Multishot for High Spatial Resolution

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Conventional Cartesian *non-diffusion* pulse sequences acquire k-space in multiple excitations (a.k.a. shots). As the phase errors originating from motion during the diffusion preparation time are random in nature and large compared to the phase used to spatially encode the image, the use of multi-shot sequences with diffusion gradients is not straightforward, and in most cases severe image ghosting will result.

Single shot diffusion-weighted pulse sequences

A single shot pulse sequence fills the entire k-space after a single excitation and diffusion preparation. Therefore, the spatially nonlinear phase over the object caused by motion appears as a static effect for all k-space lines. Hence, the only effect on the data is that the reconstructed complex image will contain this phase after reconstruction (which is ignored anyway for the *magnitude* DW images). Because of its high SNR efficiency, single-shot Echo Planar Imaging (ss-EPI) sequence remains the most widely used pulse sequence for diffusion imaging.

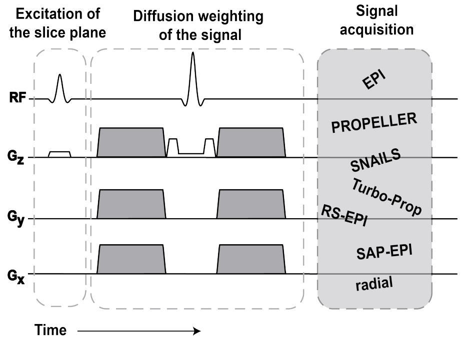

Figure 1. A simplified Stejskal-Tanner diffusion sequence with many optional readouts

The main drawback of ss-EPI is that, because it reads out all k-space lines sequentially along the phase encoding direction, undesired phase (a.k.a. off-resonant spins) from *other sources than motion* will accumulate during the readout train. This phase accrual will appear large in comparison to the encoding phase induced by the small phase encoding blips in the EPI train, and will result in geometric distortions in two forms. The first type is the nonlinear geometric distortions originating form the static susceptibility gradients (field inhomogeneities) near tissue-air interfaces, and may be up to several centimeters. The second largest source of off-resonances is object *in*dependent, namely *eddy currents* arising from the diffusion gradients. The slowly decaying eddy current terms give rise to an erroneous affine transformation (i.e. some combination of scaling, translation, shear) of the diffusion-weighted image, seldom more than a few millimeters. Although this may not sound as severe, it is a problem because the image warping changes with the diffusion direction played out, resulting in a misregistration across the diffusion-weighted images.

Increasing a) the field strength, b) frequency encoding resolution or c) the phase encoding FOV, makes the off-resonance sensitivity to increase correspondingly. This is why it is hard to achieve high resolution with DW-EPI, in particular at high field strengths.

The so far most successful and widely used way to reduce the off-resonance sensitivity is to reduce the effective phase encoding FOV and unfold it in the reconstruction process via parallel imaging, such as SENSE (1) or GRAPPA (2). Using e.g. a modern 32-channel head coil, acceleration factors (and hence distortion reduction factors) up to about R=4-5 become feasible, if the lost SNR from acquiring R times less k-space lines is compensated for by more averages or diffusion directions.

There are also certain DWI applications, such e.g. of the cervical spine (3) or the optic nerve (4), where a narrow final FOV along the phase encoding is suitable because of the shape of the anatomy. For these scenarios, the geometric distortions in DW-ssEPI may be reduced by reducing the final phase FOV, but measures to avoid the aliasing of tissue are needed. The first variant of this was named *zonally magnified* EPI (5), where the excitation planes of the 90 and the 180 pulses are tilted slightly to end up with a Spin-Echo signal from only a swath of the object's anatomy. Alternative methods to avoid aliasing for reduced FOV DW-EPI acquisitions have recently been proposed recently (3, 6, 7).

Single-shot DW-spiral is, similar to EPI, sensitive to off-resonances, but the phase evolution of these off-resonant spins are now evolving from the center to the periphery of k-space. This gives rise to a blur in the image instead of EPI's uni-directional displacement (and signal pileup) of the anatomy.

Multi shot diffusion-weighted pulse sequences

While the solutions are different, the common rationale for not using single-shot techniques is to achieve higher image resolution with less geometric distortions and/or blurring, at the expense of longer scan times. Mentioned above is that the unreliable phase in DWI makes *interleaved* multi-shot Cartesian imaging prone to image ghosting. For this reason, *non*-Cartesian k-space trajectories have been much more successful in this regard.

There have been several variants of diffusion-weighted radial acquisitions (8-10), where one or more radial spokes across a circular k-space are read out after each diffusion preparation. Radial spokes acquired in different TRs (excitations) will be shifted due to the untrustworthy diffusion phase. However, since the radial spokes are all intersecting the k-space center, they are also inherently self-navigated along the radial direction. By Fourier transforming each radial line to the image domain, taking the magnitude of the data, and then Fourier transforming it back to k-space, the peak signals of the radial spokes will all be aligned in the center of k-space. However, as the correction is 1D, it cannot correct for shifts perpendicular to the radial direction.

Another set of diffusion-weighted pulse sequences are PROPELLER (11), Turboprop (12), SAP-EPI (13), and X-PROP (14), which all acquire a center strip, or blade, of k-space after each diffusion preparation (albeit in different ways and with different pros and cons). In subsequent excitations, the blades are rotated to fill the entire k-space. What makes these propeller sequences distinct form standard interleaved multi-shot imaging is that each blade is acquired at full image FOV, making *each blade* free from ghosting in a similar fashion as ss-EPI. In addition, each blade serves as its own 2D navigator echo, which first allows us to remove all (or just the slowly varying annoying phase) of each image blade separately, similar to been described for radials above, but this time we can correct the undesired translation in the k-space blade (arising from non-zero image phase from e.g. brain motion) in both directions. Second, rigid 2D motion correction can be performed to correct for translations and rotations in the image domain.

In PROPELLER, each blade is read out with RF refocusing pulses similar to SSFSE, why it is free from geometric distortions. The non-CPMG problem still exists however, but is mitigated with good 180 flip angles and by employing an intra-blade phase ordering scheme that puts the even echoes in the center of the blade (15). This pulse sequence has been successfully implemented on several commercial systems, and is today widely used. *Turboprop* is a modification of PROPELLER with small EPI trains inserted between the RF refocusing pulses similar to the GRASE sequence, and thereby trading lower SAR and shorter scan times for some limited off-resonance sensitivity. About the same time as Turboprop, diffusion-weighted SAP-EPI was proposed, which uses only an EPI train to read out the blade in k-space. The key in SAP-EPI is that the frequency encoding direction is set along the short-axis of the blade (hence its name), which increases the k-space traversal speed along the phase encoding (long-axis of the blade) and thereby reduces the sensitivity to off-resonances. Because the final gridded image resolution is due to the length of the blade, geometric distortions and image resolution become uncoupled (unlike in ss-EPI, where higher resolution also means more problems). More recently, the X-PROP technique was proposed (14), which is similar to the Turboprop sequence in terms of sequence timing but where the individual EPI echoes between the refocusing pulses are separated into different blades. Thereby, each blade, built up from lines acquired following different refocusing pulses in the readout train, will contain the same phase accrual due to off-resonances, which then can be removed before gridding the blades together.

Another very promising pulse sequence for diffusion imaging is the RS-EPI sequence (16-18). Sharing the same intra-blade k-space trajectory as SAP-EPI, they are similar in off-resonance sensitivity, but in RS-EPI the blades are put side by side, vertically, in k-space. With all blades having the same phase encoding direction, the residual geometric distortions in the final gridded image are unidirectional too, which has an advantage at very high resolutions (~ 480x480), as SAP-EPI - like any non-Cartesian technique - will be prone to some residual blurring if not all artifacts are completely removed. However, as only one of the vertical blades in the k-space passes through the k-space center, RS-EPI also needs a second blade readout through the k-space center as 2D navigator. This extra readout makes it slightly less scan time efficient compared to SAP-EPI. Both SAP-EPI and RS-EPI benefit largely to be combined with parallel imaging to reduce geometric distortions further.

Diffusion-weighted SNAILS (19), is a multi-shot spiral sequence with a k-space density that increases with its distance from the center. The central portion of k-space is first acquired like a single-shot spiral, every time capturing the low spatial frequencies of the phase, whereas the rest of k-space is read out sparsely in each excitation. Similar to the propeller sequence family, the fully sampled central portion of k-space for each shot can be used to correct for phase and motion corruption of the data. As each spiral arm is not in its own sub-Cartesian space, the reconstruction and correction becomes more complex than for propeller trajectories, but this has been well explained in Ref (19). Blurring is, again, however hard to remove completely.

Yet another way to avoid both motion induced phase problems and geometric distortions is to flip the M_{xy}-signal after the diffusion preparation back into the longitudinal direction. The *new* (diffusion-weighted) M_z can then be used to read out multiple k-space lines using a series of small excitation flip angles like in STEAM-DWI (20), where also the TR needs to be short between the low-flip angle pulses to avoid too much T_1-recovery of non-diffusion-weighted spins. However, in flipping back of the magnetization to M_z, half the SNR lost, and further SNR is lost due to the use of the small flip angles.

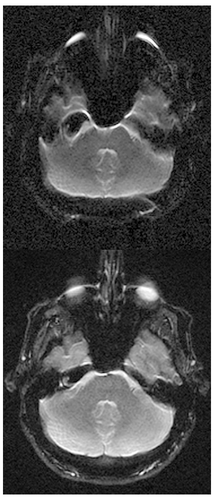

Figure 2. ss-EPI at 1.5T and 288x288 resolution. top: R=1, bottom: R=3. Note the reduction in geometric distortions.

3D and 3D multi-slab diffusion-weighted pulse sequences

Finally, in this overview of diffusion-weighted pulse sequences is balanced steady-state free precession (bSSFP) (21). With a new excitation prior to each readout, also bSSFP does not suffer from the geometric distortions encountered in EPI-based imaging. DW-bSSFP differs substantially from the other sequences in that the diffusion-weighting is an accumulated effect over multiple TRs originating from a small diffusion gradient after each readout. Unlike e.g. a classical Stejskal-Tanner diffusion preparation, the b-value in bSSFP is a function of T_1, T_2 and flip angle. It is therefore in general difficult to use this method for quantification. Moreover, bSSFP is not particular robust against motion. Nevertheless, see e.g. Ref (22) for methods using navigators and cardiac gating with some good DWI examples.

By adding a second EPI readout and a slab phase encoding gradient before the first echo, a GRAPPA accelerated Cartesian EPI sequence may be converted into a 3D multi-slab sequence (23), where ~15 mm thick slabs are phase encoded in about 10 steps, which after Fourier transformation in the through-plane direction give rise to sharp Fourier encoded 1.3-1.5 mm slices. With the relatively thin slab profiles, it has been empirically found that a 2D (in-plane) phase correction to deal with the random diffusion phase occurring from one TR (and k_z encoding) to the next, making the navigation portion reasonably simple.

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