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T_1 and T_2 Selective Method for Improved SNR in CSF-Attenuated Imaging: T_2-FLAIR

Eric C. Wong,* Thomas T. Liu, Wen-Ming Luh, Lawrence R. Frank, and Richard B. Buxton

We present here a method for improving SNR in CSF-attenuated imaging relative to the standard technique of using an inversion pulse and imaging at the null point of CSF. In this new method the inversion pulse is replaced with a 90_x–180_y–90_x preparation sequence that provides T_1 and T_2 selectivity. This allows the tissue magnetization to recover more rapidly, allows for the use of shorter TR values, and reduces T_1 weighting. Magn Reson Med 45:529–532, 2001. © 2001 Wiley-Liss, Inc.

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For several forms of brain imaging it is necessary to attenuate signal from CSF in order to visualize the desired tissue components. One example is diffusion imaging, where the high apparent diffusion coefficient (ADC) of CSF complicates the measurement of the ADC and/or diffusion tensor in brain tissue (1). An application that is of particular interest to our group is a dynamic blood volume imaging technique that uses flow weighting gradients to dephase the blood signal (2–4). Here again, CSF complicates the analysis because the ADC of CSF is intermediate between those of brain tissue and flowing blood. Another example is clinical T_2-weighted FLAIR imaging for the detection of brain lesions (5–8), in which an inversion preparation is used with image acquisition at the null point of CSF in order to improve the conspicuity of long T_2 brain lesions.

We introduce here a modification of the FLAIR technique that improves the SNR of CSF-suppressed images by taking advantage of the fact that both the T_1 and the T_2 of CSF are long compared to that of other tissues. We refer to this new technique as T_2-FLAIR. This technique was originally reported in abstract form in Ref. 9.

Preparation schemes that encode magnetization with T_1 and/or T_2 information prior to imaging sequences have been used for many years (see, for example, 10). The most closely related to the present work is an angiography technique (11), in which the magnetization of tissues with similar T_1 (blood and muscle) were separated based on differences in T_2 and then converted into longitudinal magnetization, with image acquisition occurring at the null point of muscle.

METHODS

In T_2-FLAIR, the inversion pulse of FLAIR is replaced with a 90_x-τ-180_y-τ-90_x sequence. For spins with T_2 that are long compared to 2τ, the sequence is essentially an inversion pulse, as the second 90° pulse inverts any magnetization that is formed by the spin echo created by the first two pulses. However, for spins with T_2 that are short compared to 2τ, the sequence behaves like a saturation pulse, because very little magnetization exists to invert at the time of the spin echo. The evolution of magnetization for CSF and brain tissue are shown in Fig. 1 for an inversion time that was adjusted to null CSF. In this figure, the magnetization plotted is transverse between the two 90° pulses and longitudinal at other times. The relaxation times used in this figure and for parameter optimization (CSF: T_1/T_2 = 4591/1721 ms; Brain (average of gray and white): T_1/T_2 = 815/68.4 ms) were measured in healthy volunteers on our scanner. The expression for the longitudinal magnetization available for imaging is

$$M_z/M_0 = 1 - (1 + (1 - e^{-(TR-TI-2\tau)/T_1})e^{2\tau/T_2})e^{-TI/T_1} \quad [1]$$

where TI is the time between the second 90° pulse of the T_2-FLAIR preparation and the imaging excitation pulse, and M_0 is the longitudinal magnetization of fully relaxed tissue. Longitudinal magnetization that is generated by T_1 relaxation during the 2τ period is destroyed by the second 90° pulse and therefore does not enter into Eq. [1]. We assume here that the imaging pulse sequence effectively destroys all of the available magnetization, such as a gradient echo, spin echo, or fast spin echo train with a 90° initial RF pulse. For other imaging techniques, the steady-state signal across TRs would have to be calculated and Eq. [1] modified accordingly.

T_2-FLAIR was implemented on a 1.5T GE LX ECHOSPEED system with a standard head RF coil. The imaging technique used was a 16-shot interleaved spiral with FOV 24 cm × 5 mm, TE 3 ms, and 256 × 256 resolution.

RESULTS

Using Eq. [1], the TI that nulls the CSF signal was calculated for a range of values for TR and τ. At each value of TR and τ, the signal from brain tissue at this value of TI was also calculated. The brain signal divided by the square root of TR is a useful index of SNR efficiency because it is a measure of SNR per unit scan time. Contours of this index are shown in Fig. 2, and demonstrate a broad peak centered at τ = 89.3 ms and TR = 2576 ms, a much shorter TR than is typically used with FLAIR. The bottom edge of this plot corresponds to conventional FLAIR, which is de-

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*Correspondence to: Eric C. Wong, Thornton Hospital Radiology 7756, 9300 Campus Point Drive, La Jolla, CA 92037. E-mail: ecwong@ucsd.edu

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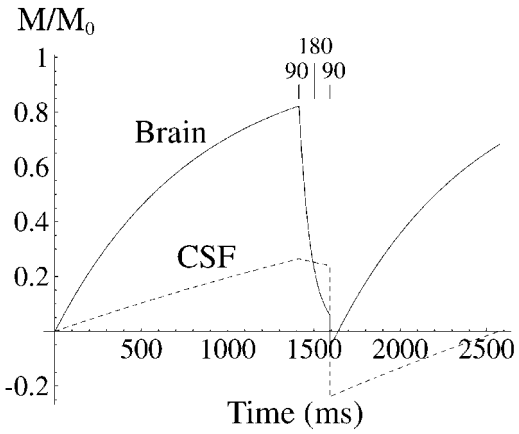

FIG. 1. Evolution of magnetization over one TR period for brain tissue (solid) and CSF (dashed). Magnetization is transverse in the 90°-τ-180°-τ-90° period and longitudinal at other times.

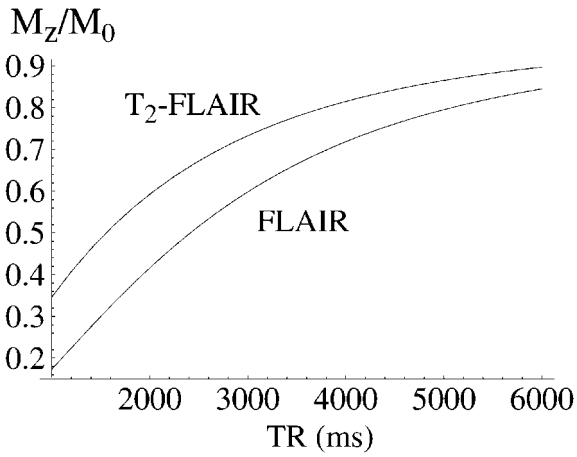

FIG. 3. Longitudinal magnetization available for imaging for conventional FLAIR and T_2-FLAIR (τ = 89.3 ms) as a function of TR.

scribed by Eq. [1] with $\tau = 0$. For conventional FLAIR, this index peaks at TR = 4182 ms, and is 16% below the peak for T_2-FLAIR.

The calculated brain signal for conventional FLAIR and for T_2-FLAIR at τ = 89.3 ms as a function of TR are shown in Fig. 3. The T_2-FLAIR signal is higher at all TR values, with an increase of 99% at TR = 1000 ms, and 6% at TR = 6000 ms. The longitudinal magnetization available for imaging using conventional FLAIR at TR = 4000 ms is 0.72 M_0. This same magnetization is available using T_2-FLAIR at a TR = 2869 ms, allowing for significantly shorter scan times without sacrificing SNR.

The T_2 contrast resulting from the T_2-FLAIR preparation is reversed from that of typical T_2-weighted images. Longer T_2 species are more completely inverted by the T_2-FLAIR preparation, resulting in lower signal (provided that image acquisition occurs after the zero crossing of the longitudinal magnetization). In conventional T_2 weighting longer T_2 species give higher signal. For clinical T_2-weighted FLAIR imaging a conventional long TE imaging sequence can be used in conjunction with a T_2-FLAIR preparation. The net contrast between long T_2 lesions and brain tissue were calculated for both T_2-FLAIR and FLAIR for a range of lesion T_1 and T_2 values, using Eq. [1] multiplied by , and TE = 120 ms. Figure 4 shows contours of the *difference* in this contrast between T_2-FLAIR and FLAIR for TR = 4000 ms and τ = 200 ms (T_2-FLAIR). These values of TR and τ result in good lesion-to-brain contrast over a wide range of lesion T_1 and T_2 values, and are not the same as the values that simply maximize brain

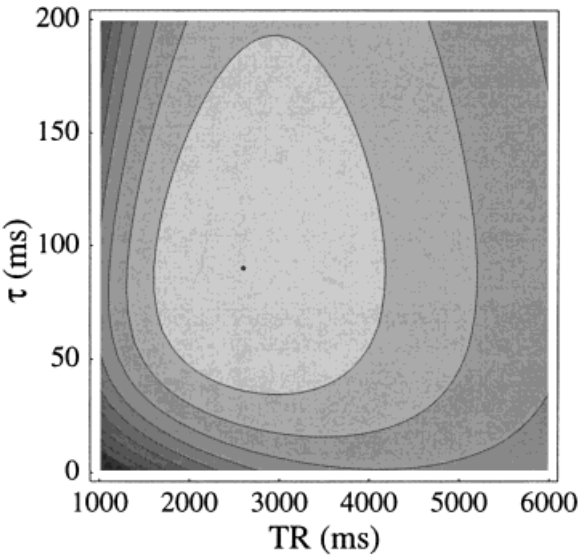

FIG. 2. Calculated SNR per unit time ( ) from brain tissue as a function of TR and τ for T_2-FLAIR at values of TI that null the CSF signal. A peak occurs at τ = 89.3 ms and TR = 2576 ms. Isocontours are separated by 5%.

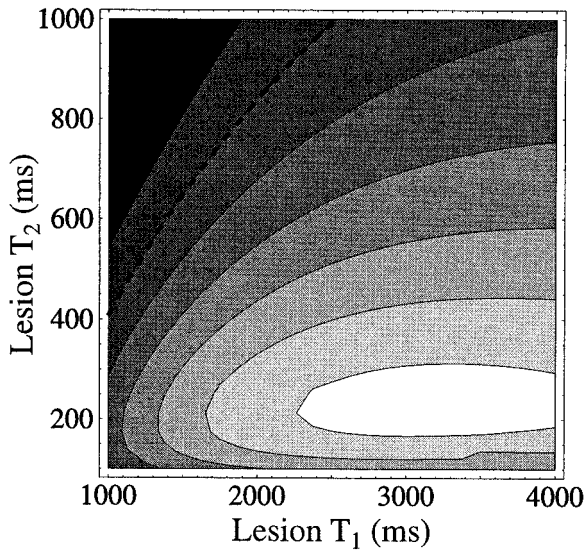

FIG. 4. Difference in lesion/brain contrast between T_2-FLAIR and FLAIR as a function of lesion T_1 and T_2. The signal was calculated for a T_2-weighted sequence with TE = 120 ms. The dashed line describes relaxation values for which T_2-FLAIR and FLAIR provide the same lesion/brain contrast. Lesion/brain contrast is higher with T_2-FLAIR for points below and to the right of that line. Isocontours are separated by 0.02 M_0.

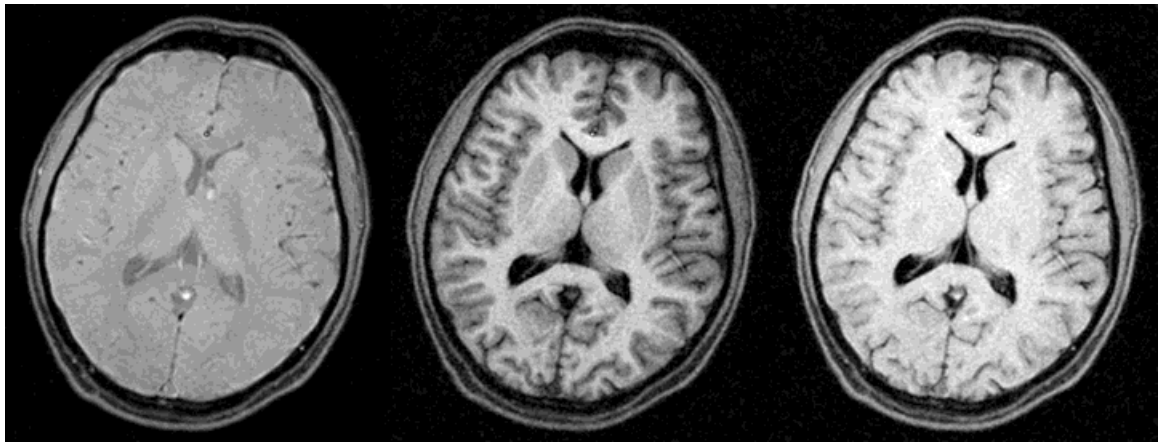

FIG. 5. Spiral images acquired at TR = 2576 ms. From left to right: without CSF suppression, FLAIR (TI = 1110 ms), and T_2-FLAIR (τ = 89.3 ms, TI = 984 ms). The FLAIR and T_2-FLAIR images are on the same absolute gray scale, while the signal of the nonsuppressed image is scaled down by a factor of two. The SNR in the T_2-FLAIR image is higher than that of the FLAIR image by 33%.

signal, as in Fig. 2. In Fig. 4 the dashed line represents lesion relaxation values for which T_2-FLAIR and FLAIR give the same lesion/brain contrast. To the lower right of this line, T_2-FLAIR creates greater contrast, while to the upper left of this line FLAIR creates greater contrast. In this application, T_2-FLAIR serves to increase the CNR by increasing the overall SNR across tissues. For very long T_2 lesions, the negative T_2 weighting imparted by the T_2-FLAIR preparation outweighs the overall SNR improvement. Smaller values of τ also lead to increased negative T_2 weighting, which is the reason that values of τ should be higher in this application than for maximization of raw SNR.

Brain images are shown in Fig. 5 without CSF suppression, with conventional FLAIR, and with T_2-FLAIR, all at TR = 2576 ms. These images were acquired at short TE (3 ms) to demonstrate the contrast inherent to the CSF suppression schemes, independent of additional T_2 or diffusion weighting. For both suppression techniques the CSF signal is indistinguishable from the background noise. Note that the tissue contrast in T_2-FLAIR is typical of saturation recovery with little gray-white contrast, while that of FLAIR is more heavily T_1-weighted. The calculated increase in the brain signal with T_2-FLAIR at this TR is 29%, and the measured increase using a whole brain region of interest is 33%. This discrepancy is probably dominated by the fact that the signal was calculated for the average T_1 of gray matter and white matter, while the image contains more white matter than gray matter.

DISCUSSION

T_2-FLAIR improves the SNR of CSF-suppressed images over conventional FLAIR for any tissue with shorter T_2 than that of CSF and allows for the use of shorter TR in these sequences. For diffusion tensor imaging these advantages can be used in two different ways. First, if multiple diffusion directions are being acquired (12) and the total imaging time is limited by the time required for collection of a single average in each diffusion direction, then the high SNR efficiency of T_2-FLAIR at short TR can dramatically reduce the scan time. For example, in Fig. 2 it is demonstrated that the same value of SNR/$\sqrt{\text{TR}}$ as the most efficient FLAIR technique (TR = 4182 ms) can be achieved using T_2-FLAIR with parameters of approximately TR = 1200 ms and τ = 75 ms, a reduction in TR of 71%. Second, if multiple averages are being used in each diffusion direction to improve SNR, then the value of should be optimized irrespective of TR, and the peak in this metric is higher in T_2-FLAIR by 16% over conventional FLAIR.

The conspicuity of brain lesions in clinical CSF-suppressed T_2-weighted images using T_2-FLAIR depends on the distribution of T_1 and T_2 values in the lesions of interest. Over a wide range of relaxation values, the increase in the brain signal created by T_2-FLAIR outweighs the negative T_2 weighting of the preparation scheme (Fig. 4). However, the ultimate utility of T_2-FLAIR for this type of imaging will have to be evaluated by a clinical trial. An additional practical issue in the implementation of T_2-FLAIR for this application is that the time required for the preparation sequence can limit the number of slices in a multislice application. For conventional FLAIR, the inversion pulse is typically on the order of 10 ms, and is short compared to the time required for image acquisition. The time required for the T_2-FLAIR preparation is generally not short compared to the image acquisition, and for applications in which the TR period is completely filled with image acquisition and preparation pulses for multiple slices, the use of T_2-FLAIR can reduce the maximum number of slices for a given TR. For example, if a 200 ms FSE echo train is used for image acquisition, and T_2-FLAIR is implemented with a τ of 100 ms (2τ = 200 ms), then up to half of the total scan time is used for the preparation pulses. On the other hand, if this is a significant constraint then this can be taken into account in the optimization of scan parameters, and a smaller value of τ used at the expense of some of the SNR advantage of T_2-FLAIR. Note in Fig. 2 that the peak in the SNR per unit time is rather broad and that significantly smaller values of τ can be used to allow more slices with little penalty in SNR.

The T_2 contrast in T_2-FLAIR images is reversed from that of typical T_2-weighted images. We are using this atypical

T_2 behavior to our advantage in a new dynamic blood volume imaging method for studies of brain activation. In this application, dynamic changes in T_2 due to blood oxygenation changes with activation confound the CBV measurement due to T_2 weighting in the image acquisition. We use T_2-FLAIR preparation in this technique because it both eliminates the CSF signal and makes it possible to null the overall T_2 weighting by balancing the positive T_2 weighting inherent in the image acquisition with negative weighting from T_2-FLAIR.

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