# Multiband Simultaneous Multi-Slice Acquisitions in BOLD at 7T

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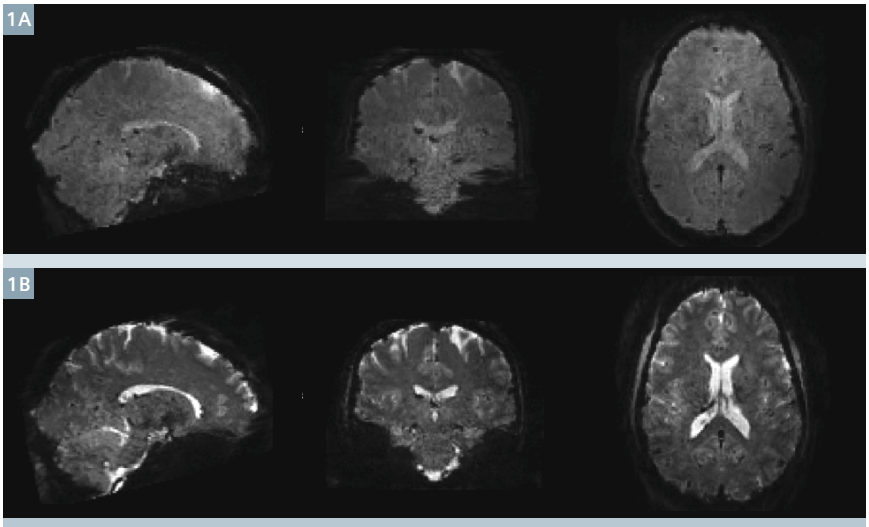
The use of 7 Tesla MRI[1] to study human brain function was motivated by the promise of higher signal-to-noise ratios (SNR), larger BOLD-based fMRI contrast, and improved functional specificity [1, 2]. Intrinsic gains in BOLD sensitivity make the acquisition of higher resolution images attractive. In addition, lower resolution studies at high fields typically become dominated by physiological noise [3-5], as increases in signal are accompanied by increases in physiological noise, albeit some of this noise may actually be signals of interest in resting-state fMRI. Consequently, high-field gains in sensitivity are often traded in for spatial resolution or other applications which may be SNR starved at low fields. Problematic to increases in spatial resolution are the subsequent increases in acquisition times during any single readout train, and the longer volume TRs, due to the many more slices needed to cover the same volume. Accordingly, the high-resolution fMRI prospects at high magnetic fields have historically been limited to small fields-of-view in isolated parts of the brain, as was the first 7T fMRI study in humans nearly fifteen years ago [6]. While this study, and several follow-up studies, capitalized on the advantages of 7T fMRI using reduced FOV approaches [7-10], many applications, such as resting-state studies of functional connectivity, which require the simultaneous monitoring of several cortical areas, were not attractive for 7T applications. For resting-state fMRI, increases in the spatial resolution could, however, allow for more clear delineations of neuronal processes from those of a vascular nature, a reduction of partial volume effects, or more accurate cortical parcellations of functional areas. For more localized higher-resolution studies, such as layer specific fMRI, increases in the volume coverage [7] would allow monitoring of feedback signals associated with neuronal processing, which can originate from very distant brain regions. In addition, increases in volume coverage of high-resolution studies would allow for improved motion correction, a bottleneck in high-resolution studies of humans.

Reasons like these inspired the use of multiband (MB) excitation, which promised to increase the temporal efficiency of high resolution 2D EPI acquisitions at 7T [11]. This initial 7T fMRI study, followed by the subsequent announcement of the NIH's Human Connectome Project (HCP), which aimed to map functional and structural connectivity at high spatial and temporal resolutions across 1200 subjects, sparked several more studies and developments in multiband technology [12-15]. One of the first studies, supported in part by the HCP, explored the possibility of acquiring high-resolution resting-state data at 7T over the whole brain. This study demonstrated robust detection of resting-state networks across the brain at varying spatial resolutions, down to 1 mm isotropic [16]. It also demonstrated the potential advantages of higher spatial resolutions for resting-state fMRI and the obvious temporal inefficiency limitations (due to the required long TRs). This study employed conventional single band single-shot EPI with acceleration along the phase-encode direction only. At the time, the MB technique was not available for mainstream use or for



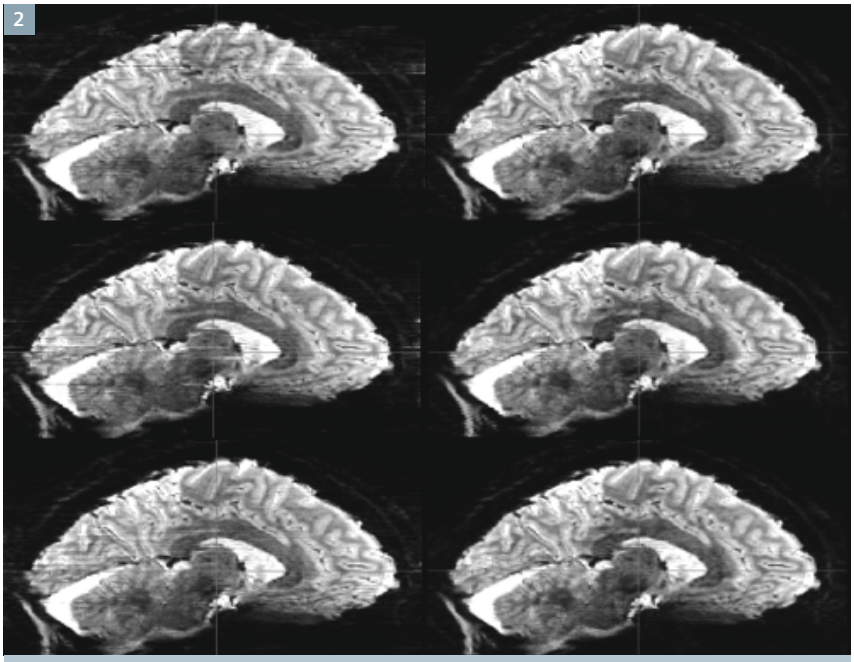

1 HCP fMRI images at 3T **(1A)** and 7T **(1B)**. EPI images acquired using the HCP protocol at 3T and 7T. (3T: 2 mm, TR 0.72 s, multiband (MB) 8. 7T: 1.6 mm, TR 1.0 s, MB 5, iPAT 2).

[1] 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.

high throughput studies like the HCP, as it required saving raw data and doing offline image reconstructions. It was thus not used in this initial 7T resting-state study. Subsequently, through support from the HCP, the MB technique was fully integrated, optimized, and packaged for use on Siemens scanners and has become the default choice for functional and diffusion imaging protocols at sites across the world (http://www.cmrr.umn.edu/multiband/). While the technique, referred to as either multiband, simultaneous multi-slice (SMS), or slice acceleration, was originally proposed for 7T fMRI [11], its subsequent translation to 3T was comparatively straightforward as in-plane accelerations were not a requirement, and issues related to $B_0$ and $B_1$ were drastically reduced at 3T [17, 18]. Ironically, this resulted in unprecedented image qualities, accelerations, and SNRs at 3T and it became imperative for the ubiquitous technical challenges at high fields to be dealt with in order for the MB technique to be competitive and equally attractive at 7T. Outlined below are some of the technical issues and advances that have since made MB slice accelerations at 7T routine, and the possibility of acquiring higher spatial resolutions over the entire brain with conventional TRs or faster, a reality.

High-field, high-resolution imaging requires the use of in-plane accelerations if full field-of-view images with high in-plane resolutions are desired. As such, the use of slice accelerations directly competes with in-plane accelerations in terms of the use of the spatial encoding information available from the coil sensitivity profile. At 3T, because in-plane accelerations are not always required, much higher slice-acceleration factors can be used [15]. While the total achievable acceleration factors are higher at 7T [19], slice-acceleration factors used at 3T are typically higher than those used at 7T, as is evident by the HCP fMRI protocol (Fig. 1). In addition, the use of in-plane accelerations is accompanied by additional under-sampling SNR losses and increased sensitivity to motion. In-plane reference scans acquired with segmented EPI acquisitions, unlike reference scans for multiband images (i.e. single band reference), are highly sensitive to subject motion, including physiology, which becomes increasingly more problematic at high resolutions, and can result in additional ghosting or banding artifacts in the EPI images (Fig. 2). This can result in significantly reduced temporal SNR and compromised image quality in accelerated BOLD images at 7T. To address this, we explored using gradient recalled echo or FLASH scans for calibration, acquiring a single line of *k*-space after each RF pulse [20-22]. This approach, now standard on 7T acquisitions, does not exhibit noticeable sensitivity to subject motion (Fig. 2) and results in higher temporal SNR. Current and future efforts are still highly focused on improving image quality (i.e. ghost and artifact reduction) for EPI applications at 7T, specifically those employing high amounts of acceleration both in the slice and in plane directions [11, 23, 24].

The combined use of high fields and multiband pulses results in significant $B_1$ limitations. First, the conventional approach to generating a MB RF pulse simply sums the single banded waveforms, which quickly reaches the peak power limitation of the system. To deal with this, one can reduce RF bandwidth by increasing the pulse durations or use RF techniques such as VERSE [25] or PINS [26], albeit at the cost of poorer slice profiles, especially in the presence of $B_0$ inhomogeneities. The use of approaches, such as time and phase shifting of the RF pulses [12] or parallel transmit [14], promises to relax peak power and SAR requirements without compromising the slice profile, while also providing increased signal homogeneity and SNR across the brain. At 3T, although such $B_1$ limitations can also arise, they do not significantly affect gradient echo BOLD imaging and tend to be manageable in MB-accelerated diffusion protocols. However, the use of slice-accelerated diffusion imaging at 7T requires the aforementioned approaches to deal with $B_1$ limitations, and these are currently being developed for use in 7T applications [27]. $B_1$ management is one of the primary ongoing efforts aimed at improving both diffusion and BOLD MB acquisitions at 7T.



2 Reduction of motion sensitivity in auto calibration scans. Comparison of in-plane accelerated EPI images, from three different acquisitions, using standard segmented EPI as reference scans (left column) versus the same three scans reconstructed with a single GRE reference scan (right column). (7T, 1.25 mm, MB 3, iPAT 3)

Common to both high-resolution BOLD and diffusion studies at 7T, made possible by slice-acceleration approaches and the extremely high channel counts, is the unprecedented amount of data being acquired and the rate at which it is acquired. It is not uncommon for the image reconstruction time to substantially exceed the data acquisition time. Users of the multiband sequence quickly noticed that an hour of scanning time would require several hours of image reconstruction time. In addition, the hard disk space where the raw data was stored could be filled in an hour or so, meaning data needed to be transferred off the raw disk or it would be overwritten. As such, in the early days of 2D slice-accelerated BOLD imaging, specifically at 7T, scans were limited to less than an hour and real-time feedback on image quality was unavailable. A significant effort was invested in reducing the reconstruction bottleneck so that such slice-accelerated sequences could be used in more conventional studies and in high throughput studies like the HCP. One of the more significant improvements was achieved with the use of GPU enabled computers reducing the reconstruction time by a factor of 3 or 4, bringing it to near real-time levels. For a 1 mm 7T BOLD fMRI protocol that uses an MB factor of 3 with a 32-channel coil, raw data is generated at a rate of nearly 5 GB/min. For a 10 minute resting-state scan, this amounts to around 50 GB of raw data. With the use of a GPU enabled image reconstructor at the scanner, as is now standard on the MAGNETOM Prisma 3T, DICOM images can be generated in real time. In addition to offline reconstruction no longer being needed, the immediate feedback on image quality and subject performance is also invaluable. For example, if data quality has been compromised, as is often the case with clinical and other vulnerable populations, re-scans can be considered while the subject is still available. Further, applications such as real-time fMRI can now also consider using MB techniques as the data can also be analyzed in real time as well.

## Conclusions

The HCP has to date collected data in nearly 150 subjects (including 40 min of diffusion, 1 hr of resting-state, and 1.5 hrs of task fMRI – per subject) on a commercial 7T system. All of these scans employ slice accelerations (combined with in-plane) and have yielded impressive data sets at high spatial and temporal resolutions (Fig. 3). This is a testament to the robustness of the technique, the scanner hardware, and the general applicability at 7T, which has allowed 7T to provide a unique contribution of very high resolution whole-brain images of structural and functional connectivity to an already impressive HCP data set from 3T. Going forward, continued technical improvements in slice accelerated technology at 7T are likely to not only enhance and enable the countless possibilities of high resolution imaging applications at 7T, including submillimeter resolutions over the entire brain (Fig. 4), but will also likely directly translate into improvements at lower fields.

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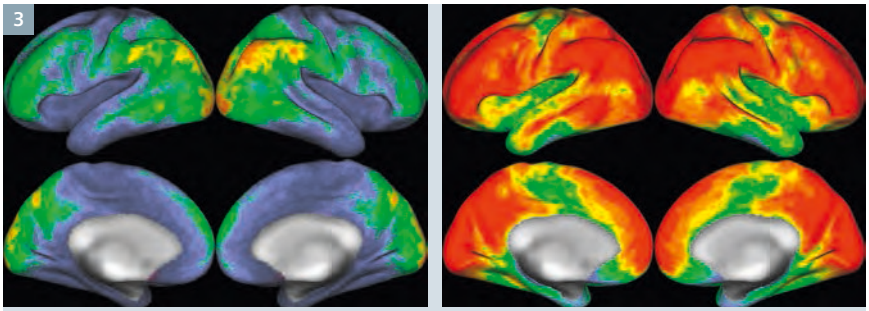


3 Functional contrast-to-noise from 3T and 7T HCP data sets. Maps were generated from 24 subjects using an hour of resting-state fMRI data acquired at 3T or 7T (3T: 2 mm, TR 0.72 s, MB 8. 7T: 1.6 mm, TR 1.0 s, MB 5/iPAT 2).
*Images courtesy of Steve Smith and Matt Glasser for the HCP.*

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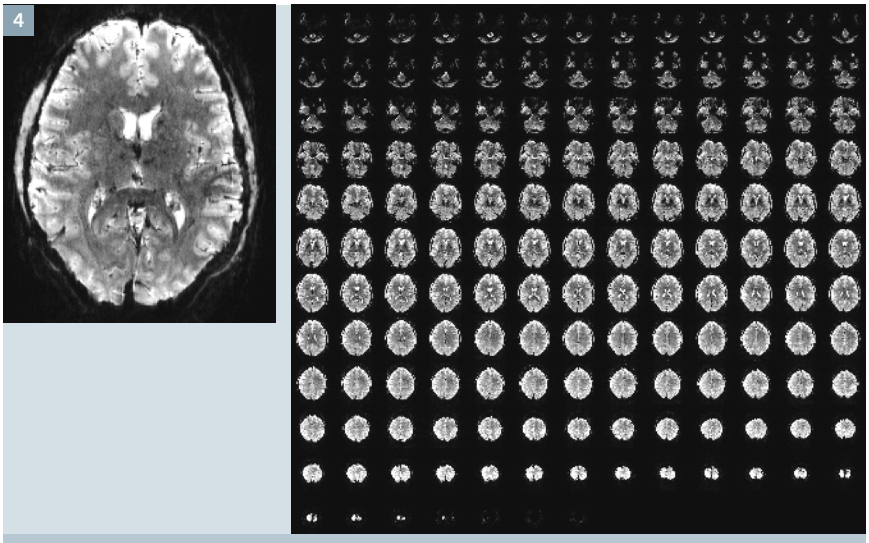

4 Sub-millimeter whole brain fMRI at 7T. A single image acquired using: 0.9 mm isotropic, iPAT 3, MB 3, TR 3.7 s and 150 slices. A zoomed view of one slice is also shown.

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