Exploring the Limits of RF Shimming: Single Slice and Whole Brain Field Optimizations at up to 600 MHz with Transmit Arrays of up to 80 elements

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INTRODUCTION: Simulation and experiment have shown that separate control of magnitude and phase of individual coil drives in a transmit array can be used to provide significant improvement in homogeneity of RF fields, flip angles, and available signal intensity in high field MRI (1-4). Due to Maxwell's equations and wavelength effects, however, there are fundamental limits of what homogeneity can be achieved by RF shimming alone with any number of coils (1). Here we investigate the possibilities of reducing inhomogeneities at very high frequencies with a large number of coils. With a large number of coils, results are impressive (though some limitations can be seen) even for whole-brain RF shimming at 600 MHz.

METHODS: The finite-difference time-domain method was used to model a human head within 16-element and 80-element (see Figure 1) elliptical, stripline coil arrays at 300, 400, 500, and 600 MHz. The field produced by each element was calculated and recorded. Then the results were loaded into home-built C codes and an optimization routine was used to vary the magnitudes and phases of the individual coils with the goal of improving homogeneity of the available flip angle, gradient echo signal intensity, and spin echo signal intensity, respectively:

$$\alpha = \gamma\tau\left|\sum_{n=1}^{N} {}^{n}\mathbf{B}_1^+\right|$$

$$SI_{GE} = \left|\sin(\gamma\tau\left|\sum_{n=1}^{N} {}^{n}\mathbf{B}_1^+\right|)\right|$$

$$SI_{SE} = \left|\sin^3(\gamma\tau\left|\sum_{n=1}^{N} {}^{n}\mathbf{B}_1^+\right|)\right|$$

where γ is the gyromagnetic ratio, τ is the pulse duration, and the summation of the circularly-polarized vector components ${}^{n}\mathbf{B}_1^+$ is performed for every coil (n=1 to N where N is either 16 or 80) in the array. Current sources were applied to reduce coupling effects. Standard deviation divided by the average of either α, SI_{GE}, or SI_{SE} is minimized to improve homogeneity.

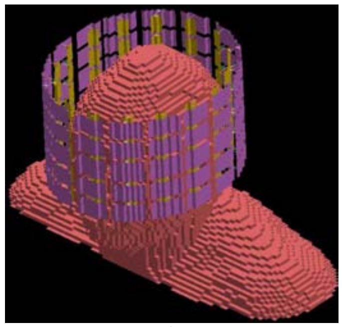

Figure 1: Shaded surface representation of the 3D head model within the 80-element elliptical array.

Table 1. Relative standard deviation of α, SI_{GE}, and SI_{SE} for 16- and 80- coil arrays at different frequencies for different ROIs (whole brain or different slices) before and after optimization.

Freq. (MHz)	# of Coils	Region of Interest		Flip Angle (α)		SI_{GE}		SI_{SE}	
		Name	# of Voxels	Before	After	Before	After	Before	After
300	16	brain	10226	0.202	0.156	0.146	0.0388	2.577	0.109
	80	brain	10226	0.324	0.053	0.316	0.0046	0.786	0.018
	16	sagittal	541	0.214	0.051	0.140	0.0037	0.400	0.015
	80	sagittal	541	0.316	0.006	0.308	0.0001	0.673	0.0003
	16	coronal	461	0.264	0.023	0.186	0.0012	0.520	0.004
	80	coronal	461	0.330	0.059	0.321	0.0001	0.736	0.0003
	16	axial	645	0.138	0.060	0.096	0.0072	0.294	0.015
	80	axial	645	0.203	0.006	0.195	0.0065	0.637	0.0003
400	80	brain	10226	0.501	0.075	0.485	0.0094	1.098	0.032
500	80	brain	10226	0.525	0.109	0.500	0.0181	1.199	0.054
600	16	brain	10226	0.413	0.222	0.282	0.0979	1.066	0.213
	80	brain	10226	0.512	0.124	0.490	0.0470	1.181	0.109
	16	sagittal	541	0.304	0.055	0.196	0.0082	0.412	0.026
	80	sagittal	541	0.405	0.009	0.381	0.0002	0.877	0.001
	16	coronal	461	0.586	0.126	0.344	0.0559	0.742	0.097
	80	coronal	461	0.675	0.019	0.649	0.0353	1.431	0.054
	16	axial	645	0.370	0.122	0.263	0.0230	0.438	0.067
	80	axial	645	0.467	0.012	0.451	0.0003	1.105	0.001

RESULTS: A representation of the head model in the 80-element elliptical stripline array is given in Figure 1. Figure 2 shows the GE signal intensity distribution in the 80-coil array at 300 and 600 MHz before and after optimization. After finding optimal coil magnitudes and phases, the signal intensity distribution is very homogeneous at each frequency. Table 1 lists the relative standard deviation for different region of interest (ROI) at different frequencies.

DISCUSSION: Table 1 quantitatively indicates that increasing coil number or reducing region of interest (e.g., from whole-brain to any single plane) can significantly enhance the homogeneity. Due to the nature of the sine function, GE SI reaches the best homogeneity. With the simple optimization algorithm used there is no assurance that the optimum found is the global optimum. It is found that the optimal conditions (currents) are different when the optimizing objectives are different, ie, optimizing homogeneity of flip angle, SI_{GE}, or SI_{SE}. A similar automated process might be applied in vivo: after individual fast low-contrast B1 maps are acquired for each coil, the optimal drive for the array can be calculated and then applied to the coil. For a 16-coil array, optimization requires only a few minutes and can be accelerated further.

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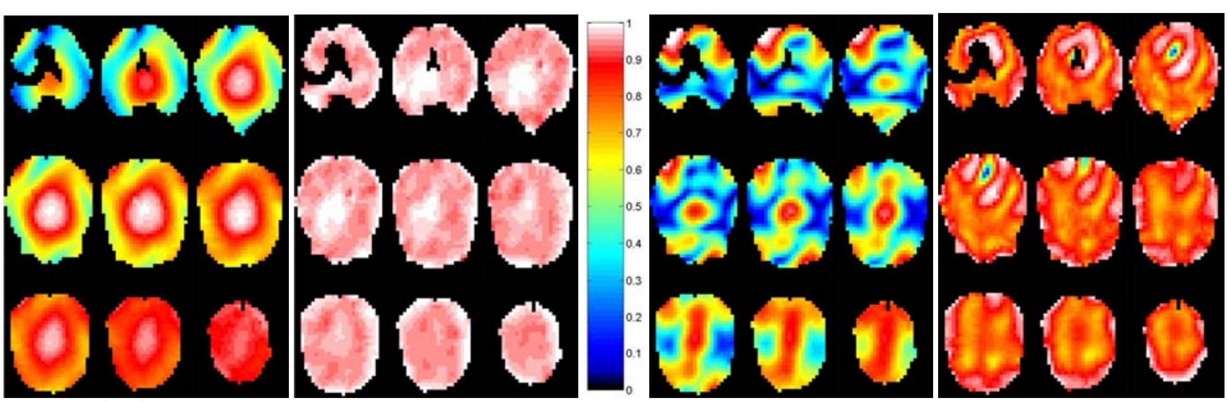

Figure 2: GE Signal intensity distributions optimized for the whole brain in 80-element array. 9 axial slices at 1cm intervals for each result. From left to right: 300 MHz before optimization, 300 MHz after optimization, 600 MHz before optimization, and 600 MHz after optimization.

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