DIFFUSION IMAGING

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BASICS: Diffusion, the translational movement of molecules via thermally driven random motions (Brownian motion), is one fundamental property of water that can be used for novel image contrast. The strength of the interactions between individual molecules is responsible for the degree of molecular mobility, quantified by the diffusion coefficient, D (units of mm^2/s). In tissue, molecular motion is also hindered by cellular structures such as membranes and thus is characterized by the *apparent* diffusion coefficient or ADC. Typical MRI measurements of diffusion allow ~ 40 ms for water to diffuse on the order of 10 μm, a very small displacement but one that is measurable by MRI. Diffusion can be the same in all directions (isotropic, e.g. gray matter, CSF) or have a preferential direction (anisotropic, e.g. white matter) **(Fig 1)**. The micro-structural characteristics and metabolic status of the tissue can then be inferred from the measured diffusion properties, either magnitude and/or direction.

IMAGING DIFFUSION: Diffusion-weighting can be applied to a standard spin-echo sequence by adding two equal gradient pulses, one prior to and one after the refocusing 180 degree rf pulse. The first gradient pulse *labels* the position of the water molecules (actually the hydrogen nuclei) in the sample by a phase shift. After some time is allowed for the molecules to diffuse, the second gradient pulse is applied to measure the degree of molecular displacement since the first gradient pulse. Water molecules that have not moved are totally refocused (i.e. rephased) whereas molecules that have moved are only partially refocused. This additional dephasing due to diffusion causes signal attenuation in the image. Consequently, regions with faster diffusion, like CSF, experience greater signal loss. The degree of diffusion sensitivity of the sequence is given by the "b" value where b depends on the duration, strength, and separation of these two additional gradients. A b of 1000 s/mm^2 is typically used for the diffusion-weighted images of brain and a "b0" scan refers to a non-diffusion-weighted image, usually T2-weighted given the long spin-echo time. A plot of the ln(signal intensity at various b values/signal intensity at b0) versus b yields a straight line, the slope of which yields a pixel-by-pixel map that reflects *only* the degree of water diffusion (i.e. the ADC map). Since only the diffusion parallel to a gradient can cause signal attenuation, the ADC along different directions in the tissue can be measured by applying the diffusion-sensitizing gradients along distinct spatial axes (e.g. X, Y, Z, or some other arbitrary direction). Single-shot echo planar imaging (EPI) is the most common acquisition of choice for diffusion imaging since it is very fast and minimizes any patient-related motion artifacts. The main drawbacks of single-shot EPI are image distortions/signal dropout due to eddy currents and susceptibility, low spatial resolution, and less than optimal signal-to-noise ratio. However, advances in new non-EPI methods, parallel imaging, and higher static magnetic fields are improving these limitations for diffusion imaging.

DWI or DTI MAPS: Summary diffusion maps such as mean diffusivity/Trace ADC (bulk diffusion coefficient independent of direction) and fractional anisotropy/FA (directionality of diffusion) are calculated from the ADC maps for the individual gradient directions **(Fig 2)**. Most clinical applications of diffusion-weighted imaging (DWI) acquire 4 scans (b0 and 3 diffusion in orthogonal directions) to yield the Trace ADC. Much current research focuses on diffusion tensor imaging (DTI) which needs a minimum of 7 scans (b0 and 6 diffusion in different directions) to yield the Trace ADC, FA, and the necessary information for tractography extraction of various white matter fibres.

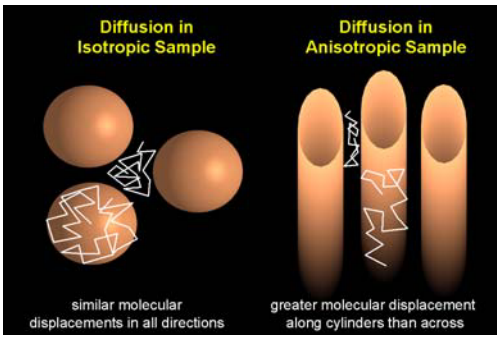

Figure 1. Cellular structures hinder water diffusion in tissue. The two extremes of diffusion are isotropic and anisotropic diffusion. Anisotropy effects are either minimized (e.g. for most clinical imaging) or accentuated for fibre tracking.

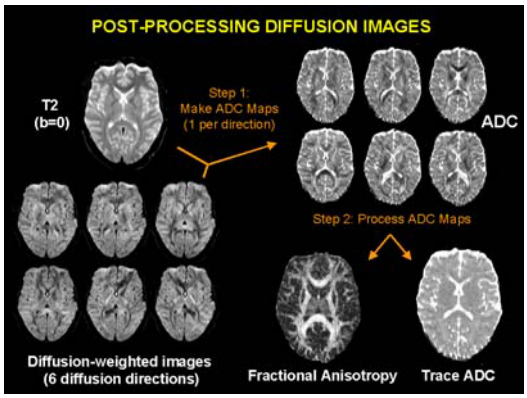

Figure 2. Non- (b=0 s/mm^2) and diffusion- (b=1000 s/mm^2) weighted images with multiple gradient directions yield individual ADC maps which are further processed to maps of fractional anisotropy (FA) and mean diffusivity (Trace ADC).