmit coils, parallel excitation techniques enable suppressing the aliasing lobes resulting from the reduction of the sampling density in excitation k-space. The composite B1 field is modulated in space and time by adjusting the parallel RF pulses transmitted by each coil and combined with suitable synchronous gradient activations in order to generate a target excitation profile.

The possibility of transmitting separately with multiple coils locally distributed around the sample can be also exploited to improve the homogeneity of RF excitations and minimize the absorption of RF energy by tissues [4], which are both critical issues for MR imaging at high magnetic field strength. However, the calculation of the weights that enable combining the multiple excitations to obtain the final profile relies on the inversion of ill-conditioned sensitivity matrices, which may cause spatial amplification of the specific absorption rate (SAR). That can be seen as something similar to geometry factor [2] in the receive case and also here it may limit the acceleration capabilities of the technique. Zhu showed how the extra degrees of freedom inherent with the system can be exploited to search the solution space for the set of weights that lead to minimum SAR, resulting in a trade-off between level of acceleration and patient heating [4].

Introduction

As such optimization is explored further, it will be important to investigate the intrinsic constraints of the technique. In the case of parallel imaging (aka parallel MRI), it has been shown that there is an inherent electrodynamic limitation to the achievable signal-to-noise ratio (SNR) for any physically realizable coil array and the behavior of ultimate intrinsic SNR has been extensively studied [5, 6]. In those works, coil sensitivities were expanded in a complete set of valid solutions of Maxwell's equations and the optimal SNR was calculated by finding a linear combination that minimized the total noise power. A similar approach can be followed in the case of parallel transmission to establish a theoretical lower bound on the RF power deposited in the subject, given a particular acceleration factor and target excitation profile.

A method is proposed in this article to investigate the performance limits of parallel excitation, based on electrodynamic analysis of the transmitted RF fields within the framework of minimum SAR pulse design [4, 7]. The procedure requires calculating a set of optimal current patterns whose application in parallel results in the excitation of a uniform profile, while transferring the smallest possible RF energy to the subject. The analysis is then carried forward and a relative measure of the lowest achievable SAR is determined for different values of the main magnetic field strength (BO) and for various reduction factors. The spatial distribution of RF power within the subject during each optimal excitation pulse is also considered.

Materials and Methods

The design of parallel excitation pulse sequences that yield minimization of SAR consists in finding the current patterns that, when used to drive the elements of a transmit coil array, result in the minimization of the RF power deposited in the subject, while exciting the target profile without producing aliasing lobes within the field of view (FOV) [4]. That constrained minimization problem yields the solution:

$$\tilde{\mathbf{g}}_p = \Phi^{-1}\mathbf{C}_p^*\left(\mathbf{C}_p\Phi^{-1}\mathbf{C}_p^*\right)^{-1}\mu_p$$

where $\tilde{\mathbf{g}}_p$ is a vector containing the optimal current patterns associated to the pth excitation pulse for each coil, Φ is a matrix that contains the overlap integrals of the electric fields from the individual coils, $\mathbf{C}_p$ is a spatial-weighting map, whose elements come from B1 fields of the transmit coils, μ_p is a vector whose non-zero elements are the values of target profile at the locations excited during the pth pulse. The symbol $*$ denotes the conjugate transpose. This result enables calculating the minimum RF power dissipated on average during the P total RF cycles constituting the excitation:

$$\tilde{\xi}_p = \frac{1}{P}\sum_{p=1}^{P}\left(\tilde{\mathbf{g}}_p^*\Phi\tilde{\mathbf{g}}_p\right) = \frac{1}{P}\sum_{p=1}^{P}\left[\mu_p^*\left(\mathbf{C}_p\Phi^{-1}\mathbf{C}_p^*\right)^{-1}\mu_p\right]$$

In order to find the theoretical lower bound of the RF power deposited in a given subject during a particular parallel excitation experiment with any coil configuration, we considered an hypothetical net transmit coil and we expressed its transmitted electromagnetic field as the linear combination of the contributions of a complete set of actual transmit coils. The electric field associated to these basis functions was then used to compute the correlation matrix Φ, whereas the right-hand circularly polarized component of the magnetic fields in the basis set was used to fill up the elements of the matrix $\mathbf{C}_p$. Knowledge of the net electric field during each optimal excitation sampling interval enables calculation of the power deposition at each pixel location as a function of time and thus provides us with spatial SAR distribution while moving through excitation k-space. A uniform target profile throughout a section in the center of a homogeneous sphere with diameter of 20 cm (**Figure 1**) was employed to calculate ultimate intrinsic SAR and to investigate where and when SAR peaks occur. The algorithm was implemented on a standard PC using MATLAB (Mathworks, Natick, USA). Calculations were performed for different main magnetic field strength values and for various acceleration factors. The electromagnetic properties of the material were chosen as in a previous study [6].

Results and Discussion

Figure 2 (a) shows calculated theoretical minimum RF power dissipation as a function of BO for unaccelerated parallel MR excitations. This preliminary result suggests that the optimization method outlined here can yield significant SAR reductions at high field. **Figure 2 (b)** shows that, for the same optimal excitation, the peak value of the RF power deposited in the sample monotonically increases with BO. Spatial SAR distribution during excitation of the center of k-space using theoretically optimal current patterns varies for different values of BO. **Figures 3** and **4** show this result in the case of unaccelerated and 4-fold accelerated parallel excitation respectively.

Conclusions

We have described a procedure for calculating ultimate SAR for a given sample geometry and k-space excitation scheme. Preliminary results indicate that significant SAR reductions are possible using parallel excitation at high magnetic field strength.

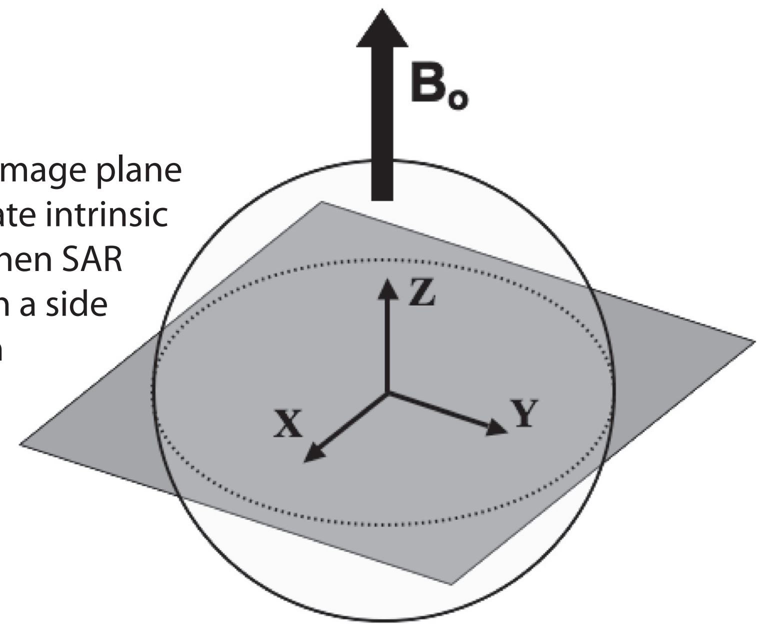

Figure 1. Schematic diagram of the image plane and the FOV used to calculate ultimate intrinsic SAR and to investigate where and when SAR peaks occur. The FOV is a square with a side of 20 cm. A uniform target excitation profile over the circular section was employed in the calculations.

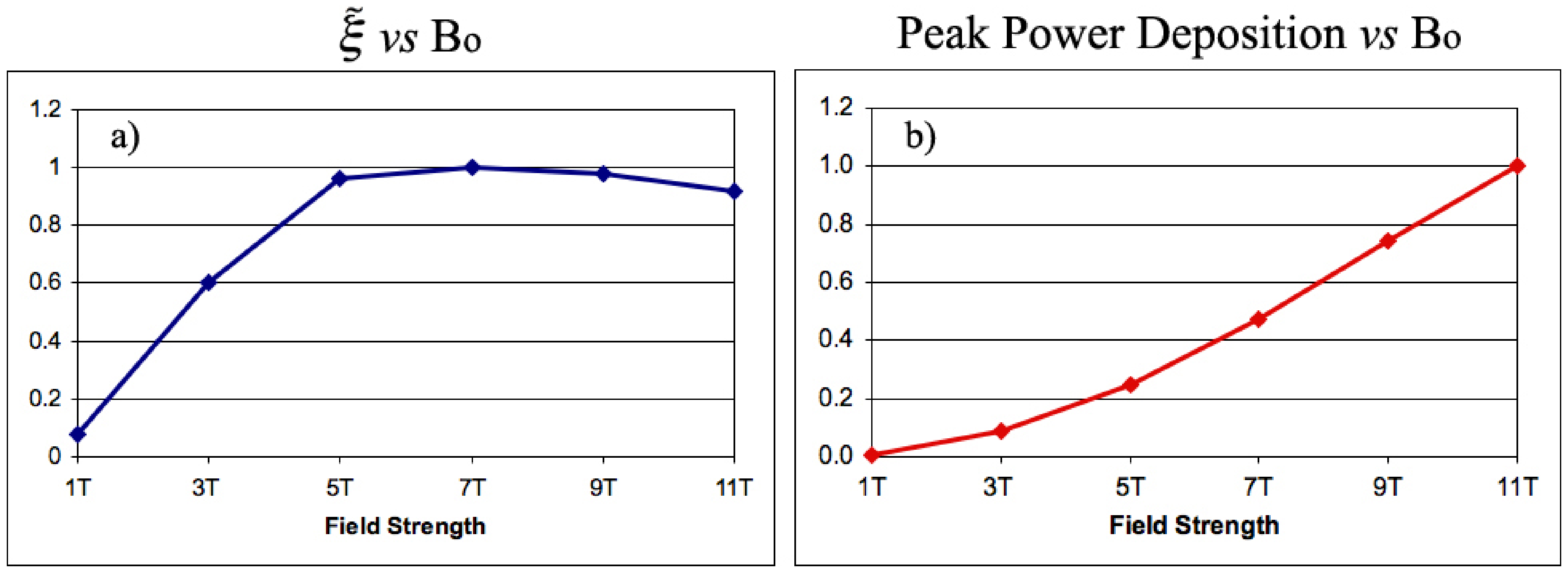

Figure 2. a) Theoretical minimum RF power dissipated on average during an unaccelerated parallel excitation as a function of BO. b) Behavior of peak SAR during the same optimal excitations of a). In each plot, values are normalized to the largest number.

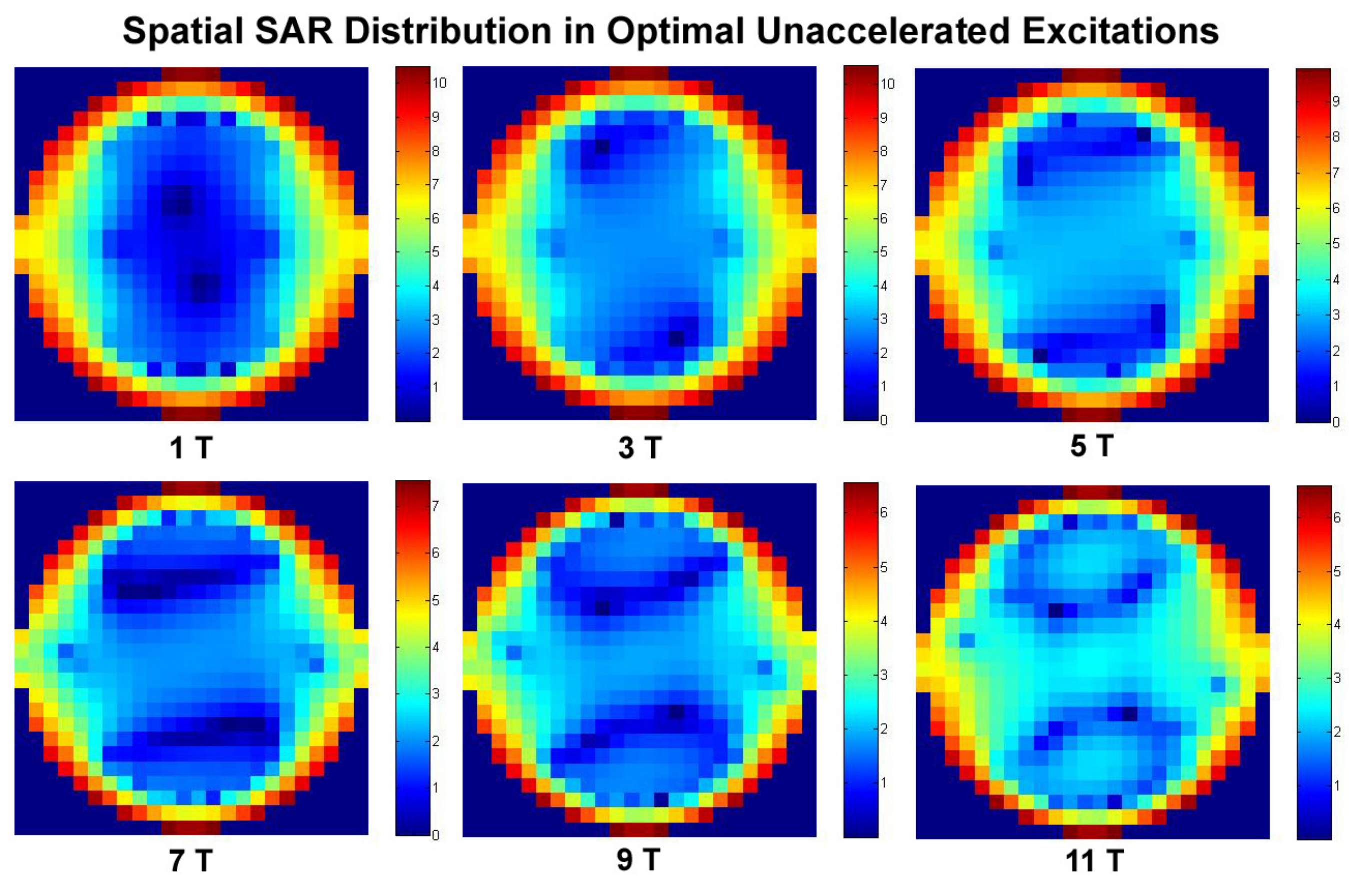

Figure 3. SAR distribution (log scale) within the FOV during fully sampled parallel excitation of the center of k-space with optimal current patterns at different field strengths. Each sub-plot is normalized to its minimum value.

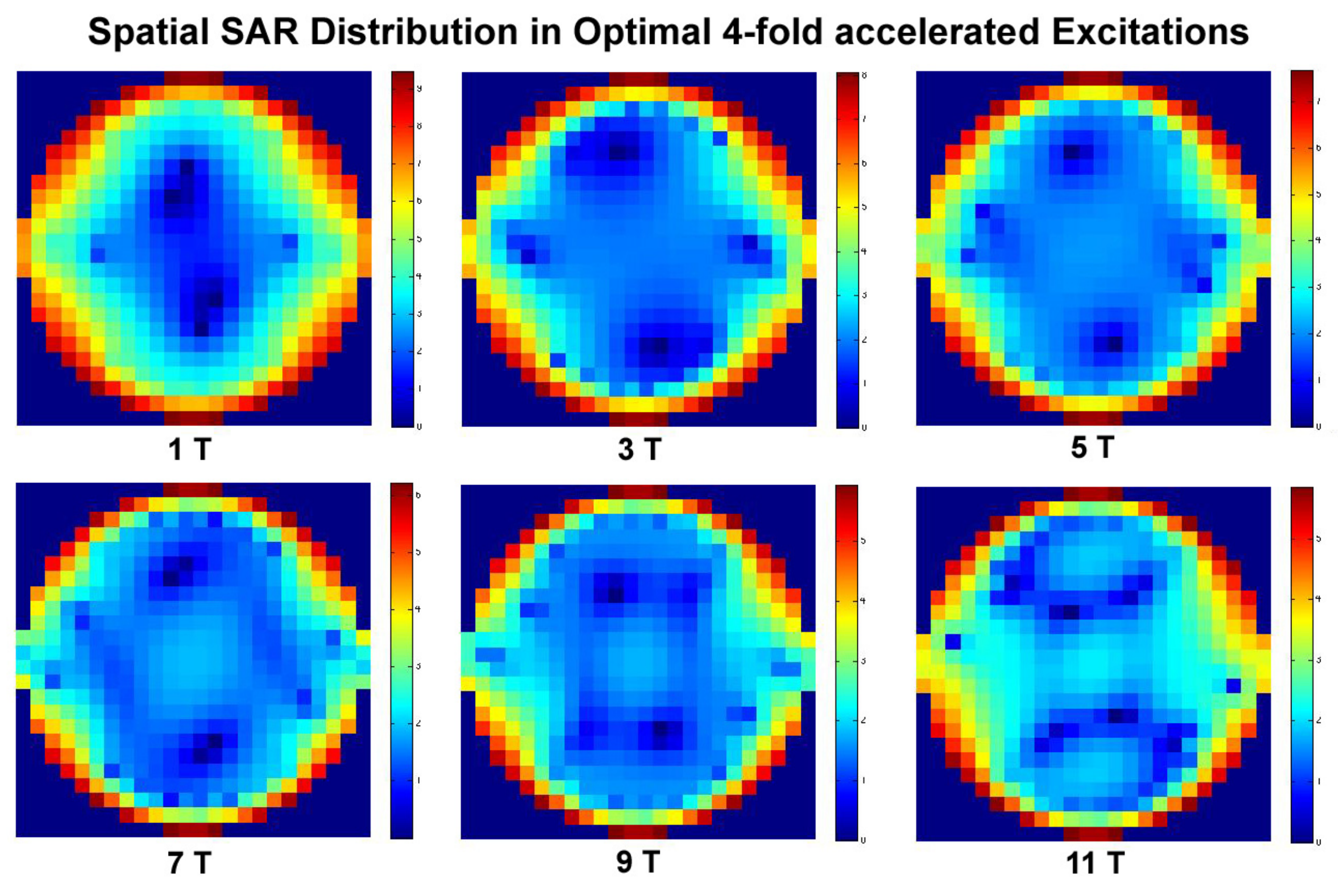

Figure 4. SAR distribution (log scale) within the FOV during 4-fold accelerated parallel excitation of the center of k-space with optimal current patterns at different field strengths. Each sub-plot is normalized to its minimum value.

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