

Technical note: Use of a double inversion recovery pulse sequence to image selectively grey or white brain matter

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Abstract

The design of a double inversion recovery (DIR) sequence, to image selectively grey or white brain matter, is described. Suitable choice of inversion times allows either cerebrospinal fluid (CSF) and white matter to be suppressed, to image the cortex alone, or CSF and grey matter to be suppressed, to image the white matter. The DIR sequence was found to give clear delineation of the cerebral cortex.

Inversion recovery (IR) sequences can be used to null the signal of a single tissue by appropriate choice of the inversion interval TI. For the case where the *z*-magnetization is fully recovered this is:

$$TI = \ln 2 \cdot T_1$$

where T_1 is the tissue's longitudinal relaxation time. The most common example of this is the STIR sequence [1], where TI is chosen to suppress fat.

The use of an additional inversion pulse allows two tissues (e.g. fat and fluid) to be nulled simultaneously, and is termed a double inversion recovery (DIR) sequence [1]. This works best if they have very different relaxation times. Figure 1 outlines a simple explanation of the DIR sequence applied to nulling cerebrospinal fluid (CSF) and white matter signals. In the interval TI_1 between the inverting pulses, brain tissue magnetization recovers almost fully, while CSF, with its substantially longer T_1 , recovers to only a small fraction of M_0 , the equilibrium magnetization. The second inversion interval TI_2 is chosen to null white matter magnetization. Grey matter, with a longer T_1 , remains negative and generates a signal. CSF magnetization recovers slowly to pass through the null point at the same time as white matter.

The morphology of the brain is complex. In the sulci, for instance, the complex folds can mean that all three tissues (grey and white matter, and CSF) can lie within the same voxel. Methods of segmentation (e.g. [2]), are based on computer analysis of differences in image intensity caused by differences in relaxation times and proton density between tissues. The DIR technique offers a method of segmenting the brain directly, without

the need for image post-processing. Post-processing which assigns a voxel to only one tissue type inherently ignores the problem of partial tissue volumes within the voxel. The DIR method is not limited primarily by spatial resolution, but by the efficiency of the suppression pulses.

Theory

The sequence consists of two inversion pulses preceding a conventional spin-echo sequence. The inversion times TI_1 and TI_2 are defined in Figure 1. The interval between the 90° and the refocussing 180° radiofrequency (rf) pulses is τ , and equals $TE/2$ for the sequence used.

The value of the available *z*-magnetization M_A present immediately prior to the 90° imaging pulse can be calculated from the Bloch equations, assuming dynamic equilibrium from one TR interval to the next, and that all transverse magnetization decays or is spoiled after signal observation, before the sequence repeats. The method is described by Redpath [3], and gives

$$M_A = M_0(1 - 2E_2 + 2E_1E_2 - E_c(2E_\tau^{-1} - 1))$$

where

$$E_1 = \exp(-TI_1/T_1)$$

$$E_2 = \exp(-TI_2/T_1)$$

$$E_c = \exp(-TR/T_1)$$

and

$$E_\tau = \exp(-\tau/T_1).$$

For a 90° imaging pulse the NMR signal is therefore

$$S = k.M_A E_\tau^2 \Delta V$$

where ΔV is the volume of the voxel, and k is a measure of the overall system gain.

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In order to null the signals from the two tissues it is necessary to choose TI_1 and TI_2 to satisfy

$$1 - 2E_2 + 2E_1E_2 - E_c(2E_\tau^{-1} - 1) = 0$$

at both T_1 values. This can be done graphically as follows. Rewrite the above equation to give

$$E_2 = (E_c(2E_\tau^{-1} - 1) - 1)/(2(E_1 - 1)).$$

TI_2 can then be plotted as a function of TI_1 for the particular T_1 to be nulled, since

$$TI_2 = -T_1 \ln E_2.$$

A second curve is produced for the second tissue to be nulled, and the intercept of the two curves gives the TI_1 and TI_2 required to null both tissues simultaneously.

In order to calculate sequence timings, knowledge of the expected T_1 values of grey and white matter, and CSF is required. Henriksen et al [4] conducted a multi-centre trial to measure human T_1 values *in vivo* using normal volunteers. The scanners used had been previously calibrated using the Eurospin T_1 set of test gels. The conclusion was that the empirical fit of T_1 versus frequency proposed by Fischer et al [5] gave a good description of the T_1 values of grey and white matter obtained at the various field strengths used. Henriksen's curves show that the expected T_1 values for grey and white matter are 920 ms and 530 ms, respectively, at 40.5 MHz. The variation of Henriksen's measurements from this fit is sometimes large, by as much as 10% for grey matter and 20% for white matter. Condon et al [6] concluded that the T_1 of CSF exceeded 3 s at 6 MHz.

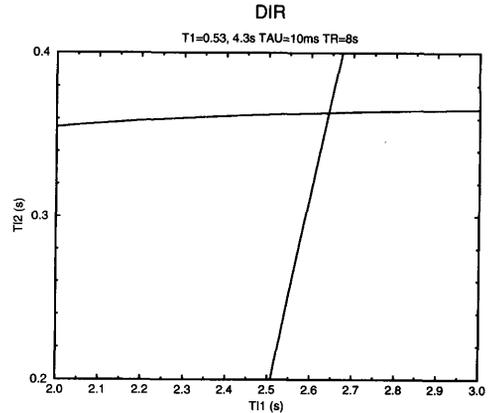


Figure 2. The TI_2 value needed to null white matter (horizontal curve) and CSF (vertical curve) is plotted as a function of TI_1 for a DIR sequence with $TR = 8$ s and $\tau = 10$ ms. The intersection of both curves gives the TI_1 and TI_2 values necessary to null both tissues simultaneously.

Hopkins et al [7] measured the T_1 of CSF *in vivo* at 6.2, 25 and 60 MHz, and found it to equal 4.3 s, with no evidence of field dependence. They took care to calibrate their measurements using distilled, deoxygenated water.

Figure 2 graphs the required TI_2 value to null (i) white matter and (ii) CSF, as a function of TI_1 , for $TR = 8$ s, $\tau = 10$ ms, assuming T_1 values of 530 ms for white matter, and 4.3 s for CSF. The curves intersect at $TI_1 = 2650$ ms, and $TI_2 = 360$ ms, giving the required timings of a DIR sequence to null both tissues simultaneously. The timings needed to null grey matter and CSF were found to be $TI_1 = 2850$ ms, and $TI_2 = 600$ ms for the same TR and τ , using the same method, and assuming a T_1 for grey matter of 920 ms. The exercise was repeated at TR values of 4 s and 6 s. Table I summarizes the findings.

Figure 3 plots the theoretical magnitude of the available magnetization M_A (as a fraction of M_0) versus T_1 , for values of TI_1 and TI_2 appropriate to null CSF and white matter, at TR values of 4 s and 8 s, with $\tau = 10$ ms. The curves show the expected nulls at T_1 equal to 530 ms and 4.3 s. The theoretical curves for the other settings listed in Table I also showed nulls for M_A at the appropriate T_1 values. These curves confirmed the validity of the graphical estimates of the inversion times.

Table I. Estimated inversion times

TR (ms)	Null WM		Null GM	
	TI_1 (ms)	TI_2 (ms)	TI_1 (ms)	TI_2 (ms)
4000	1700	350	1800	510
6000	2250	360	2400	570
8000	2650	360	2850	600

The estimated inversion times required to null white (WM) and grey matter (GM) are given for various TR values. The T_1 of white matter, grey matter, grey matter and CSF are assumed to be 530 ms, 920 ms and 4.3 s, respectively.

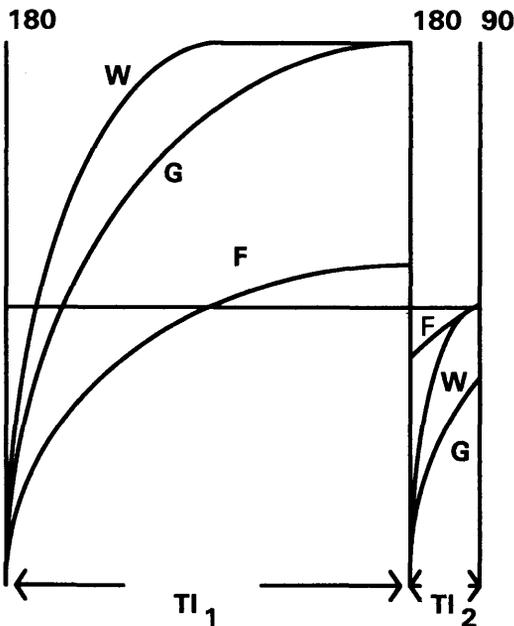


Figure 1. The evolution of M_z through the inverting intervals TI_1 and TI_2 is sketched for cerebrospinal fluid (F), grey (G) and white (W) matter.

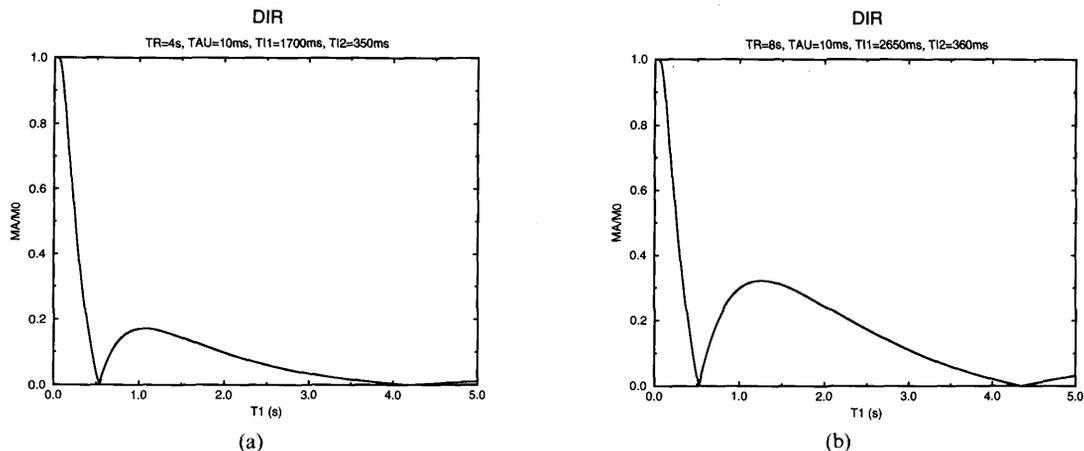


Figure 3. The magnitude of the available z -magnetization M_A is plotted against T_1 for DIR sequences appropriate to null CSF and white matter at (a) $TR = 4$ s and (b) $TR = 8$ s, assuming $\tau = 10$ ms. T_{I1} and T_{I2} values are taken from Table I.

Methods

The study was performed on a 0.95 T Siemens Impact scanner (Siemens AG, Erlangen, Germany), operating at a proton resonance frequency of 40.5 MHz, using the system's circularly polarized transmit-receive head-coil.

The DIR sequence was programmed by adding an additional inversion pulse to a conventional spin-echo inversion sequence. The inversion pulses used were single side-lobed sinc pulses of duration 5.12 ms apodized using a Hanning window. For the 5 mm slice thickness used, the pulses were applied in the presence of a constant slice-selective gradient of 3.6 mT m^{-1} . In order to increase the number of slices possible in multislice mode, the rf pulses were interleaved so that the first inversion pulse for each slice was allocated to the first half of the TR interval, with the second inversion pulse and spin-echo readout pulses allocated to the second half. Thus a set of N inversion pulses are followed by N sets of ($180^\circ T_{I2} 90^\circ \tau 180^\circ \tau$ echo) in each TR interval. A digital storage oscilloscope with electronic callipers (type PM3331, Philips, Eindhoven, Netherlands) was used to check that the rf pulse timing intervals had been correctly programmed.

The inversion timings required in practice were estimated by scanning a normal 31-year-old male volunteer for the white matter nulled DIR scan, and a normal 23-year-old male volunteer for the grey matter nulled DIR scan. First a multislice T_2 weighted transaxial multislice scan ($TR = 4000$ ms, $TE = 128$ ms) was acquired parallel to the radiological baseline, with the central slice through the anterior horns of the lateral ventricles. This scan exactly matched the field of view (FOV), slice-width, slice-gap and slice positions of the subsequent DIR scans. It effectively acted as an anatomical reference, allowing the structures seen in the DIR scans to be identified. For the white matter nulled DIR scan, T_{I2} was varied in steps of 50 ms from 250 to 350 ms to null frontal white matter adjacent anterior to the

lateral horns of the ventricles, and then T_{I1} was varied in steps of 100 ms from 2000 to 2400 ms to null the CSF within the horns. For the grey matter nulled scan a similar procedure was adopted, except that the efficiency of grey matter suppression was estimated from the cortex as a whole. All the DIR scans used $TR = 8$ s and $\tau = 10$ ms. Other TR values were not investigated. Finer increments in the variation of T_{I1} and T_{I2} would have been desirable, but this was precluded by the long scan times required (see below).

Once the inversion timings needed to selectively image grey and white brain matter had been determined, normal volunteers were scanned to measure the degree of suppression which could be routinely achieved. The T_2 weighted reference scan was obtained as before (FOV = 230 mm, slice-width = 5 mm, gap = 2.5 mm). The DIR scan set, either grey or white matter selective, was then acquired at matching slice positions with the same FOV and slice parameters. The matrix used was 192×256 , resulting in an acquisition time of 25.6 min for the DIR image set, using a single acquisition (NSA = 1). Three slices only were acquired in interleaved order (*i.e.* the slice excitation order was 1, 3, 2). Seven volunteers (five male, two female), ranging in age from 25 to 42 years (average age 30 years, sample standard deviation 6 years), were scanned with the grey matter selective DIR sequence. For the white matter selective sequence five male volunteers were scanned, ranging in age from 25 to 42 years (average age 29 years, sample standard deviation 7 years).

The degree of suppression achieved was estimated by measuring the signal difference to sum ratio

$$D = (S_1 - S_2)/(S_1 + S_2)$$

for pairs of tissues, where S_1 and S_2 are the means of their respective signals, taken from region of interest (ROI) measurements. D is independent of the system

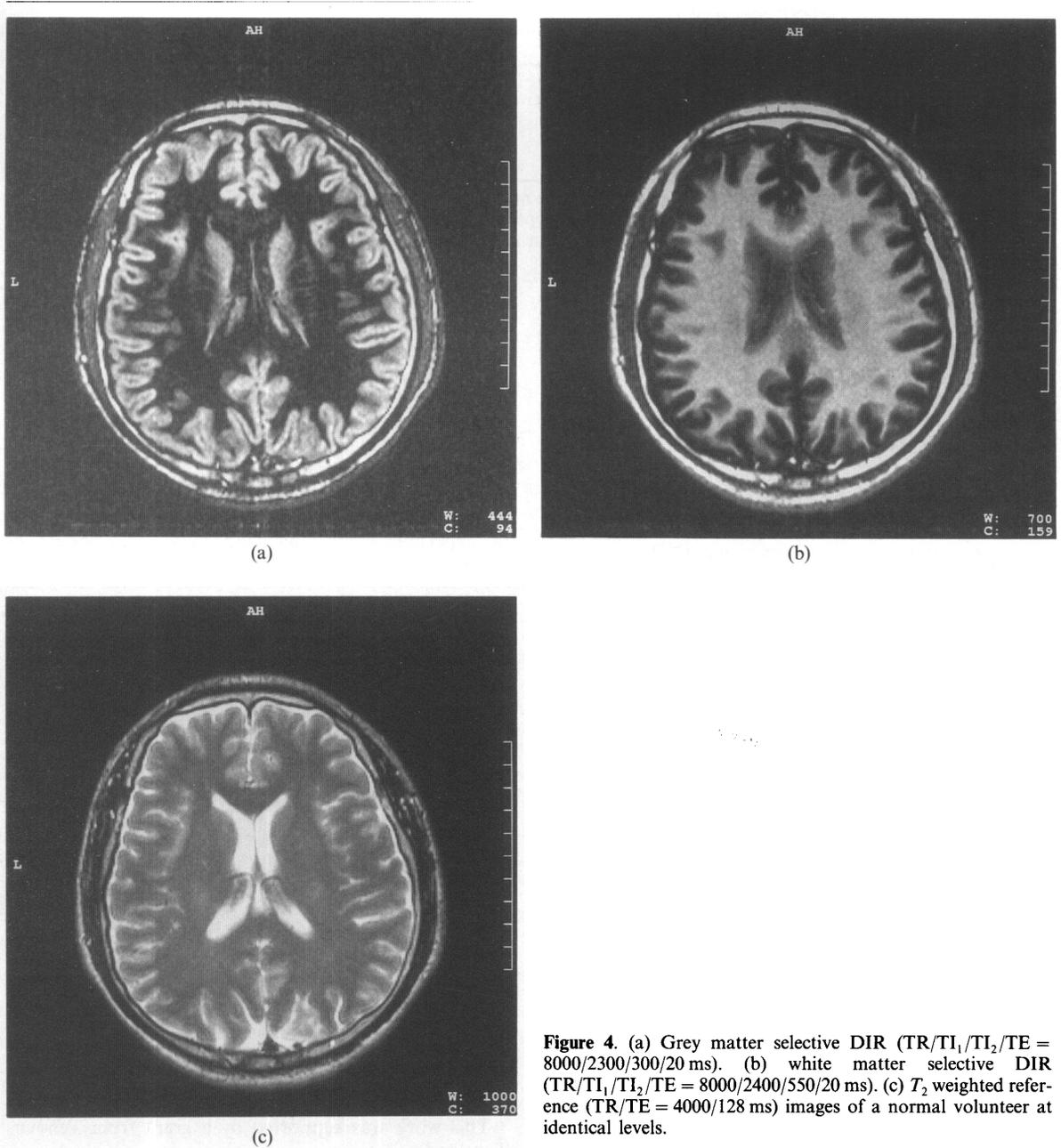


Figure 4. (a) Grey matter selective DIR (TR/TI₁/TI₂/TE = 8000/2300/300/20 ms). (b) white matter selective DIR (TR/TI₁/TI₂/TE = 8000/2400/550/20 ms). (c) T_2 weighted reference (TR/TE = 4000/128 ms) images of a normal volunteer at identical levels.

gain k , and is therefore a useful figure for comparing contrast between different types of scan, and between different subjects. Ideally D should equal ± 1.0 , for complete suppression of the signal from one of the pair of tissues. Since the magnitude of the Fourier transform was used for image formation, the average signal in air is not zero, as might be expected, but is a small positive number, reflecting the intrinsic white noise level

in the image [8]. Therefore, even for tissue and air, the magnitude of D is less than 1.0. Only for an infinite signal-to-noise ratio (SNR) would the ideal value be achieved.

For each volunteer's white matter suppressed scan a single D value was calculated for (i) grey and white matter, (ii) grey matter and CSF and (iii) grey matter and air. The air region was taken outside the head, in an area

Table II. Measured D ratios

Tissue pair	T_2 Weighted SE	WM suppressed	GM suppressed
GM/WM	0.24 ± 0.04	0.80 ± 0.08	-0.87 ± 0.02
GM/CSF	-0.38 ± 0.01	0.78 ± 0.08	—
WM/CSF	-0.57 ± 0.03	—	0.69 ± 0.07
GM/Air	0.92 ± 0.01	0.88 ± 0.02	—
WM/Air	0.87 ± 0.02	—	0.91 ± 0.01

The range of D values obtained for the normal volunteers are given for the white matter suppressed and grey matter suppressed DIR sequences. Values for the T_2 weighted spin-echo (SE) reference scan are given for comparison.

unaffected by image artefacts. A similar exercise was repeated for the grey matter suppressed scans. The CSF measurement was taken within the anterior horns of the lateral ventricles, the white matter measurement anterior and lateral to this, from within the frontal hemispheres. The cortex ROI was chosen from the thickest and most uniform area possible, adjacent to the longitudinal fissure.

Results

The optimum inversion times for DIR scans with TR/TE = 8000/20 ms were found to be $TI_1 = 2300$ ms and $TI_2 = 300$ ms for the white matter and CSF suppressed scan, compared with the predicted values of 2650 ms and 360 ms, respectively. For the grey matter and CSF suppressed scan the required values were found to be $TI_1 = 2400$ ms and $TI_2 = 550$ ms, compared with predicted values of 2850 ms and 600 ms, respectively.

Figure 4a shows a selective DIR transverse scan of the cortex of a normal male 27-year-old volunteer, at the level of the lateral ventricles. Figure 4b shows the corresponding selective DIR image of the white matter. Figure 4c shows the T_2 weighted spin-echo reference image for comparison.

Table II shows the degree of suppression which was achieved as measured by the signal difference to sum ratio D , given as the mean and sample standard deviation of the group. A negative value of D means that the second tissue of the pair has a higher signal than the first. D ratios have not been computed for tissue pairs where both were suppressed, or for a suppressed tissue to air.

Discussion and conclusions

The long TR necessitates a very long acquisition time, which probably precludes the routine clinical use of the DIR sequence for selective imaging of grey or white matter. However, rapid spin-echo acquisition methods [9, 10] may allow acquisition times to be reduced to more acceptable levels. The cortex-selective sequence allowed a maximum of only six slices, and the white matter selective sequence only three slices, for the timings used. Improved interleaving schemes, such as those proposed for conventional inversion recovery sequences [11], should allow larger numbers of slices to be scanned.

Good degrees of unwanted signal suppression were achieved for the group of normal volunteers with the grey matter selective sequence. Good cortex suppression was achieved with the white matter selective sequence, but CSF suppression was poorer than with the cortex-selective DIR sequence. This indicated that the initial white matter selective sequence timings, as determined by scanning the first volunteer, were sub-optimal for the group as a whole.

If the rf transmission field is inhomogeneous, the use of hyperbolic-secant inversion pulses [12] should be considered to correct any resulting variation of tissue suppression across the FOV. Although the head coil used in this study both transmits and receives, it has good rf magnetic field homogeneity, so that the sinc inversion pulses supplied by the manufacturer gave satisfactory results.

Specifically designed pulse sequences can be used to assess CSF volumes by magnetic resonance imaging (MRI) [13]. Computerized image segmentation methods, applied to MR images, can also be used to produce separate maps of brain tissue and CSF [2]. The DIR sequence offers a method of further segmenting brain tissue into grey and white matter regions, by using the T_1 differences between tissues to null unwanted signals.

MRI has value in assessing cortical atrophy by measuring CSF volumes [13, 14]. An increase in CSF volume is taken to imply a decrease in brain tissue volume. By further segmenting brain tissue into grey and white matter components, DIR methods have the potential to provide further information, and therefore may have value as a research tool.

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