Electrodynamic analysis of SAR and transmit homogeneity for RF shimming on a dielectric cylinder

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Introduction

In RF shimming [1,2], a single RF current waveform is modulated in amplitude and phase at each coil of a transmit array, in order to control the distribution of electromagnetic (EM) fields and compensate for B_1 inhomogeneities. An algorithm to minimize the specific absorption rate (SAR) for a given target profile using RF shimming has been recently proposed and evaluated in simulations for the case of a homogeneous spherical sample [3]. That study showed that SAR reduction and profile inhomogeneity correction is a trade-off optimization, which is inherently limited by electrodynamics [3]. Spherical geometries are useful approximations to simulate brain imaging, but transmit inhomogeneities for ultra-high-field MRI are particularly deleterious in body imaging, and modeling the efficacy of RF shimming for these applications is also important. In this work we study the performance of RF shimming in exciting uniform flip angle distributions inside a dielectric cylinder. We investigate both the case of finite transmit arrays and the ultimate intrinsic case, corresponding to perfect profile fidelity with the theoretical minimum RF power deposition.

Methods

The full-wave EM fields inside a dielectric cylinder of radius r = 15 cm and length L = 40 cm were derived from a complete basis of current modes, defined on a cylindrical surface concentric with the sample and with radius 1 cm larger, using a dyadic Green's function formulation [4]. A SAR-optimized RF shimming algorithm, previously described in the case of a spherical object [3], was used to simulate MR excitation of a uniform (i.e. equal to 1 everywhere) target profile, for both coronal and transverse fields-of-view (FOVs). The basis set of EM fields was employed to calculate ultimate intrinsic SAR, the lowest possible SAR for a given flip angle distribution, independent of any particular array geometry. We studied ultimate SAR and the associated optimal current patterns, for different values of the main magnetic field strength, assuming dielectric properties of dog skeletal muscle [4]. The same computational framework was applied for the case of finite cylindrical window coil arrays, by appropriately weighting the basis modes to model the current distributions of each transmit element. Different array
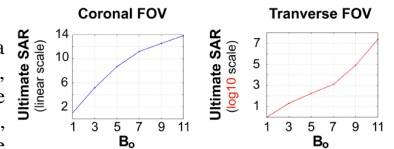
Fig. 1. Normalized ultimate intrinsic SAR vs. magnetic field strength in RF shimming for a uniform target excitation profile along a coronal (left) and a transverse (right) plane through the center of a dielectric cylinder.

configurations were generated by arranging identical coil elements around the cylinder and along its axial direction.

Results

Fig. 1 shows ultimate intrinsic SAR as a function of main magnetic field strength, for the cases of a uniform target profile along a coronal plane (left) and a transverse plane (right) through the center of the cylindrical sample. SAR growth is sub-linear for the coronal FOV, whereas it is exponential for the transverse FOV. This is likely due to the fact that the particular optimization algorithm [3] used in this work tries to match not only the amplitude, but also the phase of the desired excitation profile, which is notably more difficult in a transverse plane. The algorithm uses the remaining degrees of freedom to minimize SAR, which explains why adding more coils results simultaneously in better profile homogeneity and increased RF energy deposition (Fig. 2). In the ultimate case, where a hypothetical infinite array is used, perfect homogeneity and low SAR can be always achieved (Fig. 2). With an 8-element array, RF shimming cannot compensate for transmit field inhomogeneities, and the coils are exploited to reduce SAR instead. Using 64 or 128 transmit elements good homogeneity can be obtained in both FOVs, although the SAR penalty is considerable. Figure 3 shows optimal net current patterns (made up of optimally-weighted basis currents) at 7T magnetic field strength. (The portion of the infinite cylindrical surface which corresponds to the length of the finite coil arrays of Fig. 2 is shown in light blue). We notice that to excite a homogeneous coronal
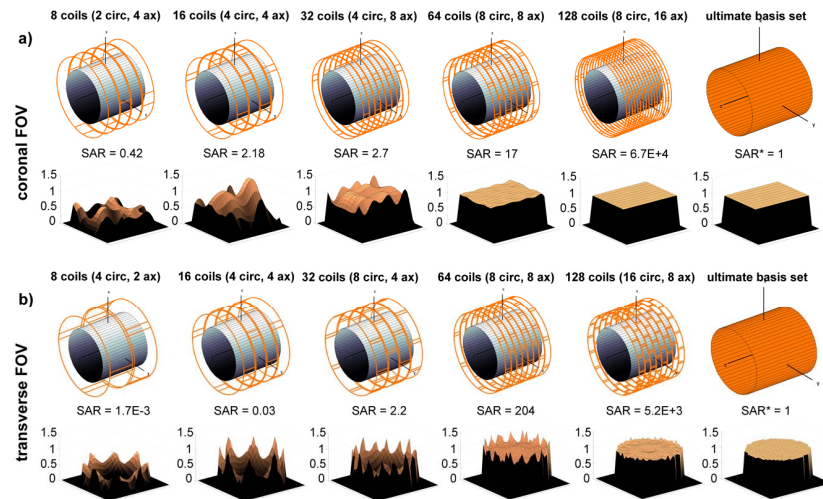
Fig. 2. Actual excited profile using RF shimming for various transmit coil configurations at 7T magnetic field strength, in the cases of a uniform target excitation profile along a coronal (a) and a transverse (b) FOV. The quantities reported are relative measures of SAR and for each FOV are normalized to the corresponding ultimate intrinsic value (indicated with an asterisk).

profile, the optimal current distribution has constant amplitude along the axial direction, whereas it becomes more complex for a transverse uniform profile.

Discussion and Conclusions

In this work we have investigated transmit homogeneity and SAR for RF shimming using different array geometries, in the cases of a coronal and a transverse FOV. We also calculated ultimate intrinsic SAR and studied its behavior as a function of main magnetic field strength. Fig. 2 illustrates that good homogeneity in a given plane may in principle be achieved with RF shimming at high field strength. However, as indicated by the high values of relative SAR for large numbers of coils in Fig. 2, the SAR price for achieving this homogeneity can be prohibitively high. Furthermore, the right-hand panel of Fig. 1 shows that even in the ultimate case, high homogeneity has an unacceptable SAR price at high field strength. However, a significant part of this price may result from enforcing homogeneity in the phase as well as in the amplitude of excitation. Phase distribution is likely to account for the strong difference in ultimate SAR behavior for coronal and transverse planes. Examination of the EM field modes appropriate to the cylindrical geometry shows that the constraint of constant phase at all azimuthal angles (as in the transverse case) is in fact far more stringent than that of constant phase across a single diameter (as in the coronal case). Future work will explore relaxation of the phase constraint, which has been proposed for practical RF pulse design [5], but which is nontrivial to include in the ultimate intrinsic SAR framework used here. In the coronal case, the current distribution resulting in perfect profile fidelity (Fig. 3) might be reproduced using as few as 8 channels in an optimized coil design.
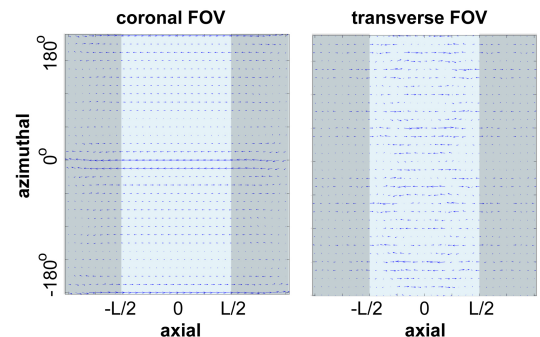
Fig. 3 Optimal current patterns corresponding to the excitation of a uniform coronal (left) and transverse (right) profile with the theoretical smallest SAR, using RF shimming at 7T. The current distribution was calculated by applying the optimal modulation coefficients to the current basis functions. The plots represent 2D "unwrapped" views of a portion of the 3D cylindrical surface.

References

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