MKPM 기법을 이용한 확산효과 감소

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Reduction of Diffusion Effect Using MKPM Technique

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INTRODUCTION

The investigation of microscopic objects, such as single cells, by the method of magnetic resonance imaging requires an understanding of the effects of diffusion in order to correctly interpret the obtained imagings. On the time scale(milliseconds) of typical measurements, water molecules can diffuse a distance as large as or larger than the spatial resolution of the instrument. Therefore, techniques of image reconstruction for conventional macroscopic MRI, can lead to distorted density profiles of images in MRI microscopy. So, such as conventional gradient echo(GE) and spin echo(SE) images demonstrate the existence of edge enhancement and signal distortion along the read-out gradient caused by the effects of self-diffusion during an imaging pulse sequence (3,4,5,6).

From the SE experiment, the echo amplitude I(x,y) dependent of the diffusion effects decays as a function of the pulse spacing τ. And, this relation is given by

$$I(x,y)\Big/I_0(x,y) \propto \exp(-2\tau^3\gamma^2G^2D/3) \qquad [1]$$

where G is the applied field gradient, D is the spatially dependent self-diffusion coefficient, and γ is the gyromagnetic ratio. However, to reduce the possible diffusion or inhomogeneity effects from the Eq. [1], there is a need of a short read-out gradient duration. An application in an extremely short read-out gradient would be a "Single K-space Point frequency Mapping(SKPM)" that can obtain images free of diffusion, susceptibility, and chemical shift effects, but it requires very long data acquisition time such as $N^2 \times TR$ (2).

Therefore, we introduce the MKPM method to improve the long data acquisition time of the SKPM method, is free from artifacts due to the diffusion or susceptibility effect (1,2). In MKPM technique, M sampling points are acquired within a given TR, thereby total imaging time is reduced M times, that is, the total data acquisition time is $N^2 \times TR / M$. So, compared to the conventional gradient echo imaging technique, we show the potential usefulness for the diffusive relaxation of the new NMR microscopic imaging technique by the experiments focused on the diffusion effect.

METHODS

K-space analysis of NMR imaging has been wide spread recently, and has facilitated the understanding of many complex NMR imaging situation, such as spiral scan or echo planar imaging. Although k-space analysis of the conventional spin echo techniques as well as echo planar techniques rely on phase encoding in one coordinate, signals are read out by what is called frequency encoding or the read-out gradient. This read-out gradient is usually applied for a prolonged time compared with the phase encoding gradients to cover a line-data in k-space.

The prolonged read-out gradient usually introduces a number of undesirable artifacts such as chemical shift, susceptibility, diffusion artifacts normally observable in spin echo as well as gradient echo imaging pulse sequence (3,4,6). In principle, a short gradient(read-out) would cover only a relatively narrow band of frequency, and would consequently limit the resolution in the read-out direction, e.g., x-direction resolution degradation in cases where a short x-gradient is used as a read-out or frequency encoding gradient. Normally, a short gradient pulse length in the read-out direction can be compensated by a proportionally stronger gradient as the time length of the gradient is reduced together with an employment of fast sampling, so that a constant gradient amplitude × time relation is maintained.

For the sake of simplicity, let us assume that we have a one-dimensional case of NMR imaging with an object space density function $\rho(x)$, then the NMR signal $S(t)$ can be written as

$$S(t_x) = \int_{-\infty}^{\infty} \rho(x) e^{-i(xK_x)} dx$$

$$\text{or} = \int_{-\infty}^{\infty} \rho(x) e^{-ix\gamma \int_0^t xG_x(t')dt'} dx. \qquad [2]$$

In the conventional NMR imaging sequence, $G_x(t')$ is considered as a read-out gradient and can be a constant amplitude with a finite duration, i.e., read-out time duration. In this case Eq. [2] can be rewritten as

$$S(t_x) = \int_{-\infty}^{\infty} \rho(x) e^{-ix\gamma G_x t_x} dx. \qquad [3]$$

A complete data set, then, will represent the frequency spectrum the object from direct current to a maximum frequency of $\gamma G_x t_x / 2\pi$, where t_x is the read-out gradient time duration. If time is discrete, i.e., $t_x = n\Delta T_x$, Eq. [3] can be written as

$$S(n\Delta T_x) = \int_{-\infty}^{\infty} \rho(x) e^{-ix\gamma G_x n\Delta T_x} dx. \qquad [4]$$

Equation [4] represents a specific frequency component corresponding to a time $n\Delta T_x$ for a given constant strength gradient G_x. Therefore, Eq. [4] can also be written as a function of $K_x(t)$, which is given by

$$K_x(t) = K_x(n\Delta T_x)_{\Delta Gx} = \gamma \int_0^{t_x} G_x(t')dt'$$

$$= \gamma \int_0^{n\Delta T_x} \Delta G_x dt' = \gamma \Delta G_x n\Delta T_x. \qquad [5]$$

In Eq. [5], $G_x(t')$ is assumed as ΔG_x. Conversely, one can also write Eq. [5] as

$$K_x(g_x) = K_x(n\Delta G_x)_{\Delta Tx} = \gamma \int_0^{g_x} \Delta T_x dg_x'$$

$$= \gamma \int_0^{n\Delta G_x} \Delta T_x dg_x' = \gamma \Delta T_x n\Delta G_x. \qquad [6]$$

The basic difference between Eq. [5] and Eq. [6], however, is that Eq. [5] is continuous in time within a given TR while Eq. [6] is not, since time is fixed to a short period ΔT_x with $n\Delta G_x$ as a variable for a given TR. Therefore, Eq. [6] represents only one frequency component at a given sequence, that is it represents only one point in K_x. The next K_x point, therefore, can only be obtained in the next sequence with an increment of ΔG_x. Equation [5] is simply a line scan technique, while Eq. [6] is a point scan method in k-space (2).

But, k-space point mapping technique is inevitably inefficient for data acquisition compared with the k-space line scan technique, one can improve the scanning time by extending the single point scan to a group consisting of multiple points (1). Then the frequency component can be written as

$$K_x(t;k) = K_x(m\Delta T_x; k\Delta G_x')$$

$$= \gamma \int_0^{m\Delta T_x} \Delta G_x dt' + \gamma \int_0^{k\Delta G_x'} \Delta T_x dg_x'$$

$$= \gamma \Delta G_x m\Delta T_x + \gamma \Delta T_x k\Delta G_x' \qquad [7]$$

where $m = 1,2,\ldots,M$, $k = 1,2,\ldots,N/m$. In Eq. [7], m represents the sampling number in a group shown in Fig 1 (b) and k represents the group number. If M(m=M) sampling points are acquired within a given TR, next gradient offset required is $M\Delta G_x$, i.e., $\Delta G_x' = M\Delta G_x$. The duration of each data acquisition time is prolonged to M times within a given TR, but total imaging time is now reduced by M times. So, the MKPM technique as shown in Fig. 1 (a), will then lead to a proportionally improved data acquisition time without loss of the advantages gained by the original single k-space point scan technique.

EXPERIMENTS

In this article, we demonstrate the existence of signal distortion caused by the effects of the self-diffusion during an imaging pulse sequence based on the GE method which had very long read-out gradient duration time. To show these signal distortion phenomena due to the diffusion are compensated by the MKPM method, experiments were performed with 2.0T whole body NMR system. As shown in Fig. 2, a phantom contains three inner tubes(diameter = 2.35 mm) were filled with acetone and dimethyl-sulfoxide(DMSO), and distilled water($CuSO_4$ solution) at the room temperature.

First, conventional gradient echo imaging using the two dimensional Fourier technique was performed. 128 × 128 images were obtained within a TR of 100 msec and TE of 16 msec. The slice thickness was 2 mm and Field of view was 10 mm. Next, MKPM imaging which was extended sampling point to 4 points for each TR was performed. TR and TE were 100 msec and 6 msec, respectively, other imaging parameters were same as those of gradient echo imagings.

As expected, the gradient echo image shown in Fig. 3 (a), that shows the seriously signal distortion due to the self-diffusion of water molecules in the distilled water and acetone tubes, and signal enhancement due to the diffusion effect, such as the edge enhancement around boundaries. The signal distortion of tubes is dependent on the different diffusion coefficients. Then, the MKPM image free from the diffusion effect shown in Fig. 3 (b), which shows that the signal distortion of the inner tubes are compensated, however, the edge enhancement around boundaries is obscurely shown. From these experiment results, the influence of diffusion or susceptibility is removed by a MKPM technique with short TE and time duration of read-out gradient.

DISCUSSIONS AND CONCLUSION

As shown in Fig. 3 (a) and (b), the signal distortion due to the diffusive relaxation in the tubes where materials have different diffusion coefficient, removed in MKPM imaging compare to GE imaging. And, different from the other conventional gradient echo imaging techniques, MKPM imaging technique is possible to the reduction of TE, therefore, an imaging of the material with short T_2 is available. But, more analyses and experiments for the edge enhancement due to diffusion effect are needed, the MKPM technique is useful for the reduction of the diffusion effect. Those potential advantages are expected to be applied in many areas of NMR imaging where diffusion or susceptibility effects are of the prime concern, such as NMR microscopy.

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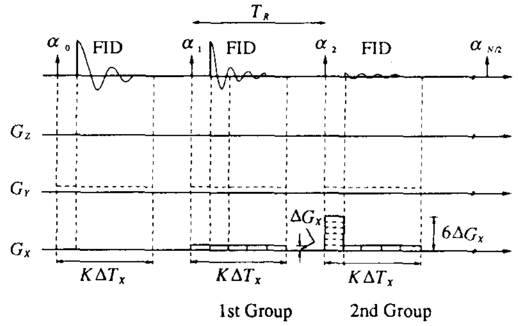
FIGURE CAPTIONS

Figure 1 : (a) Extended multipoint k-space point mapping technique(MKPM) which extends the ΔT by a multiple of n. Using the MKPM technique, one can overcome the long data acquisition time. (b) K-space correspondence of the pulse sequence given in (a). Note here that the n=5 is used as an example. This 5-point MKPM technique reduces scanning time by a factor of 5.

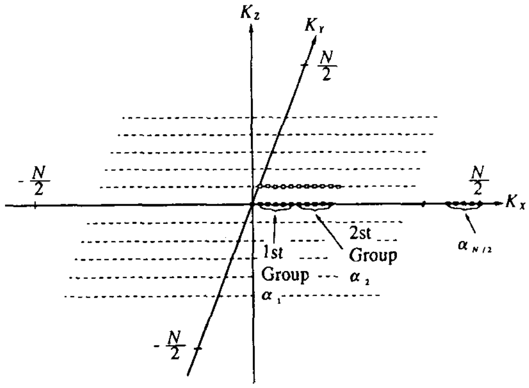
Figure 2 : Phantom configuration used in experiments. The field of view is 10 mm, and the diameter of inner cubes is 2.35 mm. And, the diffusion coefficients of the used materials are shown below

Acetone --- $(4.32\pm0.26)\times10^{-9}$ (m^2/sec)
Water --- $(2.19\pm0.20)\times10^{-9}$ (m^2/sec)
DMSO --- $(0.84\pm0.15)\times10^{-9}$ (m^2/sec).

Figure 3 : Obtained image in diffusion effect focused experiment, (a) GE technique image with TR/TE=100/16 (msec), which shows the greatly signal distortion in the tubes filled with distilled water and acetone. (b) MKPM technique image with TR/TE=100/6 (msec), which shows the signal distortion shown in Fig. 3(a) is compensated, however, the edge enhancement around boundaries is vaguely shown.



(a) MKPM Pulse Sequence



(b) K-space Data Sampling

Figure 1

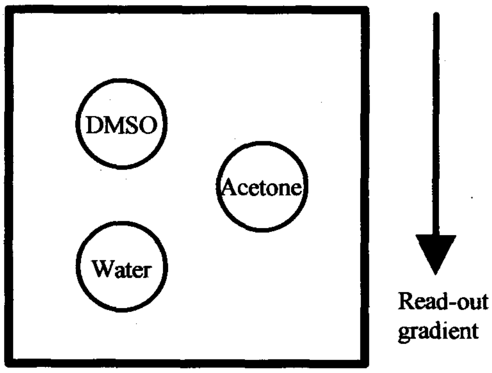
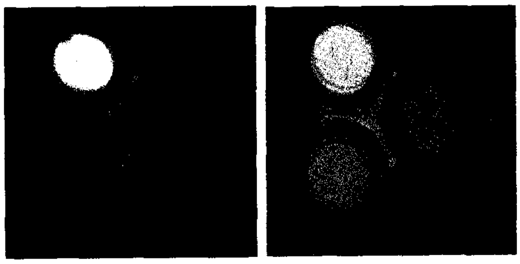


Figure 2 : Phantom Configuration



(a) GE Image (b) MKPM Image

Figure 3