RF Power Reduction with Parallel Excitation

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Introduction

MR imaging commonly employs a volume transmit coil for inducing a relatively homogeneous B_1 field during excitation. With certain sequences or at high field strength, the volume-coil approach may face RF power absorption (SAR) and/or flip angle uniformity issues. A parallel excitation system composed of a distributed array of transmit coils and supporting driving sources enables acceleration of multi-dimensional excitation (1,2), which allows the creation of a desired flip angle distribution (including a uniform one) at a manageable pulse length. In this study, we examine the impact of the parallel system on SAR management. Conceptually, a focused excitation of only the region of interest may primarily use the coils in its close proximity hence avoiding power deposition over an unnecessarily large volume. Given a desired flip angle profile, we explicitly show that a parallel RF pulse design can exploit the extra degrees of freedom inherent of the parallel system to tailor the E field and realize SAR reduction.

Methods and Results

The principle is described here with a focus on the minimization of SAR averaged over the subject volume and the excitation period, as defined by

$$\mathrm{SAR}_{\mathrm{ave}} = \frac{1}{P}\sum_{p=0}^{P-1}\frac{1}{V}\int\frac{\sigma(\mathbf{x})}{2\rho(\mathbf{x})}\left|\mathbf{E}(\mathbf{x}, p\Delta t)\right|^2 dv \qquad [1]$$

In Eq. [1], σ denotes tissue conductivity; ρ, density; V, the size of the irradiated volume; and P, the number of time points in the excitation period. With a quasi-static model, one can show that $|\mathbf{E}(\mathbf{x},p\Delta t)|^2$ is a quadratic form in $[I_1(p\Delta t) \ldots I_N(p\Delta t)]$, a vector with samples of the N coils' current waveforms at $t=p\Delta t$. Sorting out the volume integral and temporal averaging, one can further express the right-hand side as $\mathbf{s}^H\mathbf{F}\,\mathbf{s}$, where $\mathbf{F}$ is a positive definite matrix, vector $\mathbf{s}$ collects a total of NP samples of the current waveforms and ^{H} denotes conjugate transpose. Provided that the E field scales linearly with the driving source functions, a quadratic relationship in the form of $\mathrm{SAR}_{\mathrm{ave}} = \mathbf{s}^H\mathbf{F}\,\mathbf{s}$ generally holds between $\mathrm{SAR}_{\mathrm{ave}}$ and source function samples. In the presence of biological objects or at high frequencies, accurate estimate of $\mathbf{F}$ may have to rely on calibration measurements.

Fig. 1

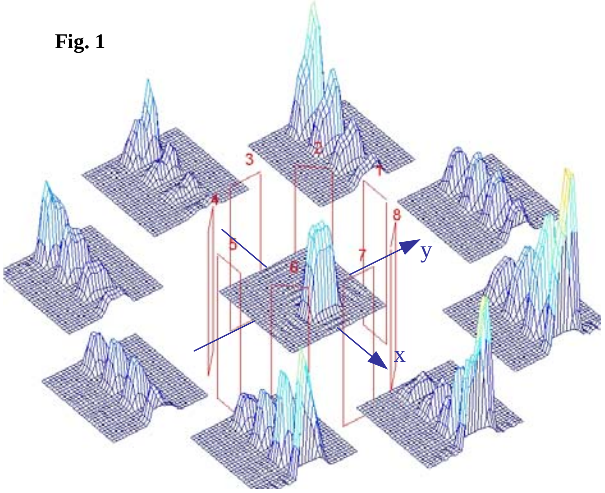
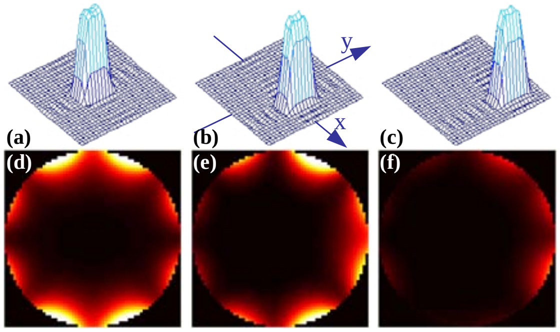


Fig. 2



Given $g(\mathbf{x})$, a desired small-flip-angle excitation profile, the parallel RF pulses can be derived by sampling the Fourier transform of spatially weighted versions of $g(\mathbf{x})$ (1):

$$W_n(\mathbf{k}) = \int h_n(\mathbf{x})g(\mathbf{x})e^{-j2\pi\mathbf{k}\cdot\mathbf{x}}d\mathbf{x} \qquad [2]$$

The requirement of creating the desired profile (producing a main lobe matching the profile and, if with acceleration, simultaneously suppressing aliasing lobes) translates into constraints on the spatial patterns of the $h_n(\mathbf{x})$'s. The constraints can be expressed with linear equations (3). In the case of rectilinear traversing of excitation k-space, one may express the constraints one location in the FOV at a time: $\mathbf{C}_{(\mathbf{x})}\mathbf{h}_{(\mathbf{x})} = \mathbf{e}_1$, where subscript $_{(\mathbf{x})}$ denotes the spatial dependency, vector $\mathbf{h}_{(\mathbf{x})}$ represents $[h_1(\mathbf{x}) \ \ldots \ h_N(\mathbf{x})]^T$, matrix $\mathbf{C}_{(\mathbf{x})}$ carries, in an appropriate order, samples of the coils' effective B_1 fields at $\mathbf{x}$ and locations aliased with $\mathbf{x}$, and $\mathbf{e}_1 = [1\ 0\ \ldots\ 0]^T$. Pooling all equations, we obtain

$$\mathbf{C}_{\mathrm{all}}\,\mathbf{h}_{\mathrm{all}} = \mathbf{e}_{\mathrm{all}} \qquad [3]$$

where $\mathbf{C}_{\mathrm{all}}$ is a block-diagonal matrix with $\mathbf{C}_{(\mathbf{x})}$'s on the diagonal, and $\mathbf{h}_{\mathrm{all}}$ and $\mathbf{e}_{\mathrm{all}}$ are, respectively, concatenated $\mathbf{h}_{(\mathbf{x})}$'s and $\mathbf{e}_1$'s. If the acceleration is less than N-fold, Eq. [3] is underdetermined and admits multiple solutions. This results in a family of parallel pulse designs that all meet the excitation profile requirement. Rather than selecting a nominal design that corresponds to the minimum-norm solution, one may explicitly search in the family for a set of coordinated source functions that induces an E field with minimum ensuing RF energy deposition. This is feasible because the linear relationship (Eq. [2]) between the $W_n(\mathbf{k})$'s and the $h_n(\mathbf{x})$'s allows further expressing $\mathrm{SAR}_{\mathrm{ave}}$ as $\mathbf{h}_{\mathrm{all}}^H\mathbf{V}\,\mathbf{h}_{\mathrm{all}}$ and the search boils down to a readily solvable problem of minimizing a quadratic function subject to linear constraints (4):

$$\text{minimize } \ \mathbf{h}_{\mathrm{all}}^H\mathbf{V}\,\mathbf{h}_{\mathrm{all}} \quad \text{subject to } \ \mathbf{C}_{\mathrm{all}}\,\mathbf{h}_{\mathrm{all}} = \mathbf{e}_{\mathrm{all}} \qquad [4]$$

Parallel excitation of a ∅18cm cylinder (uniform σ and ρ) inside an 8-element transmit array (Fig.1) were simulated. The elements were distributed azimuthally on a ∅27cm shell (+z = B_0 direction). 2D parallel excitation pulses were used to induce flip angle distributions of various profiles (x-y). In one study, focused excitation of an arbitrarily located rectangular ROI were carried out with 2D pulses designed (Eq. [4]) for 3.8-fold acceleration (EPI trajectory shortened to 8 lines with a 3.8-fold increase in Δ_{kx}) and $\mathrm{SAR}_{\mathrm{ave}}$ minimization. For one example case, Fig.1 shows, across the center axial plane, the x-y localization patterns due to each of the eight coils and the profile resulting from the parallel excitation. Fig.2 (a-c) summarize the results from cases with the ROI located respectively, at the center, off the center, and near the edge of the cylinder, all of which indicate virtually full suppression of aliasing lobes and excellent match to the desired profiles. Fig.2 (d-f) show correspondingly the accumulated RF power deposition as functions of (x,y). The normalized $\mathrm{SAR}_{\mathrm{ave}}$ values were 1, 0.71 and 0.28, representing respectively 14, 22 and 37 percent reductions from the $\mathrm{SAR}_{\mathrm{ave}}$ values of counterpart nominal designs. The reduction in power deposition in the latter two cases agrees with the intuition on the benefit of local coils, and the improvements over the nominal designs indicate the significant advantage of tailoring the E field. Results from other cases also suggest that exciting larger ROI's tend to increase RF power deposition. Finally, we note that the induction of both spatial and temporal variations of the composite B_1 field (vs. manipulation of B_1 temporal variation only, as is the convention) during excitation is the key to the desirable characteristics of parallel excitation, and that the design of a parallel transmit array has a big impact on accomplishing acceleration and/or reducing RF power.

1. Y. Zhu, *Proc. ISMRM 10th Scientific Meeting*, p 190, 2002. 2. U. Katscher, et al., Transmit SENSE, *MRM* 49:144-150, 2003.
3. Y. Zhu, Parallel Excitation with an Array of Transmit Coils, *MRM* (in press). 4. G.H. Golub, et al., *Matrix computations*, 1996.