

2D vs. 3D Acquisition Strategies

ADVANCED DIFFUSION ACQUISITION: TARGETED METHODS

Highlights:

- 2D EPI is the most common pulse sequence for diffusion MRI, but geometric distortions and voxel shape are concerns. 2D EPI is fast, SNR efficient and the image reconstruction simple, making it suitable for diffusion scans with many slices and diffusion directions.
- 3D diffusion-weighted (DW) sequences have emerged, aiming for higher SNR efficiency and small and sharp cubic voxels. The diffusion-phase needs to be measured and corrected due to the multi-shot nature of 3D imaging. 3D acquisitions require longer scan times, but the hope is that an increased SNR efficiency can compensate for this, also in diffusion MRI. With recent advances, 3D DW acquisitions may challenge the standard 2D DW-EPI for full coverage brain scans.

Target audience: Researchers and MR staff interested in pulse sequences for diffusion MRI.

Learning Outcomes: Knowledge about the pros and cons of 2D and 3D pulse sequences for diffusion-weighted MRI.

For nearly two decades (1), the 2D single-shot echo planar imaging (EPI) sequence has for diffusion imaging been the primary sequence of choice due to its speed, SNR efficiency, and reconstruction simplicity. The simplicity comes from its single-shot nature that freezes the spatiotemporally varying phase over the imaged object caused by ever so little uncontrolled motion during imaging ('diffusion-phase'). In single-shot mode, the undesired diffusion-phase is trivially removed when taking the magnitude of the image. On the contrary, for any type of multi-shot diffusion imaging, i.e. where k-space is built up over multiple TRs, this tricky diffusion-phase needs to be measured during imaging (using extra navigator information) and corrected for during the reconstruction.

Single-shot 2D EPI acquisitions are not free from drawbacks and the most apparent issue is its strong off-resonance sensitivity in the phase encoding direction that leads to geometric image distortions. For this reason, many navigated multi-shot 2D pulse sequences have been developed using EPI, Spiral, SSFP and FSE readouts (2-6). Among these, the DW-PROPELLER (2) and the RS-EPI (7,8) sequences are today commercially available alternatives to 2D DW-EPI.

For most brain diffusion studies involving fiber tractography, small isotropic voxels are desired, typically at or below $\sim 2 \times 2 \times 2 \text{ mm}^3$. To achieve this goal, the slice thickness needs to be decreased, which leads to several side effects for a 2D technique such as DW-EPI.

First, to maintain the same full brain coverage, the number of slices needs to be increased as the slice thickness is reduced, which in turn implies the need for a longer TR (and hence scan time) to fit in all slices. In most cases, the TR is already much larger than the T1 values of the tissue and hence there is no SNR gain to expect from additional T1-recovery. Therefore, the SNR efficiency ($\text{SNR} / \sqrt{\text{scan time}}$) decreases by about the square root the number of slices.

Second, in EPI, the chemically shifted fat signal needs to be removed. This is often accomplished by using a water-only SPectral SPatial (SPSP) RF excitation. With this RF pulse, narrow slices are however difficult to produce (especially at high fields) due to its design and RF and gradient limitations. Alternative ways of avoiding fat signal in DW-EPI is e.g. to use a non-slice selective fat saturation, followed by a regular 90° RF excitation, the latter which may be a longer RF pulse with a reduced *excitation bandwidth* to produce a narrower slice for the same maximum gradient amplitude. Often, the efficiency of fat suppression is however reduced compared to that of a SPSP RF excitation.

Third, we have the problem of voxel shape fidelity with 2D-EPI. In the phase encoding direction, T2-decay and off-resonance phase accrual during the EPI readout makes the PSF (point spread function) in the image domain to broaden, leading to a signal smearing in this direction. However, except from in distorted areas of the brain, this blurring is rather small, and most DW-EPI images still appear sharp in comparison to many alternative readouts. In the slice direction, as for any 2D sequence, the voxel shape is governed by the combined slice-selective ability of the RF pulses involved. For twice-refocused diffusion preparations, commonly used in DW-EPI to reduce the effects of eddy currents, we have one 90° RF excitation and two 180° RF refocusing pulses – each having a non-rectangular slice profile. The 180° RF pulses also have straddling crusher gradients used to spoil the undesired FID at the slice edges, but which also have a slice-narrowing (and "slice-rounding") effect (9). To make the FWHM (full-width-half-maximum) of the (excited and refocused) slice be close to the desired thickness, the excitation band of each RF pulse may therefore need to be widened. For 2D diffusion scans with no slice gap, the consequence of this is that spins at the edges of neighboring slices will be affected ('cross-talk') if the TR is not long enough. This, in combination with the already reduced signal at these edges due to the RF pulse shapes makes the local tissue microstructure signal suppressed. It is currently unclear to what extent this affects assumptions about partial voluming effects in fiber tracking, but further studies on this topic would certainly be interesting.

To avoid the above issues with non-ideal slice profiles and aiming for a higher SNR efficiency from 3D encoding, several groups have over the last decade suggested various 3D DW acquisition strategies. One of the first publications were made by Golay et al. (10), who used a gated and navigated 3D EPI acquisition, the latter with an impressively small voxel size of $0.8 \times 0.8 \times 0.8 \text{ mm}^3$, however only covering a small z-FOV of 16 mm.

To overcome geometric distortions, many researchers have suggested various 3D SSFP (Steady-State-Free-Precession) readouts, using either a 'driven equilibrium' (DE) diffusion preparation (11) or a small diffusion gradient that gradually builds up a diffusion-weighting across TRs (12-14). With a DE preparation, phase navigation is not needed as the diffusion phase affects the longitudinal magnetization, and subsequently the magnitude (instead of the phase) of the signal. However, due to T1-relaxation, the amount of diffusion weighting were reduced for signal acquired further away from the DE preparation time. The problem with the other type of diffusion preparation is its image contrast dependence due to the interactions between the diffusion phase and the steady-state condition. This makes diffusion-weighted images in primarily the S/I direction to appear darker. Nevertheless, recent work in 2012 by O'Halloran et al. (13) has demonstrated improved image quality of SSFP type readouts for diffusion using rotating spirals with real-time phase and motion correction throughout the scan. In their work, the signal saturation in the S/I direction was largely reduced. Both O'Halloran et al. (13) and Jung et al. (14) have shown 3D SSFP type of acquisitions with full brain coverage.

Two 3D multi-slab readout types that use the classical Stejskal–Tanner diffusion preparation have been proposed recently by Frank et al. (15) and Engström and Skare (16). Frank et al. used a FSE train with variable-density (VD) spiral readouts, where the 3D encoding were made using 4 k_z encoding steps per excitation, with a total of 16 k_z encodes. To correct for the diffusion-phase, a 2D approximation of the spatially varying phase was assumed and a low-resolution phase information was for each k_z step obtained from the center of each VD-spiral trajectory. In Ref. (16), k_z encoding steps were added to a parallel-imaging-accelerated 2D DW-EPI sequence with a second 2D slab EPI readout for phase navigation, and with a phase correction strategy similar to Frank et al. Using both a Stejskal-Tanner diffusion preparation and a parallel imaging driven EPI readout, the images were similar in nature as the standard EPI sequence, but without the associated slice profile issues and with an improved SNR efficiency for scans with full brain coverage.

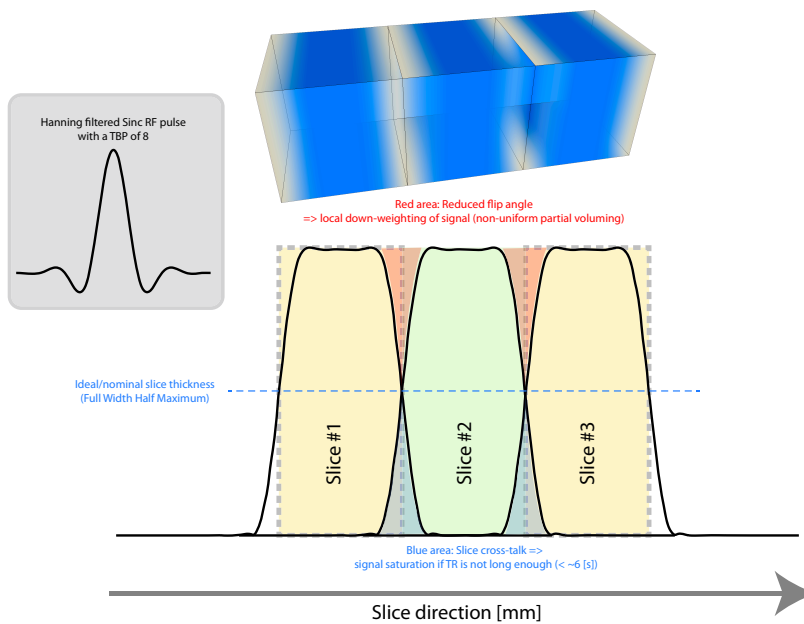


Figure 1. Illustration of slice profiles and cross-talk in 2D imaging. An RF pulse (gray box) with a time-bandwidth-product (TBP) of 8 (i.e. 8 zero crossings), dampened by a Hanning filter at the edges to avoid ripples across the slice. For small flip-angles, the slice profile becomes the Fourier transform of the pulse as shown for three adjacent slices (yellow-green-yellow). Even though the RF pulse here is fairly well modulated, the slice profiles show significant transition bands. The red areas indicate where the flip angle (and signal) is reduced. For short TRs, the slices will also saturate each other ('cross-talk', blue areas), which will further reduce the signal at the slice edges. In standard 2D diffusion imaging, the 2-3 RF pulses involved will in combination make the slice profile yet less rectangular with increased cross-talk effects. This is of course a general problem for any 2D imaging sequence, but in the context of diffusion imaging, it is not entirely clear to what extent this weighted partial voluming affects e.g. fiber tracking methods and multi-compartment diffusion models (cf. 'blue' 2D encoded voxels above for three neighboring slices). Is it a problem at all? Adding head motion during the 2D acquisition of multiple diffusion directions, may have additional effects in this regard.

References

- Butts K, de Crespigny A, Pauly JM, Moseley M. Diffusion-weighted interleaved echo-planar imaging with a pair of orthogonal navigator echoes. *Magn Reson Med* 1996;35(5):763-770.
- Pipe JG, Farthing VG, Forbes KP. Multishot diffusion-weighted FSE using PROPELLER MRI. *Magn Reson Med* 2002;47(1):42-52.
- Liu C, Bammer R, Kim DH, Moseley ME. Self-navigated interleaved spiral (SNAILS): application to high-resolution diffusion tensor imaging. *Magn Reson Med* 2004;52(6):1388-1396.
- Miller KL, Pauly JM. Nonlinear phase correction for navigated diffusion imaging. *Magn Reson Med* 2003;50(2):343-353.
- Trouard TP, Theilmann RJ, Altbach MI, Gmitro AF. High-resolution diffusion imaging with DIFRAD-FSE (diffusion-weighted radial acquisition of data with fast spin-echo) MRI. *Magn Reson Med* 1999;42(1):11-18.
- Butts K, Pauly J, de Crespigny A, Moseley M. Isotropic diffusion-weighted and spiral-navigated interleaved EPI for routine imaging of acute stroke. *Magn Reson Med* 1997;38(5):741-749.
- Porter DA, Heidemann RM. High resolution diffusion-weighted imaging using readout-segmented echo-planar imaging, parallel imaging and a two-dimensional navigator-based reacquisition. *Magn Reson Med* 2009;62(2):468-475.
- Porter D, Mueller E. Multi-shot diffusion-weighted EPI with readout mosaic segmentation and 2D navigator correction. 2004; Kyoto, Japan. p 442.
- Bernstein MA, King KF, Zhou XJ. *Handbook of MRI Pulse Sequences*. Burlington (MA): Elsevier Academic Press; 2004.
- Golay X, Jiang H, van Zijl PC, Mori S. High-resolution isotropic 3D diffusion tensor imaging of the human brain. *Magn Reson Med* 2002;47(5):837-843.
- Jeong EK, Kim SE, Parker DL. High-resolution diffusion-weighted 3D MRI, using diffusion-weighted driven-equilibrium (DW-DE) and multishot segmented 3D-SSFP without navigator echoes. *Magn Reson Med* 2003;50(4):821-829.
- McNab JA, Gallichan D, Miller KL. 3D steady-state diffusion-weighted imaging with trajectory using radially batched internal navigator echoes (TURBINE). *Magn Reson Med* 2010;63(1):235-242.
- O'Halloran RL, Aksoy M, Van AT, Bammer R. 3D isotropic high-resolution diffusion-weighted MRI of the whole brain with a motion-corrected steady-state free precession sequence. *Magn Reson Med* 2012.
- Jung Y, Samsonov AA, Block WF, Lazar M, Lu A, Liu J, Alexander AL. 3D diffusion tensor MRI with isotropic resolution using a steady-state radial acquisition. *J Magn Reson Imaging* 2009;29(5):1175-1184.
- Frank LR, Jung Y, Inati S, Tyszka JM, Wong EC. High efficiency, low distortion 3D diffusion tensor imaging with variable density spiral fast spin echoes (3D DW VDS RARE). *Neuroimage* 2010;49(2):1510-1523.
- Engström M, Skare S. Diffusion-Weighted 3D Multislab Echo Planar Imaging for High Signal-to-Noise Ratio Efficiency and Isotropic Image Resolution. *Magn Reson Med* 2013;10.1002/mrm-24594.