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주파수 변조를 이용한 MR DANTE 고속 영상법

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DANTE Fast MR imaging Using Frequency Modulation

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INTRODUCTION

The original DANTE sequence and its variations have limitation in excitation profile (a sinc function-like excitation) due to the finite duration of the DANTE pulse-train. This sinc function-like selection profile excites only a small fraction of the spins in the pixel thereby results in poor signal to noise ratio (only about ~1% of 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, phases of individual RF pulses in the DANTE pulse train were modulated so that more spins in the object were excited (1~3). We have introduced a new FM (Frequency Modulation) DANTE sequence and analyzed the signal intensity and excitation profiles.

THEORY

Signal Intensity in DANTE Fast Imaging

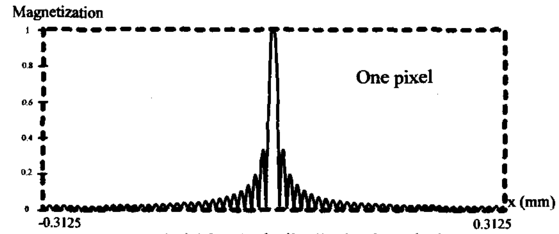
In DANTE fast imaging the one dimensional signal intensity within one pixel in the image domain along the x-direction is given by

$$S_{pixel} = \int_{-1/2\tau}^{1/2\tau} \mathrm{Sel(f)}\, df \qquad [1]$$

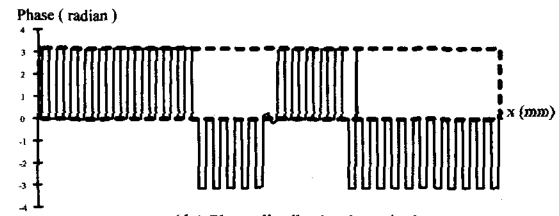
where τ is the time interval between adjoining RF pulses in the DANTE excitation pulse train and *Sel(f)* is the image domain selection function of each pixel in x-direction. As is implied in Eq. [1], the signal intensity will be maximum when all the spins within each pixel are excited.

Figure 1 shows the excited spin distribution in the pixel obtained by the simulation of the Bloch equations. In the simulation, time interval between the adjacent RF excitation pulses is set to a 320 μsec, 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 shown in Fig. 1, the excited spins within a pixel by the original DANTE sequence occupy only a small fraction within the large rectangular box shown with the broken lines. An expanded view of the both magnitude and phase distribution of the spins within a pixel are shown in Fig. 1 (a) and (b). Therefore, the signal intensity of the original DANTE sequence is too small to be of any practical use, as far as imaging is concerned.



(a) Magnitude distribution in a pixel



(b) Phase distribution in a pixel

Fig.1
Excitation profiles of the original DANTE sequence

Frequency Modulation (FM) Technique

In the FM, selection profiles of the pixels are determined not by the envelope of the pulse train but by the bandwidth of the sweeping frequency as well as the sweeping rate (6~9). The salient point of the FM technique is that the amplitudes of the pulses in the DANTE RF pulse train are identical thereby produce equal amplitude echo signals. The general form of a FM function is given by

$$R(t) = A\exp[i\int 2\pi f(t)dt], \qquad [2]$$

where $f(t)$ is a frequency sweep function and A is a constant. An FM pulse having linear sweep function is called "Chirp" pulse and has a form $\exp[\, i\pi\alpha t^2\,]$ where α is the sweep velocity and is defined as (9)

$$\alpha = \frac{\mathrm{BW}}{t_s} \quad \text{or} \quad \frac{\text{Frequency Bandwidth}}{\text{RF sweep time}}, \qquad [3]$$

where BW is frequency bandwidth and t_s is RF sweep time.

An FM pulse has two components, namely real and imaginary as shown in Fig. 2(a). In reality, it is in the sampled form of the FM pulse shown in Fig. 2(b) that is used for imaging. Because of the sampled nature of the pulse train the resulting image domain data obtained by the FM DANTE pulse train is also a series of rectangular shapes as shown in the right side of Fig. 2(b). In figure 2 (a), a selection profile obtainable using a continuous FM pulse pair with linear sweep is shown as a reference.

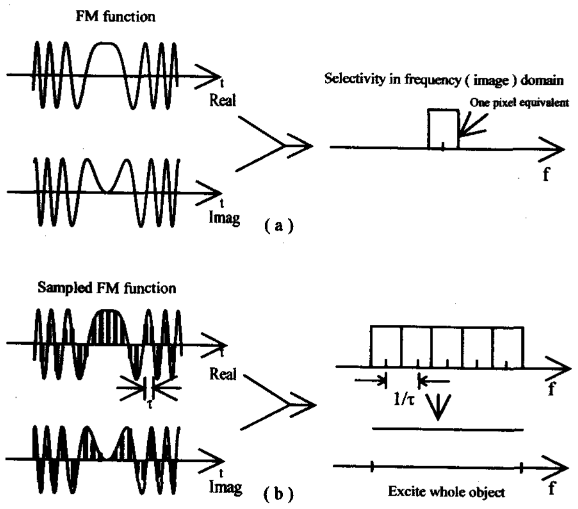


Fig. 2

Spin Phase Distribution

Because of the spin phase dispersion within the pixel in the DANTE fast imaging, the SNR of the FM DANTE sequence was not improved proportionally as the pixel selection profile is improved. This is due to the fact that the FM function generates a quadratic phase within the pixel(10). Figure 3 (b) shows the signal intensity of a pixel as a function of quadratic phase β developed within a pixel. As is seen, the signal decreases as the strength of the quadratic phase. Since in the FM, the velocity of the frequency sweep can easily be changed it is possible to improve the signal intensity of the FM DANTE sequence by a suitable adjustment of α. Therefore, to improve the SNR in the FM DANTE sequence, the sweep velocity should be increased. As seen in Eq. [3], the sweep velocity can be increased by either increasing the frequency bandwidth or decreasing the sweep time. Reducing the sweep time can be realized by reducing the number of pulses, for example by using interlacings(4). Figure 4 shows an example of the interlaced FM DANTE pulse sequence with which diffusion effect dependent signal attenuation can be reduced.

COMPUTER SIMULATIONS

An FM DANTE pulse train is designed for the simulation study, which consists of 64 pulses with a pulse interval of 320 μsec. To select rectangular excitation profile in the pixel, sweep velocity α is set to 152.59 kHz/sec with a RF pulse duration of 20.48 msec (7). Under this condition, it is expected that a pixel size of around 0.625 mm will be selected when 11.7 G/cm gradient is applied.

As shown in Fig. 5(a) (non-interlaced basic FM DANTE sequence), most of the spins excited in the pixel show nearly a rectangular excitation or selection profile. From this excitation profile, it is expected that NMR signal will be larger and therefore the better SNR.

However, even though all the spins within each pixel are excited as shown, and corrections of the encoded quadratic phases of the echo signals are made, the signal intensity is still not proportionally increased due to the non-

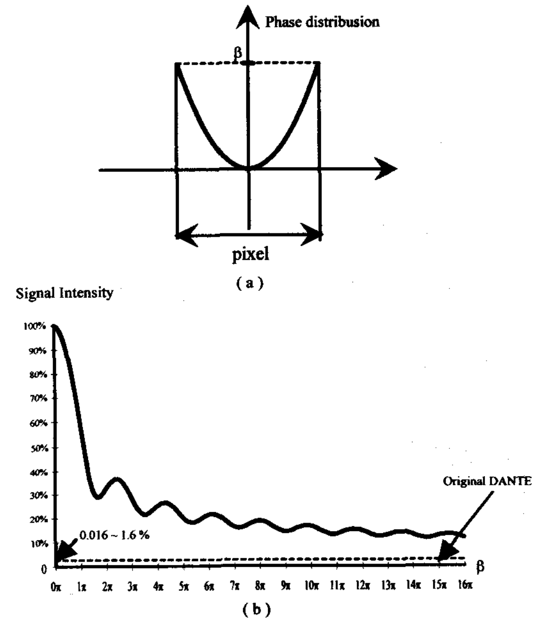


Fig. 3

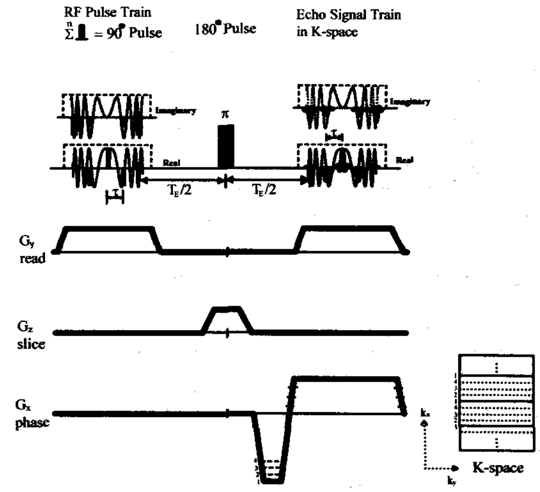


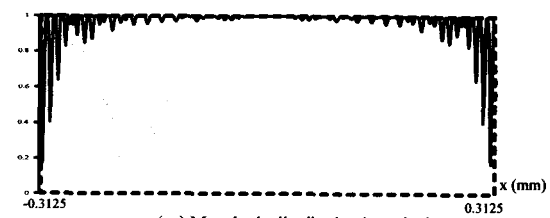
Fig.4

Interlaced FM-shaped DANTE Pulse Sequence (Four Interlacings)

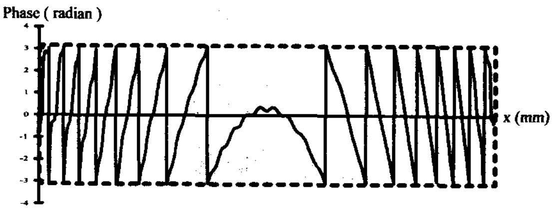
linear phase distribution within each pixel which again due to quadratic nature of the FM DANTE RF pulse as shown in Fig. 5(b). This signal loss due to the phase distribution in a pixel can be reduced further by increasing the sweep velocity α as a dicussed earlier. Simulation of a four-interlaced FM DANTE sequence is attempted by reducing sweep time to a 5.12 msec thereby sweep velocity α is increased to 610.36 kHz/sec. Figure Fig. 6 (a) and (b) show the expanded versions of the magnitude and phase distribution in the pixel. Obviously further SNR improvement can be achieved by increasing the number of interlaces but with penalty of longer imaging time.

EXPERIMENTAL RESULTS

In the experiments, the time interval of the RF pulse was set to 448μsec and the number of RF pulse was 64 with image matrix size of 64x64. A circular phantom whose diameter is 20 mm was constructed and within the phantom two tubes with different diameters were inserted, one with inner diameter of 3 mm and the other with 1mm, respectively. The pixel bandwidth was then set to 2.23 kHz/sec and slice thickness of all the images obtain in the experiments were 3mm. Figure 7 (a) shows the images obtained by the original DANTE sequence and Fig. 7(b), (c) show images obtained by the FM DANTE sequence with the sweep velocity of α = 77.85 kHz/sec and = 311.4kHz/sec with the non-interlaced basic FM sequence and four-interlaced FM DANTE sequence respectively. As it is seen, SNR was improved substantially by using FM sequences and especially using the interlacings. In addition, signal attenuation due to the diffusion effect has also been reduced with the interlacings.



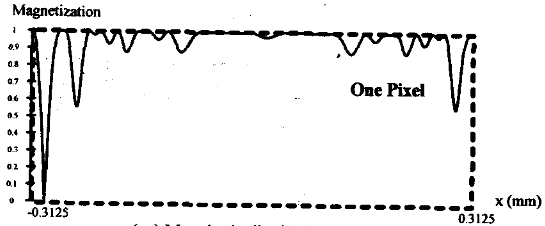
(a) Magnitude distribution in a pixel



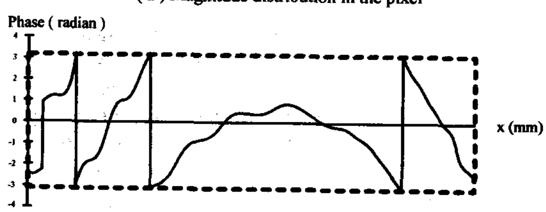
(b) Phase distribution in a pixel

Fig. 5

Selection Profiles Obtained by the Non-Interlaced FM DANTE Pulse



(a) Magnitude distribution in the pixel



(b) Phase distribution in the pixel

Fig. 6

Selection Profiles Obtained by the 4-Interlaced FM DANTE Pulse

(a) Original DANTE (NA = 8)

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

64 X 64 : Image Matrix Size
TR = 1 sec : Repetition Time , T=8 sec
NI : Number of Interlacings
NA : Number of Averaging
Power = 1/3 = α = 30°

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

Fig. 7

Experimentally Obtained Images by the Original DANTE, FM DANTE Sequences

DISCUSSIONS AND CONCLUSIONS

As is known, the original DANTE pulse train selects or excites only a small fraction of the spins in each pixel, thereby resulting in a small signal (2). To improve the SNR, sinc shape excitation profile in each pixel has to be improved and diffusion effect as well as phase dispersions within the pixel should be minimized. These goals have been achieved by the interlaced FM DANTE sequence. In the simulations, the interlaced FM DANTE sequence shows signal to noise ratio improvement of more than 30 times compared with the original DANTE sequence when sixteen interlaces were applied. Although there are a number of improved DANTE fast imaging sequences such as the DUFIS and OUFIS, FM techniques offer better SNR. Both the simulations of the Bloch equations and experimental results show that the interlaced FM DANTE sequence can offer practically usable fast imaging with substantially improved SNR compared with the originally proposed DANTE fast imaging sequence as well as its variations (2,5).

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