3D FAST FLAIR: A CSF-NULLED 3D FAST SPIN-ECHO PULSE SEQUENCE

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Since its introduction, the fluid attenuated inversion recovery (FLAIR) sequence has found many applications in the central nervous system (CNS), because of its heavy T₂ weighting and excellent cerebrospinal fluid (CSF) suppression. More recently fast spin-echo based variants have been developed that greatly reduce scan time; such sequences are often referred to as “fast FLAIR.” We present what we believe to be the first implementation of FLAIR using a three dimensional (3D) fast spin-echo-based pulse sequence, which combines the cerebrospinal fluid suppression and good lesion contrast of two-dimensional fast FLAIR with the advantages of a three-dimensional sequence such as higher signal-to-noise ratio (SNR) per unit time, thinner slices (giving reduced partial volume effect) and the ability to reformat the data in an arbitrary plane. © 1998 Elsevier Science Inc.

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INTRODUCTION
Since its introduction in 1992 by Hajnal et al.¹ fluid attenuated inversion recovery (FLAIR), has been used for many applications in the central nervous system (CNS) where the combination of heavy T₂ weighting and highly effective cerebrospinal fluid (CSF) suppression has proved useful (e.g. see Ref. 2). More recently, fast-spin-echo/turbo-spin-echo (FSE/TSE)-based variants of FLAIR (generically known as “fast FLAIR”) have been introduced. These greatly reduce scan time while maintaining the long repetition times (TRs) required for optimum contrast.³ These sequences have been successfully applied in many cerebral disease states,⁴ for example tumours,⁵ cerebrovascular disease,⁶ epilepsy,⁷ and multiple sclerosis.⁸,⁹,¹⁰,¹¹ In the brain-stem and spinal-cord reports have been more mixed, with some groups reporting success,¹² and others reporting a loss of sensitivity compared to conventional SE or fast SE.¹³,¹⁴ Even with the use of fast FLAIR sequences, signal to noise remains relatively poor, because a long echo time (TE) is required to increase the otherwise low tissue contrast. This is likely to become more of a problem as two-dimensional (2D) fast FLAIR is pushed toward thinner slices.

Epstein et al.¹⁵ have described a FLAIR implementation based on non-selective inversion combined with three-dimensional (3D) driven equilibrium magnetization prepared rapid gradient echo (MP-RAGE) acquisition.

We present what we believe to be the first implementation of FLAIR using a 3D FSE-based pulse sequence. 3D FSE is a hybrid, multi-slab, sequence that typically uses only 8–16 phase-encoding steps in the “slice” direction rather than the 64 or 128 used by a true 3D sequence. Despite this, it maintains many of the advantages of a true 3D acquisition, including higher signal-to-noise ratio (SNR) per unit time than 2D multi-slice acquisition. This allows thinner slices, minimising the partial volume effect between small lesions and the surrounding tissue and allowing arbitrary reformatting in any plane for improved anatomical visualisation.

Pulse Sequence
Most inversion recovery (IR) pulse sequences fall into one of two categories. An N-slice sequential IR sequence has the form shown in Fig. 1a, where the readout covers a single line of k-space for conventional spin-warp sequences, several k-space lines for FSE. This ordering is most efficient when the inversion time (TI) is short. An
interleaved sequence, shown schematically in Fig. 1b is more efficient for long TIs. Listerud et al.\textsuperscript{16} have recently introduced a third IR variant in which the inversion pulse for a particular slice is played out several readout periods before that slice is acquired, possibly during the preceding TR period (Fig. 1c). This optimum interleaved (OIL)
scheme can be very efficient, because the minimum time between the inversion pulse and the following readout period (denoted TJ by Listerud et al.) is limited only by the duration of the inversion pulse itself and the time to switch the associated gradients. The penalty paid for this efficiency is that the TR, TI, and number of slices to be collected can no longer be chosen totally independently, because:

\[
TI = (N_{\text{skip}} \frac{(TR/N_{\text{slices}})}{2}) + TJ, \tag{1}
\]

where \(N_{\text{skip}}\) = number of slices “skipped” between the inversion pulse and data acquisition and \(N_{\text{slices}}\) = number of slices collected within a TR period.

Most multi-slice sequences are implemented using spin-warp\(^{17}\) encoding. Such 2D sequences (including OIL FLAIR) use frequency selective radiofrequency pulses to define scan planes, which are then divided into pixels by in-plane phase and frequency-encoding gradients.

Scan time and SNR are determined by:

\[
\text{Scan time} = TR \times N_{\text{acqs}} \times N_{\text{slices}} \tag{2}
\]

\[
\text{SNR} \propto V \frac{N_{\text{acqs}} \times N_{\text{slices}}}{BW},
\]

where \(N_{\text{acqs}}\) = number of excitations (signal averages), \(N_{\text{slices}}\) = number of phase encode steps, \(V\) = voxel volume, and \(BW\) = receiver bandwidth.

3D sequences use a second phase-encoding gradient to define the scan planes, and have scan time and SNR given by:

\[
\text{Scan time} = TR \times N_{\text{acqs}} \times N_{\text{slices}} \times N_{\text{slab}} \tag{3}
\]

\[
\text{SNR} \propto V \frac{N_{\text{acqs}} \times N_{\text{slices}} \times N_{\text{slab}}}{ETL},
\]

where \(N_{\text{slices}}\) = number of slices per acquisition, and \(TR, N_{\text{acqs}}, N_{\text{slices}}\) are as above.

With suitable choices of ETL and number of slabs, a hybrid 3D FSE with a relatively long TR can thus give a scan time comparable to that of a true 3D sequence with a much shorter TR. Implemented in this way, 3D FSE combines the benefits of 3D encoding (thin slices and high SNR per unit time) with those of 2D FSE (relatively long TR and thus high inherent SNR, \(T_2\) weighting, and minimal susceptibility artifacts).

The inversion scheme of Listerud et al. inherently requires multi-slice data acquisition and therefore cannot be applied to a true 3D acquisition. It can, however, be applied to a hybrid sequence such as 3D FSE. We have implemented the method within the 3D FSE sequence, applying an inversion pulse to each “slab” several readout periods before its own readout. The resulting 3D fast-FLAIR sequence maintains the signal to noise advantages of 3D FSE over 2D FSE and, because FLAIR requires a long echo time to maintain reasonable tissue contrast, the long ETL needed for an acceptable scan time is less of a problem than for standard 3D FSE. An additional advantage of the 3D-fast FLAIR sequence is that it is less susceptible to inflow effects than a similar 2D fast FLAIR sequence, because CSF signal is suppressed from a complete slab (15 mm thick in our case) rather than a single slice (1–5 mm thick).
MATERIALS AND METHODS

The pulse sequence was implemented on a GE Signa EchoSpeed (General Electric, Milwaukee, WI, USA). Two acquisitions of eight slabs each were collected, with the odd numbered slabs being collected during the first acquisition and the even numbered slabs during the second, to minimize any crosstalk between adjacent slabs due to imperfect slice selection. Within each slab, 10 through-slab phase-encoding steps were acquired; after Fourier transformation, six slices were retained and the remaining four were discarded to minimize the wrap round artifact. The slab positions and thickness were set to allow for these discarded slices, so that the complete set of 16 slabs gave 96 contiguous 1.5-mm-thick slices. Other parameters were TR = 4600 ms, TE\(_{\text{eff}}\) = 137 ms, ETL = 24, echo spacing = 10.5 ms, receiver bandwidth = 31.25 kHz. The inversion time, TJ, was set to 15 ms, which with the inversion pulse applied three slabs in advance gave an effective inversion time (from Eq. (1)) of ((4600/8)*3) + 15 = 1740 ms. The in-plane matrix size was 256*192 and the field of view 25 cm, giving nominal pixel dimensions of 0.97 mm × 1.3 mm × 1.5 mm. Total scan time was 13 min. To evaluate the sequence, scans performed on a normal control, and a patient with muscular sclerosis.

For comparison purposes the normal control was also scanned with a multi-slice 2D OIL FLAIR sequence. 28 contiguous 5-mm slices were collected in two acquisitions of 14 slices each. Other parameters were TR = 11000 ms, TE\(_{\text{eff}}\) = 144 ms, ETL = 8, echo spacing = 24 ms, receiver bandwidth = 7.8125 kHz. The inversion time, TJ, was set to 260 ms, which with the inversion pulse applied three slices in advance gave an effective TI of (((11000/14)*3) + 260 = 2617 ms. The in-plane matrix size was 256*144 and the field of view 24 × 18 cm, giving nominal pixel dimensions of 0.93 mm × 1.25 mm. Total scan time was 8 min.

RESULTS

Figure 2a shows a representative axial slice through the ventricles of a normal volunteer, acquired with the new 3D fast FLAIR sequence. For comparison, Fig. 2b) shows a similar slice, in the same volunteer, acquired using the more conventional 2D OIL FLAIR sequence. While gray/white matter contrast are similar and CSF suppression is good in both scans, the 3D sequence gives much sharper definition of the sulci. The high signal from the choroid plexus (seen in these slices only in the 3D case), and the thin bright line around the ventricles, are normal findings on fast-FLAIR images. The scalp appears brighter in Fig. 2a than 2b. This is probably due to the longer Echo Train Length (ETL) of the 3D sequence; a similar difference in fat signal seen when comparing FSE and conventional SE images has been explained by the effects of J-coupling and magnetisation transfer contrast, both of which increase with increasing number of radiofrequency pulses.

Despite the much smaller voxel size of the 3D fast-FLAIR sequence (1.89 mm\(^3\) vs. 5.81 mm\(^3\)) overall image quality is similar in the two images. A simple SNR figure, calculated from the mean signal in a region of frontal white matter and the mean signal in an artifact free air region, is 16 for the 2D sequence compared with 10 for the 3D version. This is in good agreement with theoretical SNR calculations based on Eqs. (2) and (3), which suggest that the SNR for the 2D sequence should be approximately 1.7 times that of the 3D sequence.

Figure 3 shows two representative slices from the 3D fast FLAIR dataset of the MS patient; CSF suppression is good within both the ventricles and sulci, and lesion contrast is high. Periventricular, deep white matter, and
sub-cortical lesions are all clearly visible. Figure 4 shows
a representative 3D fast FLAIR slice of the patient with
hippocampal sclerosis. As the hippocampus is most eas-
ily visualised in the coronal plane, images were obtained
with slabs oriented in this direction; the image has thus
not been reformatted for display. The high signal lesion
in the right hippocampus is clearly visible; the surround-
ing low signal (CSF) area suggests hippocampal atrophy.

CONCLUSIONS

We have demonstrated a new, efficient, 3D fast
FLAIR sequence that combines the CSF suppression and
good lesion contrast of 2D fast FLAIR with the advan-
tages of a 3D sequence such as thinner slices (giving
reduced partial volume effect). Our sequence gives vox-
els less than half the size of those given by Epstein et al.
for the only other 3D FLAIR sequence reported to date
(0.97 × 1.3 × 1.5 mm = 1.89 mm³ vs. 1.0 × 1.25 × 3.9
mm = 4.9 mm³). Our sequence has a slightly longer scan
time (12:55 vs. 10:41 min), but has contrast closer to
“conventional” 2D FSE-based sequences. The near iso-
 tropic voxels make the data suitable reformattting in an
arbitrary plane, and also allow 3D registration (for serial
studies, for example). The OIL interleaving method used
places restrictions on the choices of TR, TI, and number
of slices, but we have found suitable combinations to
give thin slice, full brain coverage in clinically accept-
able scan times. We have demonstrated applications of
the technique in muscular sclerosis and epilepsy, and
expect 3D fast FLAIR to be similarly useful in other
CNS diseases. In particular, its lower slice thickness
should allow more accurate depiction of small pathological
lesions.

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