Cortical layers one by one: T2*, phase and susceptibility at 80µm resolution

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Introduction At ultra-high fields (7T and above) small changes in the orientation and/or magnetic susceptibility of anatomical building blocks such as fibres, vessels, cell layers, become detectable by MRI and give rise to an extremely rich contrast which was not apparent at standard magnetic fields. Based on this effect, much of the high field structural imaging relies on T2* and phase contrast. The observed orientation dependence of the phase contrast [1] can be removed under the assumption that the local field originates from a susceptibility distribution [2]. However, the reconstructed susceptibility also shows orientation effects which are strong enough to allow for fibre tracking in the white matter [3]. The impact of these novel methods on the current understanding of the human brain is steadily increasing. However, the nature of the underlying effects is still debated, in particular the influence on the susceptibility contrast of myelin, iron and microscopic fibre orientation. The present study was aimed at contributing to the clarification of these aspects by high-resolution T2*, phase, susceptibility and diffusion imaging of the motor cortex at 9.4T.

Materials and methods Measurements were performed on a home-built 9.4T animal scanner comprising a 21cm horizontal bore Magnex magnet equipped with a 12cm ID, 600mT/m, 100µs rise time Agilent gradient coil and interfaced to a TimTrio Siemens console. A 7cm surface coil was used for both RF excitation and signal receive. Studies were performed of a block of cortical tissue containing the central sulcus and, thus, primary motor as well as sensory cortex. The tissue had been obtained 6 hrs post mortem from the left hemisphere of a female subject, aged 38, without known neurological disorders. The tissue was fixated using 2.6% phosphate buffered paraformaldehyde and MR-scans were performed after about 1 year of fixation. All procedures had been approved by the local ethics committee in Frankfurt. A3D multi-echo gradient echo sequence was used with parameters: FOV 60x52.5mm^2, matrix 768x672x208 (resolution of 80µm^3), TR=100ms, α=20^o, BW=100Hz/px, TE_1=4.9ms, ΔTE=9.23ms, 3 echoes, 2 averages. The whole slab was covered by two overlapping consecutive acquisitions and the whole procedure was repeated 6 times. The complex data were averaged off-line and a whole-volume data set was reconstructed from the two overlapping slabs. M_0 and T_2* maps were obtained after monoexponential fitting of the magnitude data. The phase for each echo was unwrapped using PRELUDE [4], the field map was calculated from the evolution of phase with echo time and filtered with a combination of low order polynomials, spherical harmonics and dipolar fields [5]. Starting from the filtered field map, the susceptibility was reconstructed according to the method presented in [2] without prior spatial information. Diffusion data with a resolution of 160x160x300 µm^3 were acquired using a PGSE sequence with TR=10s, TE=45ms, b=3000mm^{-2}s and 12 directions. Mean diffusivity (ADC) and fractional anisotropy (FA) maps were calculated using fsl [4]. More details are included in [6]. Unless otherwise specified, the data processing was done with Matlab (Mathworks Inc).

Results and Discussion The striking presence of two dark bands inside the cortex is best visualised in Figure 1 (whole slice and zoomed regions) which represents the GRE magnitude image at TE=14ms. Phase contrast in the same regions is shown in Fig. 2, and an extremely high level of sensitivity to microscopic structure can be identified in both the WM and GM. The phase contrast between WM and GM varies substantially with the position and can reach maximum values of 5.5-6Hz.The T2* contrast (Fig. 3) between WM and GM is very good, and the three-peaked histogram for the whole block (not shown) is well able to discriminate between WM (9.3ms, FWHM 1.5ms), bulk GM (11ms, FWHM 1.8ms) and the hyperintense outer region of the cortex (13.5ms, FWHM 3ms). Fig. 4 shows a magnified region of the phase map (left) and the susceptibility (right) calculated for the same region. Part of the orientation effects present in phase contrast are well corrected by the susceptibility reconstruction (arrows in Fig. 4). However, the visualisation of the two bands, which now appear bright, shows the same orientation effects as in the phase. This is consistent with other studies [3] which show that orientation effects can still be present after the susceptibility reconstruction and assign them to the presence of oriented fibres. The banded structure in the cortex is visible in the phase images as well. A clear orientation effect in the visualisation of the cortical substructure is present, as expected, for phase contrast, but it is also strikingly present in the magnitude of the signal in a complementary way. When the cortex is parallel to the main magnetic field (B0 is parallel to the vertical axis of the images) the bands are visible in the magnitude (left and right zoomed regions) but hardly in the phase images. When the cortex becomes perpendicular to the field the contrast disappears from the magnitude images but is very well visible in the phase.

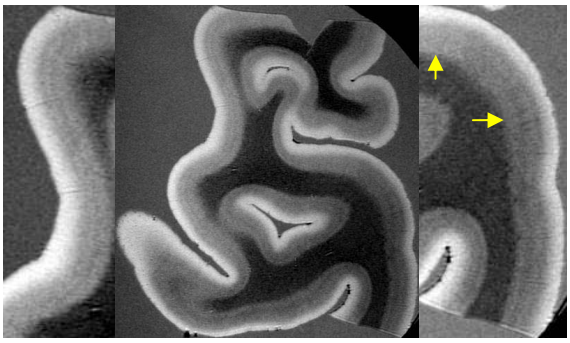


Figure 1: magnitude, TE=14.1ms

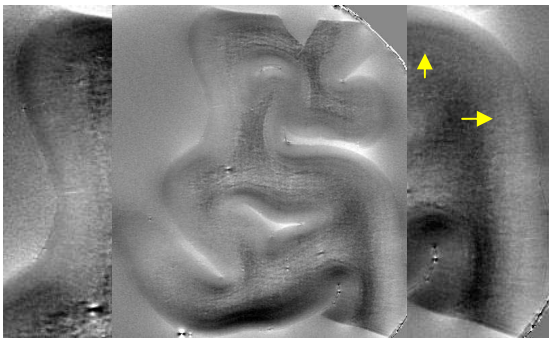


Figure 2: filtered phase map, [-11 13]Hz

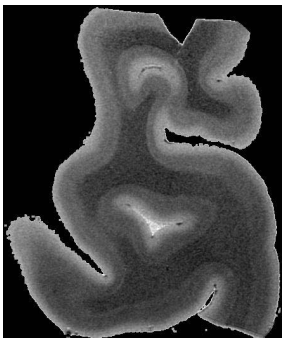
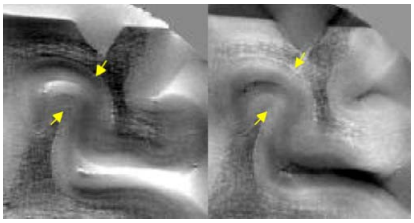


Figure 3: T2* map, [6 20]ms

In addition, the T2* values increase from 9.8ms (parallel to B0) to 11.6ms (perpendicular to B0) for the piece of cortical ribbon shown in the right zoomed images. Given the small range of variation for T2* inside the cortex, this is a very substantial effect. The details of the orientation-dependent changes in T2* and phase are not consistent with a simple picture of fibres (dark bands) embedded in bulk matter with little orientation. Indeed, in this case T2* will decrease simultaneously with the increase in phase contrast when the fibres become perpendicular to the field. A more complex picture is in place, which needs to consider the main orientation of axons in the cortex (radial). Simulations based on microscopic structure as clarified by histology (work in progress) and orientation inferred from the diffusion data will help clarify this complex effect. In conclusion, this multi-parameter high-resolution study of the motor cortex provides a powerful example of how important tissue microstructure is in determining MR contrast at high fields. Furthermore, a clear visualisation of two cortical bands by MRI is, we believe, reported here for the first time.



References

[1] J. Duyn et al., PNAS 104, 11796(2007); [2] L deRochefort et al., Magn Reson Med 63, 194(2010); [3] Li et al., NeuroImage, in press; [4] S.M. Smith et al. NeuroImage, 23(S1),208(2004); [5] Lindemeyer, J., 2011, ESMRMB, SoftDOI: 10.1007/s10334-011-0268-5,p. 507; [6] Oros-Peusquens AM et al, submitted to present ISMRM.