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Prospective and retrospective motion correction in diffusion magnetic resonance imaging of the human brain

Tobias Kober [a,b,c,*], Rolf Gruetter [a,b,d], Gunnar Krueger [c]

[a] Laboratory for Functional and Metabolic Imaging, École Polytechnique Fédérale de Lausanne, Switzerland
[b] Department of Radiology, Centre Hospitalier Universitaire Vaudois and University of Lausanne, Switzerland
[c] Siemens Schweiz AG, Healthcare Sector IM&WS S, Renens, Switzerland
[d] Department of Radiology, University of Geneva, Switzerland

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ABSTRACT

Diffusion-weighting in magnetic resonance imaging (MRI) increases the sensitivity to molecular Brownian motion, providing insight in the micro-environment of the underlying tissue types and structures. At the same time, the diffusion weighting renders the scans sensitive to other motion, including bulk patient motion. Typically, several image volumes are needed to extract diffusion information, inducing also inter-volume motion susceptibility. Bulk motion is more likely during long acquisitions, as they appear in diffusion tensor, diffusion spectrum and q-ball imaging. Image registration methods are successfully used to correct for bulk motion in other MRI time series, but their performance in diffusion-weighted MRI is limited since diffusion weighting introduces strong signal and contrast changes between serial image volumes.

In this work, we combine the capability of free induction decay (FID) navigators, providing information on object motion, with image registration methodology to prospectively – or optionally retrospectively – correct for motion in diffusion imaging of the human brain. Eight healthy subjects were instructed to perform small-scale voluntary head motion during clinical diffusion tensor imaging acquisitions.

The implemented motion detection based on FID navigator signals is processed in real-time and provided an excellent detection performance of voluntary motion patterns even at a sub-millimetre scale (sensitivity $\geq$ 92%, specificity $>$ 98%). Motion detection triggered an additional image volume acquisition with $b = 0$ s/mm^2 which was subsequently co-registered to a reference volume. In the prospective correction scenario, the calculated motion-parameters were applied to perform a real-time update of the gradient coordinate system to correct for the head movement.

Quantitative analysis revealed that the motion correction implementation is capable to correct head motion in diffusion-weighted MRI to a level comparable to scans without voluntary head motion. The results indicate the potential of this method to improve image quality in diffusion-weighted MRI, a concept that can also be applied when highest diffusion weightings are performed.

Introduction

Diffusion-weighted magnetic resonance imaging (DW-MRI) has become a valuable tool for the investigation and diagnosis of various diseases. Enabling unprecedented insight into brain anatomy, it opens up new perspectives for brain and body imaging, most prominently for the diagnosis of acute stroke (Kloska et al., 2010). It is also increasingly used to investigate other pathologies, including cancer (Charles-Edwards and deSouza, 2006), neurological diseases like multiple sclerosis (Filippi and Agosta, 2010) and impairments in other parts of the body (Koh and Collins, 2007). The capability to visualise the directionality of diffusion through diffusion tensor imaging (DTI, Basser et al., 1994) allows, in conjunction with tractography, more detailed investigation of the brain's architecture and integrity. High angular resolution diffusion imaging (HARDI) methods like q-ball (Callaghan and Xia, 1991; Tuch, 2004) and diffusion spectrum imaging (Tuch et al., 2002; Wedeen et al., 2005) have been used to further improve the precision to measure and visualise complex white matter architecture; however, at a cost. The required employment of up to several hundred diffusion encoding directions lengthens the scan times, consequently increasing the probability that subject motion will occur during the acquisition.

The sensitivity of diffusion imaging to stochastic Brownian motion of free water molecules in the micrometre range also implies an extreme susceptibility to macroscopic or bulk motion of the object being imaged (Tijssen et al., 2009). To extract information on diffusion, the image volume has to be sampled numerous times using different diffusion encoding directions and weightings. This renders diffusion imaging also prone to inter-shot motion.

* Corresponding author at: Ecole Polytechnique Fédérale de Lausanne, LIFMET-CIBM, Station 6, 1015 Lausanne, Switzerland. Fax: +41 21 69 37960.
E-mail address: tobias.kober@epfl.ch (T. Kober).

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Similar to DW-MRI experiments, functional MRI (fMRI) also acquires series of brain volumes and therefore faces similar motion problems arising from patient head movements during the acquisition. Established image registration methods (retro- and prospectively, see Friston et al., 1995; Thesen et al., 2000; Ward et al., 2000), however, cannot be directly applied to diffusion images. The low signal-to-noise ratios (SNR) and the changing contrasts due to the different diffusion encoding directions and weightings hamper the co-registration or even render it impossible at higher diffusion weightings. Motion susceptibility of diffusion MRI hence remains an open issue.

Different approaches have been proposed to mitigate motion artefacts. Post-processing techniques can help to improve the data quality retrospectively. Rejecting outliers in a diffusion dataset (Chang et al., 2005), optimised gradient optimisation schemes for partial datasets (Dubois et al., 2006), and retrospective corrections (Atkinson et al., 2000; Miller and Pauly, 2003; Rohde et al., 2004) have all been shown to increase the quality of corrupted diffusion imaging series.

One can also improve diffusion acquisition techniques. The use of bipolar gradient schemes reduces susceptibility to motion as well as to eddy currents and is widely employed (Prasad and Nalcioglu, 1991). The use of motion-insensitive sampling strategies, such as Turboprop/PROPELLER (Pipe, 1999; Pipe and Zwart, 2006), which was also implemented with a simultaneous parallel imaging reconstruction (Liu et al., 2005), can be used to mitigate motion artefacts. Another straightforward approach is the expedition of the measurement itself, explaining that most diffusion scans are performed using single-shot EPI. In addition, new techniques attempt to reduce overall scan time by introducing parallel imaging to the slice direction (Breuer et al., 2005; Setsompop et al., 2010). Others apply non-Nyquist-obeying radial acquisitions along with constraint reconstruction techniques (Alexander et al., 2006; Mistretta, 2009) or simultaneously refocused EPI sequences in conjunction with parallel imaging in slice direction (Feinberg et al., 2002, 2010). Although all these approaches attempt to reduce the likeliness or the impact of motion in diffusion MRI, they do not remedy its effects.

External devices have also been proposed to track and correct head motion (Forman et al., 2010; Qin et al., 2009; Zaitsev et al., 2006). Once set up, these techniques may provide very precise motion information up to the micrometre scale. They necessitate, however, elaborate experimental skills and a sophisticated setup. Landmarks, typically markers attached to the skin or bite bars, have to be applied to track the movements. This renders the clinical application of those techniques more difficult.

Furthermore, navigator data have been used to detect and correct for motion in diffusion imaging, in particular for segmented turbo spin-echo (de Crespigny et al., 1995; Dietrich et al., 2000; Ordidge et al., 1994) or interleaved EPI (Bammer et al., 2002; Butts et al., 1996, 1997; Nunes et al., 2005) diffusion acquisitions to reduce incoherencies between the segments. Navigator-based motion monitoring has also been implemented in real-time (Porter and Heidemann, 2009; Weih et al., 2004). A similar technique uses spiral trajectories to oversample k-space and gain information about motion and phase errors (Liu et al., 2004). Also, generic MRI motion navigator techniques as floating (Kadah et al., 2004), orbital (Fu et al., 1995), spherical (Welch et al., 2002), spiral (White et al., 2010) or cloverleaf (van der Kouwe et al., 2006) navigators can be employed for diffusion imaging. These techniques are however either restricted to 3D acquisitions or would increase the minimally achievable echo time considerably, which is both disadvantageous for diffusion imaging.

More recently, free induction decay (FID) navigators, which monitor the k-space centre without any spatial encoding, have gained interest. First employed for mitigating respiration- and system-induced B_0 shifts (Hu and Kim, 1994; Pfeuffer et al., 2002), they have also been employed for shimming (Splitthoff and Zaitsev, 2009). Brau and Brittain proposed to use the navigator's DC component to monitor chest motion for gating abdominal acquisitions (Brau and Brittain, 2006); we have previously utilised them to detect head motion in anatomical imaging (Kober et al., 2011).

This work aims at combining the properties of FID motion detection navigators with traditional image registration methods. Our goal was to establish an optimised diffusion acquisition scheme that detects motion, updates the gradient coordinate system in real-time to correct for the motion, and includes an automatic repetition of the motion-corrupted diffusion weighted volumes.

Theory

Coil arrays have become essential components of a modern clinical MRI scanner (Roemer et al., 1990). Ideally, they overcome the limited spatial sensitivity of a single local surface coil by surrounding the imaged object with an array of small coil elements to provide the superior SNR properties of surface coils. Due to a local coil element's steep spatial sensitivity profile, the received signal magnitude and phase may change significantly when the object's position is varied with respect to the coil. This property is exploited for head motion detection in the presented work. For a single-coil-element, the relationship between distance and signal strength can be calculated by means of the laws of electromagnetism. In a realistic in vivo experiment, however, various complicating factors (loading, head geometry, coil coupling and others) render an analytical approach unfeasible. Hence, our detection method is derived from experimental data.

In our experiments, we use a product 32-channel head coil array (based on (Wiggins et al., 2006)). The helmet design of this RF coil ensures close coverage of the subject's head and favours the detection of head movements as outlined above. During the course of the imaging sequence, a short period of free induction decay is repetitively sampled with every coil element after the RF excitation pulse preceding the diffusion-encoding. The placement before the diffusion-encoding ensures insensitivity to diffusion-related contrast changes. A real-time algorithm monitors the FID data over time, comparing the current FID's amplitude and phase with those of an earlier FID. Motion is detected if the FID signal change exceeds an empirical determined threshold. In the presented implementation, an additional imaging volume without diffusion encoding is inserted and registered to a reference volume to characterise the occurred motion. An optional procedure can subsequently be triggered to prospectively correct for the subject motion.

Materials and methods

Sequence modifications

The short FID readout was added after the slice re-winder of the first RF pulse in a twice-refocused spin echo diffusion-weighted EPI sequence (see Fig. 1). The number of acquired data points and the readout bandwidth of the FID navigator were matched to the settings of the imaging readouts, sampling 168 points with each TR and coil element (twice the matrix size, due to automatic oversampling in frequency direction).

To incorporate the additional FID readout, the readout pre-winder gradient pulses and the slice re-winder had to be separated. Consequently, the implementation resulted in a slightly increased echo time (TE) of approximately 1 ms compared to the product diffusion imaging sequence.

Motion detection algorithm and data flow

Incoming FID navigator data were processed using the real-time feedback framework of the scanner's image processing environment. Navigator data from the first volume were used to identify slices with less than 20% of the maximal measured slice energy, i.e. the absolute integral of the strongest coil element in a slice. This simple threshold