Investigating the characteristics of focusing by a coil array under different conditions with Debye's potential and genetic algorithm

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Synopsis

An array has the capability of beam-forming or focusing by adjusting the magnitude or phase of the current flowed on each element. Focusing by an array is a common scheme in various fields of engineering, and now we try to characterize the abilities of focusing by the B_1 coil array in MRI. Two reasons support this idea: Firstly most human tissues are dielectrics that shorten the wavelength of B_1, and secondly the B_0 strength of commercially-available MRI scanners is still rising. Debye's potential and genetic algorithm are used together to simulate the B_1 distribution produced by the coil array under various conditions. Results show that increasing the number of the coils always helps to focus better. On the other hand, increasing the radius of the coils or increasing the B_0 strength doesn't ensure a better performance of focusing.

Methods

(1)Debye's potential is used to construct a 3D analytical model that can compute the B_1 field in a sphere excited by a circular surface coil [1]. Its accuracy has been proved by the measurements of B_1 along the axis of a real circular coil (fig.1; the coil's radius is 8.5cm) and Keltner's paper [2]. In order to make our analysis simpler, we assume an ideal feed/decoupling network exists behind the coils and cancels out all the mutual coupling; otherwise the analysis will become more complicated. Under the decoupling conditions, the B_1 field produced by a coil array is a superposition of that produced by individual coils. The whole simulation model consists of a sphere (radius=10cm) and an array comprising several circular coils with equal individual size and equal spacing (fig.2). The center of each coil just lies on the sphere's surface. We choose a two-dimensional 20-degree sector as the target region (the blank region in the sphere in fig.2) to focus on; it lies on the plane defined by the coils' axes and the sphere's center. The sphere is assumed to have the electrical characteristics of the human brain tissue, which is typical because it has a medium permittivity ε and a little higher conductivity σ among various human tissues [3]. In addition, the human brain can roughly be modeled as a 10cm-radius sphere.

(2)Two kinds of number of coils (6 or 12), two kinds of individual coil's size (radius=5cm or 10cm) and four kinds of B_0 strength (1.5T, 3T, 4T or 8.22T) are used in the simulation; hence there are totally 16 kinds of conditions.

(3)A real-coded genetic algorithm [4] is applied to find the relative current magnitude on each coil and the fitness value. It has a population of 100. An 80% crossover rate and a 20% mutation rate are applied to enlarge the search space. Direction-based crossover is used to increase the efficiency of convergence. Fitness is defined as:

$$\text{fitness}=\frac{(\text{average of } B_1 \text{ inside the target region})}{(\text{standard deviation of } B_1 \text{ inside the target region})*(\text{sum of } |B_1| \text{ outside the target region})}$$

Tournament selection with 2% elite selection is used as the selection criteria. Each condition is optimized for three times, and under the same condition the fitness value after convergence is almost the same for each time. Fig.3 shows a typical case.

Results and discussion

The fitness value under each condition is listed in table 1. Fig.4~8 are some B_1 patterns corresponding to table.1, and the legend under the figure denotes (number of coils, radius of each coil, B_0 strength). Some results can be derived from the fitness values and the corresponding patterns:

(1)Increasing the number of coils always helps to focus better. Both the fitness values and the corresponding patterns support this inference.

(2)Changing the coils' size influences the performance of focusing in a trade-off manner. As shown in fig.4~8, although by using large coils the main beam becomes narrower and fits the target region well, the side lobes broaden simultaneously(fig.4~6) and degrade the fitness value. On the other hand, the B_1 penetration depth isn't good enough at a lower B_0 (fig.7) and the main beam is still broad at a higher B_0 (fig.8), if the small coils are used.

(3)Increasing the B_0 strength doesn't always cause the coil array to focus better. Ideally when B_0 rises, the wavelength of B_1 shortens; a better resolution and fitness value should be obtained. We infer that the frequency-dependent characteristics of the human tissue (permittivity decreases with frequency; conductivity increases with frequency) [3] also play a role, and hence render the results complicated to interpret.

Up to now we can't synthesize arbitrary patterns by this technique, such as a donut shape. Compared with the gradient-encoding methods, the resolution achieved by our method isn't satisfactory either. However, it may have some applications if the echo time must be very short and the resolution isn't a major concern, such as regional spectroscopy of some short-T_2 nuclei. It is because, after the first slice selection, ideally the target region can be selected by the RF coil array. Likewise in voxel-shape spectroscopy, the second and third soft RF pulses & slicing gradients can be replaced with a hard RF pulse; the minimum TE hence decreases. If the B_1 can be focused in a 3D manner, the first soft RF pulse and slicing gradient also can be replaced to further reduce the minimum TE. We will continue to study arbitrary 2D/3D focusing methods and validate this approach on a multiple-channel MRI scanner in the future.

References

[1]JM Jin, *Electromagnetic Analysis and Design in Magnetic Resonance Imaging*, chap 5, CRC press, 1999.[2]Keltner et al., Magn. Reson. Med. 22, pp.467-480, 1991. [3]Gandhi et al., Magn. Reson. Med. 41, pp.816-823, 1999.[4]YR Samii et al., *Electromagnetic Optimization by Genetic Algorithms*, Wiley-interscience,1999.

Table 1 fitness value(value scaled by 10^4)

		B0 strength(Tesla)			
coil radius	no. of coils	1.5T	3T	4T	8.22T
10cm	6	2.22	2.37	2.28	2.46
	12	2.74	3.04	3.05	2.91
5cm	6	2.71	2.66	2.53	2.58
	12	2.77	2.74	2.63	2.74

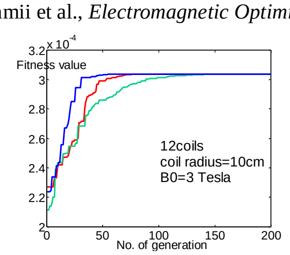

Fig.3 convergence curve for 3 times

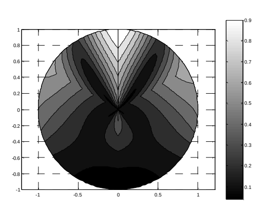

Fig.4 (6coils, 10cm, 3T)

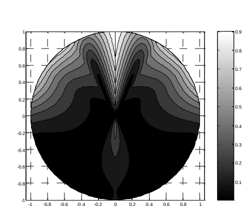

Fig.5 (12coils, 10cm, 3T)

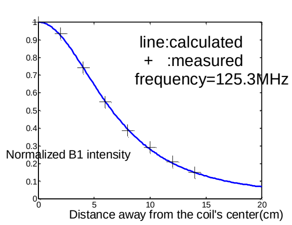

Fig.1 validation of the single coil model

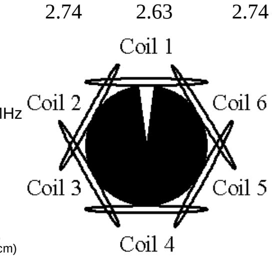

Fig.2 geometry and the target region

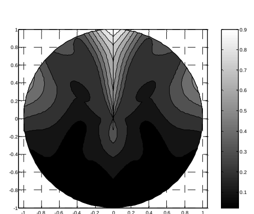

Fig.6 (12coils, 10cm, 8.22T)

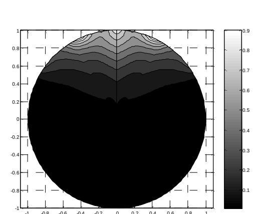

Fig.7 (12coils, 5cm, 3T)

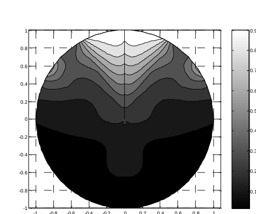

Fig.8 (12coils, 5cm, 8.22T)