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MR DANTE 고속 영상에서 SNR의 개선에 관한연구

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= Abstract =

Improvement of SNR in DANTE Fast MR Imaging

Y. M. Ro*, S. T. Chung**, I. K. Hong**, and Z. H. Cho**

A pixel profile in the conventional DANTE sequence is so poor that the excited area by DANTE sequence is a small portion of a pixel. This causes poor signal to noise ratio in DANTE image. In this paper, a frequency modulated(FM) DANTE imaging sequence is proposed to improve pixel profile in DANTE image. A DANTE pulse train is shaped by an FM function so that all the spins within a pixel are excited, thereby improving the signal to noise ratio. It also shows that the pixel profiles are dependent on the sweep in FM signal. Computer simulations and experimental results obtained using a 7.0 T NMR imaging system are presented.

Key words : MR DANTE, FAST Imaging, SNR Improvement.
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INTRODUCTION

DANTE pulse sequence for selective excitation[1,2] has been introduced for the suppression of the solvent peak in MR spectroscopy and for the tagging sequence for the motion detection in MR imaging[3]. Recently, the DANTE sequence was applied to ultra fast MR imagings and proposed sequences such as DUFIS and OUFIS[4,5].

Most of the fast imaging sequences such as EPI and SEPI require extremely fast gradient pulse switching[6,7,8]. Fast imaging using the DANTE pulse sequence, however, has the advantage that it does not require high speed gradient switching. This leads that the DANTE fast imaging sequence can be easily implemented on conventional MRI systems. In spite of this advantage of the original DANTE sequence, it has limited pixel profile in an image due to the finite duration of the DANTE pulse-train. Only a small fraction of the spins in each pixel are selected and thereby resulting in a poor signal to noise ratio (only about ~1% of a normal MR imaging sequence). Therefore, this poor signal to noise ratio(SNR) has been the main drawback of the original DANTE sequence. To improve the signal to noise ratio, the phases of individual RF pulses in the DANTE pulse train were modulated to excite more spins in the object[3,4]. Recently, the phase modulating technique was further extended and optimized to maximize the excitation profiles of the whole object[11].

In this paper, we propose an improvement of pixel profile in DANTE sequence using FM(Frequency Mod-

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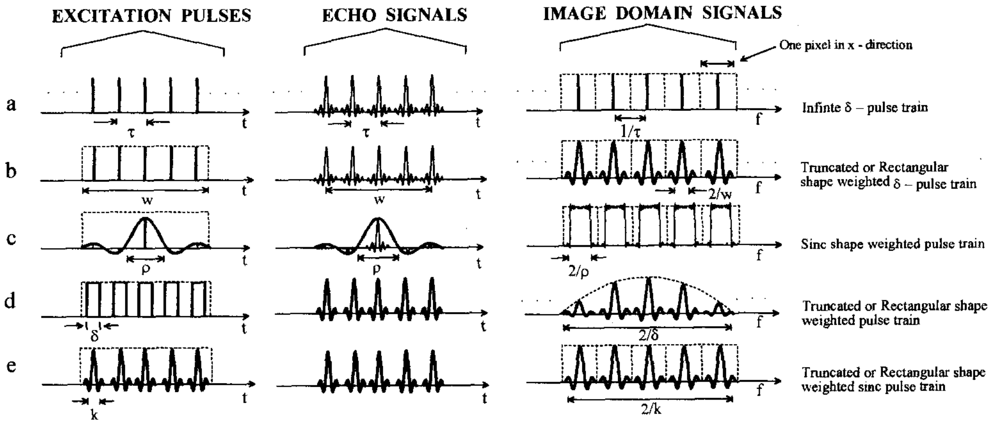


Fig. 1. Diagrams of the various pulse trains, expected echo signals, and their corresponding Fourier transforms : (a) An infinite pulse train with pulse separation t. (b) Same pulse train truncated by a time window W. (c) A pulse train of sinc shape envelope truncated by a time window W. (d) A truncated rectangular pulse train having a finite width d. (e) A truncated sinc shaped pulse train

ulation) technique. The RF pulse sequence is modulated by an FM function so that entire pixel is excited and SNR is improved significantly. The proposed FM technique in DANTE sequence is more systematic way than the others and thereby facilitating the application of DANTE sequences.

THEORY

1. Pixel Profile in DANTE Imaging

A DANTE pulse sequence consists of a series of RF pulses separated by a time interval τ as shown in Fig. 1(a). On the assumption of small flip angle, an image domain data, Fourier transform of DANTE sequence, is also an infinite pulse train of delta functions separated by $1/\tau$ in the frequency or image domain. If the pulse train is truncated with a time window W as shown in Fig. 1(b), the image domain data would be an infinite pulse train of sinc functions with a width 2/W. These sinc profiles in pixels are the results of the Fourier transform of the envelope of the pulse train which, in this case, is a rectangular function.

In general, the equation demonstrating DANTE RF pulse train is :

$$s_\tau(t) \cdot w(t), \tag{1}$$

where $s_\tau(t)$ is defined as a δ-function series or train with pulse interval of τ and $w(t)$ is the envelope of pulse train. For example, in the original DANTE sequence, $w(t)$ is a rectangular function. In the image or frequency domain, spins in the object are selected as a function of the Fourier transform of Eq.[1]. The Fourier transform of a δ-function series is again a δ-function series convolved with the Fourier transform of the envelope or weighting function. Resultant spin excitation functions appearing in the image domain, therefore, can be written as,

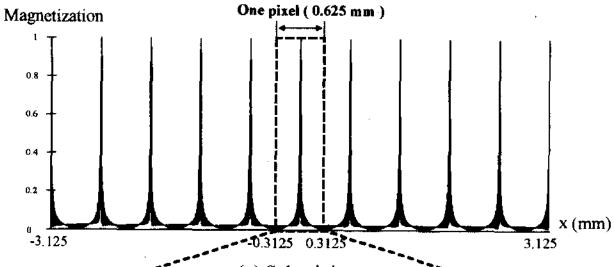
$$S_{\frac{1}{\tau}}(f) * Sel(f), \tag{2}$$

where * is convolution operator. In Eq.[2], $Sel(f)$ is a pixel profile in the image domain. In the normal DANTE sequence, $Sel(f)$ would be a sinc-shape profile because the envelope of the RF pulse train, $w(t)$, is a rectangular function; therefore, only a small fraction of spins in each voxel can be excited so that signal sensitivity is small.

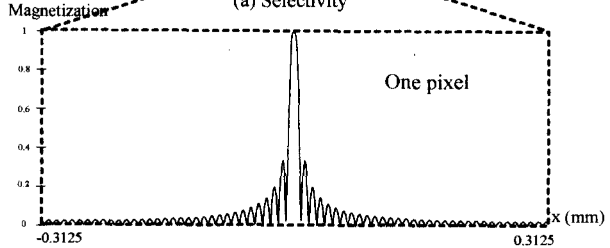
2. Signal Intensity in DANTE Imaging

To analyze the signal intensity within one pixel in the DANTE imaging sequence, let us assume one dimensional signal whose corresponding frequency or image domain profiles in the x-direction. Since the signal intensity within each pixel will be proportional to the pixel profile it can be written as,

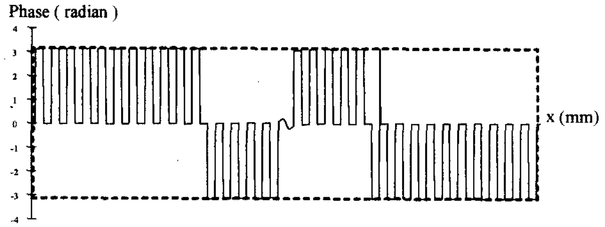
$$S_{pixel} = \int_{-1/2\tau}^{1/2\tau} Sel(f)\,df \tag{3}$$



(a) Selectivity



(b) Magnitude distribution in a pixel



(c) Phase distribution in a pixel

Fig. 2. The computer simulated excitation profiles of the original DANTE pulse train. **(a)** shows excitation or selectivity profiles, **(b)** is the expanded version of the selectivity or excitation profile of one pixel located at the center, and **(c)** is the corresponding phase distribution, respectively

where τ is the time interval between the adjoining RF pulses in the DANTE excitation pulse train and $Sel(f)$ is pixel profile in the image domain. In Eq.[3], f is defined as $\frac{\gamma G_x x}{2\pi}$ where γ is gyromagnetic ratio, and G_x is gradient strength in the x-direction. As it is implied in Eq.[3], the signal intensity will be maximum when all the spins within each pixel are excited, *i.e.*, when the selection function in image domain is a rectangular function whose width is the same as the bandwidth of each pixel. As mentioned previously, in the original DANTE fast imaging sequence[4], $Sel(f)$ in Eq.[3] is a sinc function.

Figure 2(a) shows the excitation profiles of the original DANTE sequence and (b) and (c) show a pixel profile which consists magnitude and phase, respectively. These excitation profiles are obtained by simulation of the Bloch equations and represent the excited spin distributions in the image domain, i.e. $Sel(\frac{\gamma G_x x}{2\pi})$. In the simulation, the time interval between the adjacent RF excitation pulses is set to 320 msec and the total number of pulses was 64, i.e., total readout time was 20.48 msec. The gradient applied with the DANTE pulses was 11.7 G/cm in the x-direction. As is seen, excited spins within a pixel constitute only a small fraction of the large rectangular box(which represents a pixel) shown with the broken lines. The sinc function covers not only a small portion of each pixel. Further the phase distribution of the spins within each pixel is also non-uniform so that the signal is further reduced by spin phase dispersion. The signal intensity of the original DANTE imaging shown in Fig. 2 is only about 1.6 % of the maximum signal intensity. Signal intensity of the original DANTE sequence, therefore, is far from practical use as far as imaging is concerned. This disadvantage has been partially improved by the recently proposed DUFIS and OUFIS[4,11] by modulating the phases of the RF pulses. These improved techniques, however, still suffer signal loss due to poor pixel profile and non-uniform phase.

3. Frequency Modulation(FM) Technique

In MR imaging, the selection of the pixels in the object can be performed not only by amplitude modulated(AM) RF pulses but can also be performed using the frequency modulated(FM) RF pulse. In FM, selection profile of each pixel is determined by the bandwidth of the sweep frequency and the sweep rate [10,11,12,13,14,15]. Further, the FM technique provides that the magnitudes of the DANTE RF pulse train are identical, thereby, it produces relatively equal magnitude echo signals. In addition, The general form of an FM function is given by

$$\begin{aligned} R(t) &= A\exp[i\textstyle\int 2\alpha\pi t\,dt] \\ &= A\exp[i\pi\alpha t_2] \qquad (4) \end{aligned}$$

where αt is a frequency sweep function and A is a constant. Figure 3(a) shows a typical FM function with a linear sweep and its resulting frequency domain selection profile. Also shown are the real and imaginary components of such an FM function. An linear sweep function where the frequency is swept linearly with time is $f(t) = \alpha t$. An FM pulse having a linear sweep function has the quadratic of phase distribution as given in Eq. [2], i.e., $\exp[i\phi] = \exp[i$

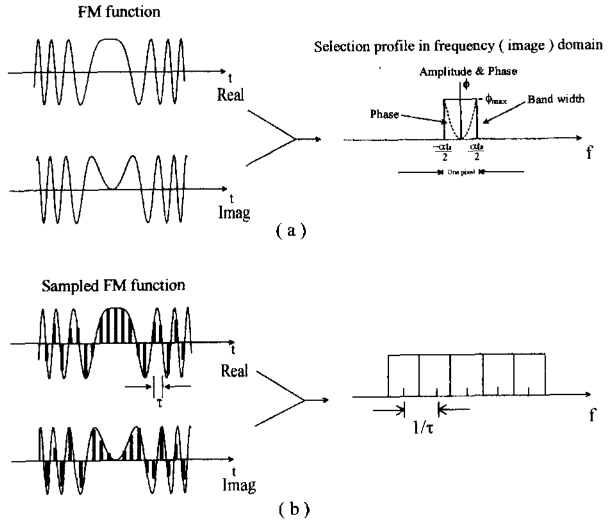


Fig. 3. (a) FM pulses and their corresponding frequency domain spectrum(or image domain excitation profile). (b) FM DANTE pulse(sampled version). In the later, frequency spectra become repetitive thereby covers entire image domain in x-direction

$\pi\alpha t_s^2$]. The frequency velocity, α is defined by BW/t_s where BW is the frequency bandwidth and t_s is the RF sweep time.

By applying an FM RF pulse with a sweep velocity and a RF duration(or sweep time) of t_s, i.e., from $-\frac{t_s}{2}$ to $\frac{t_s}{2}$, the frequency range from $-\alpha\frac{t_s}{2}$ to $\alpha\frac{t_s}{2}$ would be linearly swept. Consequently, a rectangular shape profile of thickness of αt_s Hz will be selected in the frequency domain as shown on the right side of Fig 3.

In a sampled form of FM DANTE pulse train the resulting pixel profiles are a series of rectangular function as shown in Figure 3(b). For an FM DANTE sequence, the bandwidth selected by the FM function is set to be the same as the pixel bandwidth in the x-direction of the DANTE sequence, i.e., $1/\tau = \alpha t_s$. Note that the magnitudes of the FM DANTE pulses are always same, thereby guaranteeing equal magnitude echo signal train.

An FM function produces a quadratic phase distribution within a pixel as shown in Fig. 4(a) and Fig. 4(b) shows the signal intensity of a pixel as a function of the maximum phase ϕ_{max} developed at the edge of a pixel. The signal decreases as the strength of the quadratic phase increases. This ϕ_{max} value is the maximum phase that will be developed by the sweep time t_s if a fixed bandwidth is given, i.e., $\phi_{max} \cong \mathrm{BW} \cdot t_s$. It is, therefore, important to reduce the value of ϕ_{max} and it can be achieved by reducing the t_s.

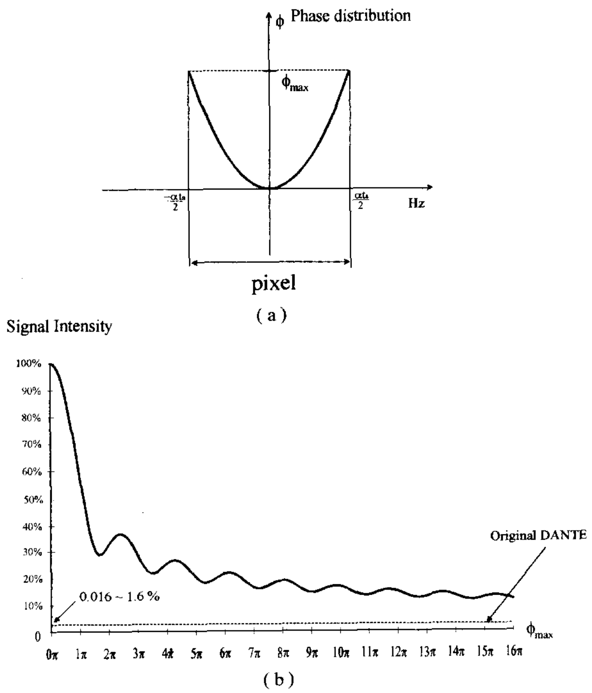


Fig. 4. (a) Phase distribution within each pixel. Note phase distribution follows quadratic distribution. (b) The overall signal intensity vs. the strength of the maximum quadratic phase max generated by the FM DANTE pulse. The signal intensity calculated is based on one pixel

The quadratic phase generated by the FM function is related to the sweep velocity, e.g., the faster the sweep velocity the smaller the quadratic phase in the frequency domain[16,17]. Therefore, to improve the SNR in the FM DANTE sequence, the sweep velocity should be increased. The sweep velocity can be increased either by increasing the frequency bandwidth or decreasing the sweep time. Increasing the frequency bandwidth, however, is difficult since it requires an extremely short sampling time as well as strong gradient. Reducing the sweep time, however, can be realized by reducing the number of pulses by using interlacing[8]. The latter has other advantages since the long data acquisition time of the original DANTE sequence also induces strong diffusion dependent signal attenuation. Therefore, short sweeping time improves SNR also by reducing the diffusion dependent signal attenuation. Figure 5 shows an example of the

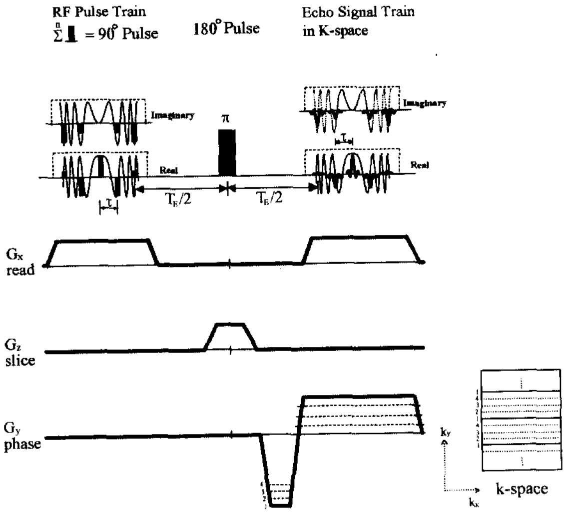
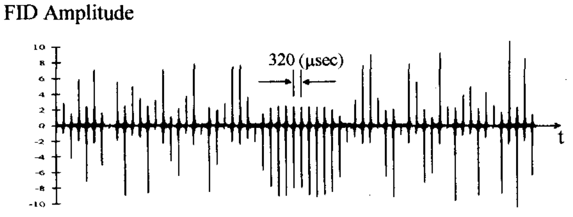
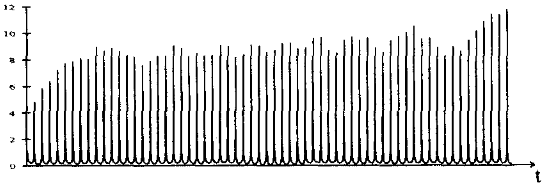


Fig. 5. An illustration of the FM DANTE pulse sequence and interlacing which can be incorporated into the method (e.g. four interlacing)



(a) The Real Part

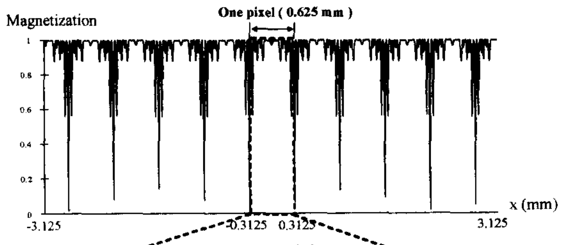
(b) The Imaginary Part



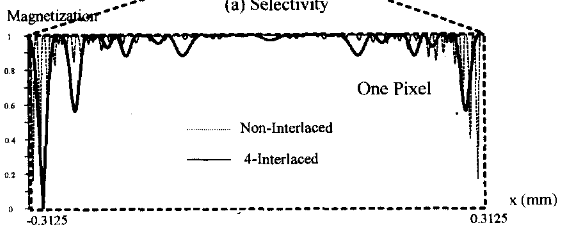
(c) The Magnitude

Fig. 6. Echo signals(real, imaginary and the magnitude) obtained by the FM DANTE sequence. 64 echoes are spaced with an equal interval of 320 msec. Note that the magnitudes of the echoes are quite uniform, except in the beginning

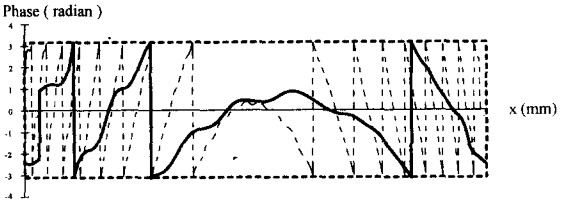
interlaced FM DANTE pulse sequence with which the diffusion effect dependent signal attenuation can be reduced.



(a) Selectivity



(b) Magnitude distribution in the pixel



(c) Phase distribution in the pixel

Fig. 7. The selectivity profiles obtained after excitation by FM DANTE pulses of two different interlacings. **(a)** shows excitation profiles in x-direction. One pixel profiles located at the center is expanded and shown below. **(b)** and **(c)** are the expanded versions of the magnitudes and phase distributions, respectively. Note that the large quadratic phase distributions in the pixel, for the case of two interlacings(dotted line) and an improved phase distribution for the case of four interlacings(solid line)

COMPUTER SIMULATIONS

Using the Bloch equations, computer simulations were performed with the original DANTE spin echo sequence. In the simulation, the total RF power of the DANTE pulse train was made to result in a 90° flip, the RF power of each small pulse was, therefore, set to 90°/N, where N is the number of pulses in the train. FM DANTE pulse train was designed for the simulation study which consists of 64 RF pulses in a train with a pulse interval of 320 μsec. To select a rectangular excitation profile in the pixel, the sweep velocity was set to 152.59kHz/sec with an RF pulse duration of 20.48msec[10]. Under this condition, it is expected that a pixel size of around 0.625 mm will

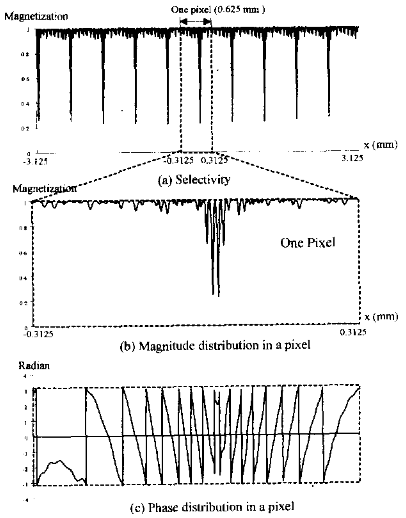


Fig. 8. (a) The selectivity profiles obtained after excitation by the Multi-phase OUFIS DANTE pulse. This is shown for reference. (b) shows the expanded magnitude of one pixel at the center. (c) is the expanded version of the phase distribution. Note the severe quadratic phase distribution

be selected when a 11.7 G/cm gradient is applied.

To obtain the echo signal train we have applied a sampled FM DANTE. The resultant spin echo signals are shown in Fig. 6. As shown, the magnitudes of the echo signals are relatively uniform. Note that diffusion effects were not included in the simulations. The phases of the echo signals are found to have a quadratic phase distribution since the FM pulse has a quadratic phase[10,17]. This quadratic phase distribution causes phase differences in the y-encoding direction. Therefore, phase correction was performed on each echo signal before Fourier transform for the final image reconstruction.

Figure 7(a) shows the pixel profiles in the image domain obtained by computer simulation of FM DANTE sequence with non-interlacing and 4-interlacing. As shown, nearly rectangular functions are excited in the pixel. From this pixel profile, NMR signal would be larger, and therefore, a better SNR.

As mentioned previously, in the FM DANTE sequence this signal loss due to the phase distribution in each pixel can be reduced further by increasing the sweep velocity α, that is by decreasing the RF sweep time t_s by interlacing. Simulation of a four-interlaced FM sequence was performed by reducing the sweep time down to 5.12 msec so that the sweep velocity becomes increased to 610.36kHz/sec. In Fig. 7(b), the magnitude or selection profiles obtained by a four-interlaced FM sequence are also shown for comparison with non-interlaced FM DANTE(see solid lines vs. dotted lines). Fig. 7(b) and (c) show the expanded versions of the magnitude and phase distributions in the pixel. As mentioned above, by increasing α, the quadratic phase in each pixel is reduced proportionally at the boundary of the pixel thereby increases signal intensity. The signal intensity of the four-interlaced FM sequence is now improved up to 26%. Obviously, further SNR improvement can be achieved by increasing the number of interlaces at the cost of longer imaging times. The signal intensity was further improved(due to the improved selectivity and phase distribution) with eight-interlaced FM sequences and increased as much as 37%. Figure 8 shows the selection profile of multi-phase OUFIS sequence which was optimized to improve SNR in DANTE sequence [11] for comparison. As is seen, the phase distribution in a pixel is highly nonuniform while the magnitude in a pixel was well excited.

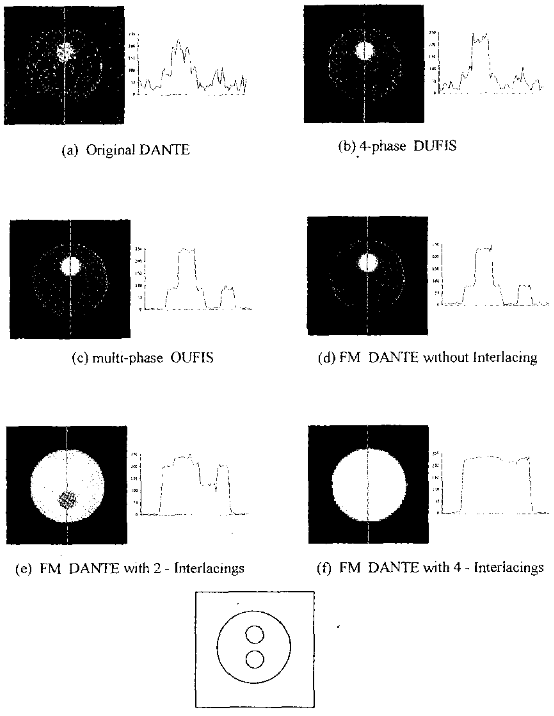
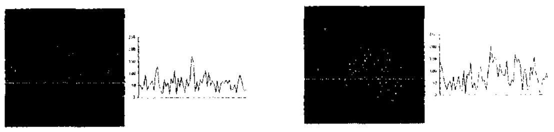
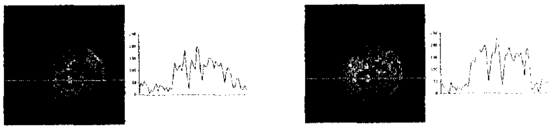

(a) Original DANTE
(b) 4-phase DUFIS
(c) multi-phase OUFIS
(d) FM DANTE without Interlacing
(e) FM DANTE with 2 - Interlacings
(f) FM DANTE with 4 - Interlacings
Phantom image

Fig. 9. Phantom designed for the experiment. Objects of various diffusion coefficients were inserted to test the diffusion effect dependent signal attenuation



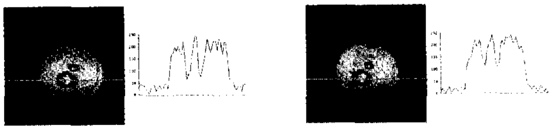
(a) Original DANTE (NA = 8)

(b) 4-phase DUFIS (NA = 8)



(c) multi-phase OUFIS (NA = 8)

(d) FM DANTE without Interlacing (NA = 8 , NI=0)



(e) FM DANTE with 2 - Interlacings (NA = 4 , NI = 2)

(f) FM DANTE with 4 - Interlacings (NA = 2 , NI = 4)

NI	Number of Interlacings
NA	: Number of Averaging

Fig. 10. Experimentally obtained 2D images(pixels); **(a)** by using original DANTE sequence, **(b)** by the four phase modulation DUFIS, **(c)** multi-phase OUFIS, **(d)** by the FM DANTE without interlacing **(e)** by the FM DANTE with 2 interlacings and **(f)** by the FM DANTE with 4 interlacings. The repetition time is 1sec. Note that all the images are obtained with identical imaging time

To compare the proposed FM DANTE sequence technique with the other existing phase modulating techniques, 2D image simulations were performed by adding the encoding gradient to the 1D simulation discussed earlier. Phantom consists of three circles which have same signal intensities but different diffusion coefficients, i.e., 2×10^{-5}cm^2/sec, 0.5×10^{-5}cm^2/sec, and 8×10^{-5}cm^2/sec, respectively for large, upper small and lower small circle. For SNR comparison, noise was added to the echo signals before the final 2D image reconstruction. Figure 9(a) shows an image obtained using the original DANTE sequence with added noise. As shown in Table. 1, SNR of the original DANTE sequence was 1.87 in the large circle. As shown in Fig . 9(b), the original phase modulated DANTE sequences such as four phase(0°-180°-0°-0°) DUFIS, SNR were improved up to 3.39 in the large circle. Figure 9(c) show images obtained by the optimized sequences(OUFIS)[11] with iterations. As seen, the SNR appears to be further improved and reached nearly as 10.84 in the large circle for multi phase OUFIS. Finally an image obtained by the FM DANTE sequence without interlacing is shown in Fig. 9(d) and the SNR is improved further in comparison with the OUFIS. Note here that FM method does not require any iterations for designed RF pulses as OUFIS does. In the simulation of the FM DANTE imaging of two and four interlacings, the SNR in the large circle were further improved to 34.80 and 42.18, respectively as shown in Fig. 9(e) and (f).

Table 1. Signal to noise comparison of various DANTE sequences. Note that the data acquisition times were set to an equal to have a fair comparison, i.e., product of the number of averaging and number of interlacings is made equal for all the images.(See and compare with Fig. 10)

SNR = signal/noise

	Large circle SNR ($D=2\times10^{-5}$cm^2/sec)	Upper small circle SNR ($D=0.5\times10^{-5}$cm^2/sec)	Lower small circle SNR ($D=8\times10^{-5}$cm^2/sec)
Original DANTE	1.87	4.22	1.13
2-phase DUFIS	2.48	5.62	1.24
4-phase DUFIS	3.39	8.26	1.52
2-phase OUFIS	10.31	25.67	3.39
Multi-phase OUFIS	10.84	26.80	3.59
FM DANTE without interlacing	11.31	28.01	3.58
FM DANTE with 2-interlacings	34.80	42.37	24.41
FM DANTE with 4-interlacings	42.18	45.59	42.17

Note : These simulation results are obtained with equal data acquisition times

Table 2. SNR estimated from the images obtained by experiment(compare with Table 1).

SNR = signal/noise

	Noise	Signal	SNR
Original DANTE	58.39	65.00	0.90
2-phase DUFIS	65.71	91.13	1.39
4-phase DUFIS	55.20	95.31	1.73
2-phase OUFIS	23.43	152.91	5.37
Multi-phase OUFIS	21.00	130.90	6.23
FM DANTE without interlacing	19.67	132.89	6.75
FM DANTE with 2-interlacings	17.48	182.31	10.23
FM DANTE with 4-interlacings	12.57	200.15	15.92

Note : These comparison results are for equal data acquisition times

EXPERIMENTAL RESULTS

To verify the sensitivity gain of the proposed FM DANTE sequence obtained in simulation and to compare the results with the other existing DANTE sequences, experiments were performed with a 7.0 T MRI system. In the experiments, the time interval of the RF pulse was set to 448msec and the number of RF pulses was 64 with an image matrix of 64×64. A circular phantom of diameter 20 mm was constructed and used. Within the phantom, a 3mm diameter and 1mm diameter tube were inserted. The pixel bandwidth was then set to 2.23kHz/sec and the slice thickness of all the images obtained in the experiments were 3mm. Total RF flip angle of the DANTE pulse was set to 90°. Figure 10(a) and (b) show the images obtained by the original DANTE and four phase modulated DUFIS sequences, respectively. As seen, the SNR was improved by phase modulation. The results of further optimization of the phase modulation technique(OUFIS) are shown in Fig. 10(c). Lastly, images were obtained using the FM DANTE sequence with sweep velocities of α=77.85kHz/sec, 155.7kHz/sec, and=311.4kHz/sec(or RF sweep times of 28.67msec, 14.33msec and 7.17msec), respectively and the results are shown in Fig. 10(d), (e) and (f). As is seen, the SNR was improved substantially by using the FM sequences, especially with interlacings. Table. 2 shows the SNRs calculated from the images shown in Fig. 10. As is seen, SNR improvements are achieved by interlacing techniques due to the reduction of diffusion effect with the same data acquisition time.

DISCUSSIONS AND CONCLUSIONS

In this paper we have proposed an improvement of pixel profile using FM DANTE sequence and compared the method with the other existing fast DANTE imaging techniques such as the original DANTE fast imaging sequence and its variations (DUFIS and OUFIS). Both computer simulations of the Bloch equations and experimental results show substantial improvement of SNR by FM DANTE sequence over other existing fast DANTE imaging sequences. As is known, the original DANTE pulse train selects or excites only a small fraction of the spins within each pixel, thereby, produces only a small signal[4]. Although further improvement of the original DANTE fast imaging was attempted and obtained substantial improvement, it appears that the diffusion effects as well as phase dispersion within the pixel still exist. Since the optimized methods such as OUFIS are obtained by iteration method, it is cumbersome to generate an optimum DANTE sequence for wide range of different resolution requirements. These goals have been alternatively achieved theoretically and much simpler way by the proposed FM DANTE sequence.

The proposed FM DANTE sequence has two main advantages : First, a larger number of spins within the object are excited by improving the shape of the pixel profile, thereby improves the SNR. Also, the method provides echo signals with uniform magnitude which assures uniform signal intensities along the phase encoding direction. However, simple FM DANTE sequence expected gain was not realized due to the quadratic phase distribution of the spins in the pixel and diffusion dependent signal attenuation[14, 15]. This diffusion effect in the DANTE has been unambiguously solved by FM technique, especially for those images with large matrix sizes, or high resolution images such as 128×128 or 256×256. Since the data acquisition time was relatively long in this case the signal was attenuated severely by the strong diffusion effect. FM DANTE with interlacing uniquely resolves the diffusion effect dependent signal attenuation problem and thereby improved SNR.

In conclusions, both the Bloch equation simulations and experimental results show that the proposed FM DANTE sequence can offer a useful fast imaging with substantially improved SNR compared with the originally proposed DANTE fast imaging sequences as well as its optimized variations[4,11].

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=국문초록=

기존의 단테 시이퀀스에서 선택된 픽셀의 모양은 한 픽셀이 포함하는 영역중 적은 부분만을 포함하기 때문에 SNR이 매우 나쁘다. 결국 이것으로 단테 영상법에서 신호대 잡음비가 적은 영상을 얻는다. 본 논문에서는 주파수변조(FM) 방법을 이용해서 픽셀의 모양을 개선하는 방법을 제안하여 단테 영상법에서 신호대 잡음비를 높이고자 한다. 제안된 방법으로 연속된 단테 펄스를 FM 함수를 이용하여 만들고 한 픽셀의 영역에 있는 모든 스핀을 선택한다. 따라서 높은 신호대 잡음비를 얻을 수 있었다. 또한 FM 함수의 주파수 선택 범위 속도와 픽셀 모양과의 관계도 보였다. 컴퓨터 모의 실험과 7.0 T NMR 시스템을 이용한 실험으로 방법의 타당성을 증명 하였다.