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QUALITY OF GRADIENT MAGNETIC FIELDS ESTIMATION

Eva Gescheidtova* — Radek Kubásek ** — Karel Bartušek ***

Imaging techniques based on the principle of nuclear magnetic resonance (MRI) can be used in the study of molecular transport phenomena in biological systems such as self-diffusion processes. The precision of determining the diffusion constants depends on generating the gradient pulse with high precision. For the purpose of determining the characteristics of time behaviour of gradient pulses a simple measuring method was developed and experimentally tested on a 4.7 T tomograph. The method is based on the principle of measuring the instantaneous frequency of MR signal in the presence of gradient pulse after the excitation of a thin defined layer of the examined specimen placed outside the gradient field centre. Using the above method, errors were found in the amplitude and time integral of generated gradient fields and in determining the diffusion constants for biological tissues.

Keywords: NMR, MR, Gradient field, Gradient measurement

1 INTRODUCTION

Pulsed magnetic field gradient NMR experiments constitute a very useful tool for investigating molecular transport phenomena such as self-diffusion processes. In the conventional NMR experiment the technique introduced by Stejskal and Tanner [1] employs a pair of time-dependent inhomogeneous magnetic fields (the so-called pulsed field gradients) superposed on a static magnetic field B_0 for the purpose of coding and reading the position of nucleus spins in the specimen during the measurement. Additional gradients of magnetic field B_0 may result from the inhomogeneity of the magnetic field of the magnet or they are generated by the differences in magnetic susceptibility within the heterogeneous specimen (vegetal and cell tissues, porous materials, etc.). Diffusion measurement by PFG NMR methods may be spoiled by the interference of basic field gradients and pulsed field gradients. Not negligible is the effect of the parameters of pulsed field gradients (such as the amplitude, rise time and length of pulse) on the precision of measuring the diffusion coefficients in biological tissues featuring short relaxation times T_1 and T_2. These parameters are affected by the NMR device and its quality.

In the present work the problem is addressed of checking the properties of generated pulsed field gradients. A novel NMR measuring sequence was proposed which will determine with sufficient precision the whole time behaviour of pulsed gradients and enable calculating the difference in the time integrals of gradient pulses in the positive and the negative polarity. To measure the time characteristics of magnetic field gradients different MR methods are used, the most interesting among them being [2] to [5]. All of them were used for setting precisely the pre-emphasis compensation in MR topographic systems. Proposed for the same purpose were the IF, IFSE and IFSES techniques of measuring instantaneous frequency [6], [7], which enable measuring precisely the trailing edges of a single gradient pulse. They have a disadvantage in that they do not enable measuring the whole time behaviour of gradient pulse.

2 THEORY

For pulsed magnetic field gradients the decay of spin echo signal is proportional to their time integral. The time behaviour of gradients in the simplest measuring sequence (PFG) is illustrated in Fig. 1, where G_1 and G_2 are the amplitudes of the first and the second gradient pulse.

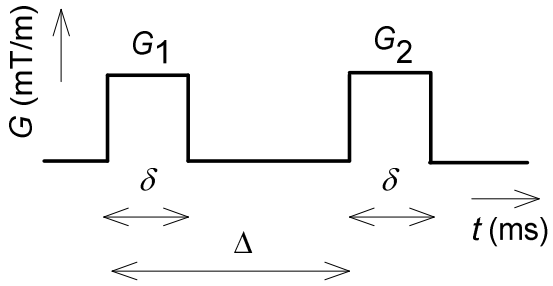

Fig. 1. Waveform of gradients in PFG measuring sequence

The decay of NMR spin echo caused by the diffusion process (while neglecting all relaxation processes) can usually be calculated according to the relation (1)

$$\ln \frac{M(t_e)}{M_0} = -D\gamma^2\delta^2 G^2 \left(\Delta - \frac{\delta}{3}\right). \quad (1)$$

If the amplitudes (or time integrals) of the two gradients are not identical, an error appears in determining the diffusion coefficient δD. The magnitude of this error, established by numerical calculation for the error in amplitude of the generated gradient G_1 is illustrated in Fig. 2 for a simple measuring sequence.

Similar errors are caused by the different time lengths of gradient pulses, e.g. by time quantization. On these grounds it is of advantage to measure the time characteristics of gradient pulses and know their time integrals.

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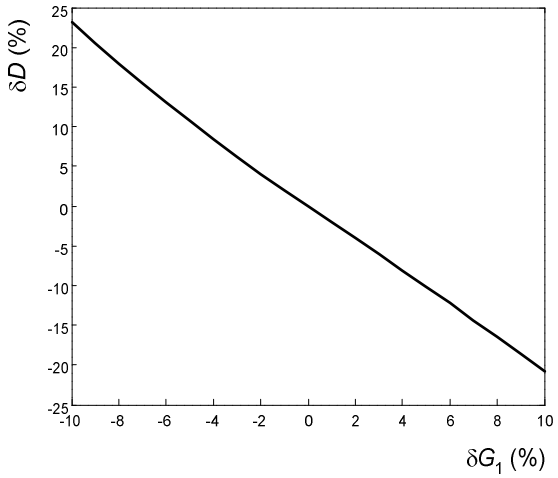

Fig. 2. Dependence of error in diffusion coefficient δD on magnitude of error in amplitude δ_{G1} of generated gradient G_1

3 MEASURING METHOD

The principle of measuring the waveform of gradient pulse consists in determining the changes in instantaneous frequency of MR signal produced by the resonance of nuclei excited in two thin layers positioned symmetrically about the gradient field centre, as shown in Fig. 3. The average inductions of magnetic field $B(x_{n,t})$ are measured in the excited layer in the +xn and $B(-x_{n,t})$ positions in the $-x_n$ layer,[8] to [10].

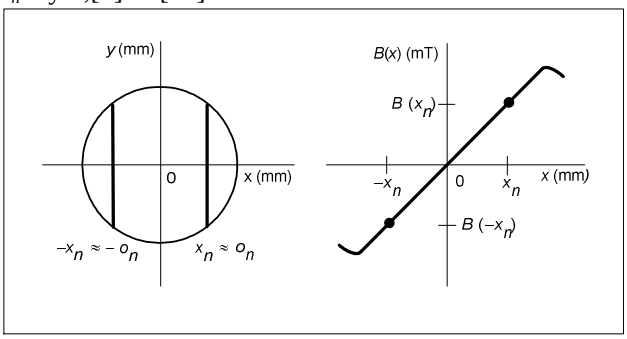

Fig. 3. Position of excited thin layers in working space of MR device

From the differences of the two inductions measured the magnitude of gradient can be calculated according to the relation

$$G_x(t) = \frac{1}{2x_n}\left[B(x_n,t) - B(-x_n,t)\right]. \quad (2)$$

Under the above conditions the instantaneous frequency of MR signal will be directly proportional to the induction of magnetic field $B(\pm x_{n,t})$. The measuring sequence has two stages – the preparatory and the executive stage as shown in Fig. 4. In the preparatory stage the selective $\pi/2$ hf pulse is used to excite in the presence of gradient G_{rs} nuclei in the selected thin layer.

The sum of the $B(x_{n,t})$ and $B(-x_{n,t})$ inductions measured determines the change in basic homogeneous magnetic field according to the relation

$$B_{0x}(t) = \frac{1}{2}\left[B(x_n,t) + B(-x_n,t)\right]. \quad (3)$$

This is followed by a non-selective π pulse, which in time t_e will excite a spin echo with its centre at the end of preparatory stage. At the end of the preparatory stage the magnetization vectors of all the nuclei excited are of identical direction and phased, and the MR signal acquires its maximum value. In the executive stage of measuring sequence the FID signal of all nuclei in the selected layer can be detected. When no gradient pulse is applied in the executive stage of measuring sequence, the instantaneous frequency of MR signal carries information about the average value of magnetic field induction in the excited layer, inclusive of the inhomogeneities of basic magnetic field. When gradient pulses are applied in the course of signal decay, there is a change in instantaneous frequency of the MR signal, which is proportional to the magnetic field induction at the place of excited layer.

The measuring sequence has two stages – the preparatory and the executive stage as shown in Fig. 4. In the preparatory stage the selective $\pi/2$ hf pulse is used to excite in the presence of gradient G_{rs} nuclei in the selected thin layer.

4 EXPERIMENTAL VERIFICATION

Using a 4.7 T/200 mm MR tomography, the waveforms of gradient pulses were measured and the time integrals were determined for each pulse separately. The measuring results for gradient pulses G_x, G_y and G_z and the magnitudes of changes in basic magnetic field B_{0x}, B_{0y} and B_{0z} due to gradient pulses are given in Figs 5 and 6.

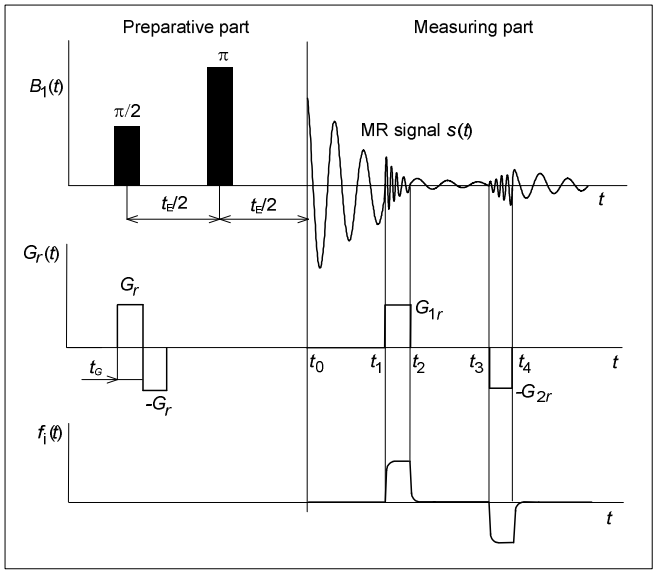

Fig. 4. Measuring sequence for measuring the time characteristics of gradient pulses

For a spherical specimen of 3.6 mm in diameter a layer 0.78 mm thick is excited by an RF pulse 18 ms long at a gradient G_r = 18 mT/m (r is the space coordinate x, y or z). For the chosen offset ±7000 Hz the layer excited is at a distance of ±9.2 mm from gradient field centre. Two gradients of 2 ms in length were applied with positive and

negative amplitude. The time distance between them was 3 ms.

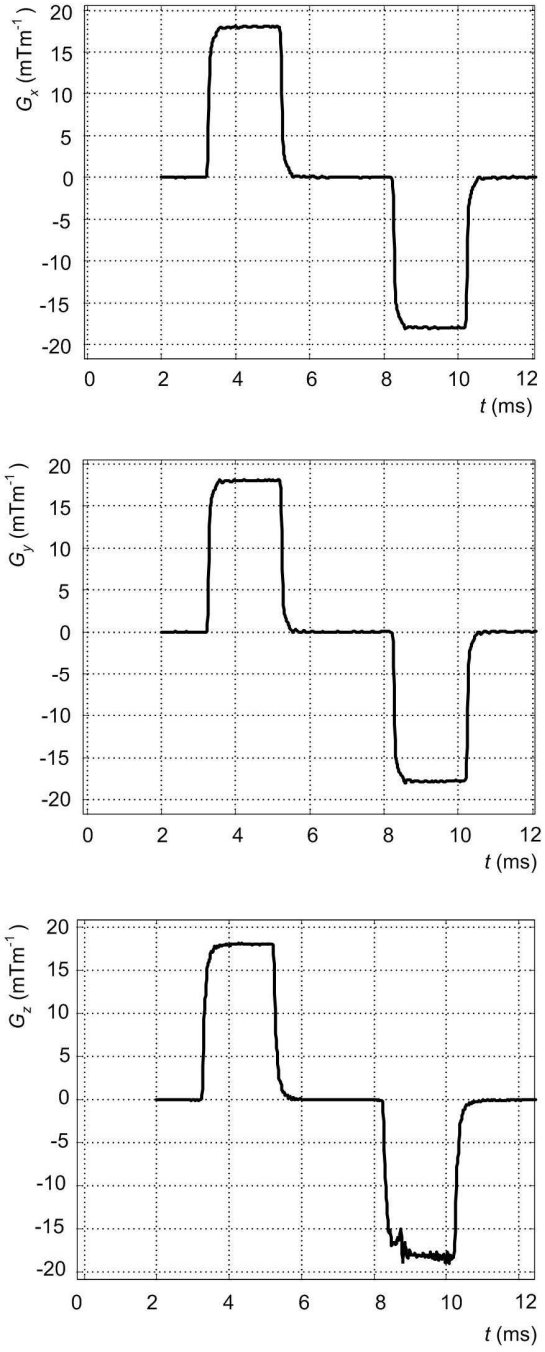

Fig. 5. Time waveform for $G_x = G_y = G_z = 18$ mT/m

It follows from the above waveforms that the pulse rise time is about 0.4 ms for all gradients. The change in basic field is different for the positive and the negative pulse. Its magnitude is ca. 20 μT and is due to ground currents in the control part of the gradient system. The beginning and also the other time changes in gradient pulse are shifted by 280 μs, which corresponds to 28 samples of digital signal. This shift is due to the anti-aliasing filter of MR tomograph. For the measured gradient pulses G_r of positive and negative amplitude the relative amplitude errors $\delta\pm G_r$ were determined. The results are given in Table 1.

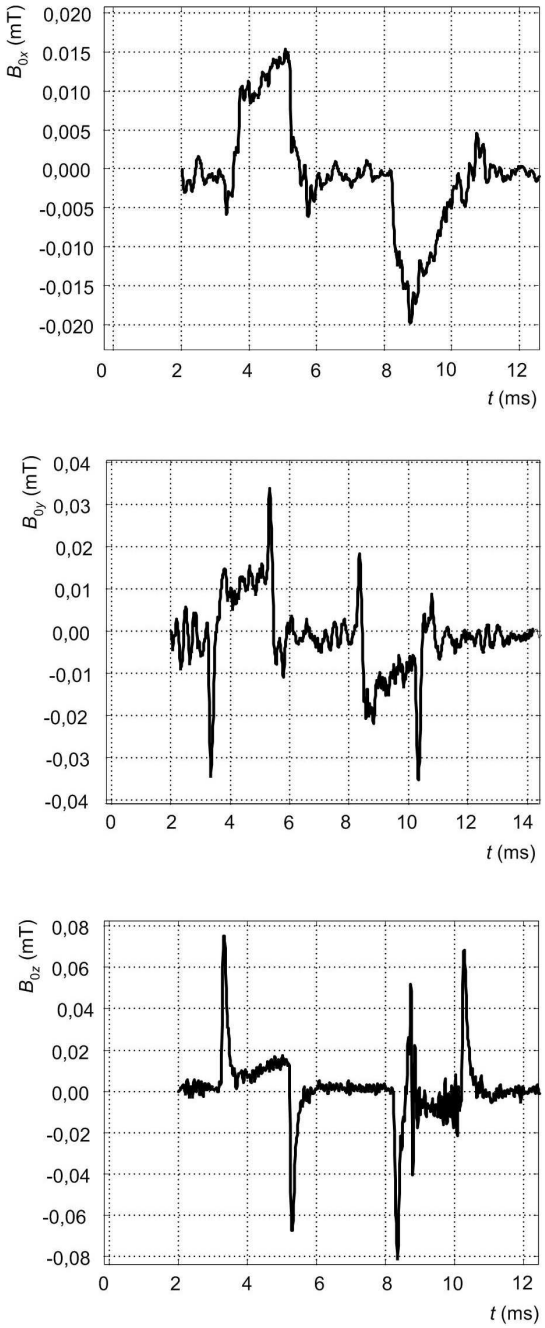

Fig. 6. Resultant time waveform of a change in basic field B_{0r} due to gradient pulses

At the same time, relative errors of the time integral of each gradient pulse with positive and negative polarity were calculated. The results are given in Table 2. According to Fig. 2 the relative errors of measuring diffusion coefficients will be twice the relative errors of the time integral of gradient pulse.

Table 1: Amplitude error of generated gradient in direction r (for $G_r = 18$ mT/m)

Direction of gradient	δ_{+Gr} [%]	δ_{-Gr} [%]
G_x	1.13	0.76
G_y	1.08	-0.18
G_z	1.00	1.80

Table 2: Error in time integral of generated gradient in direction r (for G_r = 18 mT/m, t_G = 2ms)

Direction of gradient	Integral error for $+G_r$ (%)	Integral error for $-G_r$ (%)
G_x	-1.06	-1.71
G_y	-1.28	-2.78
G_z	-1.65	-1.47

5 CONCLUSION

In the paper a simple method is described for measuring a short pulse of magnetic field gradient for the verification of the precision of measuring diffusion coefficients in biological systems. Based on the resultant time waveform of gradient pulses relative errors of the time integral have been determined for each pulse separately. In the techniques of diffusion measurement the relative error in determining the diffusion constant will be twice the relative error of the time integral of gradient pulse.

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