MR 영상에서 확산현상에 의한 경계강조

○홍인기[1], 노용만[2], 조장희[1]

1. 한국과학기술원 정보및 통신공학과
2. 대전대학교 컴퓨터 공학과

Edge Enhancement due to Diffusion Effect in Magnetic Resonance Imaging

○I.K.Hong[1], Y.M.Ro[2] and Z.H.Cho[1]

1. Dept. of Information & communication Engineering, KAIST, Seoul, Korea
2. Dept. of Computer Engineering, Taejon University, Taejon, Korea

1. ABSTRACT

Due to the self-diffusion of nuclear spins, the edge of phantoms is enhanced in the magnetic resonance imaging (MRI), especially in the case of microscopy [1]. According to several published works, theory has been established that the edge enhancement is caused by the motion narrowing around bounded regions due to diffusions of nuclear spins during data acquisition. It is found, however, that the signal decreases due to the diffusion attenuation and image is distorted as edge of the image is sharpened. In this paper, we will investigate this signal loss during data acquisition and its effects on image, i.e., image edge enhancement due to the diffusion phenomenon. This result is new and different from the previously discussed edge enhancement due to the diffusion, namely, by motion narrowing effect or spin bouncing effect at the boundary.

2. INTRODUCTION

The effect of diffusion on a NMR signal in homogeneous magnetic field has been studied for a long time, and among those works Hahn's formula of echo signal strength is most well known. According to Hahn's formula, the echo signal decays as $\exp(-D\gamma^2G^2t^3/3)$ where D and G are diffusion coefficient and the magnitude of magnetic field gradient, respectively, and t is the data acquisition [2]. This formula implies that the echo signal is strongly affected by the gradient field and as it is known gradient field in NMR microscopic imaging is relatively high [3]. There are two important effects on NMR image resolution due to the diffusion, first is the finite phase variation due to the Brownian motion of the spins under the applied gradient field and second is the signal decay due to the diffusion and its eventually line broading effect on image. More recently, however, a controversial edge enhancement by diffusion effect is reported by Putz. It is known as the edge enhancement effect due to the motion narrowing. In addition to this motion narrowing edge enhancement effect, we have an additional edge enhancement effect due to the selective attenuation of the low frequency part of the echo signal and consequently results in enhancement of the high frequency part. This effect, as we will report, appear significantly in the image domain and improved edges in the image.

3. THEORY

1. Edge Enhancement

When one examines the effects of diffusion within microscopic compartments, one predicts a distortion of the frequency spectrum of the transverse magnetization due to the well-known effect of motional narrowing. Diffusing spins do not processes at a constant Larmor frequency, but rather experience the local frequencies along their diffusion paths. The spectra observed reflect the diffusive movements of the spins. The observed magnetization signal conveys only the average frequency over full precession of the magnetization vector. In Fig.1 various diffusion trajectories are visualized. Schematic (straight) diffusion trajectories have been drawn for time intervals ΔT that are comparable to a period of precession. In case of slow diffusion (Fig.1(a)) the mean positions of the diffusion trajectories are distributed evenly over the whole diffusion interval. In the case of fast diffusion (Fig.1(c)) "reflection" at the boundaries pushes the mean positions toward the center of the diffusion interval. As a result, the frequency of the resonance signal - actually the average frequency over a time interval of length ΔT - will be shifted toward the center frequency.

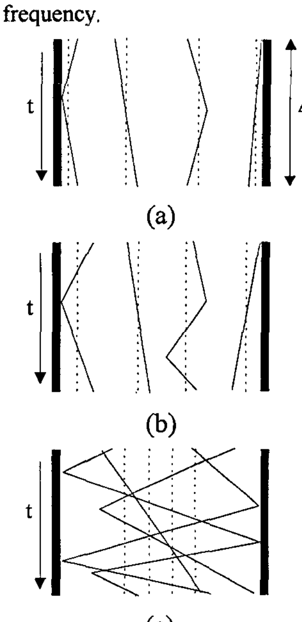

Fig. 1

The spectra observed by motion narrowing imply that the particle density will be misrepresented if it is assumed to be proportional to the signal intensity. Image reconstruction based on this assumption will transform diffusion-induced distortions of frequency spectra into diffusion-induced distortions of spin density. Interpreting Fig. 3(b) without these considerations would lead to the erroneous assignment of a large spin density at the center of the diffusion space. It is desirable to derive a control parameter which allows one to estimate to what extent bounded diffusion will distort the frequency distribution and, thereby, the reconstructed image. Such a parameter should depend on the gradient G, the size of the diffusion interval in the direction of the gradient, and the diffusion constant D.

2. Data Acquisition and High Pass Filtering Effect

The edge enhancement by the diffusion is affected by two ways. First, the motion narrowing by the free diffusion causes the edge enhancement. This edge enhancement by the motion narrowing is said in the previous topic. Second, above mentioned signal losses cause the edge enhancement. Signal loss is the function of the time. If we experiment with gradient echo or spin echo, etc., the first echo signal is negative high frequency term and echo center is DC term in reconstruction (Fig. 2). So first signal is less affected than the center signal. And first signal is less reduced than the later signal. Because this first signal which is negative high frequency in the reconstruction, is less reduced than the later signal, the edge of image is shown like enhanced. This edge enhancement looks like high pass filtering effect. Relatively the spin density of edge is not enhanced, but another frequency term is reduced, i.e., the negative high frequency terms have relatively same magnitude but the DC term and the positive high frequency terms have relatively smaller magnitude. So the reconstructed image would be shown as the edge of image enhanced.

If diffusion effect is small, the motion narrowing effect is relatively larger than signal loss. So the edge enhancement of image is mostly affected by the motion narrowing. However, if diffusion effect is large, signal loss is larger and the edge enhancement of image is affected by the signal loss.

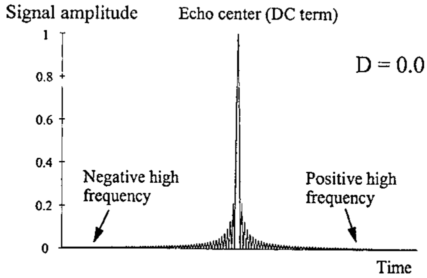

Fig. 2

4. SIMULATION

For a particular native relaxation rate and external magnetic field strength, the program simulates independent "spins" (spin ensembles) by solving the Bloch equations classically and representing diffusion as random walk. Molecular diffusion process can be simulated by the random walk model. The spatial distribution by the random walk approaches the binomial distribution if the number of trial is large. The binomial distribution approaches the normal distribution in the limit of the infinite number of trial, and the approximation is very good if the number of trial is not less than 10 when the probabilities of two events are same. Since the diffusion equation predicts a normal distribution when the initial density distribution has the delta function form, we made the number of the random walk steps in a simulation always not less than 10 to match this macroscopic prediction. Spin positions are randomly changed to one step left or right by equal probability at every monte carlo step. The spatial and phase distribution of the nuclear spins which diffuse freely in an infinite space is very close to the normal distribution.

The NMR signal S(t) is

$$S(t) = \iiint M(x, y, z; t) dxdydz \qquad [1]$$

where M(x,y,z;t) is transverse magnetization. M(x,y,z;t) can be known by the solving of Bloch equation. The position x,y,z of each spin will be randomly generated with monte carlo simulation. The moving length of each spin by diffusion is

$$R = \sqrt{2D\Delta t} \qquad [2]$$

where D is diffusion coefficient, Δt is the each moving step duration.

To investigate the effect of motion narrowing, if the spin reaches a boundary it will be reflected. This reflection is performed to give a reasonable displacement by conserving the length of the step. To remove the effect of motion narrowing, the spins spread out infinitely without bound. The main difference between two is that in the phase distribution the symmetry center is not at the boundary, and the probability near the boundary is almost zero. The probability near the boundary decreases because the number of spins which stays at the wall to have the maximum phase value decreases with time. This small difference between the spatial and phase distribution is the source of image distortion. For example, if nuclear spins are distributed uniformly in a box, the measured spatial distribution should be uniform and time invariant. Therefore, if the phase distribution is exactly same with the spatial distribution, the phase distribution per unit time should be also uniform in a limited region and time-invariant. This means that the image is not distorted at all event in the presence of diffusion. But if we remove the bound, the spatial and phase distribution of the nuclear spins which diffuse freely in an infinite space are very close to the normal distribution. So the expected reconstructed spectrum of echo signal must not have the edge enhancement. However, in Fig.4(b) the edge enhancement happens. This edge enhancement induced by high pass filtering effect. Fig. 3(a) and Fig. 4(a) are echo signal corresponding to the motion narrowing effect, no bounded moving spins. In Fig. 3(a) and Fig. 4(a), the negative high frequency terms have the value of itself but the other terms, i.e., DC term and positive high frequency term, decrease with time.

This echo signal is reconstructed, i.e., fourier transformed. The corresponding reconstructed spectrum of echo signal is Fig. 3(b) and Fig.4(b). The signal loss could be known to Fig. 3(a) and Fig. 4(a), the part of first negative high frequency is not reduced but the later parts of echo signal, i.e., low frequency parts, are reduced. So the later parts of echo signal become noisy. So the magnitude in Fig. 3(b) and Fig. 4(b) is decrease with diffusion constant D.

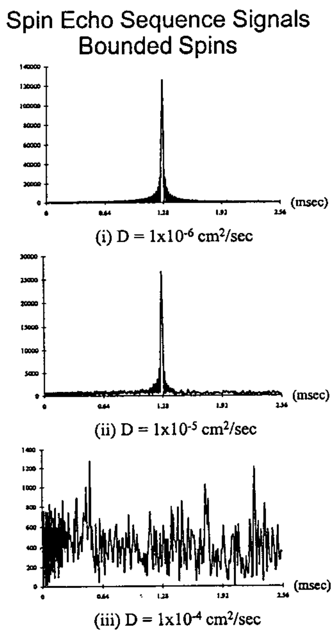

Fig. 3(a)

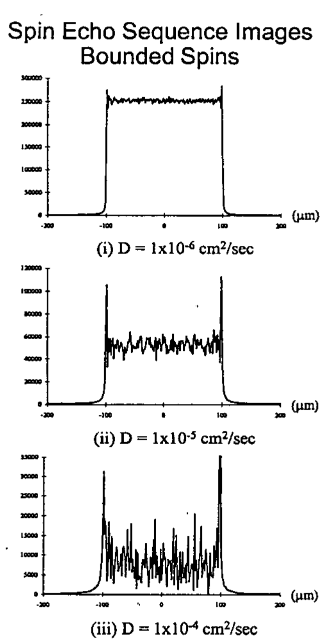

Fig. 3(b)

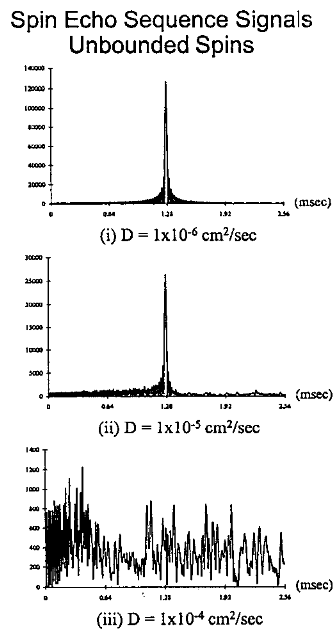

Fig. 4(a)

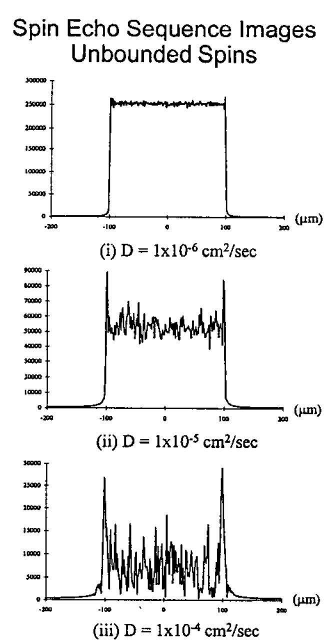

Fig. 4(b)

5. RESULTS

We have demonstrated by means of monte carlo and bloch equation simulation that diffusion plays an important role in generating image contrast on a microscopic length scale. Recently, it is known that the edge enhancement by diffusion is generated by motion narrowing [1, 4]. But through previous high pass filtering effect simulation, the edge enhancement by diffusion is generated by signal loss and motion narrowing. However, the high pass filter effect due to the signal loss effect dominates the edge enhancement of images if diffusion coefficient is larger. Such observations could demonstrate

the viability of motional narrowing effects and high pass filtering effects for edge enhancement in biological microscopic MRI.

6. REFERENCE

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7. FIGURE CAPTIONS

Fig. 1 Schematic explanation of motional narrowing near compartmental walls. (a,b,c) Representative spins diffusion in a one-dimensional diffusion space as time evolves from top to bottom. The spin paths are shown as solid lines; their average positions over the presented paths are shown by vertical dashed lines. The rate of diffusion increases from (a) to (c): (a) $D << (\Delta z)^2/\Delta T$, (b) $D \approx (\Delta z)^2/\Delta T$, (c) $D >> (\Delta z)^2/\Delta T$.

Fig. 2 The echo signals shows that the first signal is the negative high frequency and the later signals are DC term and positive high frequency.

Fig. 3 The echo signal and its 1-D image made by bounded spins. (a) The echo signal, (b) 1-D image shows the edge enhancement. The edge enhancement cause by motion narrowing effect and high pass filtering effect due to diffusion effect.

Fig. 4 The echo signal and its 1-D image made by unbounded spins. (a) The echo signal, (b) 1-D image. The edge enhancement cause by only high pass filtering effect due to diffusion effect.