Ultra-high resolution in vivo multi-parameter mapping of the human brain

Kerrin J Pine[1], Luke J Edwards[1], Martina F Callaghan[2], Pierre-Louis Bazin[1], and Nikolaus Weiskopf[1]

[1]Department of Neurophysics, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany, [2]Wellcome Trust Centre for Neuroimaging, UCL Institute of Neurology, London, United Kingdom

Synopsis

We present the first multi-parameter maps of R1, R2* and effective proton-density (PD*) acquired at 400 µm isotropic resolution at 7T. Prospective motion correction (PMC) by external optical tracking was used to reduce motion artifacts, as well as to avoid a co-registration step during calculation of the maps. The maps allow for characterizing of subtle subcortical and cortical features such as the line of Gennari in the visual cortex.

Introduction

Recent years have seen revived interest in quantitative MRI (qMRI) of the human brain, e.g. using the multi-parameter mapping (MPM) protocol [1]. This is driven largely by the link between key MR parameters and the absolute concentrations of myelin and iron in neural tissue [2] and the insight that such qMRI measures can enable. As a result, there is a demand for methods which map several parameters not only accurately and robustly, but also at sufficiently high spatial resolution (e.g. dimensions smaller than 400 µm) to characterize intracortical structures such as columns and laminae. Imaging at such high resolution mandates the use of ultra-high field strength to have sufficient signal-to-noise ratio (SNR), as well as effective motion correction since the amplitude of physiologically-driven motion is of the same order as the voxel size. In this work we acquired 400 µm isotropic 3D images using prospective motion correction (PMC) [3,4] with external optical tracking at 7T, from which maps of R_1, R_2* and effective PD (PD*) could be constructed with unprecedented isotropic spatial resolution.

Methods

A healthy volunteer was scanned over three sessions on a 7T MR system (Magnetom 7T, Siemens Healthineers, Erlangen, Germany) using a gradient and radio-frequency (RF) spoiled multi-echo 3D gradient echo sequence at 400 µm isotropic resolution (TR 31.8 ms, 8 echoes equally spaced between 3.4 and 21.6 ms) and with matrix size 560/640/416 (phase/read/slice). In each session, both PD-weighted (flip angle α=5°) and T_1-weighted (α=28°) volumes were acquired in addition to calibration data to correct for RF transmit field non-uniformity. With partially parallel imaging (factor 2) applied in both phase-encoding directions (ky and kz), the acquisition of each volume lasted 32 minutes. In two of the three sessions, the PMC system (Kineticor, HI) was enabled. Using the system's ability to lock a reference position and maintain the positioning between scans, both intra- and inter-scan motion was corrected prospectively. Due to the size of the acquired datasets, raw data were streamed offline and images subsequently reconstructed externally using a SENSE-based algorithm. Sensitivity maps were estimated from integrated k-space reference lines (N_{ky}=84, N_{kz}=88).

Maps were created from the weighted datasets using custom MATLAB tools (MathWorks, MA) written within SPM12 (http://www.fil.ion.ucl.ac.uk/spm/) as previously described [4]. Since all motion-corrected data were anchored to the initial head position, co-registration between the weighted volumes within a session was not required, thus the acquired resolution was preserved during calculation of the maps. For higher SNR, individual maps from the two sessions with PMC activated were co-registered and averaged using the CBS Tools in MIPAV (http://www.nitrc.org/projects/cbs-tools/).

Results and discussion

Motion summary statistics, along with a subset of the motion traces from the tracking system, are shown in Figs. 1-2. These show for all PMC-enabled scans a similar, low level of motion. Even the small unavoidable physiological motion reduced the image quality and effective resolution but was well corrected by PMC (Fig. 3). The 400 µm resolution MPM reliably delineated cortical and subcortical anatomical structures with a high contrast-to-noise ratio (CNR) across the whole brain (Fig. 4). In some comparably small regions, particularly in the inferior temporal lobe, inhomogeneity in the transmit RF field affected the R_1 map (Fig. 4). The high resolution and CNR allowed for delineation even of subtle intracortical features such as the line of Gennari in the primary visual cortex (Fig. 5).

Conclusion

Ultra-high resolution mapping of multiple physical parameters (PD*, R_1, R_2*) offers unique insights into the cortical microstructure, particularly with regard to myelination and iron concentration. We present MPMs at unprecedented resolution, which show subtle myeloarchitectonic features, such as the line of Gennari in the primary visual cortex (arrows Fig. 5). Such high quality of the maps can only be achieved by scanning at 7T with fast optical PMC.

The quantification of multiple parameters allows for a more precise investigation of the underlying microstructure and MR contrast mechanisms than conventional contrast weighted imaging [5] or T_1 mapping [6], which are often used for estimating myelin content. Such very high-resolution parameter maps are likely to find many applications e.g. in subject-specific cortical parcellation and in laminar mapping of myelination and iron concentration.

Acknowledgements

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References

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Figures

Session 1			
	Mean	SD	Max
Acqn. 1	0.95	0.32	2.36
Acqn. 2	1.64	0.52	2.49

Session 2			
	Mean	SD	Max
Acqn. 1	0.80	0.69	2.66
Acqn. 2	1.46	0.78	4.80

Figure 1: Motion over the four PMC-corrected acquisitions, summarised as the mean, standard deviation and maximum Euclidean displacement (mm) of the tracked motion during each acquisition (relative to its final position), for two sessions.

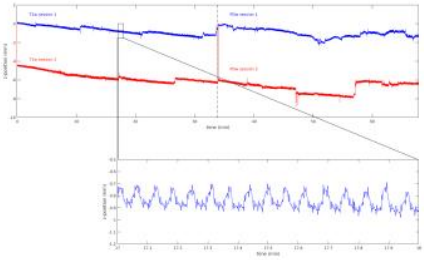

Figure 2: Motion traces as recorded by the tracking system of a healthy, highly compliant volunteer (Upper: motion during entire acquisition of T_1-, PD-weighted volumes at each of two sessions; motion along the magnetic field (z) axis. Lower: during one minute of the first acquisition, boxed). Cardiac pulsation (small peaks at ca. 1 s intervals) and respiration related movement of the order of 200 μm (higher amplitude harmonics with ca. 4 s periodicity) were significant compared to the targeted image resolution of 400 μm.

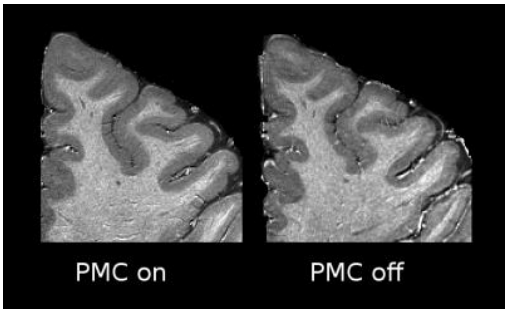

Figure 3: Zoomed axial view of R_1 maps from single session data with PMC on and PMC off. Despite high image quality in both cases, the PMC system demonstrates improvement in grey/white matter tissue delineation and enhanced detail.

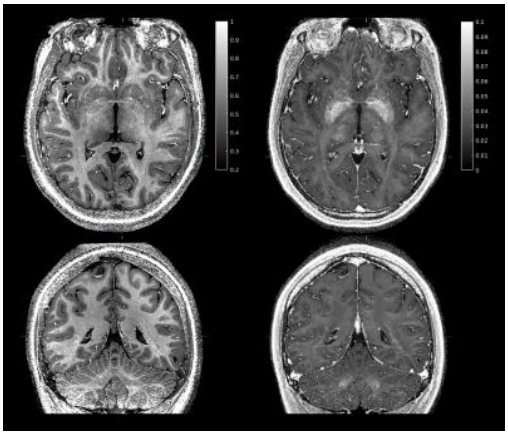

Figure 4: Axial and coronal views of R_1 and R_2* maps (averaged across two sessions). The maps show even subtle cortical and subcortical structural details. The R_1 map shows exquisite gray/white matter contrast and a highly accurate delineation of the cortex. In some parts of the cerebellum and temporal lobe shading artifacts were observed due to locally very low RF transmit field amplitudes. In the R_2* maps basal ganglia structures and the dentate nucleus with high iron content are well visible. The optic radiation is also well visualized in the R_2* maps.

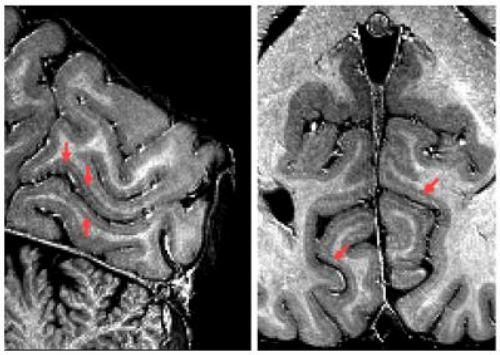

Figure 5: Sagittal and axial views of R_1 maps of the occipital lobe including the striate cortex (averaged across two sessions). The highly myelinated line of Gennari is well visible as a thin hyperintense stripe (red arrows). The detection of this well established ca. 300 µm thick myeloarchitectonic feature demonstrates the high effective resolution and myelin sensitive contrast in the R_1 map.