자기공명영상촬영을 위한 표면경사자계코일의 저전력설계

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Low-Power Design of the Surface Gradient Coil for Magnetic Resonance Imaging

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ABSTRACT

A new low-power, high-order optimization scheme to design surface gradient coils (SGC) is proposed for magnetic resonance imaging (MRI). Although previous SGCs have been designed and constructed just to get strong linear gradients, this paper proposes more systematic ways of SGC design by minimizing electrical power consumption in the gradient coil and by removing unnecessary high-order field distortions in the imaging region. By assuming continuous current flow on the coil surface which may be or may not be planar, power consumption in the coil is minimized. According to the simulation results, the SGC designed by using the proposed scheme seems to produce much more uniform linear gradient field using less electrical power compared to the previously proposed SGCs.

INTRODUCTION

The purpose of this paper is to design and implement MRI surface gradient coils (SGC) with less power consumption and better linearity.

SGC was introduced about two years ago for microscopic or high-resolution imaging of a limited volume near the surface of the subject (1).

In spite of vast amount of research on conventional cylindrical-shape gradient coils (2-6), works for SGC have been limited to only actual implementation to achieve high gradient intensity.

This paper proposes more systematic ways of SGC design to achieve lower power consumption and better linearity while considering some design problems related to only SGCs(1). In this paper, the following factors are considered in designing the SGCs. (i) *Lowest power consumption.* This is implemented by minimizing the sum of the squares of the current elements on the surface of the SGC. (ii) *Suppression of high-order, non-linear components.* More complex gradient patterns, e.g., for z-directional SGC design, zy, z^2y, zx^2 components, are removed in SGC design (7). (iii) *Minimization of vibration of the coil.* (iv) *Consideration on the location (or depth) and shape (or length) of the imaging volume.*

METHOD

For a given linear gradient direction, one should decide up to which order and which components among them will be removed. Then for a given gradient intensity, the distribution of the current elements is optimized for the lowest power (by minimizing the square sum of the currents) while removing the unnecessary components. From the Biot-Savart's law, the z-directional (main-field direction) magnetic field intensity at (x,y,z) from a unit current flowing to x direction at (x_0,y_0,z_0) is expressed as:

$$B_{z,n} = \frac{\partial}{\partial x_0}\left[\frac{-\dfrac{\mu_0}{4\pi}\dfrac{y_0 - y}{(y_0-y)^2+(z_0-z)^2}\,(x_0 - x)}{\sqrt{(y_0-y)^2+(z_0-z)^2+(x_0-x)^2}}\right] \quad (1)$$

From this equation, a general form of the $x^l y^m z^n$ gradient at $x=y=z=0$ (center of the imaging volume) can be written as

$$G_{l,m,n} = \left[\frac{\partial^l}{\partial x^l}\frac{\partial^m}{\partial y^m}\frac{\partial^n}{\partial z^n}\left[B_{z,n}\right]\right]_{x=y=z=0} \quad (2)$$

Numerical calculation of $G_{l,m,n}$ is done by recursively calling C-routines. It should be noted that, although the gradient components from z-

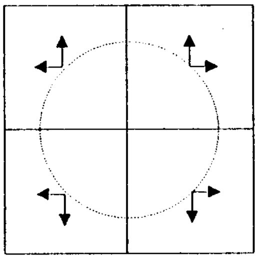


Fig. 1. Eight outward current elements of four adjacent pixels. The current sum going out of the circle (dotted line) is set to zero for current continuity.

directional current are zero because the z-directional current does not generate z-directional field, the z-directional currents are also calculated to make the current continuous. The $G_{l,m,n}$'s corresponding to these z-directional current elements are, of cause, zero.

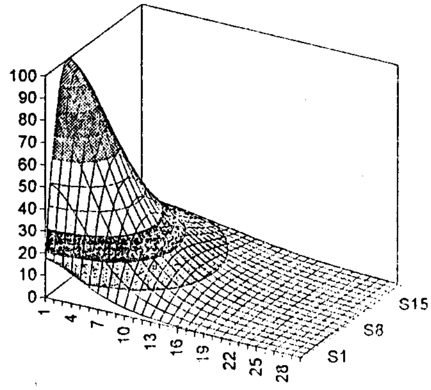
Then the optimal 2-D current distribution is obtained by minimizing the cost $e^2 = \boldsymbol{i}^t\boldsymbol{i}$, where $\boldsymbol{i}$ is a column vector for the current distribution (for both x- and z- directional currents), while satisfying the following two conditions.

(1) $\boldsymbol{G}\,\boldsymbol{i} = \boldsymbol{l}$. This condition is to remove the selected high-order gradient terms with a constant linear gradient. Here, $\boldsymbol{G}$ is $G_{l,m,n}$ as a matrix form with the linear gradient at the first row and other components (to be removed) at the other rows and $\boldsymbol{l} = [1\ 0\ 0\ \ldots]^t$.

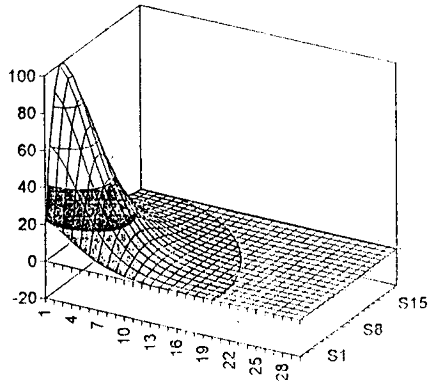
(2) $\nabla \cdot \boldsymbol{i} = 0$. This condition comes from the current continuity. The z-directional and the return current are taken care of by using this restriction. In our simulation, eight outward current elements are selected for four adjacent pixels as shown in Fig. 1 and the sum of the currents are set to zero.

If the above two conditions are combined and written as a matrix form, $\boldsymbol{N}\,\boldsymbol{i} = \boldsymbol{l}$, the solution becomes

$$\boldsymbol{i} = \boldsymbol{N}^t[\boldsymbol{N}\boldsymbol{N}^t]^{-1}\,\boldsymbol{l}. \quad (3)$$



(a) $G_{1,0,0}$



(b) $G_{1,1,0}$

Fig. 2. Perspective views of (a) $G_{1,0,0}$ and (b) $G_{1,1,0}$ for $0 \le x \le 20$ cm and $0 \le z \le 30$ cm.

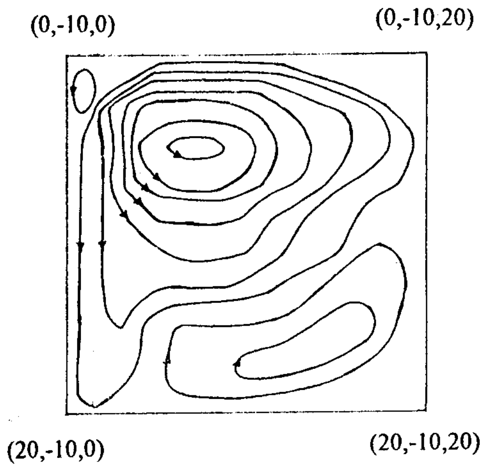


Fig. 3. Wire arrangement for $0 \le x \le 20$ cm and $0 \le z \le 20$ cm. The distribution is optimized by using the proposed design scheme. The arrows show the direction of the current.

RESULTS AND DISCUSSIONS

An x-directional SGC is designed as follows. Current distribution for the y = -10cm plane for -20 ≤ x ≤ 20 cm and -20 ≤ z ≤ 20 cm was optimized for the minimum power while having no xy components. The two perspective views in Fig. 2 show $G_{1,0,0}$ and $G_{1,1,0}$, respectively (for 0 ≤ x ≤ 20 cm and 0 ≤ z ≤ 30 cm). Figure 3 shows the optimized wire distribution for x ≥ 0 and z ≥ 0. This coil has a symmetric current pattern about the z = 0 plane (even) and the x = 0 plane (odd). Errors from the ideal linear gradient coil for x = 0 to 5 cm (with y = z = 0) are shown in Fig. 4 for our coil (___) and the coil proposed in (1) (----). Our design shows substantial improvement over the previous design. One of the advantages of our design scheme is the fact that any unnecessary high-order gradient components can be selectively removed. Since the xy component has been removed in our design, the dependency of the gradient intensity on the distance to the coil has to be small. Figure 5 shows the x gradient intensity for x = z = 0 and 5 ≤ L ≤ 14 cm, where L is the distance to the coil, showing the effectiveness of our design scheme considering that xy component was removed for L = 10 cm (or y = 0).

SGC designs for other directions were done in similar ways and the experimental performance of the coils has been in good agreement with the theory.

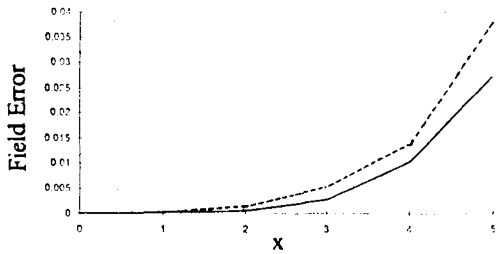


Fig. 4. Linearity comparison. Errors from the ideal linear gradient field for 0 ≤ x ≤ 5 cm (with y = z = 0) are shown for our coil and the coil proposed in (1).

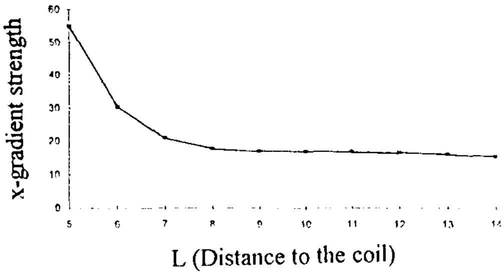


Fig. 5. Gradient intensity for x = z = 0 and 5 ≤ L ≤ 14 cm (L : distance to the SGC). It shows almost constant gradient for 8 ≤ L ≤ 14 cm showing the effectiveness of our design scheme.

REFERENCES

1. Cho, Z.H., Yi, J.H., *J. Magn. Reson.*, 94, 471, 1991.
2. Turner, R., Bowley, R.M., *J. Phys. E.*, 19, 876, 1986.
3. Edelstein, W.A. *et. al.*, European Patent Application 84112346.6, 1984.
4. Mansfield, P., Chapman, B., *J. Magn. Res.*, 72, 211, 1987.
5. Turner, R., Proc. SMRM VII, 26, 1988.
6. Oh, C.H., Hilal, S.K., U.S. Patent No. 5,122,748, 1992.
7. Oh, C.H., Yi, Y., Kim, M.G., *et. al.*, Proc. SMRM XII, p. 1310, 1993.