# MR FORMATION

Modern diffusion-weighted (DW) sequences all trace their origin to the pulsed gradient spin echo **(PGSE)** technique developed by Edward Stejskal and John Tanner [Stejskal EO, Tanner JE. Spin diffusion measurements: spin echoes in the presence of time-dependent field gradient. J Chem Phys 1965; 42:288-292. (This is the "classic").] in the mid-1960. As shown in the diagram right, symmetric, strong diffusion-sensitizing gradients **(DG's)** are applied on either side of the 180°-pulse. The phases of stationary spins are unaffected by the DG pair since any phase accumulation from the first gradient lobe is reversed by the second. Diffusing spins, however, move into different locations between the first and second lobes, falling out of phase and losing signal.
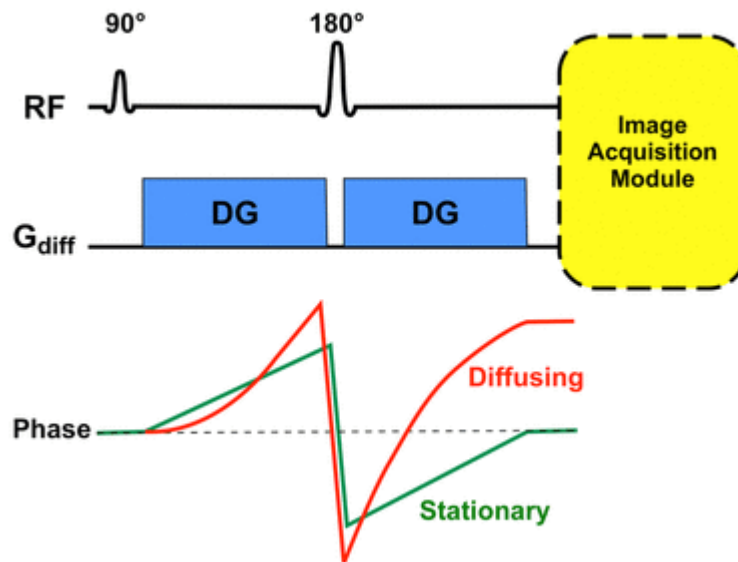
Immediately following the second DG, an image acquisition module is played out. This is typically an echo-planar sequence using rapidly oscillating phase and frequency gradients that generate multiple gradient echoes. Rapid image acquisition is generally required to minimize the effects of bulk motion (such as vascular pulsations) on the DW images. Other modules (such as fast spin echo) are possible, but are not as widely used at the present time.

Modern implementations of DWI retain the basic features of Stejskal's and Tanner's original **PGSE** technique [Stejskal EO, Tanner JE. Spin diffusion measurements: spin echoes in the presence of time-dependent field gradient. J Chem Phys 1965; 42:288-292. (This is the "classic").] with certain modifications [Sinnaeve D. The Stejskal–Tanner equation generalized for any gradient shape—an overview of most pulse sequences measuring free diffusion. Concepts Magn Reson Part A 2012; 40A:39-65.]. To suppress chemical shift artifacts, all commercial DWI sequences utilize some sort of fat suppression method. This may be a chemically-selective fat saturation pulse or a nonselective "STIR-like" inverting pulse applied immediately before the 90°-pulse. Alternatively, the 90°-pulse itself may be selectively tuned to excite water protons only. To suppress eddy currents and reduce spatial distortion artifacts [Alexander AL, Tsuruda JS, Parker DL. Elimination of eddy current artifacts in diffusion-weighted echo-planar images: the use of bipolar gradients. Magn Reson Med 1997; 38:1016–21.] a

"twice-refocused" PGSE sequence may be used. This technique employs a second 180°-refocusing pulse <mark>[Reese TG, Heid O, Weisskoff RM, Wedeen VJ. Reduction of eddy-current-induced distortion in diffusion MRI using a twice-refocused spin echo. Magn Reson Med 2003; 49:177-182.]</mark> just before the image acquisition module begins. A third common modification to reduce eddy current artifacts involves the use of bipolar (rather than unipolar) DG's.

With the core pulse sequence defined as above, the following steps are automatically performed to generate DW images and their associated maps:

B0 image

The DW pulse sequence is first run with the DG's turned off or set to a very low value. This generates a set of **b0 ("b-zero") images** that are T2-weighted and will serve as a baseline for later calculated maps. (For abdominal imaging **b50 images** are often obtained, the small but nonzero gradient amplitude helping to suppress signal in vessels). And the figure below shows an example of b0 images.
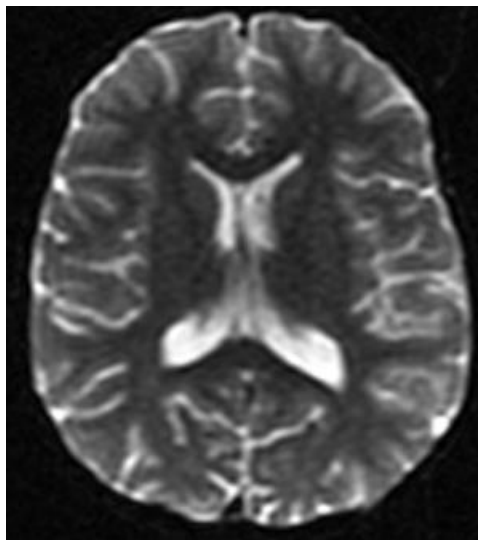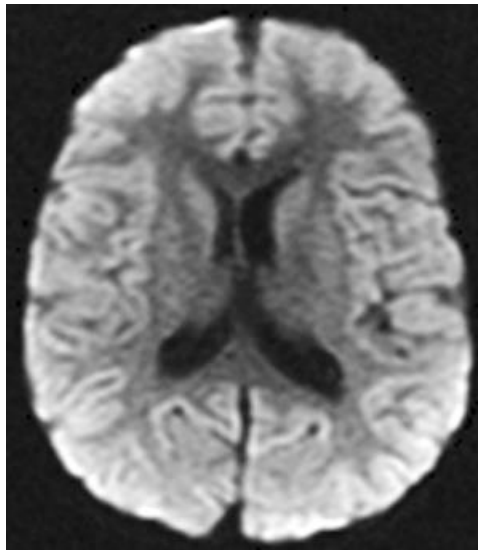

DW source image

The DW sequence is then run with the DG's turned on individually or in combination and at various strengths. This produces **DW source images** sensitized to diffusion in multiple different directions. And the figure below shows an example of DW source images.
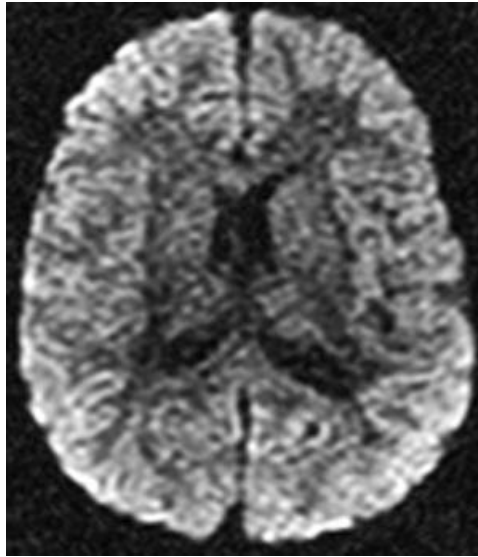
Trace DW image

  The DW source images are combined to produce a set of **Trace DW images,** the first-line images used for clinical diagnosis. And the figure below shows an example of Trace DW images.


Apparent Diffusion Coefficient (ADC) map

  An **Apparent Diffusion Coefficient (ADC) map** is then calculated using the data from the b0 and source images. The ADC map is used to clarify abnormalities seen on the trace images. And the figure below shows an example of ADC map.
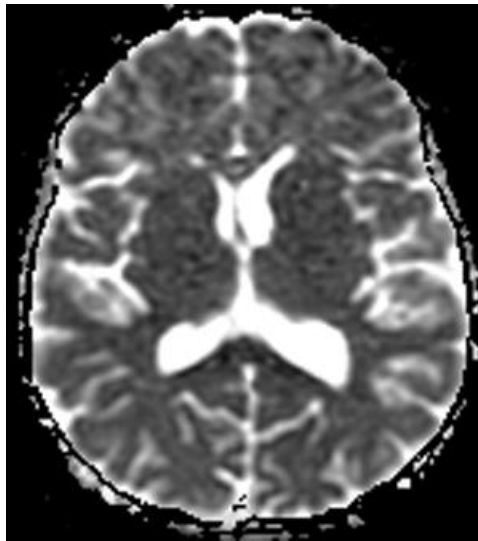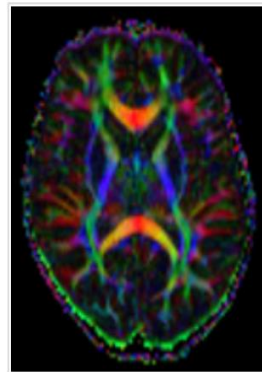
Additional calculated image sets

Further advanced processing can be optionally performed, creating additional calculated image sets for analysis. These may include **exponential ADC maps**, **fractional anisotropy images**, **principal diffusion direction maps**, and **fiber tracking maps**. The figure below illustrates these advanced processing and the additional image sets.
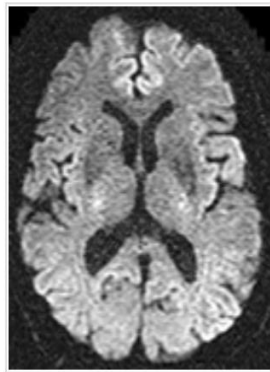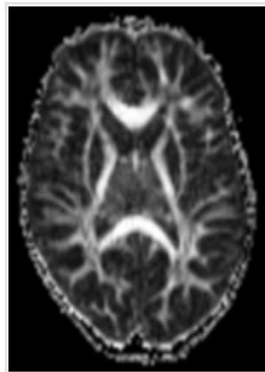
Exponential ADC map   Fractional Anisotropy map   Principal Diffusion Direction map   Fiber-tracking map
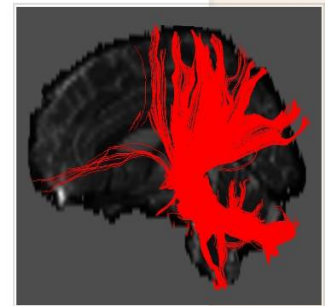
IMAGE QUALITY AND ARTIFACTS

Resolution, SNR and contrast

DW images are usually of lower resolution than conventional MR images like T2WI. This is due to multiple factors like low strength scanners, faster image acquisition techniques like Single-Shot Echo Planar Imaging and limitations of general acquisition parameters like field of view (FOV), slice thickness, etc. Lower strength scanners contribute weaker signals to the image compared to high strength scanners and thereby provide lower resolution than the low strength scanners. Fast acquisition techniques like SS-EPI concentrate on acquiring images in a very short time before complete signal

decay and therefore have limitations on the maximum achievable resolution of DW images. General MR acquisition parameters like FOV, slice thickness, matrix size etc. are also related to spatial resolution. Increasing FOV but maintaining same matrix size would decrease resolution of image (in-plane spatial resolution of an image can be calculated by dividing FOV with matrix size) and increasing the matrix size would increase the in-plane resolution if FOV remains constant. In general, the resolution along the slice direction (through-plane) is poorer compared to direction of image (in-plane). However, the maximum resolution achievable by optimizing these parameters is limited by the hardware limitations of scanner. Low resolution can be a challenge in radiotherapy planning treatment since DW images, along with ADC maps are used in conjunction with T2-weighted images, which typically are of higher resolution. Given the difference in the respective resolutions, if ADC and T2WI were to be super-imposed, due to the low resolution of ADC/DWI, it would over estimate lesion area due to its lower resolution. And in general, higher resolution images are preferred since they offer more data and accurate details compared to lower resolution images.

In addition to low resolution, DW images also suffer from low SNR, because of the presence of large amount of noise. Image contrast is also a crucial issue since higher contrast is very beneficial in delineating the regions of abnormality accurately using diffusion coefficient values from ADC maps. Lower SNR and contrast-to-noise-ratio (CNR) can limit the ability of accurate interpretation of ADC maps and DW images.

Artifacts

DW images are often susceptible to various artifacts like distortion, ringing etc. which arise from a multitude of factors. One of the most important artifacts in DW images is distortion. Distortion in images can occur due to field inhomogeneity and differences in magnetic susceptibility in the region being imaged.

Widely used 3T scanners were introduced in early 2000s and were adapted quickly due to their ability to achieve increased spatial resolution, higher SNR and better contrast than 1.5T machines. However, increasing field strength contributed to higher magnetic susceptibility related artifacts in the image. The B1 magnetic field, in which the patient is placed, becomes more inhomogeneous as field strength increases, contributing to more errors in image acquisition [Stafford RJ. High Field MRI: Technology, Applications, Safety, and Limitations. American Association of Physicists in Medicine (AAPM); 2005.]. Sequences like EPI require very homogeneous magnetic fields so that the proton spins conform to the spin rate and do not dephase, ensuring accuracy in imaging. However in several cases, like at air-tissue interfaces for instance, protons at the interface undergo phase change different from the expected due to magnetic susceptibility differences thereby causing geometric distortion in the image. **Figure 4A** shows a T2 weighted image and **Figure 4B** shows the corresponding DW image of a phantom. The phantom is placed in air and scanned due to which distortion occurred around the edges with air-interfacing in the DW image, **Figure 4B**.
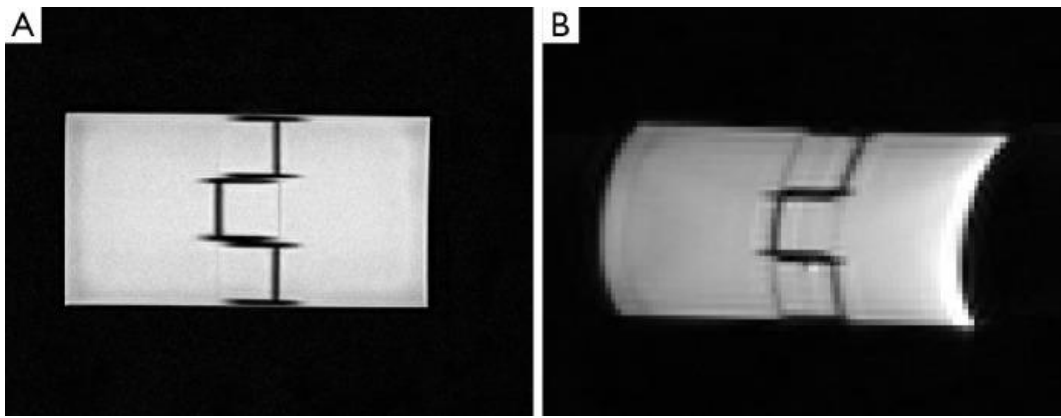
This distortion can also be observed when imaging is done in tissues with metal implants, due to field variation in the region. This susceptibility related artifacts can also be caused by the gradient system, which could introduce inhomogeneity in magnetic field. Powerful and rapidly switching gradients induce local currents called eddy currents, which in turn produce local magnetic fields of their own, disturbing the field homogeneity. These eddy currents contribute to distortion and image shift, by manipulating the gradient strengths experienced by spins [Le Bihan D, Poupon C, Amadon A, Lethimonnier F.Artifacts and pitfalls in diffusion MRI. J Magn Reson Imaging 2006;24:478-88.], which affect accurate image interpretation and ADC estimation and thereby, clinical diagnosis. Eddy currents can also cause other artifacts such as ghosting [Le Bihan D, Poupon C, Amadon A, Lethimonnier F.Artifacts and pitfalls in diffusion MRI. J Magn Reson Imaging 2006;24:478-88.].

Apart from distortion, EPI sequences are sensitive to motion, microscopic or macroscopic, arising from various factors. Macroscopic motion leads to severe motion related artifacts resulting in ghosting or blurring of the DW image. For DW imaging, this could affect diffusion measurements greatly and might render incorrect data. Even though precautions can be taken to minimize voluntary patient movement, involuntary movements like breathing, blood flow or mechanical vibrations arising from patient table of the scanner are still unavoidable.

Technological advancement in addressing the challenges

DW images often have lower image quality compared to other conventional MR images due to image quality issues like distortion, noise, low resolution and presence of artifacts, most of which arise due to the usage of faster image acquisition techniques such as EPI, essential for capturing the diffusion signal before it becomes null.

Most of these challenges can be circumvented by altering DW-MR protocol factors like echo time (TE), gradient strengths, changing image acquisition techniques etc. Broadly, the approaches to counter the inherent challenges associated with DWI fall into four categories: hardware upgrading or improvements, usage of contrast agents, optimizing acquisition parameters, and software based postprocessing techniques. None of these approaches fully address all the challenges individually, as these might come with their own challenges like increased acquisition time, etc.

Challenges of DWI and some approaches to address these challenges

Challenge	Some common approaches to address challenges
Low resolution	Hardware improvements Increasing field strength of scanners Multi-shot sequences Post-processing Interpolation techniques; super-resolution reconstruction
SNR	Hardware improvements Increasing field strength of scanners; High strength gradients Multi-shot sequences Acquisition parameters Averaging
Contrast Acquisition time	Contrast agents Hardware improvements Increasing field strength of scanners; high strength gradients Single-shot sequences Parallel imaging Acquisition parameters Optimal TR, TE, number of b-values
Distortion from susceptibility differences and eddy currents	Hardware improvements Increasing field strength of scanners; high strength gradients; shimming coils Non-EPI based sequences Calibration scans and pre-emphasized pulses Acquisition parameters Increasing receiver bandwidth or decreasing peak gradient amplitudes Post-processing Acquiring field maps and correction algorithms
Motion artifacts	Hardware improvements Single-shot EPI; Non-EPI based sequences; Cardiac and Respiratory triggering or bi-polar gradient pulses Navigator based and readout-segmented acquisition methods Acquisition parameters Averaging
ADC accuracy	Acquisition parameters Optimal number of b-values Diffusion modelling in tissue Post-processing