Optimization of Scan Parameters for \( T_1 \)-FLAIR Imaging at 1.5 and 3T using Computer Simulation

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Purpose: We attempted to optimize scan parameters for \( T_1 \)-weighted fluid-attenuated inversion recovery (\( T_1 \)-FLAIR) sequence at 3 and 1.5 tesla (T) using computer simulation.

Methods: We measured the \( T_1 \) and \( T_2 \) relaxation time values (\( T_{1v} \) and \( T_{2v} \)) of gray (GM) and white matter (WM) at 3 and 1.5T, generated computer-simulated \( T_1 \)-FLAIR (CS-\( T_1 \)-FLAIR) images using those values, and compared the simulated and actual \( T_1 \)-FLAIR images to verify the contrast reliability of our computer simulation. We mathematically and visually evaluated CS-\( T_1 \)-FLAIR images at various repetition times (TR) and echo times (TE).

Results: At 3T, the measured relaxation values for GM were \( T_{1v} \), 1524 ms, and \( T_{2v} \), 85 ms, and for WM, \( T_{1v} \), 750 ms, and \( T_{2v} \), 65 ms. At 1.5T, the measured relaxation values for GM were \( T_{1v} \), 1251 ms, and \( T_{2v} \), 99 ms, and for WM, \( T_{1v} \), 623 ms, and \( T_{2v} \), 75 ms. Contrast of CS-\( T_1 \)-FLAIR and actual \( T_1 \)-FLAIR images was identical. An optimal TR of 3140 ms was determined for \( T_1 \)-FLAIR at 3T and 2440 ms at 1.5T based on mathematical evaluation. The optimal TR ranges were 2400 to 3900 ms at 3T and 1800 to 3200 ms at 1.5T based on visual assessment of CS-\( T_1 \)-FLAIR. A shorter TE provided better \( T_1 \) contrast.

Conclusion: We optimized \( T_1 \)-FLAIR by focusing on its most important scan parameters using computer simulations and determined that a longer TR was suitable at 3T than at 1.5T. Our computer simulation was useful for determining the optimal scan parameters.

Keywords: optimal scan parameters, TR, \( T_1 \) FLAIR, 3T MRI

Introduction

The advantages of high field systems have been demonstrated clinically since the introduction of the 3-tesla magnetic resonance (MR) system. However, several physical parameters change as magnetic field strength increases. Some of these changes benefit MR imaging or MR spectroscopy. The improved signal-to-noise ratio (SNR) at 3T than 1.5T offers better image quality and reduces acquisition time. Tissue relaxation rates depend on field strength. With high field strengths, \( T_1 \) relaxation time will increase because \( T_1 \) relaxation slows down. The contrast of gray (GM) to white matter (WM) will be reduced at 3T. Early studies of the 3T MR system showed that adequate \( T_1 \) contrast images could not be obtained with the 3T system as with 1.5T systems. In contrast, better contrast of \( T_1 \)-weighted images (\( T_1 \)WI) obtained by fast spin-echo (FSE) has been reported at 3T than 1.5T after adjustment of various scan parameters.

\( T_1 \)WI is important for clinical applications and essential for evaluating brain anatomy and morphology. Use of a \( T_1 \)-weighted fluid-attenuated inversion recovery (\( T_1 \)-FLAIR) sequence, recently adopted to improve \( T_1 \) contrast, has become a standard protocol in some institutions. The \( T_1 \)-FLAIR...
sequence is characterized by application of an additional 180° radiofrequency (RF) pulse before the spin-echo (SE) sequence that increases T₁ contrast. Al-Saeed and associates showed better contrast-to-noise ratio (CNR) and other advantages of T₁-weighted FLAIR imaging over the more widely used T₁-weighted fast spin-echo (T₁-FSE) sequence at 1.5T with comparable acquisition time. There have been no reports on image contrast or optimal scan parameters for T₁-FLAIR at 3T or higher.

In this study, we developed computer simulation software to reproduce MR images at various pulse sequences. The software was programmed using MATLAB (Mathworks, Natick, MA, USA) and simulated MR images using numerical calculations. The computer-simulated MR images (CS-MRI) were generated by equations for various sequences using T₁ relaxation value (T₁v), T₂ relaxation value (T₂v), and proton density (PD) for each brain component and scan parameter, including long repetition time (TR), echo time (TE), and inversion time (TI). Actual MR images demonstrated noise and artifacts as well as the signal intensity of various tissues; CS-MRI demonstrated only the signal intensity of tissue. CS-MRI may provide more precise visual understanding of changes in contrast in response to variation in relaxation time.

In the present study, we determined the optimal scan parameters for T₁-FLAIR at 3T and 1.5T using CS-MRI.

Materials and Methods

Reliability of computer simulation software

We verified contrast reliability of our computer simulation software by comparing actual and simulated MR images that generated with measured T₁v and T₂v of the identical subject. We measured the relaxation times of various tissues in healthy volunteers and compared contrast between actual and computer-simulated T₁-FLAIR images (CS-T₁-FLAIR) generated using relaxation times measured from the same subject.

Measurement of relaxation time

We measured the T₁v and T₂v in 5 healthy volunteers (3 men, 2 women; aged 27 to 35 years; mean age, 30 years) who underwent scanning at both 3 and 1.5T (Achieva; Philips Medical Systems, Best, The Netherlands) using an 8-channel receiver head coil. All subjects underwent T₁-FLAIR, T₂-FSE, T₂-FLAIR, and MR angiography during the same imaging session to confirm the absence of abnormalities. Written informed consent was obtained in accordance with the institutional review board of our hospital.

We measured tissue relaxation time using the 2-dimensional (2D)-mixed SE sequence, a method used to measure the T₁v and T₂v during a single acquisition. We measured T₁v by inversion recovery and measured T₂v by multi-echo sampling. The mixed-SE pulse sequence began with the application of an inversion pulse with 2 inversion times and 2 effective echo times, which generated 4 self-coregistered images, each with different levels of T₁ and T₂ weighting. We processed the images acquired directly to generate quantitative maps illustrating the distributions of T₁ and T₂ based on native spatial resolution and anatomical coverage of the directly acquired 2D-mixed SE scan. The sequences performed at 1.5 and 3T used parameters: field of view (FOV), 230 x 184 mm; acquisition matrix, 128 x 128; reconstruction, 256 x 256; voxel size, 0.9 x 0.9 x 6.0 mm; scan percentage, 100%; number of slices, one; TE, 30, 60, 90, and 120 ms; TR, (SE sequence), 920 ms, or (IR sequence), 2300 ms; TI, 500 and 1420 ms; fat suppression, none; number of signals averaged (NSA), 2; and sensitivity-encoding parallel imaging (SENSE) factor, none.

We manually placed 5 circular regions of interest (ROIs) on each white (WM) and gray matter (GM) structure in the bilateral frontal lobe of each T₁v map and T₂v map calculated using the 2D-mixed SE sequence (Fig. 1). The mean ROI was used as the value for each brain component. The TI and TE used were too short for adequate measurement of T₁v and T₂v of cerebrospinal fluid (CSF), so we used previously reported values for the T₁v and T₂v of CSF.

Fig. 1. We manually placed 5 circular regions of interest (ROIs) on each white (WM) and gray matter (GM) structure in the bilateral frontal lobe. Because the volume of GM was very small, we selected and placed the ROI where it did not appear to be affected by a partial volume effect.
CS-T₁-FLAIR images

Our simulation software used various sequence equations and a 3-dimensional dataset of brain components, which comprised WM, GM, and CSF obtained by segmenting brain images from 305 healthy volunteers. CS-MRIs were generated for various sequences by imputing the $T₁v$, $T₂v$, and PD of each brain component and applying sequence parameters, such as TR and TE. For the T₁-FLAIR sequence, we calculated the simulated signal intensity (SI) of each brain component as:

$$SI = PD \times \left[ 1 - 2e^{-\frac{T_{null}}{T₁}} + 2e^{-\frac{(TR-TE)}{T₁}} - e^{-\frac{(TR/TE)}{T₁}} \right] e^{-\frac{TE}{T₂}}. \quad [1]$$

We generated 6 CS-T₁-FLAIR images with various TR/TI parameters (1500/680, 2000/880, 2500/1067, 3000/1240, 3500/1400, and 4000/1547 ms) at both 3 and 1.5T and measured each relaxation time in each of the 5 volunteers. We used previously reported PD values for GM and 0.70 mL of water/mL for WM. The TI was calculated using the $T₁v$ of the CSF (4300 ms), which was reported previously.

Actual T₁-FLAIR images

We scanned the T₁-FLAIR images at both 3 and 1.5T using the same 5 healthy volunteers who participated in the measurement of relaxation time. A single oblique-axial slice was positioned parallel to the anterior commissure-posterior commissure line at the level of the basal ganglia. The imaging parameters were adjusted to the same settings with each field strength. The actual MR images were acquired using the conventional IR sequence, and we did not use the fast acquisition technique. The actual images mathematically and visually to determine the optimal scan parameters. We analyzed 60 ROIs to determine their correlations (6 different TRs at 3T and 1.5T using 5 subjects). Simple linear regression was applied. A 2-sample paired t-test was conducted using JMP 8.0.2 software (SAS Institute, Cary, NC, USA). $P < 0.05$ was considered statistically significant.

Comparison of contrast between CS-T₁-FLAIR and actual T₁-FLAIR images

We compared contrast values of CS-T₁-FLAIR images at 3 and 1.5T with those of actual T₁-FLAIR images at 3 and 1.5T in a quantitative analysis. In general, image contrast is assessed using the CNR equation, in which the CNR is defined using the signal intensity of the WM (SI₃M) and GM (SI₃M) and the noise level (NB₀) as:

$$CNR_{W/G} = (SI_{WM} - SI_{GM}) / NB₀. \quad [2]$$

However, we could not use this equation for CS-MRI or actual MR images in this study because the CS-MRI did not contain noise or artifacts. Neither could we exactly measure background noise in the actual MR images because of noise reduction filter processing by the MR imaging hardware. Therefore, we evaluated the contrast between WM and GM using numerical equations to determine the Michelson contrast (Michelson C) for the CS-MRI and actual MR images. The equation used to determine Michelson C between WM and GM (Michelson $C_{W/G}$) was:

$$Michelson \ C_{W/G} = (SI_W - SI_G) / (SI_W + SI_G). \quad [3]$$

This equation has also been used to compare image contrast between 3T and 1.5T MR imaging in previous studies.

The GM and WM of the bilateral frontal lobes were selected as ROIs in each MR image. In each subject, we manually drew 5 ROIs, each of which contained an area of 16 pixels, in the same manner as we used in measuring relaxation time. The mean pixel value of the ROIs was treated as the signal intensity of each brain component. We analyzed the Michelson $C_{W/G}$ values of the CS-T₁-FLAIR and actual T₁-FLAIR images individually for all volunteers. We analyzed 60 ROIs to determine their correlations (6 different TRs at 3T and 1.5T using 5 subjects). Simple linear regression was applied. A 2-sample paired t-test was conducted using JMP 8.0.2 software (SAS Institute, Cary, NC, USA). $P < 0.05$ was considered statistically significant.

Determination of T₁-FLAIR scan parameters using CS-MRI

We generated CS-T₁-FLAIR images using various TR, TE with the mean relaxation time obtained from 5 volunteers at both 3 and 1.5T and evaluated the images mathematically and visually to determine the optimal scan parameters.

Mathematical evaluation

We evaluated the signal difference between WM and GM ($SD_{W/G}$) mathematically as:

$$SD_{W/G} = SI_W - SI_G. \quad [4]$$

As mentioned, we could not use the $CNR_{W/G}$ equation to compare contrast between CS-T₁-FLAIR and actual T₁-FLAIR images though the equation is generally used to determine scan parameters. We could substitute $SD_{W/G}$ for $CNR_{W/G}$ in our computer simulation because $NB₀$ is theoretically pro-
portional to the static field strength and assumed to be independent of imaging parameters, such as TR, TE, and TI. We therefore determined the optimal scan parameters using the SDW/G equation and visual assessment. We determined the optimal TR by calculating SDW/G using Equation [2], in which TR ranged from 1000 to 6000 ms (at 100-ms intervals) and TE was fixed at 12 ms. To determine the optimal TE, we simulated SDW/G using Equation [2], in which TE ranged from 10 to 50 ms (at 10-ms intervals) and TR was fixed at 2400 ms.

### Visual assessment

Three experienced neuroradiologists visually assessed contrast between WM and GM (VCW/G) to determine the range of the optimal TR that provided adequate T1 contrast. They assessed the adequacy of T1 contrast in randomly ordered CS-T1-FLAIR images generated using TRs ranging from 1000 to 6000 ms (at 100-ms intervals) and TE fixed at 12 ms. Using a 3-point scale, they assessed contrast as insufficient (0 points), acceptable (one point), or adequate (2 points) and defined the optimal TR range as the TR of images that scored greater than 5 points in total. The differences between observers were tested using a Kruskal-Wallis test with JMP 8.0.2 (SAS Institute). P < 0.05 was considered statistically significant.

### Results

**Measurement of relaxation time value**

Tables 1 and 2 summarize relaxation times measured in this and previous studies. The measured relaxation values at 3T were: GM, T1v (1524 ms) and T2v (85 ms) and WM, T1v (750 ms) and T2v (65 ms). At 1.5T, they were: GM, T1v (1251 ms) and T2v (99 ms) and WM, T1v (623 ms) and T2v (75 ms). The T1v of GM was about 21% higher and that of WM about 29% higher at 3T than 1.5T, whereas the T2v of GM was about 9% lower and that of WM about 11% lower at 3T than 1.5T.

### Table 1. Summary of relaxation time measurements at 3 tesla in the literature (mean ± standard deviation [SD])

| Year | Author       | T1v (ms) | T2v (ms) | Method     |
|------|--------------|----------|----------|------------|
| 2008 | Wright(14)   | 1600 ± 110 | 840 ± 50 | MPRAGE     |
| 2006 | Weigel(15)   | 1543 ± 50  | 907 ± 27 | TSE        |
| 2005 | Lu(6)        | 1209 ± 109 | 699 ± 38 | IR, CPMG   |
| 1999 | Gelman(16)   | 1763 ± 63  | 847 ± 43 | Look Locker|
| 1999 | Wansapura(17)| 1331 ± 13  | 832 ± 10 | SR for T1v, SE for T2 |
| 2008 | This study   | 1524 ± 45  | 750 ± 11 | Mixed TSE |

CPMG, Carr-Purcell-Meiboom-Gill; GM, gray matter; IR, inversion recovery; MPRAGE, magnetization prepared rapid gradient echo; TE, spin echo; SR, saturation recovery; TSE, turbo spin-echo; WM, white matter; T1v, T1v relaxation time value; T2v, T2 relaxation time value.

### Table 2. Summary of relaxation time measurements at 1.5 tesla in the literature (mean ± standard deviation [SD])

| Year | Author       | T1v (ms) | T2v (ms) | Method     |
|------|--------------|----------|----------|------------|
| 2008 | Wright(14)   | 1200 ± 130 | 650 ± 30 | MPRAGE     |
| 2007 | Rooney(18)   | 1188 ± 69  | 656 ± 16 | Look Locker|
| 2006 | Weigel(15)   | 1213 ± 26  | 679 ± 20 | TSE        |
| 2005 | Lu(6)        | 1048 ± 61  | 556 ± 20 | IR, CPMG   |
| 1999 | Vymazal(19)  | 1304 ± 200 | 660 ± 51 | SR         |
| 1998 | Kingsley(20) | 1113 ± 48  | 636 ± 29 | IR-SE      |
| 1997 | Cho(21)      | 1144 ± 75  | 641 ± 27 | PAIR       |
| This study | 1251 ± 41  | 623 ± 12  | 99 ± 2    | Mixed TSE method |

CPMG, Carr-Purcell-Meiboom-Gill; GM, gray matter; IR, inversion recovery; MPRAGE, magnetization prepared rapid gradient echo; SE, spin echo; SR, saturation recovery; TSE, turbo spin-echo; WM, white matter; T1v, T1v relaxation time value; T2v, T2 relaxation time value.
Comparison of contrast between CS-T1-FLAIR and actual T1-FLAIR images

Contrast of CS-T1-FLAIR images precisely reproduced the contrast of the actual T1-FLAIR images in the mathematical and visual evaluations (Figs. 2, 3). The Michelson $C_{W/G}$ of CS-T1-FLAIR images correlated strongly with that of the actual T1-FLAIR images in all cases (Fig. 4).

Determination of optimal scan parameters for T1-FLAIR using CS-MRI

In the mathematical simulation, the peak $SD_{W/G}$ of the T1-FLAIR sequence was observed with TR values of 3140 ms at 3T and 2440 ms at 1.5T (Fig. 5).

As the TR increased, the brightness of CS-T1-FLAIR images generated using the mean relaxation time of the 5 healthy volunteers increased gradually (Fig. 6), but the $VC_{W/G}$ of the images decreased gradually.

Visual assessments by the 3 neuroradiologists yielded scores over 5 points for CS-T1-FLAIR images with TR of 2400 to 3900 ms at 3T and 1800 to 3200 ms at 1.5T, and that range of TR was considered optimal TR. There were no significant differences among observers. The optimal TR value in the mathematical simulation and the optimal TR range determined by visual assessment were longer at 3T than 1.5T.

A shorter TE gave a better $SD_{W/G}$ in the numeri-
Fig. 4. Strong correlations between computer-simulated T1-weighted fluid-attenuated inversion recovery (CS-T1-FLAIR) and actual T1-FLAIR images ($R^2 = 0.896, P < 0.001$).

**Michelson $C_{W/G}$**

\[
y = 1.3952x - 0.0945 \\
R^2 = 0.8957
\]

**Fig. 5.** Curve of the signal difference between white and gray matter ($SD_{W/G}$) calculated using the mean relaxation time ($T1v$, $1524$ ms, and $T2v$, $85$ ms, of GM at 3T; $T1v$, $750$ ms, and $T2v$, $65$ ms, of WM at 3T; $T1v$, $1251$ ms, and $T2v$, $99$ ms, of GM at 1.5T; $T1v$, $623$ ms, and $T2v$, $75$ ms, of WM at 1.5T) measured in each brain component of 5 healthy volunteers. Echo time (TE) was fixed at 12 ms; repetition time (TR) was varied from 1000 to 10000 ms.

**Fig. 6.** Computer-simulated T1-weighted fluid-attenuated inversion recovery (CS-T1-FLAIR) images at 3 tesla generated using the mean relaxation time measured in each brain component of 5 healthy volunteers. Echo time (TE) was fixed at 12 ms, whereas repetition time (TR) varied from 1000 to 6000 ms (at 100-ms intervals). Not all images are shown.

Discussion

Three-tesla MR imaging is in wide routine clinical use. However, few reports address signal intensity and contrast changes induced by the variable relaxation times with 3 and 1.5T. Some studies have reported lower contrast of T1-SE images at 3T than 1.5T. Scarabino and associates attributed...
lower CNR\textsubscript{W/G} with T\textsubscript{1}-SE images to the longer T\textsubscript{1} relaxation time at 3T. Nobauer-Huhmann and colleagues\cite{Nobauer-Huhmann} noted that a TR optimized for 1.5T was too long to obtain adequate contrast at 3T. Conversely, some groups have reported better contrast of T\textsubscript{1}-SE at 3T than 1.5T after adjusting scan parameters.\cite{Fushimi,Fushimi2,Fushimi3} Fushimi's group\cite{Fushimi} showed that the CNR\textsubscript{W/G} in single-slice T\textsubscript{1}-SE images and the CNR\textsubscript{W/G} in multi-slice images with a 25\% interslice gap were both better at 3T than 1.5T using the same scan parameters. They also reported a higher CNR\textsubscript{W/G} reduction rate for multi-slice images with a 0\% gap than single-slice images at 3T. They assumed that cross-talk and/or magnetization transfer (MT) effect may have reduced the CNR during multi-slice imaging. These reports addressed T\textsubscript{1}-SE, but no reports relate to T\textsubscript{1}-FLAIR. We believe there have been no reports regarding T\textsubscript{1}-FLAIR at 3T and that ours is the first to investigate the contrast and optimal scan parameters for T\textsubscript{1}-FLAIR imaging at 3T.

The relaxation time values measured in this study did not differ significantly from the values previously reported (Tables 1, 2). Some differences between the present and previous reports might be related to variations in age of volunteers, spatial resolution, pulse sequences used for measurement, and ROI chosen for analysis. Gelman and associates showed that variation in T\textsubscript{1} relaxation times between regions of the brain often correlated with non-heme iron levels and water content; iron levels had a greater influence on GM relaxation times, whereas water content had a greater influence on the WM.\cite{Gelman} Because the GM volume was also small, its measured relaxation time might have been affected by a partial volume effect of CSF.

We had to verify the reliability of our computer simulation prior to the study. We compared CS-T\textsubscript{1}-FLAIR images with T\textsubscript{1}-FLAIR images acquired from all subjects. We compared contrast precisely, performing single-slice acquisition to eliminate such factors as cross-talk and magnetization transfer effect. Michelson C\textsubscript{W/G} values correlated strongly and the VC\textsubscript{W/G} correlated well between CS-T\textsubscript{1}-FLAIR and actual T\textsubscript{1}-FLAIR images. We considered the precise reproduction of changes in contrast in CS-T\textsubscript{1}-FLAIR images due to changes in TR as verification of the reliability of our simulation.

We found that the peak SD\textsubscript{W/G} for the T\textsubscript{1}-FLAIR sequence occurred with TRs of 3140 ms at 3T and 2440 ms at 1.5T in the numerical simulations (Fig. 5) and considered these TR values optimal for our 5 subjects. Lu's group\cite{Lu} observed peak T\textsubscript{1} contrast with TR of 520 ms at 3T and 480 ms at 1.5T in determining optimal scan parameters for the T\textsubscript{1}-SE sequence. The longer T\textsubscript{1} relaxation time measured at 3T than 1.5T would have lengthened the optimal TR. The results of both studies indicated longer optimal TR of T\textsubscript{1}WI at 3T than 1.5T. In the visual assessment, the CS-T\textsubscript{1}-FLAIR images were displayed with an adequate VC\textsubscript{W/G} when the TR ranged from 2400 to 3900 ms at 3T and from 1800 to 3200 ms at 1.5T. The lower limits of both 3 and 1.5T were approximately 95\% of the peak SD\textsubscript{W/G}; the upper limits were approximately 90\% of the peak SD\textsubscript{W/G} according to the numerical simulations. Lu’s group\cite{Lu} also reported the adjustable ranges for T\textsubscript{1}-SE sequences as 400 to 660 ms at 3T and 360 to 620 ms at 1.5T, calculated based on the constraint that 95\% of the peak contrast had to be maintained. In the current study, our derived optimal TR ranges based on visual assessments required more than 90\% of the peak contrast. Thus, although the sequences differed between the 2 studies, our optimal TR range agreed well with their definition. We believe the broader optimal TR range for T\textsubscript{1}-FLAIR than T\textsubscript{1}-SE provides greater flexibility when determining the TR that corresponds to the acquisition time or number of slices, which is easier to implement in a clinical setting.

In determining optimal TE, we found that a shorter TE gave a better SD\textsubscript{W/G} at both field strengths (Fig. 7). Therefore, the shortest TE should be selected to produce better T\textsubscript{1}-FLAIR images at each field strength.
Our computer-simulated images adequately replicated contrast without requiring actual image acquisition. Such images could facilitate precise visual understanding of image contrast in brain MR imaging and selection of optimal scan parameters. This computer simulation can be used to predict image contrast and determine optimal scan parameters when new MR systems or sequences are introduced clinically.

**Conclusion**

Our computer simulation adequately reproduced actual MR images and was useful for determining optimal scan parameters. We used computer simulations to optimize the T1-FLAIR sequence by focusing on its most important scan parameters and found that the TR selected at 3T should be longer than that at 1.5T.

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