Rapid High Spatial Resolution Diffusion MRI at 7 Tesla Using Simultaneous Multi-Slice Acquisition

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Abstract

High quality diffusion-weighted MRI (dMRI) data can be obtained with very high isotropic spatial resolution at ultra-high magnetic field strength such as 7 Tesla (T). Due to the high resolution it is necessary to acquire a large number of imaging slices for whole brain coverage, which results in long acquisition times (TA) of more than an hour. Obviously, Simultaneous multi-slice (SMS) acquisition technology is a prerequisite to significantly reduce the extensive acquisition times of these studies. However, the large energy deposition into the subject caused by the employed Multiband (MB) RF-pulses limit the efficiency of SMS methods. This can be addressed by replacing the MB pulses by Power Independent of Number of Slices (PINS) pulses[1]. However, this comes at the expense of a reduced bandwidth and increased off-resonance dependency, which degrades the image quality. With a new RF pulse design, given the name MultiPINS[1], the RF energy is further reduced and/or the pulse length is shortened. This is achieved by combining MB with PINS RF pulses. *In vivo* dMRI results were recorded with the MultiPINS approach at high spatial resolutions at 7T showing a 3-fold scan time reduction.

[1] The product is still under development and not commercially available yet. Its future availability cannot be ensured.

Introduction

Diffusion MRI (dMRI) is an essential tool in neuroscience to study the structural connectivity of the human brain *in vivo*. Due to the complex structure of the brain, it is necessary to acquire data with high isotropic spatial resolution. Sub-millimeter isotropic resolution dMRI of the human brain *in vivo* is feasible at 7T [1]. However, due to the high isotropic resolution it is necessary to acquire a large number of imaging slices, which results in long acquisition times (TA) of about an hour and more – a major limitation of this technique.

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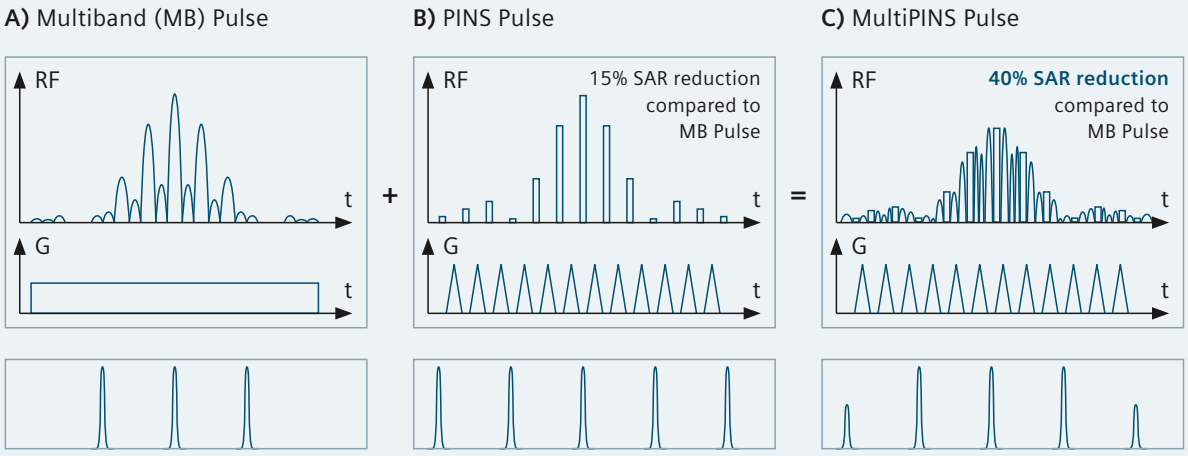


1 Example SMS RF pulses with resulting slice profiles; energy reductions that resulted from pulse settings used in this work.

Acquiring multiple slices simultaneously, and unfolding them using information from multi-channel coil arrays [2], can address this speed problem and shorten TA. The CAIPIRINHA approach [3] was developed to reduce the g-factor noise for SMS imaging and has been recently adapted to EPI acquisitions [4] (blipped-CAIPIRINHA). However, the high-energy deposition of Multiband (MB) pulses (Fig. 1A) that are typically used for SMS imaging limit the acquisition speed of SMS methods at 7T, due to SAR/power constraints – especially if high flip angles are employed [5]. For moderate slice acceleration factors (e.g. MB = 2), SMS dMRI data can be acquired also at 7T [6]. In the case of higher slice acceleration factors, the RF power will limit the acquisition speed at 7T.

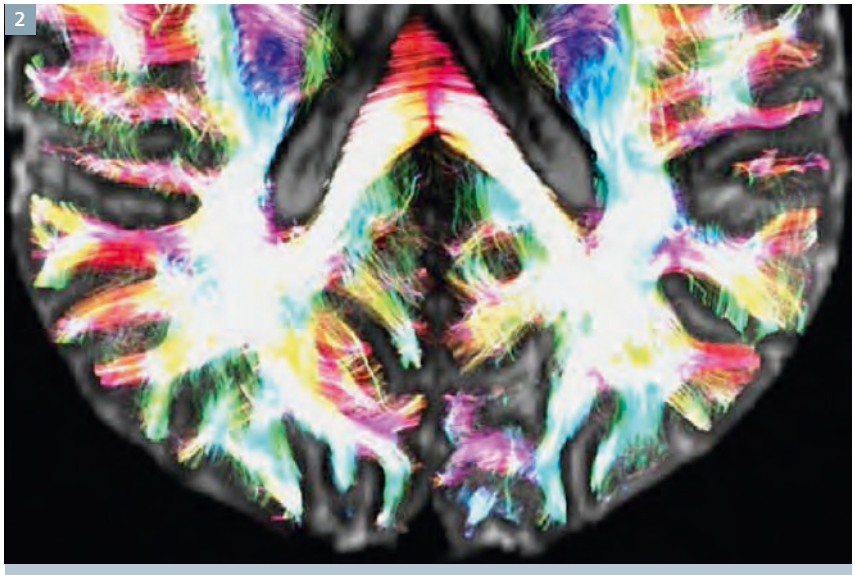
Recently Norris et al. showed that a periodic slice excitation pattern, suitable for SMS acquisition, can be created without significant increase in power deposition by multiplying a single-slice RF pulse with a Dirac comb function, to end up in a Power Independent of Number of Slices (PINS) pulse [7] (Fig. 1B). This approach has been successfully applied to 7T for structural and functional spin-echo experiments [8] as well as RF power consuming sequences such as Turbo Spin-Echo [9]. In this study, we combine ZOOPPA[1], an outer volume suppression (OVS) technique [1], for diffusion MRI at 7T with blipped-CAIPIRINHA [4] and PINS pulses [7] to obtain high spatial and angular resolution dMRI with significantly reduced TA. Furthermore, by combining MB and PINS RF excitation, we created a new 'Multi-PINS' RF pulse type[1] to further reduce power deposition for SMS excitation (Fig. 1C). For this new MultiPINS pulse, a MB RF pulse is first reshaped to follow the excitation *k*-space traversal of the blipped gradient waveform of the PINS pulse. The reshaped MB pulse can then be mixed directly with the PINS pulse to create a MultiPINS pulse with suitable excitation characteristic for SMS imaging (Fig. 1C). To minimize SAR, an optimal mixing ratio between MB and PINS (0% being pure PINS and 100% being pure MB pulse along PINS gradient trajectory) can be easily determined empirically prior to acquisition.

Methods

The high-resolution diffusion MRI data were acquired on a 7T whole-body MR scanner[2] (Siemens Healthcare, Erlangen, Germany) equipped with a 32-element head coil and a gradient system achieving a maximum amplitude of 70 mT/m with a slew-rate of 200 T/m/s. A Stejskal-Tanner diffusion-weighted EPI sequence [10] was modified to employ ZOOPPA OVS and SMS blipped-CAIPIRINHA. SMS is used to accelerate the acquisition by 3 folds, while ZOOPPA is used to reduce the imaging volume-of-interest and associated image distortion artifact. To reduce SAR/power deposition of the SMS method, a PINS/MultiPINS pulse was utilized for RF refocusing. Energy calculations were performed for the MultiPINS SMS pulses, to find out optimal energy settings with short pulse durations. *In vivo* diffusion-weighted images with 99 slices of 1 mm and 75 slices of 1.4 mm isotropic resolutions were acquired at 60 diffusion directions with a b-value of 1000 s/mm^2 and 7 interspersed b0 non-diffusion-weighted images (for motion correction). To increase the signal-to-noise ratio of the 1 mm isotropic resolution dataset, 4 averages were recorded. In the case of the 1 mm isotropic dataset, multiple fiber orientations were modeled with constrained spherical deconvolution followed by streamline fiber tracking with MRtrix (http://www.brain.org.au/software/mrtrix/). The 1.4 mm isotropic data set was acquired as a single average, resulting in a total acquisition time of about 3 minutes. Data were corrected for motion and eddy currents distortion artifacts with FSL and registered to a structural scan using Freesurfer. A color-coded FA map was calculated using the diffusion toolkit (http://www.trackvis.org/).

Results and discussion

We have shown that dMRI data at 7T can be acquired in a significantly shortened acquisition time. We recorded a 1 mm isotropic resolution with 60 diffusion directions in just 6 minutes, by applying blipped-CAIPIRINHA and ZOOPPA OVS



2 Streamline fiber tracking of 100 000 fibers (5 mm slab) of coronal and axial brain slices. Four times averaged 7T dMRI data with 1 mm isotropic resolution.

[1] The product is still under development and not commercially available yet. Its future availability cannot be ensured.

[2] MAGNETOM 7T is ongoing research. All data shown are acquired using a non-commercial system under institutional review board permission. MAGNETOM 7T is still under development and not commercially available yet. Its future availability cannot be ensured.

(see Table 1) (Fig. 2). Furthermore, a whole brain dataset with 1.4 mm isotropic resolution and 60 diffusion directions was recorded in only 3:30 minutes (Fig. 3). We used PINS/MultiPINS pulses for refocusing to reduce SAR, and thus to gain the full benefit of SMS imaging at 7T.

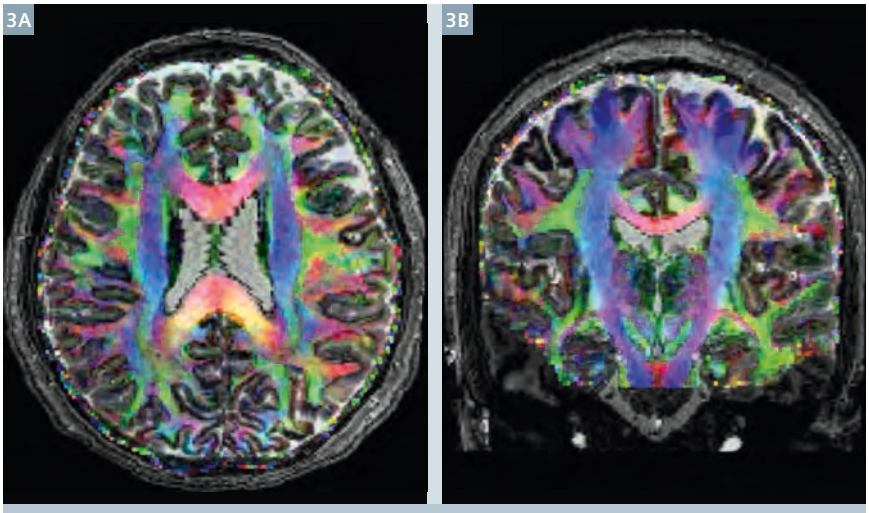
Conclusion

For ultra-high-resolution dMRI (1 mm isotropic or better) at 7T, the acquisition time becomes the major hindrance for a broad use of this application. We employed the blipped-CAIPIRINHA SMS technique in conjunction with PINS refocusing pulses as well as with a newly developed hybrid MB/PINS RF pulse to record dMRI data at 7T. The application of low power RF pulses in this SMS sequence enables the acquisition of high-resolution dMRI data at 7T in a significantly reduced scan time of 6:15 min for a 1 mm resolution dMRI scan and 3:30 min for a 1.4 mm isotropic resolution dMRI scan. The slice acceleration enables high-resolution dMRI acquisition at 7T within a timeframe short enough for clinical use, as well as combined *in vivo* anatomical, functional and diffusion studies at the same ultra-high-resolution level within a single scan session.

Table 1

Resolution	1 mm w/o SMS	1 mm MB=3	1.4 mm MB=3
TR (ms)	13600	5000	3000
TE (ms)	68	64	69
Slices	99	99	75
FOV (mm²)	180 x 125	180 x 120	180 x 180
TA (min)	4 x 15:52	4 x 6:15	1x 3:30

Comparable diffusion-weighted protocols for slice accelerated and non-accelerated with SMS blipped-CAIPIRINHA. 60 diffusion directions, b = 1000 s/mm² with different slice acceleration factors (SMS).



3 Axial **(3A)** and coronal **(3B)** views of color coded FA diffusion data recorded at 1.4 mm isotropic resolution in 3:30 min.

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