Diffusion parameters studying using magnetic resonance tomography

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Abstract

Diffusion-weighted magnetic resonance images (MRI) provide information that is present in no other imaging modality. This work describes a diffusion weighted imaging and quantitative apparent diffusion coefficient mapping. In this study the influence of a large variety of imaging parameters on the signal increase and the contrast-to-noise ratio of diffusion-weighted images experiments was determined. The optimal imaging parameters were found by quantitative analyzing of experimental datasets.

Keywords: MRI, echo-planar imaging, diffusion, apparent diffusion coefficient, image quality

1. Introduction

Diffusion-weighted magnetic resonance (MR) images is an established technique in both clinical and research settings and provides an opportunity for diffusion velocity and direction estimation. The reason for the rapid diffusion-weighted images DWI method expansion lies in its unique sensitivity at the imaging voxel scale to microscopic tissue structure characteristics. Water diffusion takes place along fibre tracts limited by myelin membrane and this important property allows us to build 3D fibre tracts models (tractography, diffusion-tensor images) [1-2]. Diffusion measurements need special MR hardware and software. Diffusion measurement accuracy depends on gradient amplitude, velocity and rise time. Echo-planar imaging (EPI) is accomplished by using gradient coils capable of a maximum amplitude of 20 mT/m, a minimum rise time of 0.1 msec, a slew rate of 200 T/m per second. This remarkable technical achievement was enabled by the rapidly switching gradient technology to power supplies, so the first generation of MRI-devices hardware had some limitations. Software should include special pulse sequences and data analysis options. In this article the influence of pulse sequence parameters on image quality and measured diffusion parameters accuracy was analyzed.

2. Echo-planar and diffusion-weighted imaging

Diffusion (or selfdiffusion) is a passive process, driven by the ambient temperature of the substance of interest (a process also known as Brownian motion). MRI is sensitive to tissue water; an analysis of diffusion describes the bulk properties observed due to the random thermal motion of millions of individual water molecules. As these molecules move within tissues, they encounter various restrictions and hindrances (for example cell membranes and macromolecules). We therefore do not observe "free" diffusion of water, and this is acknowledged by apparent diffusion coefficient. The observed diffusive process is affected in this way forms the basis of the utility of DWI. Subtle changes in the degree of restriction to diffusion (for example by a change in average intercellular spacing) are reflected in changes in the diffusion-weighted signal. The water molecules that influence the signal in a DWI acquisition can be thought of as probes of tissue microstructure.

The signal observed in a diffusion-weighted image is determined by the apparent diffusion coefficient (ADC) and a weighting factor β:
\[ S = S_0 \exp(-\beta \cdot ADC), \]

where \( S \) is the observed signal and \( S_0 \) is the signal intensity in the absence of any diffusion weighting. The \( ADC \) depends on investigating matter and diffusion anisotropy, which present in structures such as white matter tracts. The diffusion weighting term \( \beta \) is determined by acquisition sequence parameters, and has units typically expressed as \( \text{s mm}^{-2} \):

\[ \beta = \gamma^2 \delta^2 G^2 (\Delta - \delta/3), \]

where \( \gamma \) is the gyromagnetic ratio, \( \delta \) and \( G \) are the duration and amplitude of the applied diffusion sensitization gradients, and \( \Delta \) is the time interval between these gradients.

Diffusion sensitization leads to a decrease in signal intensity with increasing diffusion coefficient or increasing sensitization. As the application of a gradient is required to provide the sensitization, the direction along which the gradient is applied will affect the change in signal if diffusion is not uniform in all orientations. The raw data quality of a typical DWI acquisition is relatively poor. The signal attenuation process leads to low signal to noise ratio (SNR) for DWI. Second, the diffusion weighting process leads to a requirement for relatively long echo times \( TE \) (which in itself reduces SNR), and subsequently long repetition times \( TR \), meaning that the only practical way to obtain whole brain coverage and to apply diffusion sensitization in multiple directions is to use an ultrafast imaging technique such as echo planar imaging (EPI) to sample the signal. This leads to subsequent problems associated with EPI acquisition, including coarse pixel resolution, image distortion and signal drop-out due to susceptibility problems, and a range of image artefacts.

In echo-planar imaging, multiple lines of imaging data are acquired after a single RF excitation. Two additional gradient pulses with amplitude \( G \) and duration \( \delta \) reduce signal loss due to proton density, \( T1 \) and \( T2 \) relaxation, and increase dependence from water diffusion. EPI pulse sequence begins with 90° and 180° RF pulses, after which the frequency-encoding gradient oscillates rapidly from a positive to a negative amplitude, forming a train of gradient echoes (Fig. 1). Each echo is phase encoded differently by phase-encoding blips on the phase-encoding axis. Each oscillation of the frequency-encoding gradient corresponds to one line of imaging data in \( k \)-space, and each blip corresponds to a transition from one line to the next in \( k \)-space.

For EPI image acquisition time is about 50-300 msec with matrix no larger than 128×128 allow investigate fast processes. To increase image resolution and decrease image distortions multishot EPI-sequences are used and only a portion of the \( k \)-space data is acquired with each
shot. Diffusion images distortions are caused by susceptibility differences, T2-relaxation, main magnetic field inhomogeneities. So data processing usually includes intensity and geometrical correction.

3. Experimental data analysis

Diffusion weighted imaging was performed on a 1.5 T Signa Infinity MRI system (General Electric) using quadrature volume head coil. For estimation the degree of imaging parameters influence on image quality (spatial resolution, SNR, artifacts presence) the TE, TR, FOV, matrix and β-factor were changing. The images were occurred with TR from 6000 ms to 10000 ms; TE from 26 ms to 50 ms; imaging matrix from 64×64 to 160×160; FOV size from 200 mm to 340 mm. Two datasets were collected for each parameters combination: with β = 0 and selected β-value (Fig. 2).

![Fig. 2. Collected images: a) DWI with β = 1000; b) reference image with β = 0; c) ADC-map.](image)

Acquired images were characterized by spatial resolution required for calculations, contained image artifacts, caused by local magnetic field inhomogeneities, and aloud to calculate the diffusion coefficients with required accuracy. For each image dataset the measuring of white matter, water and noise were done, that allows to calculate diffusion coefficient, SNR and image contrast. SNR was estimated as measured signal from investigating matter relation to noise. Te contrast was estimated as relative difference of signals from two matters. ADC were measured for white matter and estimated by relative error to standard value.

Measuring matrix increasing gives rising examination time and decreasing method sensitivity. Increasing TE by 30 ms gives relative SNR decreasing by 20-30%. Increasing TR gives higher signal intensity both for diffusion weighted images and reference images. However this parameter affects total scan time and increasing scan time twice gives signal intensity increasing about 10%.

The β-factor increasing, including all gradient effects (readout and diffusion gradients) leads to image contrast increasing and method sensitivity, that was caused by higher gradient pulses amplitude. The β-factor changing affects signal intensity and SNR correspondingly. Decreasing of β-factor leads to SNR increasing and simultaneously to decreasing of image contrast for investigating tissues that can cause degradation of diagnostic value of examination. The ADC error is approximately 40-50% for β = 500, and about 20% for β = 1000, so β-factor setting equal to β = 1000 is enough for detection diffusion velocity changes in tissues.

In practice, optimal correlation of resolution, accuracy and image quality is reached by DW EPI pulse sequence acquired with TE = 28 msec, TR = 8000 msec, β = 1000, slice thickness 5 mm, FOV= 300×200 mm, 128×128 matrix, in x, y, z diffusion direction. This
parameters leads to apparent diffusion coefficient error approximately ±7% for white and gray matter according to standard values. Matrix increasing causes scan time increasing and method sensitivity decreasing. Increasing β-factor (including gradient effects) give rise to image contrast enhancement and method sensitivity.

4. Conclusion

Echo-planar images with resolution and contrast similar to those of conventional MR images can be obtained by using multishot acquisitions in only a few seconds. However, in comparison with conventional imaging, single-shot echo-planar imaging offers major advantages, which include reduced imaging time, reduced motion artifact, and the ability to image rapid physiologic processes of the human body. These capabilities open up new research fields such as DWI, which provides powerful non-invasive indications of tissue structure and cerebral connectivity.

In this study the optimal diffusion imaging parameters were found for 1.5 T field strength systems: TE = 28 msec, TR = 8000 msec, β = 1000, slice thickness 5 mm, FOV= 300×200 mm, 128×128 matrix, in x, y, z diffusion direction. Further improving molecular visualization methods related with high sensitivity to the researching processes, decreasing image artifacts, and also in resolution increasing, for example, by post-processing using.

References