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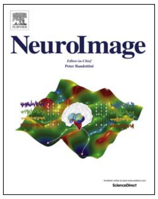

Prospective motion correction in diffusion-weighted imaging using intermediate pseudo-trace-weighted images

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ABSTRACT

Subject head motion is a major challenge in diffusion-weighted imaging, which requires a precise alignment of images from different time points to allow a reliable quantification of diffusion parameters within each voxel. The technique requires long measurement times, making it highly sensitive to long-term subject motion, even when head restraint is used. Current methods of data analysis rely on retrospective motion correction, but there are potential benefits to using prospective motion correction, in which motion is tracked and compensated for during data acquisition. This technique is regularly used to enhance image quality in blood-oxygen-level dependent (BOLD) imaging, but its application to diffusion-weighted imaging has been limited by the contrast variation between images acquired with different diffusion-gradient directions. This paper describes a novel approach to this topic that exploits the rotational invariance of the trace of the diffusion tensor to reduce the effect of this contrast variation, making it possible to perform a fast image registration using a least-squares cost function. This results in an image-based motion detection algorithm that can be applied in real time during data acquisition to adapt the slice position and orientation in response to subject motion. The motion detection capabilities of the technique were evaluated in a study of ten subjects with b-values up to 3000 s/mm². The resulting motion-parameter estimates were in close agreement with reference values provided by interleaved low-b-value images with a correlation coefficient of R=0.9634 for the voxel displacements measured across all subjects and b-values. The technique was also used to perform prospective motion correction on a standard clinical MRI system with b-values up to 2000 s/mm². The correction was evaluated in 3 subjects using interleaved low-b-value images, retrospective image registration using the AFNI processing package and mean diffusivity histogram analysis. Compared to acquisitions without motion correction, prospective motion correction based on pseudo-trace-weighted images was found to provide a robust method for substantially reducing the level of misregistration between volumes. In most cases, misregistrations were reduced to less than 0.2 mm of translation and 0.2° of rotation for an isotropic voxel size of 2 mm, yielding high-quality diffusion parameter maps even in the absence of head restraint and post-acquisition image registration.

1. Introduction

1.1. Anisotropic diffusion and magnetic resonance

Diffusion-weighted (DW) imaging using magnetic resonance (MR) is a powerful, non-invasive method for obtaining information about tissue microstructure and nerve fibre pathways by characterizing the anisotropic behaviour of water diffusion in biological tissues. One technique used to achieve this goal is Diffusion Tensor Imaging (DTI), in which an assumed tensor model is fitted to the MR signals within a series of DW images, acquired with a range of diffusion-gradient directions and b-values (Basser et al., 1994). Although, a minimum of seven DW images are required to estimate the components of the symmetric diffusion tensor, it is common practice to acquire DW images with a higher number of evenly distributed diffusion-gradient directions to avoid systematic bias and reduce confidence limits in the fitted tensor parameters (Jones et al., 1999). A wide range of DTI measurement protocols are in use, but a typical value for the number of diffusion-gradient directions is around 60.

Abbreviations: b, b-value; BOLD, blood-oxygen-level dependent; CSF, cerebrospinal fluid; DEV, maximum allowed deviation; DSI, Diffusion Spectrum Imaging; DTI, Diffusion Tensor Imaging; DW, diffusion-weighted; EPI, Echo-Planar Imaging; FA Map, fractional anisotropy map; FOV, field of view; GRAPPA, Generalized Auto Calibrating Partial Parallel Acquisition; HARDI, High Angular Resolution Diffusion Imaging; MD, mean diffusivity; MoCo, motion correction; MR, magnetic resonance; PACE, prospective acquisition correction; PSF, point spread function; psTW, pseudo-trace-weighted; R, correlation coefficient; SNR, signal-to-noise ratio; TE, echo time; TR, repetition time

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1.2. Subject motion in diffusion-weighted imaging

The motion-sensitizing diffusion gradients and the low-bandwidth Echo-Planar Imaging (EPI) (Stehling et al., 1991) readout in the phase-encoding direction conspire to make DW imaging highly susceptible to a range of image artefacts (Bihan et al., 2006). Subject head motion is one of the biggest challenges when DW imaging is used to quantify anisotropic diffusion in the brain. Firstly, robust data analysis requires, for each imaging voxel, a fixed anatomical location over the course of the measurement so that the same tissue region is sampled at each b-value and diffusion-gradient direction. Secondly, scan times are considerably longer than those of standard clinical imaging protocols, making it difficult even for highly motivated subjects to remain perfectly still for the duration of the measurement. In particular, prolonged measurement times of up to 30 min can be required when using High Angular Resolution Diffusion Imaging (HARDI) (Tuch et al., 2002) or Diffusion Spectrum Imaging (DSI) (Wedeen et al., 2005) protocols, which are typically favoured because they are not restricted by the assumed validity of the single-tensor model. Even with head restraint, there is in general a significant amount of long-term subject motion; this results in misalignment between acquired images, leading to errors in quantitative parameter maps and estimates of nerve-fibre pathways.

1.3. Motion correction in diffusion-weighted imaging

The use of image registration for motion detection is well established in other applications that acquire time-series MRI data, such as blood-oxygen-level dependent (BOLD) imaging used in brain activation studies (Friston et al., 1995). Motion correction in BOLD imaging is often further enhanced by using prospective motion correction, in which motion detection parameters determined in real time are used to adapt the acquisition during the measurement, allowing the slice position and orientation to track the subject motion. Prospective motion correction requires a fast registration algorithm that can be applied without an increase in scan time whilst preserving registration accuracy. For BOLD imaging, these conditions are met by the PACE method (Thesen et al., 2000), which uses an efficient least-squares cost function to combine low computational effort with a registration accuracy that can detect displacements corresponding to a fraction of a voxel. Despite some success in preliminary studies (Benner et al., 2011), the application of the PACE method to DW imaging is limited because the least-squares cost function is not ideally suited to the task of detecting bulk head motion between different DW images due to the contrast variation that occurs when the direction and magnitude of the applied diffusion-encoding gradient are altered. A further factor affecting image-based estimates of motion in DW imaging is the low signal-to-noise ratio (SNR) associated with high b-value images.

In standard data-processing protocols used for the analysis of DW images, motion correction is therefore restricted to the retrospective case, in which the registration of DW image volumes is accomplished after data acquisition with dedicated algorithms that are available within a range of offline data analysis packages: e.g. MCFLIRT of the FMRIB Software Library (Jenkinson et al., 2002), AFNI (Cox, 1996) or TORTOISE (Pierpaoli et al., 2010). These techniques use sophisticated cost functions developed for multimodal image registration, such as mutual information or correlation ratio, to obtain good registration results despite the contrast variation between the images being registered. However, the associated computational burden is high, making the registration algorithms unsuitable for real-time motion correction.

The availability of a robust prospective motion correction technique for DW imaging is desirable for a number of reasons. Firstly, there would be a reduction in the level of voxel displacement which has to be corrected after the measurement by image interpolation, which does not provide a perfect correction, particularly for displacements in the slice-select direction. Secondly, prospective motion correction limits spin-history effects, which can modulate the MR signal when the anatomical location of the excited slice is shifted due to subject motion. Finally, the direction of the applied diffusion gradient can be rotated in real time along with the modified slice orientation to reduce the requirement to correct b-matrices during retrospective motion correction (Leemans and Jones, 2009).

To overcome the difficulties of rapidly registering the DW images, a number of prospective motion correction schemes have proposed the acquisition of additional navigator signals, which are used for the registration process instead. One of these techniques (Kober et al., 2012) monitors a free-induction decay (FID) signal during the measurement to identify when significant motion has taken place; when motion is detected, an additional low-b-value volume is automatically acquired and registered with a reference volume to provide the motion estimates that are required for adapting the data acquisition. Another approach has been to interleave a low-resolution EPI navigator acquisition with the DW scans (Alhamud et al., 2012; Bhat et al., 2012). In general, these navigator approaches have the disadvantage of an increase in overall scan time, although this can be mitigated by using accelerated acquisition techniques, such as simultaneous multi-slice imaging (Bhat et al., 2015).

In addition to the image-based methods described above, prospective motion correction can also be performed using optical motion tracking systems (Aksoy et al., 2011; Zaitsev et al., 2006). This is an attractive option because it can be applied at high temporal resolution without modifying the data acquisition or processing. However, it has the disadvantage of the expense and complication of additional hardware and relies on the use of external markers or bite bars, which may not be suitable for all subjects or anatomical regions. For head studies with external markers, there is the potential problem that the detected motion of the scalp might not be aligned with the actual motion of the brain.

1.4. Motion correction using pseudo-trace-weighted images

This paper introduces an alternative, novel prospective motion correction technique for DW imaging, which uses intermediate pseudo-trace-weighted (psTW) images, calculated in real time during the scan, to overcome the effect of the contrast variation between individual DW images. This allows a rapid motion detection to be performed using a least-squares cost function and, because the image registration is based on the DW images themselves, there is no requirement for external tracking hardware, navigator scans or additional low-b-value images. The technique is compatible with all DTI, HARDI and DSI measurement protocols, requiring only a reordering of the diffusion-gradient directions without modifying the set of gradient vectors used by the given application. The proposed method of motion detection is verified for b-values in the range of 1000 s/mm² to 3000 s/mm² by comparison with image registration based on interleaved low-b-value images. It is also demonstrated that, when the method is used in real time to adapt acquisition parameters during human studies in vivo, there is a substantial reduction in the level of voxel displacement between DW volumes. Some of this work has previously been reported in abstract form (Hoinkiss and Porter, 2015; Hoinkiss et al., 2016).

2. Material and methods

Fig. 1 shows an overview of the proposed prospective motion correction technique, which consists of the following three steps: (1) reordering the diffusion-gradient directions prior to the scan; (2) calculation of pseudo-trace-weighted images in real time during the scan; (3) registration of psTW images and use of resulting motion parameters to adapt the image acquisition during the scan. These steps are explained in detail below.