学 術
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原 著

Development of the Dual Flip-Flop Angle Type T_2W-Fast Spin Echo Method

Flip-Flop可変型T_2W-Fast Spin Echoの開発

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【Abstract】

Fast Spin echo is a major sequence used for T_2WI. The 90 (Flip) angle - 180 (Flop) angle - echo - 180 (Flop) angle - echo train sequence is the basic pattern in FSE. Major drawbacks of the technique are the increase in SAR and decrease in CNR. To overcome these problems a Flip-Flop angle type sequence, a T_2WFSE was developed. Optimal Flip and Flop angles must be selected to develop the Flip-Flop type sequence of T_2WFSE. The Bloch equation was applied in order to develop the sequence used for the evaluation of MR signal strength in numerical simulation. Optimal Flip and Flop angles were selected by numerical simulation based on the Bloch equation for the Flip-Flop angle type T_2WFSE.

【抄 録】

FSE法はT_2撮像法の主流となっている. FSE法の基本形は90度（Flip）-180度（Flop）-echo-180度（Flop）-echo系列である. この撮像法の問題点はSARの上昇とCNRの低下である. この問題点を解決するFlip-Flop型T_2WFSEシーケンスの開発を行った. MR信号を数値シミュレーションできるBloch方程式を使用し最適化を行った. Bloch方程式の数値シミュレーションでFlip-Flop可変型T_2WFSE法の最適化を行った.

1. Introduction

In the clinical setting, imaging a wide range with a thin slice thickness in a very short time period is required in Magnetic Resonance Imaging (MRI). A T_2-weighted (T_2W) sequence is a very effective scanning method for the detection of diseases. However, its efficacy is limited by the long repetition time (TR) in T_2W imaging. This consequently increases the scan time. Relaxation Enhancement (RARE) type T_2W sequence Fast Spin Echo (FSE) was proposed as a means of shortening scan times [1). FSE is a method of shortening scan times. This technique involves the use of multi-echo spin-echo techniques that allow more data to be collected. Chunks of k-space are gathered at a time consequently reducing scan times. FSE sequence is commonly used in current clinical practice.

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Despite the advantages of the FSE technique, it is limited by two major drawbacks. The first problem is the rise in specific absorption rate (SAR) [2). The safety of radio frequency (RF) pulse exposure during clinical MRI is regulated and monitored. The RF pulse sequences used in the FSE sequence are 90°(α)-180°(2α) type, based on Spin Echo sequence. The basic pattern of RF pulses for the FSE is 90°-180° Spin Echo excitation pulse pattern followed by multiple 180° refocusing pulses. Therefore, the same number of 180° pulses are repeatedly exposed to get the required number of echoes in FSE. These 180° refocusing pulses cause the increase in SAR level which consequently increases the thermal effect [3), 4)]. The second disadvantage of FSE is the decrease in soft tissue contrast in multi-slice imaging. This reduction in image quality occurs as a result of the magnetization transfer (MT) effect caused by the RF pulse, an issue frequently encountered in the FSE method [5), 6)]. For the reasons discussed above the development of a new

FSE sequence free of these two drawbacks has been requested.

Yamaguchi proposed a method to solve these problems. This method involves modification of the shape of the RF pulse not only to reduce the SAR, but to also improve the contrast of multi-slice imaging [7]. However, MRI scanners used in clinical settings are not equipped with the ability to use Yamaguchi's method because it requires the modification of the RF pulse. Hennig et al. Proposed a technique of reducing the angle of 180° refocusing pulses to overcome the SAR issue [8), 9)]. These methods were achieved by fixing the angle of RF either the 90° pulse or the 180° pulses [10]. Hahn studied α° (Flip) - β° (Flop) instead of the RF pulse 90° (α) - 180° (2α) [11]. For this study, we developed an FSE sequence with an RF pulse pattern of α° (Flip) - β° (Flop) and evaluated it in relation to SAR reduction and contrast noise ratio (CNR) improvement.

2. Method

2.1 The in-plane signal value and echo signal value.

A combination of the angles for Flip (Excitation Pulse) - Flop (Refocusing Pulse) is important if different angles are used. Echo Time (TE) in the FSE sequence is needed for the calculation of the combination of angles. Two equations were used to simulate the MRI signal values needed to obtain the optimal Flip-Flop angles. The Equation (1) is the Bloch equation. The Bloch equation enables numerical simulation of MR signals. The RF pulse profile and gradient magnetic field strength, TR, TE, T_1 and T_2 are necessary factors in numerical simulation of the Bloch equation. Mx, My, and Mz components are calculated from the Bloch equation. The Mxy component that gives the MRI signal values is then calculated from the Equation (2) accordingly [12), 13)]. The next Equation (3) gives the echo signal value as a simplified form of the Bloch equation [14]. Although both the RF pulse profile and gradient magnetic field strength are necessary factors in numerical simulation of the Bloch equation, we used the Equation (3) to obtain an adequate calculated of the echo signal value with only TR, TE, T_1 and T_2.

$$\begin{bmatrix} \frac{dMx}{dt} \\ \frac{dMy}{dt} \\ \frac{dMz}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_2} & \gamma B_0 & \gamma B_1 \sin\omega t \\ -\gamma B_0 & -\frac{1}{T_2} & \gamma B_1 \cos\omega t \\ -\gamma B_1 \sin\varpi t & -\gamma B_1 \cos\varpi t & -\frac{1}{T_1} \end{bmatrix} \begin{bmatrix} Mx \\ My \\ Mz \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{M_0}{T_1} \end{bmatrix} \quad (1)$$

$$\text{In-plane signal value} = \sqrt{\left(\sum_{i=1}^{N} M_{xi}\right)^2 + \left(\sum_{i=1}^{N} M_{yi}\right)^2} \quad (2)$$

$$\text{Echo signal value} = k\rho\left\{1-\exp\left(-\frac{TR}{T_1}\right)\right\}\exp\left(-\frac{TE}{T_2}\right)\times\cos\{270-(Flip+Flop)\} \quad (3)$$

M_x, M_y, M_z : Components, γ : Gamma, gyromagnetic ratio, ω : Angular frequency in radians per second, B_0 : Static magnetic field, B_1 : Amplitude of the RF field, TR: Repetition time, TE: Echo time, ρ : Proton density, T_1: Longitudinal recovery time, T_2: Transverse relaxation time, *Flip*: Excitation Pulse, *Flop*: Refocusing Pulse.

2.2 The optimization of Flip-Flop.

Normalization maps were drawn to determine the optimal angles for the Flip-Flop sequence. First, the values from each equation were normalised to allow the comparison of the results. This was necessary given the difference in the outcome of the simulation with the Equation (2) and (3). Two maps were drawn. One was based on the result of the calculation using the Equation (2) for each signal from Flip-Flop. A Normalization map was also drawn using the result attained from the Equation (3). Next, the Equation (4) was used to obtain curves that have the same attenuation ratio of 1.0. An optimal curve was determined for each echo based on the Equation (4).

$$1.0 = \frac{\text{Normalized in - plane signal value}}{\text{Normalized echo signal value}} \quad (4)$$

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2.3 Parameters for the calculation of in-plane signal value and echo signal value in numerical simulation.

The detail of the used parameters are following: TR = 4,500 ms, TE = 14.2 ms, 28.5 ms, 42.8 ms, 57.1 ms, 71.4 ms, 85.7 ms, 100 ms, 114.3 ms, 128.6 ms, 142.9 ms, 157.2 ms, 171.5 ms and 185.8 ms, Flip angle = 50° - 130° (5° step), Flop angle = 110° - 180° (5° step), Slice thickness = 5 mm, The target substance was Gray Mater of brain. Gray Matter (T_1 = 809 ms, T_2 = 101 ms [15]). The total number of the numerical simulation was 6,630. The analysis software used was Mathematic 4.0 and 6.0.

2.4 The evaluation of the optimal angles on clinical equipment.

We examined the physical evaluation for imaging by the optimum Flip-Flop angle obtained by numerical simulation in the clinical machine.

2.4.1 Analysis of Flip-Flop Angle Control

When changing the Flip-Flop angle, it is necessary to check whether the Flip-Flop angle can be accurately controlled at a specified angle. In this confirmation, the crest value of the RF waveform in the magnetic field was measured by measuring the RF waveform in the magnetic field using the search coil and changing according to the Flip-Flop angle. For the measurement range, the flip angle is 60 degrees to 120 degrees and the flop angle is 120 degrees to 180 degrees.

2.4.2 RF uniformity analysis at Flip-Flop angle

At the Flip-Flop angle, there a problem is encountered as to whether the RF pulse is uniformly applied to the substance.

To verify this problem, the RF pulse homogeneity test was conducted using a tissue equivalent phantom formed with the dielectric conductor (filler: copper sulfate solution 0.055%, conductivity: about 0.3 S/m).

The imaging conditions as follows, TR/TE = 400/15 ms, FOV = 300 mm, matrix: 256 × 256, slice thickness: 10 mm, NEX = 2, Acquire image: Sagittal, MRI unit: EXCELART/Pianissimo 1.0T (Toshiba Medical Systems).

2.4.3 Physical evaluation of images

The evaluation using the optimal Flip-Flop angles was conducted on a scanner in clinical settings. Measurements of slice thickness, Signal to Noise Ratio (SNR), and SAR were conducted as physical evaluation [16]. A 1.0 Tesla MRI (Toshiba Medical Systems) was used.

2.5 Image analysis

For the evaluation of actual images, one healthy subject's brain was scanned and the CNR of gray matter and white matter on an image from multi slice imaging was measured [17), 18)]. Informed consent was obtained from the subject prior to conducting the scan. Comparisons were made between a 90° - 180° sequence and the Flip-Flop 0 sequence regarding the drop rate of CNR in multi-slice scans. Signals from gray matter and white matter were calculated by averaging five sets of data. Each size of the region of interest (ROI) was circular, 4 × 4 (total of 16) pixels. A particular slice plane was selected so we could set the ROI on both the white and grey matter areas. The scan conditions as follows: TR = 4,500 ms, Effective TE = 100 ms, Echo Train Length = 13, Slice thickness = 5 mm, Slice gap = 1 mm, Number of slices = 22, Field of View = 300 mm × 300 mm. Matrix size = 256 × 256. A 1.5 Tesla MRI system (Philips Medical Systems) scanner was used for the CNR evaluation.

3. Results

3.1 The optimization of Flip-Flop.

Normalization maps of the in-plane signal values and echo signal values are shown in Fig.1 and Fig.2. The two maps shown have completely different patterns. Fig.1 (in-plane signal value map) shows an egg-shaped curve.

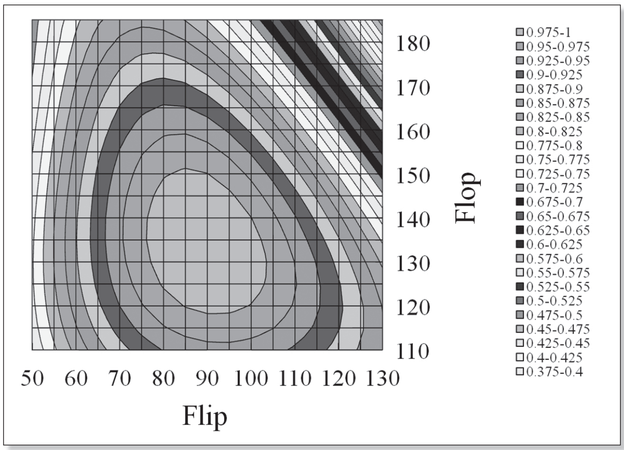


Fig.1 Normalization map of In-plane signal value

The contour diagram of the in-plane signal values obtained from the Bloch equation (Equation 1) and the in-plane signal value (Equation 2) showed an egg shape. The in-plane signal value of the center indicated.

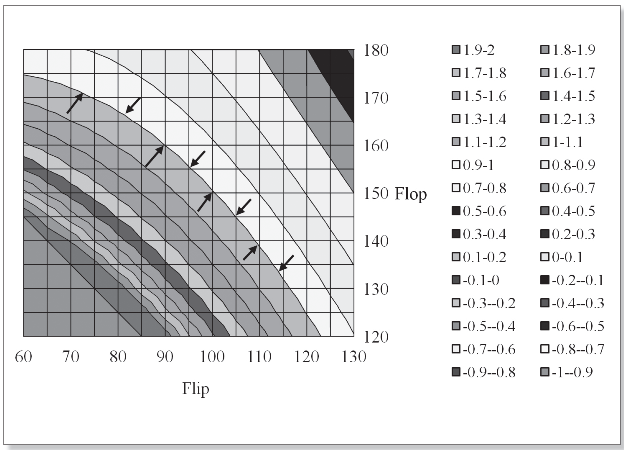


Fig.3 The optimal curve calculated from equation

The optimization curve obtained from equation 4. And a curve indicates a range showing 1.0. However, it is not possible to limit the optimum Flip-Flop angle form this curve.

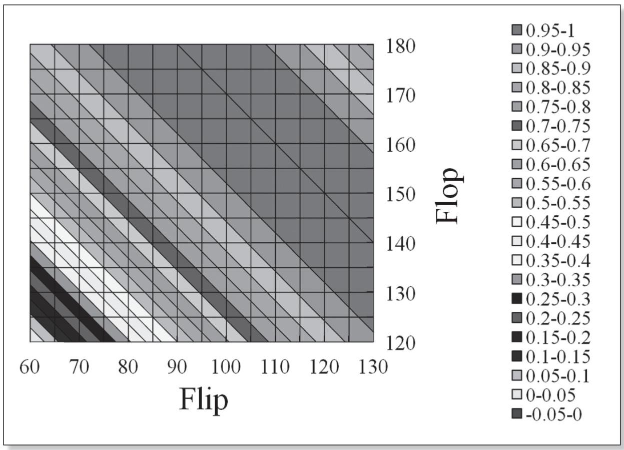


Fig.2 Normalization map of echo

Contour lines of the signal values of the Echo signal value (Equation 3) showed a linear change and showed a shape different from the Bloch equation.

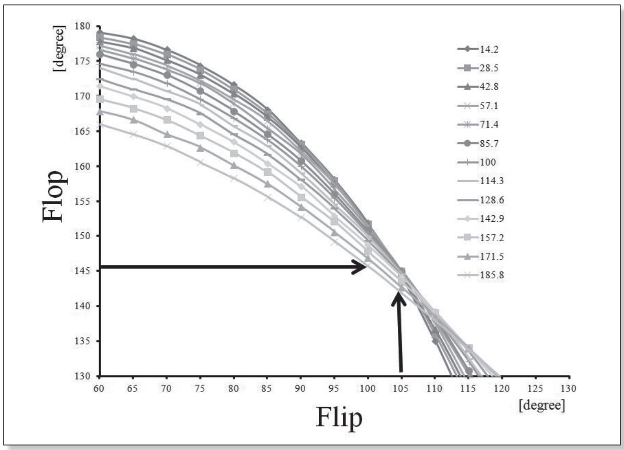


Fig.4 The curves show the optimal value when varying the TE 14.2 ms to 185.8 ms

The optimization curve shown in Figure 3 in shown for each TE. The flip-flop angle at which the optimization curve arrogates to one point wan taken as the optimum Flip-Flop angle.

The range around the maximum signal value is different to the one from 90° - 180° sequence. In contrast, the echo signal value shows a rectilinear pattern. The combination of the angle at which the signal value reaches its peak is at 90° - 180° sequence. The optimal curve calculated from the Equation (4) is indicated by arrows in Fig.3. The curve indicated by the arrows is at the level of 1.0 in signal strength.

3.1.1 Flip-Flop evaluation in relation to TE.

The diagram is shown below (Fig.4) describes the optimal value when shifting TE 14.2 ms to 185.8 ms. Optimal values of each curve are focused at the point of the combination near 105° (Flip) - 145° (Flop) sequence. It was determined that the angle combination is attributed to the value that has not been influenced by TE. TE 200 ms was not used as the results obtained largely deviated from 105° - 145° sequence.

3.2 Evaluation results on the clinical equipment.

3.2.1 Flip-Flop Angle Control

Fig.5 shows the peak value measurement

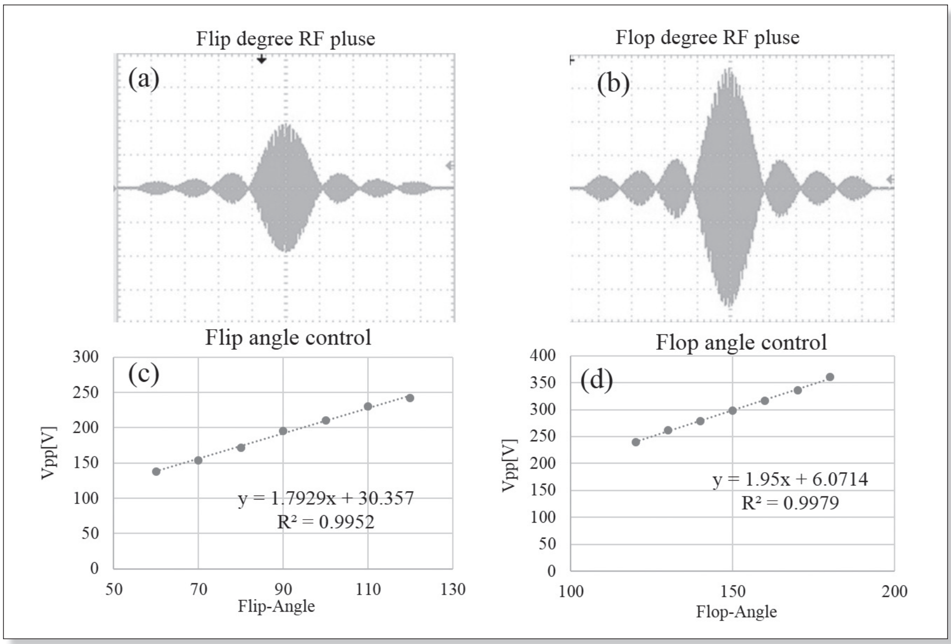
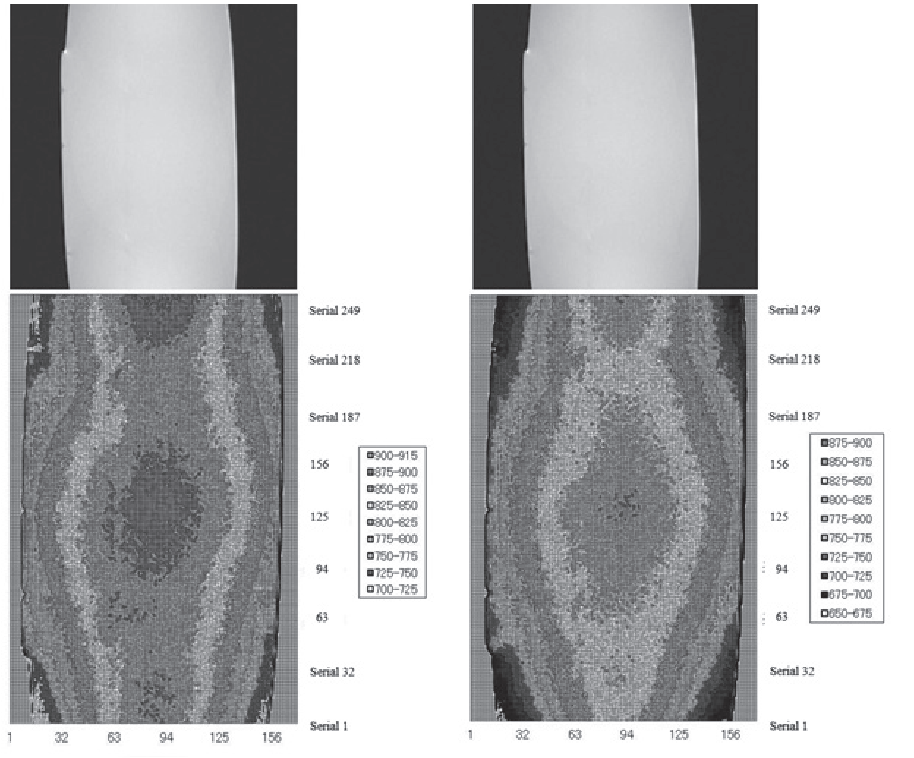


Fig.5　Accuracy of RF pulse in magnetic field

(a), (b): RF pulse waveform in magnetic field, (c): The Flip angle and the voltage of the RF pulse in the magnetic field [Vpp], (d): Flop angle and voltage of RF pulse in magnetic field [Vpp].



a) 90˚-180˚ sequence　　b) 105˚-145˚ sequence

Fig.6　Evaluation of uniformity of RF pulse

As for the 105˚-145˚ sequence in which the Flip-Flop was varied, like the 90˚-180˚ sequence, the signal value contour was not different in shape.

Table 1 The result of slice thickness and SNR measurements with two different combinations

Flip-Flop	Slice thickness [mm]	SNR
90°-180° sequence	5.7 ± 0.26	38.9 ± 0.1
105°-145° sequence	5.7 ± 0.27	39.7 ± 0.2

Image Acquisition Condition.
TR/TEeff = 4,500/100, 13 echo, ST/Gap = 5.0/1.0 mm, NS = 22 Slice, FOV = 300 mm, 256 × 256 matrix, NEMA Phantom.
Slice thickness and SNR is not different between 105°-145° sequence and 90°-180° sequence.

result of the RF pulse in the magnetic field of the search coil. The correlation coefficient of the peak value with respect to the input angle of the Flip-Flop showed high correlation and it was 0.9952 and 0.9979 at R^2.

3.2.2 RF uniformity analysis at Flip-Flop angle

Fig.6 showed the results of the RF pulse uniformity test at the optimum Flip-Flop angle. In the 90°-180° sequence, the contour plot at the center of the phantom is shown. On the other hand, even at 105°-145° sequence, contour plot showing the same shape as 90°-180° sequence was shown.

3.2.3 Physical evaluation results

The result of the physical evaluation is shown in Table 1 below. This indicates that there is no significant difference in SNR and slice thickness when using the combination of the angles of 105°-145° sequence.

3.3 The Brain imaging evaluation.

Fig.7 shows Ax T_2W images of the brain of a subject. No remarkable artifact is evident in the

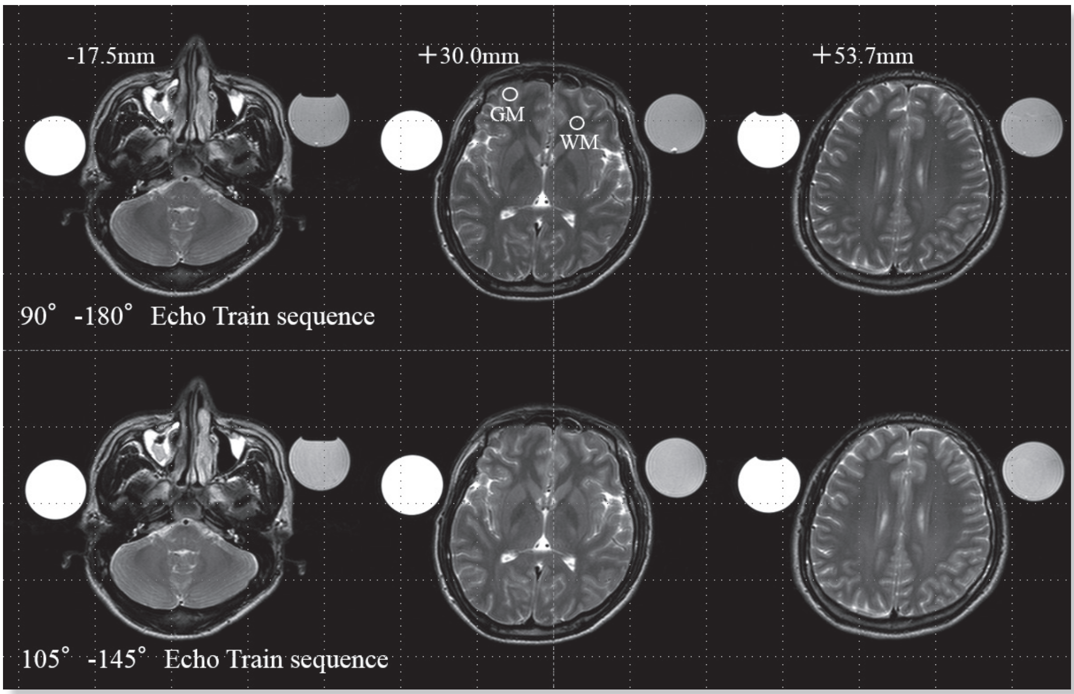


Fig.7 Images of the brain of the subject

Image Acquisition Condition.
TR/TEeff = 4,500/100, 13 echo, ST/Gap = 5.0/1.0 mm, NS = 22 Slice, FOV = 300 mm, 256 × 256 matrix, Head Coil.
Measurement points of CNR are shown. No significant artifact was obtained by 105°-145° sequenced imaging.

images. CNR of Gray Matter and White Matter for the 90°- 180° sequence and the 105° - 145° sequence are 37.8 and 47.8 respectively. There is an improvement of 20.9% in the CNR when using the 105°- 145° sequence. The SAR showed on the clinical machine for which CNR was obtained was 1.37 [W/Kg] and 2.06 [W/Kg] with 105 - 145 degree echo train and 90 - 180 degree echo train. We can reduce 33.6% of SAR with the 105°- 145° sequence compared to the 90°- 180° sequence.

4. Discussion

Factors required for diagnosis are spatial resolution or contrast resolution. The spatial resolution of multi-slice computed tomography (CT) in recent years has been superior to other medical imaging modalities. MRI maintains its advantage in contrast resolution over CT. However, low contrast resolution in FSE has been a problem in clinical practice. For this reason, minimising the degradation of contrast resolution is important for more optimal clinical practice. This article recommends the use of the Flip-Flop angle other than the angle of 90° - 180° as a viable solution to this problem.

Two equations were used in this study to calculate the MR signal values needed to obtain the Flip-Flop angle. The in-plane signal values and echo signal values are calculated from the Equations (2) and (3) The optimal value was found from the results and the optimal curve (Fig.4) was obtained to determine the Flip-Flop angle.

It is possible to obtain the Flip-Flop angle while at the same time maintaining contrast resolution. In addition, the optimal the Flip-Flop angles 105°- 145° were found from each curve having different TE. Image artifact was not seen from the angles used on brain scan images using a test subject.

The study yielded some improvement in soft tissue contrast resolution, which increased by 24.3%. In addition to that, there was also a reduction of 33.6% in SAR. The above results indicate that the contrast resolution of the FSE sequence can be improved by changing the Flip-Flop angle. Further evaluation is necessary to confirm the efficacy of the Flip-Flop method on imaging in the clinical setting.

5. Conclusion

The angle of the RF pulses used in the FSE sequence is generally 90° (α) - 180° (2α). This causes the degradation of soft-tissue contrast resolution and increases the SAR. A new FSE sequence that doesn't employ 90°- 180° RF pulse combination was designed. This new FSE sequence has a combination angle of 105° - 145° in relation to Flip-Flop. Using this technique enables us to improve the contrast resolution of soft tissue as well as reduce SAR.

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