Spatial localisation of NMR signals and electrical scanning of sensitive regions by the magnetic focusing method

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Abstract—The spatial localisation of NMR signals by the magnetic focusing method is examined and a method for electrical scanning of a spatially localised region is proposed. The small amount of signal from points of the star taper in static field focusing can almost be neglected, and the spatial localisation of the signal corresponds to the shape of a prolate spheroid in the centre region of the star-shaped focusing field. Electrical scanning of the focused region can be achieved at any position in the magnet system by superimposing linear field gradients on the focused field in the scanning direction. These are the inherent limitations of the static magnetic field focusing method. The embodiment of the scanning movement of the focused field is also confirmed.

Keywords—Electrical scanning, Magnetic focusing method, NMR, Nonlinear magnetic field gradient, Spatial localisation, Star-shaped focusing field

1 Introduction

Magnetic resonance imaging (MRI) has been widely applied in various subfields of medicine as a new diagnostic technique. Interest in obtaining accurate information about relaxation times or high-resolution NMR spectra from a restricted region within animal and human subjects has rapidly increased; data are used to examine the tissue characterisations or the metabolic functions in various organs in vivo (PARTAIN et al., 1988).

The spatial localisation is essential to in vivo NMR spectroscopy. Several methods based on switched magnetic field gradients are applied in in vivo localised spectroscopy (AUE et al., 1984; BOTTOMLEY et al., 1984; LUYKEN and DEN HOLLANDER, 1986; ORDIDGE et al., 1986). However, the exact localisation of the volume remains an important problem with these techniques. The magnetic field focusing technique is also a method of obtaining spatial localisation. The two main methods of magnetic field focusing are based on localising the static field $B_0$ and the RF field. The most commonly used method for localising the RF field is the use of a surface coil (ACKERMAN et al., 1980). This method is simple, yields a good filling factor and is widely applied in MRI and MRS. However, the selected volume is determined exclusively by the sensitive volume of the coil and boundaries are poorly defined. To achieve better localisation with surface coils, various techniques based on either phase-cycled or depth-resolved composite pulse sequences have been proposed (BENDALL and GORDON, 1983; BENDALL et al., 1984; STYLES et al., 1985; MORRIS et al., 1989). Although these techniques improve spatial selectivity, it is difficult to completely suppress signals arising from regions close to the surface coil.

Field focusing with $B_0$ makes use of the direct measurements made at the spatially localised region within the subject. The sensitive point technique is a dynamic focusing method of $B_0$ in which time varying or time independent linear magnetic field gradients are applied to localise the sensitive point (HINSHAW, 1976). Problems with this method include the poorly defined boundaries of the sensitive volume and excessive lineshape broadening (MEIER and THATCHER, 1979; SCOTT et al., 1982). The methods that use static field focusing of $B_0$, such as field focusing nuclear magnetic resonance (FONAR) (DAMADIAN et al., 1976), topical magnetic resonance (TMR) (GORDON et al., 1980; HANLEY and GORDON, 1981) and our magnetic focusing method (ABE et al., 1974; 1976; TANAKA et al., 1978) were also developed to obtain relaxation times or high-resolution NMR spectra in the localised region within the subject body. In these methods, static nonlinear magnetic field gradients are used to profile and restrict the homogeneous volume of $B_0$. Currently, these methods have a serious limitation in that the focused region must be at the centre of the main static magnetic field, which requires the experimental object to be moved for every new volume element of interest. Furthermore, the focused region does not match the shape of a spatially localised point or spheroid, but is the shape of a star (ABE et al., 1984).

We examined the spatial localisation of NMR signals by the magnetic focusing method and devised a method of
electrical scanning of the spatially localised region by the combination of the focused field and linear magnetic field gradients.

2 Spatial localisation by a star-shaped focusing magnetic field

Magnetic field focusing uses static nonlinear magnetic field gradients to localise the homogeneous volume of the main magnetic field. In the TMR method, fourth-order field gradients are used to create sharp boundaries (Gordon et al., 1980; Hanley and Gordon, 1981), but in the magnetic focusing method, second-order gradients are used (Abe et al., 1984). FONAR is similar to these methods, but it differs in that no RF gradients need to be used (Damadian et al., 1976; Damadian, 1980). These nonlinear field gradients are obtained by superposition of a magnetic field of a coaxially symmetrical coil pair and the static main field \(B_0\). The equicontour map of the resultant magnetic field has a starlike shape (Crooks, 1981).

Fig. 1 Schematic diagram of the circular coil pairs used for the generation of the star-shaped focused field. The inner coil pair is used for the generation of the focused field. The other two coil pairs are used for the scanning movement of the focused region. The mean radius of each coil is designated \(a_1\), \(a_2\) and \(a_3\), respectively. The direction of the current flow in every coil pair is also shown. The main static field of 1.4 T by the magnet system was superimposed on the z axis.

In the present study, a relatively simple circular coil pair is used (Fig. 1). The inner coil pair is used for the generation of the focused field. The other two coil pairs are explained in the following section. The resultant magnetic field \(B_f(r, z)\), which is the superposition of the field of the coil pair and the main field \(B_0\), can generally be described as

\[
B_f(r, z) = \sqrt{(B_0 + \Delta B_x)^2 + \Delta B_z^2}
\]

\[
= B_0 + C_0 + C_2 \left\{ \frac{z^2}{\rho} - \frac{1}{2} \left( \frac{r^2}{\rho} \right) \right\} + C_4 \left\{ \frac{z^4}{\rho^4} - 3 \frac{r^2}{\rho^2} \cdot \left( \frac{z}{\rho} \right)^2 + \frac{3}{8} \frac{r^4}{\rho^4} \right\}
\]

where \(\Delta B_x\) and \(\Delta B_z\) are the axial and the radial field components of the coil pair, respectively, and \(C_0, C_2, C_4\) represent the coefficients for the truncated series. \(\rho\) and \(r\) are given by the following equations:

\[
\rho = a_1^2 + b^2 \quad \text{(2)}
\]

and

\[
r = \sqrt{x^2 + y^2} \quad \text{(3)}
\]

The focused field of the coil pair \(B_f(r, z)\) can be defined by the following equation:

\[
\Delta B_f(r, z) = B_f(r, z) - (B_0 + C_0)
\]

In the TMR method, the coefficient \(C_2\) of the second-order gradient is set to zero (Hanley and Gordon, 1981), on the other hand, \(C_4\) of the fourth-order gradient is set to zero in the magnetic focusing method (Abe et al., 1984). The various coil parameters in Fig. 1 are as follows:

- \(a_1\) = mean radius of the coil (14 mm)
- \(2b\) = distance between two coils (39 mm)
- \(N\) = number of turns of winding (95 turns)
- \(I\) = current.

By using these coil parameters eqn. 4 can also be written as follows:

\[
\Delta B_f(r, z) = \frac{h z^2}{2} \cdot \left( x^2 + y^2 \right)
\]

where

\[
h = \frac{3a_1^2(4b^2 - a_1^2)N}{2(a_1^2 + b^2)^{3/2}}
\]

The equicontour map of the resultant magnetic field, a superposition of a focused field \(\Delta B_f(r, z)\) whose magnetomotive force \((N \times I)\) was 15 ampere-turns and the main static field \(B_0\) of 1.4 T, is symmetrical to the z axis. The calculated contour map, of the order of \(\pm 5\) to \(\pm 15\) PPM, compared with the central field intensity is shown in Fig. 2. The contours take a starlike shape in the x-z and y-z planes as shown in this figure. Spatial localisation, as defined by signal intensity distribution, was examined at 60 MHz with a modified pulse NMR apparatus (JEOL, FSE-60C, Japan) having an electromagnet air gap of 52 mm and a solenoid-type detector coil diameter of 33 mm. The results shown in Fig. 3 were obtained by placing a small water sample (2 mm \(x\) 4 mm) at various points, with the detector coil centred on the focused field shown in Fig. 2. In the absence of field focusing, the signal