Magnetic field and age dependence of the distribution of the longitudinal relaxation time in the living human brain

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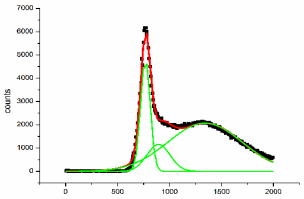
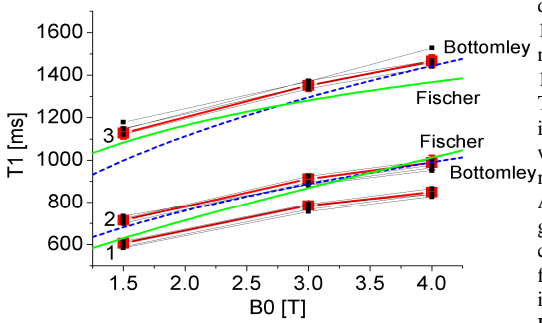
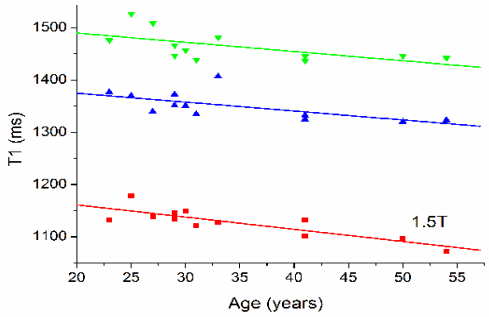
Introduction The exquisite and versatile tissue contrast of MRI is largely based on the variability of tissue relaxation times. NMR and MRI, being low sensitivity methods, greatly profit from the use of high static magnetic fields. Understandably, early predictions of T_1 convergence with increasing field [1] created doubt regarding the usefulness of high fields for *in vivo* imaging of the human brain. Indeed, all MR relaxation times show field dependence, but given the complexity of tissue this dependence cannot currently be calculated from first principles.The usefulness of, and the need for T_1 contrast does not appear to have been significantly jeopardised even at the highest fields at which *in vivo* human data have been acquired. Furthermore, given the increasing number of centres disposing of multi-scanner, multi-field environments, the investigation of the exact behaviour of the relaxation times *in vivo*, for normal as well as pathological tissue, has become more important than ever. We report here the results of a 12-volunteer study on the mapping of the T1 relaxation time at 1.5T, 3T and 4T and its field and age dependence.

Methods Measurements were performed using three nearly identical whole-body scanners, operating at field strengths of 1.5T (Siemens Avanto), 3T (Siemens Trio) and 4T (Siemens/Bruker MedSpec). The scanners have identical software platforms except for different SYNGO version numbers and very similar hardware. All three gradient coils had maximum field strengths of 40mT/m on each axis. At 1.5T and 3T, an RF body coil with very homogeneous B_1-field distribution over the head was used for RF transmit and 12-element, phased-array head coils for signal detection. At 4T, a composite transmit/receive head coil was used, consisting of a birdcage coil for transmit and an 8-element phased-array coil for signal detection. Twelve healthy volunteers (8 males, 4 females, average age 34 (SD 9) years, ranging from 23 to 54 years) were scanned at all three fields over a period of one month. The average interval during which the three scans were performed on any given volunteer amounted to 17 (SD 10) days. T_1 mapping was performed using TAPIR, a sequence based on the Look-Locker method, which uses an interleave of slice and time point read-outs for fast multi-slice acquisition whilst maintaining good temporal resolution. A five-echo read-out was used in order to speed up the acquisition process. The mapping method based on TAPIR, including B1 mapping (since RF field inhomogeneity is a limiting factor in the accuracy of quantitative methods), and validation of mapping results against spectroscopic measurements, is described in refs. [2-5]. The method was optimised separately at each field. The measurement parameters included: TR=20ms (1.5T) or 15ms (3T and 4T), TE=3.59ms(1.5T), 3.20ms (3T) or 2.50ms (4T), TI=10ms,τ=2000 ms, α=50º (1.5 and 3T) or 40º (4T), BW=455 Hz/pixel (1.5T), 815Hz/pixel(3T) or 700 Hz/pixel(4T), number of time points 16 (1.5T and 3T) or 20 (4T). The AutoAlign facility of the SYNGO software was used in order to acquire slices in close to identical positions at all three fields. Close to whole-brain coverage was achieved by measuring 41 slices using 3 sets of slices (14+13+14) of 2mm thickness and 1mm x 1mm in-plane resolution. Histograms of the T_1 distribution were created for the 41 slices for which T_1 maps were produced, separately for each slice as well as for the whole volume. A multi-component fit of the summed distribution was performed, using a superposition of two, three or four Gaussians. Each Gaussian was characterised by its centroid, full-width at half-maximum (FWHM), and maximum value.







Results and discussion Two well separated features, a narrow peak and a broader "hump" can be easily distinguished in the whole-brain histogram of T1 values at all fields employed in the present study. Fig. 1 shows the distribution at 3T. However, a fit of the histograms using two Gaussian distributions does not deliver satisfactory results. In contrast, the three-Gaussian decomposition of the T1 histograms (Fig. 1) reproduces the data well. A natural assignment of the three peaks would be, in the order of increasing T1: white matter, voxels at the border between white and grey matter, and grey matter. However, inspection of the T1 maps shows that the first and second peaks are both largely characteristic of the white matter. Some voxels with T1 values belonging to the second peak originate in the deep grey matter; some others belong to regions in which CSF, grey and white matter all overlap within one voxel. Adding another Gaussian to the 3-peak decomposition, to additionally characterise the border between grey matter and CSF, makes the fit unstable in many cases. We have therefore chosen the robust three-component fit (WM, WM-GM, GM) to characterise the whole-brain T1 distribution and compare its features between volunteers and fields. The field dependence of the longitudinal relaxation time, shown in Fig. 2 with red dots and line, has been fitted using ex vivo NMR dispersion data by Bottomley [6] and Fischer [1]. Bottomley used the simple empirical formula $T1=A\nu^B$, where ν is the NMR frequency and A and B fit parameters. The values of the two parameters have been fitted to in vivo data recently by Rooney et al. [7]; we use those parameters in our comparison, shown in Fig. 2 with dotted blue line. The continuous green line in Fig. 9a represents the formula proposed by Fischer et al.[2], that is: $1/T1=1/T1,w + D + A/[1+(f/fc)^{\beta}]$, with the parameters given in Table 2 of ref. [1]. Fischer's formula offers a slightly better overall agreement with our data, perhaps also due to the higher number of parameters. The predictions of both Bottomley's formula with parameters from Rooney et al. [7] and of Fischer's formula [1] are rather close to the measured relaxation times, but they either overestimate (Bottomley) or underestimate (Fischer) the behaviour of T1 with field strength.The discrepancy between the predicted values, using either formulae with the parameters quoted here, and the real T_1 values at 9.4T and 11.7T can be expected to be non-negligible.

The age dependence of the centroids obtained from the 3-Gaussian decomposition of the T_1 histograms was investigated. T_1 of GM was found to decrease linearly with age, as shown in Fig. 3 (red curve at 1.5T, blue curve for 3T, green curve for 4T). The results were consistent across fields, and the slope of the T_1(GM) dependence on field was found to be slightly lower for 3T (-1.7(2)) and 4T (-1.8(2)) than for 1.5T (-2.3(3)). In all cases, the probability that the correlation was due to chance was $p<0.05$. No clear correlation with age was observed for the centroids attributable to WM. Our results seem correlated with the ones reported by Neeb et al. [5], who investigated the age dependence of the water content of the white and grey matter in the whole brain. They found a clear (and quadratic) decrease in the male GM water content starting in the 6th decade of life, and a clear (and linear) decrease in the female GM water content over the whole age interval studied (20 to 70 years). These findings are in very good agreement with the behaviour of T_1 values found in the present study, with a mixed male and female collective, as can be expected due to the strong correlation between T_1 and water content. The influence of field strength on this relationship requires further investigation.

References: [1] Fischer HW et al. Magn Reson Med. 1990, 16:317-34; [2] Shah NJ et al. NeuroImage 2001, 14: 1175-1185; [3] Steinhoff S et al., Magn Reson Med 2001, 46: 131-140; [4] Zaitsev M, Steinhoff S and Shah NJ, Magn Reson Med 2003, 49: 1121-1132.[5] Neeb H, Zilles K and Shah NJ, NeuroImage 2006, 31: 1156-1168; [6] Bottomley PA et al., Med Phys 1984; 11 :425 –448; [7] Rooney WD et al., Magn Reson Med.2007, 57:308-18.