A New Spatial Localization Technique Using High-Order Surface Gradient Coils (SGC)

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고차표면 경사자계코일을 이용한 새로운 공간 선택 방법

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ABSTRACT

A new spatial localization technique using high-order surface gradient coil (SGC) is proposed. Although the Spatial Selection with High-Order gradienT (SHOT) can provide a 2-D selection with only one selective RF pulse, the high-order gradient produced by cylindrical-shape coils has not been clinically useful for clinical systems due to the large minimum selection size caused by the limited radial gradient intensity. However, by using the proposed high-order SGCs located near the imaging region, the size of volume selection can be reduced to a clinically useful 1-4 cm in diameter by applying stronger radial gradient with much less gradient driving power. A 40 cm-by-40 cm r^2 SGC has been designed and constructed, and phantom and volunteer studies have been performed. Experimental results using spatially localized MRI show good agreement to the theoretically predicted behavior.

INTRODUCTION

Since high-order magnetic field gradients can provide multi-dimensional selection with only one selective RF pulse (SHOT: Selection with High-Order GradienT), they are useful for spatial selection for localized volume spectroscopy or imaging (1,2). By using a radial gradient field to select a volume in two directions or more, one can achieve a 3-dimensional selection with only one or two selective RF pulses which leads to many advantages in spatial localization for MRS and MRI, for example, shorter minimum echo time and less selection artifact. However, due to the necessity of too much driving power to generate proper gradient intensity, its application has been limited to small-bore animal systems (1,2) or, to the selection of unreasonably large volume in case of large-bore systems, which is clinically not useful (3). To overcome this problem, the use of Surface Gradient Coils (SGC) (4) is proposed in this paper. The advantages of using SHOT with SGCs are:

(1) *Achieving a 3-D selection by using only two selective RF pluses.* After a slice is selected by a 90^0 excitation RF pulse applied with a z-gradient, the other two-directional selection is achieved by only one more selective RF pulse applied with a pulsed radial gradient (r^2). (See Fig. 1 for the 3-D selection process.)

(2) *Less gradient driving power.* Compared to the cylindrical r^2 gradient coil for a whole-body system where more than 130 Amp. (more than 10 kWatt of instantaneous power) was needed to select a 8-cm-diameter circular volume (radial direction selection) (5), 1 to 4-cm-diameter region can be selected with less gradient driving power (less than 10 Watt).

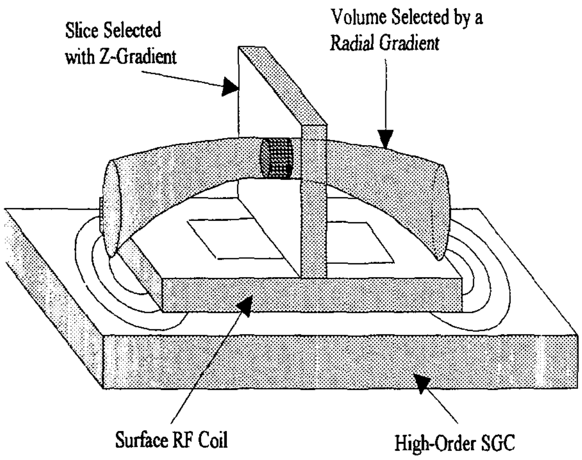


Fig. 1. 3-D selection process using a high-order (r^2) SGC. A slice is selected by applying a selective RF pulse with a z-gradient. Then spins in a radial volume is selectively refocused by a 180° selective RF pulse applied with a high-order gradient.

METHOD (6)

The r^2-SGC is designed as follows. The z-directional field at (x, y, z) from an x-directional current element at (x_0, y_0, z_0) (normalized to a unit length (m)) is

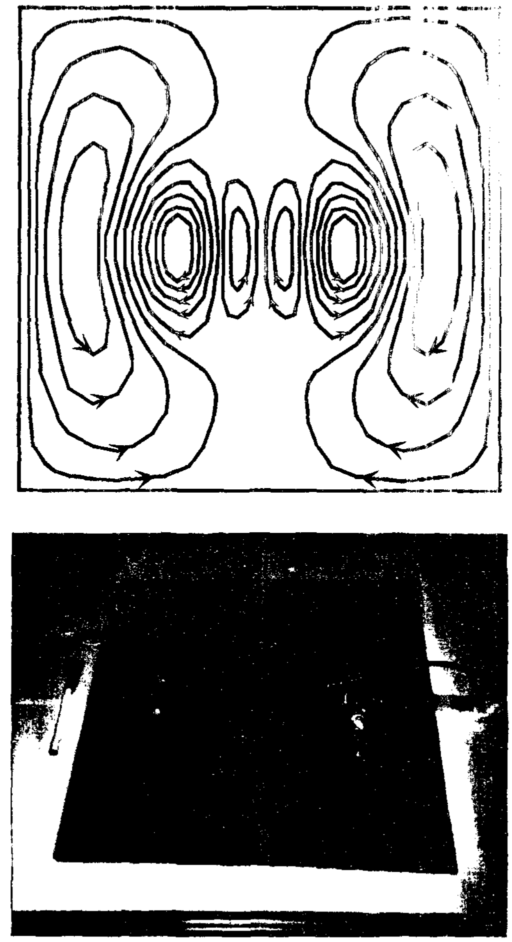
$$B_{z,n} = \frac{\partial}{\partial x_0}\left[-\frac{\mu_0 I}{4\pi} \cdot \frac{y_0 - y}{(y_0 - y)^2 + (z_0 - z)^2} \cdot \frac{x_0 - x}{\sqrt{(y_0 - y)^2 + (z_0 - z)^2 + (z_0 - z)^2}} \right], \quad [1]$$

where μ_0 is the permeability of the free space and I is the current in Ampere. From Eq. [1], the $x^l y^m z^n$-gradient component at $x=y=z=0$ becomes

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

$G0,0,0$, $G0,0,2$, $G0,1,2$, and $G2,0,0$ - $G0,2,0$ corresponding to z^0, z^2 (equivalent to r^2), yz^2, and x^2-y^2 components, respectively, are calculated for a given set of current elements in the x-z plane. Numerical calculation of $G_{l,m,n}$ is done by recursively calling C routines.

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) and $\boldsymbol{i}^t$ is its transposition, while satisfying the following two conditions.



(a)

(b)

Fig. 2. A high-order SGC for r^2 gradient generation. (a) The schematics of the SGC showing the wire layout. (b) The photograph of the r^2 SGC constructed according to the wire layout shown in (a). The wire has a 2 mm by 8 mm cross-section and epoxy is used to form the coil.

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

(2) $\nabla \cdot \boldsymbol{i} = 0$. This condition is required for the current continuity (7). Both x- and z-directional current are considered in this constraint. In our simulation, eight outward current elements are selected for every set of four adjacent locations and the sum of the currents is set to zero (6).

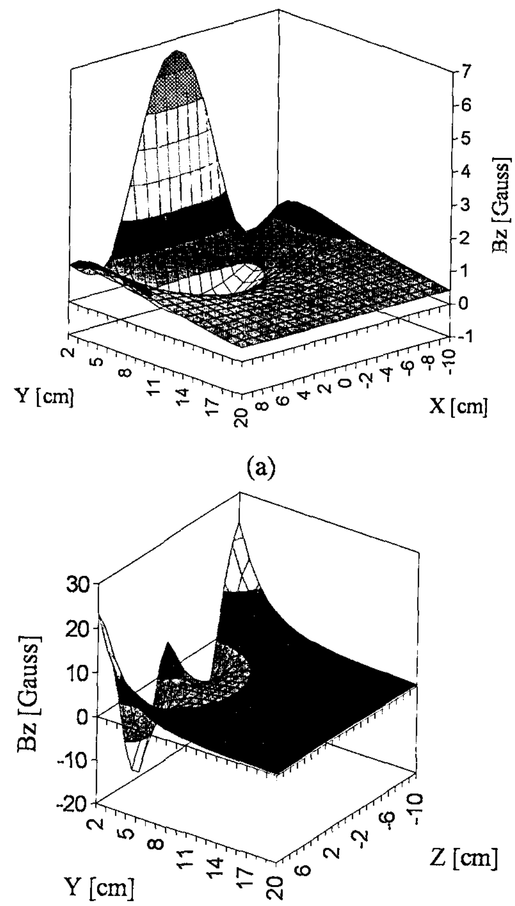


Fig. 3. The z-directional magnetic field maps calculated using the current distribution in Fig. 3(a). A 50-Amp current was assumed for the calculation. An x-y- and y-z- plane field maps are shown in (a) and (b), respectively.

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

$$i = N^t[NN^t]^{-1}\, l \qquad [3]$$

RESULTS AND DISCUSSION

An r^2- SGC has been designed and constructed and used on the 2.0-Tesla MRI system at KAIS. Figure 2 shows the wire layout, (a), and the picture of the constructed coil (with the surface RF coil on top of it) of an r^2 SGC, (b), designed for a size of 40 cm x 40 cm and an assumed imaging center 10 cm above the coil. Its calculated z-directional field

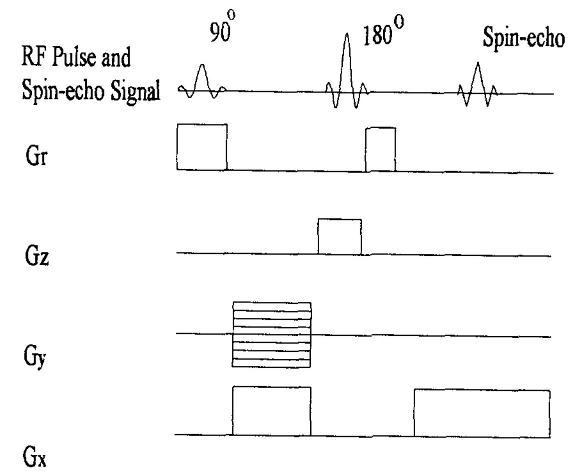


Fig. 4. The RF and gradient pulse sequences for the volume-selective MRI using the proposed high-order SGC. This pulse sequence can be easily changed for spatially selective MRS by removing the spatial encoding and read gradients.

intensity maps in the x-y and y-z planes are shown in Figs. 3(a) and (b), respectively.

The selection method using a high-order SGC has been tested by using it for volume selected imaging. The RF and Gradient pulse sequences are shown in Fig. 4. Phantom and volunteer head imaging has been performed. Isolated elliptical regions are selected as expected.

The above RF and gradient pulse sequences can be easily modified for Localized Magnetic Resonance Spectroscopy (LMRS) or Chemical Shift Imaging (CSI) by removing the read gradient and adding more encoding gradients.

ACKNOWLEDGMENTS

This work was supported by NON DIRECTED RESEARCH FUND, Korea Research foundation.

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