Measuring $T_2$ and $T_2'$ in the brain at 1.5T, 3T and 7T using a hybrid gradient echo-spin echo sequence and EPI

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Aim: To develop an accurate, straightforward method of measuring $T_2$ and $T_2'$ in the brain, and to report results at 1.5, 3 and 7T. The method used is the gradient echo-spin echo (GESE) sequence, variants of which have been reported in the past. $T_2$ results have been compared to those obtained using the spin echo EPI sequence.

The GESE Sequence: The sequence consists of a series of M gradient echoes (GE) (i.e. similar to an EPI readout gradient) superimposed on a spin echo (SE) (fig. 1). This is repeated N times, where N is the number of phase encoding steps, with a phase encoding gradient applied before the start of the readout. (In practice this was implanted using ‘EPI test mode’ on a Philips scanner). The signal obtained at each gradient echo is modelled as

$$S(t) = S_0 e^{-[t/(T_2+1)]}$$

and fitted using the Powell algorithm to give $T_2$ and $T_2'$. Here $t$ is the time between the first and central echo and $t=0$ is the time of the first echo. This sequence is insensitive to RF pulse errors since errors in either of the pulse flip angles will cause equal attenuation of all the echoes, leading to a simple reduction in SNR. It is also insensitive to $T_1$ saturation (weighting) since the time between the refocusing pulse and next 90° pulse is constant.

Method: 4 subjects (aged 24-44 years) were scanned with local Ethics Committee approval using GESE and SE-EPI sequences, on Philips Achieva 1.5, 3 and 7T MRI scanners with a SENSE head coil (SENSE factor = 2). For the GESE sequence, imaging parameters were 256x256 (RFOV 80%) matrix, 1x1x3 mm voxel size, single slice, TR=2s. Other parameters were 7T: $\Delta t=1.43$ms, M=25, total time=3mins; 3T: $\Delta t=1.43$ms, M=31, total time=3mins; 1.5T: $\Delta t=1.54$ms, M=31, total time=8mins. For the SE-EPI sequence, a single slice was acquired in a single shot (voxel size 1.5x1.5x1.5mm) at 12 TE (7T: 30-85ms; 3T: 55-120ms; 1.5T: 90-200ms) and TR>$5T_1$. On a separate occasion, high resolution SE-EPI measurements were made at 7T with 1x1x3 mm voxel size and 64x64 FOV using 8 TE (42-150ms). The GESE data was fitted using the method described above and the EPI data fitted using a linear log fit, taking account of the effect of noise at long echo times. The SE-EPI and GESE data were used to measure $T_2$ in occipital (back) and frontal grey (GM) and white matter (WM).

Results: The $T_2$ calibration curve for the GESE sequence is shown in fig. 2; similar results were obtained for other pulse sequence timings. Fig. 3 shows varying $T_2$ weighted images from the SE-EPI and GESE sequences at 1.5T from a single volunteer. Table 1 shows $T_2$ values for WM and GM using SE-EPI and GESE. It was observed that GM/WM contrast in $T_2$ maps was lost at the back of the head in all subjects at 7T, due to an apparent drop in GM $T_2$. The $T_2$ values obtained using the high resolution EPI sequence and different echo time GESE sequences agreed with those obtained using the standard SE-EPI and GESE sequences (to within the std. dev. quoted). The $T_2'$ values obtained with GESE are shown in table 2.

Discussion: Under clinical imaging conditions standard gel phantom contrast does not follow monoexponential $T_2$ with minimal diffusion effects and the GESE and SE-EPI results are in excellent agreement. $T_2$ is a difficult parameter to measure or even define in vivo because:

(i) Most tissues exhibit multieponential decay and voxels can contain components with very different $T_2$s so that if data is fitted to an apparent single exponential decay, the fitted $T_2$ depends on the echo times used and the $T_2$, $T_2'$ or $T_2''$ weighting of the imaging sequence.

(ii) Transverse decay rate is enhanced by diffusion in any local field inhomogeneities (e.g. around venous vessels or iron deposits). This can be mitigated using multiecho sequences with short interpulse spacing, but such sequences are often affected by errors due to RF pulse inhomogeneities.

Consequently there is great variability in the $T_2$ values reported in the literature. GESE and SE-EPI are insensitive to RF pulse errors and have long echo times making them more sensitive to longer $T_2$s and components and any local field inhomogeneities. Our single echo GESE and EPI results generally agree well, except for a tendency for EPI to measure longer $T_2$s than GESE in the WM, which would be expected due to the increased $T_2''$ weighting in EPI compared to GESE (fig. 3), and the CSF contribution to WM. Our $T_2$ results also compare well with results reported in the literature using similar imaging modules. The loss of GM/WM contrast in the occipital lobe of the $T_2$ maps has been previously reported, and has been attributed to increased iron content in the occipital lobe. This explanation would be consistent with the change in $T_2$ in different regions of GM reported in table 2. Inter-subject variability is less in WM which may be due to variable iron content in GM, but intra-subject variability will now be assessed to confirm this. The apparent sensitivity of this $T_2$ measurement to iron content suggests that future work should study the variations in $T_2$ and $T_2'$ in deep grey structures with age and in Parkinson’s disease. As implemented, GESE had a lower SNR than EPI; however the EPI images are very distorted in parts of the brain at 7T. Future work will optimize the SNR in the measured $T_2$ and $T_2'$ in GESE in terms of TR, TE, M and Δt, and will investigate the imaging readout module used on the results.