Combining ZOOPPA and blipped CAIPIRINHA for highly accelerated Diffusion Weighted Imaging at 7T and 3T

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Introduction: Sub-millimetre isotropic resolution diffusion MRI (dMRI) of the human brain in vivo is feasible at 7T[1]. By combining zoomed imaging and parallel imaging (ZOOPPA) high acceleration factors (AF) can be achieved with significantly lower g-factor penalty, compared to parallel imaging on its own. However, the very high isotropic resolution results in long acquisition times (TA) of about an hour, a major limitation of this technique. Acquiring multiple slices simultaneously (SMS – Simultaneous Multi-Slice), and unfolding them using parallel imaging algorithms[2], can be used to address this problem and shorten TA. The CAIPIRINHA approach[3] was developed to reduce the g-factor noise penalty for SMS imaging and has been recently adapted to EPI acquisitions[4]. High-energy deposition of Shinnar-Le Roux (SLR) multi-slice pulses typically used in SMS imaging limits the acquisition speed at 7T[5], due to SAR constraints. Recently Norris et al. showed that a theoretically unlimited number of periodic slices can be excited without a significant increase in energy deposition by convolving a single-slice pulse with a Dirac comb function, to give a 'PINS' pulse[6]. In this study, which aims at scientists with an interest in fast imaging techniques at ultra high field strength, we combine ZOOPPA [1] and blipped CAIPIRINHA[4] using PINS pulses[6] to obtain very high spatial and high angular resolution dMRI in a much shorter acquisition time.

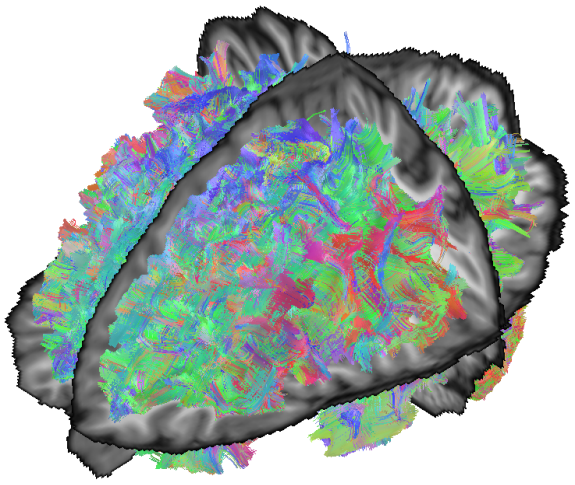

Figure 1: Fiber tracking results of 1.5mm isotropic resolution 3T whole brain dMRI data. At this field strength it is not necessary to employ zoomed imaging as distortions and T_2 decay are lower.

Methods: Experiments were performed on a 7T and a 3T whole-body MR scanner (MAGNETOM 7T and MAGNETOM Trio, Siemens Healthcare, Erlangen, Germany). At 7T, a 32-element head coil (Nova Medical, Wilmington, MA, USA) and a gradient system with a maximum amplitude of 70 mT/m and a slew-rate of 200 T/m/s was used. At 3T, a 32-element head coil (Siemens Healthcare Sector, Erlangen, Germany) and a gradient system with a maximum amplitude of 40 mT/m and a slew-rate of 200 T/m/s was used. A Stejskal-Tanner diffusion weighted EPI sequence[7] was modified to employ ZOOPPA and blipped CAIPIRINHA. To reduce SAR, a PINS pulse was utilized for RF refocusing. The 90° excitation pulse was designed using the SLR algorithm[8] and VERSE was used to reduce peak RF voltage[9]. This combination of pulses enabled restriction of the number of simultaneously excited slices to a specified value - note that the number of slices generated by the PINS pulse is limited solely by the object dimensions and the coil sensitivities. In other words, a specified number of slices are excited by the SLR 90° pulse, while the 180° PINS pulse refocuses an unlimited number of slices. Single-slice calibration data, required for the Slice-GRAPPA reconstruction[4] of slices in CAIPIRINHA, are sampled with single-slice SLR pulses, which have an off-resonance behaviour similar to the applied multi-slice pulses. This was done to ensure the unfolded slices of the calibration data have exactly the same desired z-location and coil sensitivity as the simultaneously acquired SMS data using the multi-slice pulses. In ZOOPPA, the overall AF is the product of the AF due to the reduced FOV and the parallel imaging AF. In-vivo diffusion-weighted images with isotropic resolution with 99 slices of 1 mm (7T), 1.2 mm (7T) and 1.5 mm (3T) were acquired using 4 averages of 60 diffusion directions with a b-value of 1000 s/mm^2, with 7 interspersed b0 images (see Table 1 for imaging parameters). Multiple fibre orientations were modeled with constrained spherical deconvolution[10] for each voxel, followed by streamline-tracking using MRtrix[11].

Isotropic resolution	1mm without Slice Grappa	1 mm	1.2 mm	1.5 mm (3T)
TR (ms)	13600	5000	5500	6000
TE (ms)	68	64	64	82
SMS/AF	1 / 2*1.4	3 / 2*1.5	3 / 2*1.5	3/ 2
FoV (mm^2)	180*125	180*120	180*125	190*190
TA (min)	**15:52**	**6:15**	**6:50**	**7:56**

Table 1: Comparable diffusion weighted protocols for ZOOPPA and ZOOPPA with CAIPIRINHA. 99 slices, 60 diffusion directions, b = 1000 s/mm^2 with different slice acceleration factors (SMS) and in plane acceleration factors (AF). Note: Shorter TE at 7T was achieved due to the stronger gradient system.

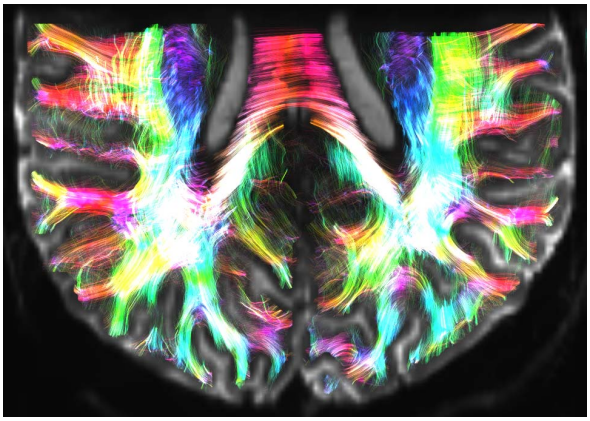

Figure 2: Streamline fibre tracking of 100 000 fibres (5 mm slab): Four times averaged 7T DW data with 1 mm isotropic resolution, 60 diffusion directions with b = 1000 s/mm^2.

Results and Discussion: We have shown that diffusion datasets with up to 1 mm isotropic resolution and 60 diffusion directions can be acquired in a significantly shortened acquisition time of about 6 minutes, by combining ZOOPPA and blipped CAIPIRINHA (see Table 1). We used PINS pulses for refocusing to reduce SAR, and thus to gain the full benefit of simultaneous multi-slice imaging at ultra-high field strength. At lower field strength, SLR pulses can be used both for excitation and refocusing, which may provide better slice profiles. The combination of SLR and PINS pulses also shows promising results at lower field strengths and might become particularly useful at this field strength for higher SMS factors, where SAR can become a speed-limiting factor.

Conclusion: For ultra-high resolution dMRI (1 mm isotropic or better), acquisition time becomes the major hindrance for a broad range of applications. To benefit from the high field strength at 7T, high in-plane AFs are mandatory to achieve a short TE, short echo spacing, and acceptable image quality. By using the blipped CAIPIRINHA technique in conjunction with PINS refocusing pulses, high-resolution dMRI at 7T with ZOOPPA can be acquired in significantly reduced scan time. This approach enables dMRI acquisition at 3T and at 7T in a short enough timeframe to allow combined in-vivo anatomical, functional and diffusion studies at the same ultra-high resolution within a single one-hour scan session.

References: [1]Heidemann RM et al. NeuroImage 2012;60:967-78. [2]Larkman D et al. JMR 2001;13:313-7. [3]Breuer F et al. MRM 2005;53:684-91. [4]Setsompop K et al. MRM 2011;67:1210–1224. [5]Eichner C. et al. In proc. ESMRMB 2012;680. [6]Norris D. MRM 2011;66:1234-40. [7]Stejskal E and Tanner J. J.Chem.Phys.1965; 42:288. [8]Pauly et a..IEEE Trans Med Imaging,10,53-65. [9]Conolly SM et al. J Magn Res.1988;78:440-58. [10]Tournier J. D. NeuroImage 2007;35:1459-72. [11]Calamante F. NeuroImage 2011;56:1259-1266.