

Magnetic Field Distribution Measurement by the Modified FLASH Method

Ján Weis, Ivan Frollo, and Luboš Budinský

Institute of Measurement and Measuring Engineering, Electro-physical Research Centre,
Slovak Academy of Sciences, Bratislava, Czechoslovakia

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Magnetic field inhomogeneities cause blurring and distortion of images gained by nuclear magnetic resonance. In order to adjust the magnetic coils finely, a precise and rapid method for measuring the magnetic field is needed. We describe a gradient echo technique of the FLASH version for mapping static magnetic fields.

Key words: NMR imaging – FLASH – magnetic field measurement – inhomogeneity – image distortion

1. Introduction

In nuclear magnetic resonance imaging of spin densities in body tissues and proton relaxation times, the quality of the images depends on the homogeneity of the static magnetic field. The undesired components of magnetic field cause geometrical and amplitude distortions of the images. Generally, a static field with a uniformity better than 10 ppm is needed. In order to generate such an accurate magnetic field, the main magnetic coils, the gradient magnetic coils and compensation coils have to be adjusted very precisely. For this reason, these superposed magnetic fields have to be measured.

Normally, a field is measured point by point using a detection probe. This is, however, extremely time consuming. Maudsley [1, 2], Braun et al. [3, 4], Sekihara [5, 6], and Kawanaka [7] proposed methods of measuring the static field of NMR imaging equipments. Generally we can consider them to be modified Fourier transform imaging methods [8]. Each method has its advantages and disadvantages.

The advantage of the Maudsley method is its relatively high precision. This method is not affected by RF inhomogeneities of the transmitting and receiving coils. The main disadvantage is the long acquisition and computing time, because for two-dimensional mapping a 3DFT measuring sequence must be used.

Sekihara's method is principally 2DFT. It uses phase information from Fourier transform. The precision of this method is significantly affected by noise and all factors which cause phase errors. Also the SENEX method proposed by Braun et al. is principally 2DFT method. The usual spin echo image is superimposed by field markers. A disadvantage is the form of the resulting map of the magnetic field which consists of alternating bright and dark zones. The distances between the dark structures correspond to certain deviations of the magnetic field. This complicates the construction of the magnetic field map, especially if the form of the inhomogeneity is not simple. Finally Kawanaka [7] proposed a 2DFT method for the estimation not only of the static magnetic field, but also of the gradient fields from spin density images. Low precision of this method results from the low precision of the position of the phantom objects in the final image.

In this paper we propose a modified form of Maudsley's method using a gradient echo method of the FLASH version. This modification significantly reduces the acquisition time, which is one of the greatest disadvantages of the original method.

2. Field Distribution Measurement

We let the stationary magnetic field B_0 be aligned along the z axis and assume that we wish to measure the field distribution in the (x, y) plane with a spatial

Reprint requests to Dr. J. Weis, ÚMMT CEFV SAV,
Dúbravská cesta 9, 842 19 Bratislava, Czechoslovakia.

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resolution of Δx , Δy over a region of width Δz . We assume that the NMR linewidth in the volume $\Delta x \Delta y \Delta z$ is smaller than the final observed frequency range corresponding to the maximum field distribution to be measured. The linewidth will be affected by the field inhomogeneity over each volume element $\Delta x \Delta y \Delta z$, which we shall assume to be so small that the resultant linewidth approaches the natural linewidth of the spin system given by $2/T_2$ (full width at half height), where T_2 is the transverse relaxation time of the spin system. The excitation of a narrow region Δz of spins can simply be achieved by defining the sample volume, using a disk shaped container filled with water. Then the distribution of the magnetic field used for imaging can be expressed by the coordinates (x, y) . Then static field $B(x, y)$ and gradient fields G_x , G_y are defined as follows:

$$\begin{aligned} B(x, y) &= B_0 + \Delta B(x, y), \\ G_x(x, y) &= g_x x + \Delta g_x(x, y), \\ G_y(x, y) &= g_y y + \Delta g_y(x, y), \end{aligned} \quad (1)$$

where B_0 is the uniform component of the static field, g_x and g_y are linear components of the gradient fields and $\Delta B(x, y)$, $\Delta g_x(x, y)$ and $\Delta g_y(x, y)$ denote undesired components. In our measurement configuration, the NMR signal is derived using the pulse sequences shown in Fig. 1: After an initial excitation RF pulse B_1 ($\alpha < 90^\circ$) the system is allowed to evolve for a time period $T = m \Delta T$, ($m = 0, 1, 2, \dots, M$) in the absence of a superimposed gradient. Any distribution of the field $B(x, y)$ over the excited volume will cause a variation in the precession frequencies of the spins during this time period. Then the spins evolve in the presence of the spatial encoding gradient G_x , G_y in the manner of the standard Spin Warp method [9]. The whole procedure of the Spin Warp method is repeated for M values of the time period T . The spin echo is sampled after quadrature detection at the angular frequency $\omega = \gamma B_0$ (γ – gyromagnetic ratio) only during the time $-\Delta\tau \leq \tau \leq \Delta\tau$, where $\tau = t - T_e$ (see Fig. 1) and T_e is the time of the echo centre, which is defined [10] as

$$\int_0^{T_e} G_x(x, y) dt = 0. \quad (2)$$

The observed signal denoted by $S(t, m, n)$ will be the sum of various signals:

$$S(t, m, n) = \iint \varrho(x, y) s(t, m, n) dx dy, \quad (3)$$

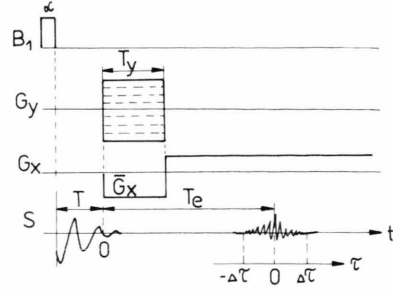


Fig. 1. RF and magnetic field gradient sequence used for the observation of the magnetic field distribution in the (x, y) plane.

where $\varrho(x, y)$ is the spin density distribution and $s(t, m, n)$ is the signal contribution related to the spin density from the volume element $\Delta V = dx dy \Delta z$. The signal contribution $s(t, m, n)$ for $t > T_y$ is given by [11]

$$\begin{aligned} s(t, m, n) &= A \exp[-(T + t)/T_2] \\ &\cdot \exp[-i \gamma \Delta B(x, y) m \Delta T] \\ &\cdot \exp[-i \gamma (\Delta B(x, y) + \bar{G}_x(x, y)) (t - T_y)] \\ &\cdot \exp[-i \gamma (\Delta B(x, y) + G_x(x, y) + G_y(x, y) n) T_y], \end{aligned} \quad (4)$$

where A is a constant expressing the sensitivity receiver, etc, and $n = -N, -N + 1, \dots, -1, 0, 1, \dots, N - 1, N$, and $\bar{G}_x(x, y) = -\text{const}$. $G_x(x, y)$ is the reversed readout gradient for $t < 0, T_y$. In our case, from (2) follows that $T_e = (1 + \text{const}) T_y$. By introducing $\tau = t - T_e$ into (4) we derive

$$\begin{aligned} s(\tau, m, n) &= A \exp[-(T + T_e + \tau)/T_2] \\ &\cdot \exp[-i \gamma \Delta B(x, y) (1 + \text{const}) T_y] \\ &\cdot \exp[-i \gamma \Delta B(x, y) \Delta T m - i \gamma \Delta B(x, y) + G_x(x, y) \tau] \\ &\cdot \exp[-i \gamma T_y G_y(x, y) n]. \end{aligned} \quad (5)$$

Defining a new coordinate system as proposed by Sekihara [12]:

$$\begin{aligned} x' &= x + \Delta B(x, y)/g_x + \Delta g_x(x, y)/g_x, \\ y' &= y + \Delta g_y(x, y)/g_y, \end{aligned} \quad (6)$$

combining (1), (3), (5) and (6) and neglecting the term describing the relaxation effect, we can write

$$S(\tau, m, n) = A \iint \varrho_e(x', y') \cdot \exp[-i \gamma (\Delta B(x, y) \Delta T m + g_x x' \tau + T_y g_y y' n)] dx' dy',$$

for observed signal, where

$$\begin{aligned} \varrho_e(x', y') &= \varrho(x, y) \\ &\cdot \exp[-i \gamma \Delta B(x, y) (1 + \text{const}) T_y]/W(x, y) \end{aligned}$$

and

$$W(x, y) = \begin{vmatrix} \partial x' / \partial x & \partial x' / \partial y \\ \partial y' / \partial x & \partial y' / \partial y \end{vmatrix}.$$

The three dimensional Fourier transform of $S(\tau, m, n)$, denoted $V(\vartheta, \xi, \psi)$, is then

$$V(\vartheta, \xi, \psi) = \iiint S(\tau, m, n) \cdot \exp[-i(\vartheta m + \xi \tau + \psi n)] d\tau dn dm.$$

In an idealized case ($\tau, m, n \in (-\infty, \infty)$) this yields

$$V(\vartheta, \xi, \psi) = C \iint \varrho_e(x', y') \delta(-\gamma \Delta T \Delta B(x, y) - \vartheta) \cdot \delta(-\gamma g_y T_y y' - \psi) \cdot \delta(-\gamma g_x x' - \xi) dx' dy',$$

i.e.

$$V(\vartheta, \xi, \psi) = D \delta(-\gamma \Delta T \Delta B(x, y) - \vartheta) \varrho_e(\xi, \psi)$$

for $\xi = -\gamma g_x x'$, $\psi = -\gamma T_y g_y y'$ and constant C and D . The absolute value [9] of $V(\vartheta, \xi, \psi)$ represents the spin density distribution $\varrho_e(\xi, \psi)$ stored in a three dimensional matrix with non-zero elements along the ϑ coordinate only at the position $\vartheta \sim \Delta B(x, y)$. The field deviation at each point therefore appears as a shift of the signal in the ϑ axis, which is directly proportional to the field strength. A two dimensional image of the field distribution is then obtained by measuring the frequency offset along the ϑ axis for each element of (ξ, ψ) of the resultant data, and then inserting these values in a two dimensional data array, which may then be displayed in a suitable manner, for instance as brightness of an image, or as the amplitude of a 3D axonometric picture (see Figure 2).

3. Experimental Results

We have tested the proposed method using a home-built NMR tomograph with a resistive magnet having a 400 mm room-temperature bore. The results were obtained at a field strength of 0.0855 T using a proton resonance of 3.64 MHz. A circular phantom, 100 mm in diameter and 5 mm thick, was positioned in the central transverse plane of the magnet. Fig. 2 shows the result of the experiment. As a check of the field distribution, the field was measured at selected points across the measured plane. This is shown in Fig. 3. The correspondence between the two measured field distributions is quite acceptable but there are some differences. In our opinion, these differences are caused by noise influence in the proposed method (Fig. 2), and on the other hand by the relatively great size of the active sample ($3 \cdot 8 \cdot 18$ mm) of the NMR gaussmeter,

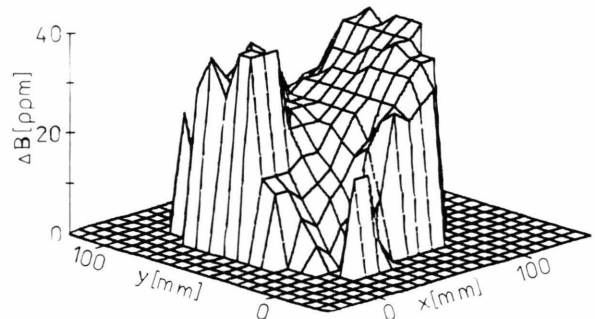


Fig. 2. 2D field distribution over a 100 mm diameter cross-sectional area measured by the proposed method.

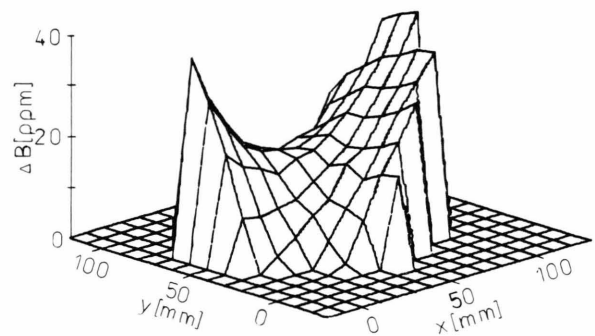


Fig. 3. 2D field distribution in selected points measured with a gaussmeter.

and also by the small measurement matrix (step 10 mm) in the plane of circular phantom (Figure 3). We used $g_x = 1.36$ mT/m, $g_y = 0.128$ mT/m, and $\Delta T = 3$ ms for the measurement matrix (32, 32, 32). These values can be determined by standard Fourier transform NMR theory. For a time repetition $TR = 200$ ms and one accumulation, the total measuring time was less than 3.5 minutes.

We note that it is not necessary to know the distribution function $\varrho(x, y) \neq 0$ though, obviously, it should be finite. Also the RF homogeneity and spatial variation of the received NMR signal are unimportant. The signal intensity will be affected but the final shift of the main maximum along the ϑ axis remains unaffected. Any undesired components of the magnetic field, e.g., $\Delta B(x, y)$, $\Delta g_x(x, y)$, $\Delta g_y(x, y)$ will produce spatial geometrical distortions of the final field distribution image, as follows from (6). These geometrical distortions can be restored by using $\Delta B(x', y')$ instead $\Delta B(x, y)$ in (6), as pointed out by Sekihara [5].

4. Conclusion

We have proposed a modification of Maudsley's method [1] for measuring the static field distribution in NMR imaging equipment. The advantage of this method is, that it does not require application of

180° RF pulses. Therefore this method can be easily implemented as a FLASH technique [13]. It takes advantage to measure the magnetic field distribution without long 300–3000 ms waiting periods (TR) between excitations. The total measuring time is then significantly reduced.

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