Journal of Neuroscience Methods 227 (2014) 83–89

Contents lists available at ScienceDirect

Journal of Neuroscience Methods

journal homepage: www.elsevier.com/locate/jneumeth

Basic Neuroscience

Reducing respiratory effect in motion correction for EPI images with sequential slice acquisition order

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HIGHLIGHTS

- We investigated the effect of respiration on motion correction of EPI images.
- Respiration introduces additional noise after motion correction for long TR.
- We proposed a new segmented motion correction for sequential acquisition order.
- The method works best for superior slices with performance comparable to RETROICOR.

ARTICLE INFO

Article history:
Received 24 September 2013
Received in revised form 10 February 2014
Accepted 11 February 2014

Keywords:
Motion correction
Respiratory noise
fMRI
EPI
Sequential acquisition

ABSTRACT

Motion correction is critical for data analysis of fMRI time series. Most motion correction algorithms treat the head as a rigid body. Respiration of the subject, however, can alter the static magnetic field in the head and result in motion-like slice shifts for echo planar imaging (EPI). The delay of acquisition between slices causes a phase difference in respiration so that the shifts vary with slice positions. To characterize the effect of respiration on motion correction, we acquired fast sampled fMRI data using multi-band EPI and then simulated different acquisition schemes. Our results indicated that respiration introduces additional noise after motion correction. The signal variation between volumes after motion correction increases when the effective TR increases from 675 ms to 2025 ms. This problem can be corrected if slices are acquired sequentially. For EPI with a sequential acquisition scheme, we propose to divide the image volumes into several segments so that slices within each segment are acquired close in time and then perform motion correction on these segments separately. We demonstrated that the temporal signal-to-noise ratio (TSNR) was increased when the motion correction was performed on the segments separately rather than on the whole image. This enhancement of TSNR was not evenly distributed across the segments and was not observed for interleaved acquisition. The level of increase was higher for superior slices. On superior slices the percentage of TSNR gain was comparable to that using image based retrospective correction for respiratory noise. Our results suggest that separate motion correction on segments is highly recommended for sequential acquisition schemes, at least for slices distal to the chest.

1. Introduction

A typical functional MRI (fMRI) dataset consists of many image volumes acquired sequentially in time. The outcome of the fMRI data analysis is greatly influenced by original image quality and data preprocessing. The data quality of fMRI is usually characterized by the temporal signal-to-noise-ratio (TSNR) before statistical analysis. There are many sources of noise in fMRI time series (Lund et al., 2006). Besides the thermal noise and hardware related signal fluctuations, physiological noise originating from cardiac pulsation, respiratory motion and neurovascular circulation contributes significant components to the noise spectrum. The physiological noise in fMRI data has been studied and characterized in great detail with many sophisticated methods available to reduce physiological noise in acquired fMRI data (Cheng and Li, 2010; Glover et al., 2000; Hu et al., 1995; Kruger and Glover, 2001; Lund et al., 2006).

As a physiological noise source, respiration can have a number of effects on fMRI time series. The characteristic frequency of respiratory noise is around 0.2–0.4 Hz, higher than Nyquist frequency of typical fMRI data sampling. The origin of respiratory noise is

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http://dx.doi.org/10.1016/j.jneumeth.2014.02.007
0165-0270/

believed to be a combination of fluctuations in susceptibility and oscillations in venous oxygenation (Raj et al., 2001; Windischberger et al., 2002). Recent prospective motion correction systems have shown physical head motion that correlates with respiration. Part of the respiratory motion artifact could be actual motion of the head due to respiration (Maclaren et al., 2013; Muraskin et al., 2013; Ooi et al., 2009). It has been shown that the low frequency functional connectivity in resting state fMRI has both a neuronal component and a respiratory-variation-related component (Birn et al., 2006). A model of bulk susceptibility effects due to air volume in the chest was proposed to characterize the respiratory-related effect, and consists of a shift of image profile (Raj et al., 2000, 2001), showing that the center of mass of the image at 1.5 T can vary by 0.2–0.4 mm due to respiration-related changes in susceptibility in the brain. The shift of center of mass of the image, mainly in the phase encoding direction, indicates a global effect of respiration on image intensity, namely a spurious motion effect in the image. The susceptibility effect is linearly dependent on the field strength of the static magnetic field. As many fMRI scans are typically conducted on scanners at 3.0 T or higher, the respiration-induced signal fluctuation becomes more severe. At 7.0 T, the respiration-induced off resonance can be as large as 7 Hz and is seen mainly in the inferior-superior direction (Van de Moortele et al., 2002). A method to reduce the respiration induced off-resonance effect during data acquisition and reconstruction by using the phase information of the center of k-space and a navigator at 7 T has been proposed (Pfeuffer et al., 2002), however, this technique is not widely available. If left uncorrected, this global respiratory effect can introduce temporal noise and produce potentially false fMRI activations. The shift of image profile is similar to a motion effect, and whether this effect can be corrected by data preprocessing, especially motion correction has not been fully investigated.

The one-shot gradient recalled Echo Planar Imaging (EPI) pulse sequence has been widely used in fMRI and acquires a full brain image with reasonable spatial resolution within seconds. Motion correction is extremely important and correcting signal fluctuations from head motion between scans is required even if the movement is in the sub-millimeter range. Although the respiration-related global shift has nothing to do with head motion, the resulting effect appears to look like head motion and should be corrected properly. For short repetition time (TR), e.g. with the multi-band EPI (Feinberg et al., 2010; Moeller et al., 2010), this spurious 'head' motion can be detected by the motion correction algorithm and be partially corrected. However, this could be a problem in regular fMRI scans which use relatively long TRs and an interleaved slice acquisition order. The slice acquisition order is typically interleaved to minimize cross-talk artifact between adjacent slices that could lower the TSNR. A typical TR to acquire a complete brain volume is typically 2–4 s, during which the respiratory phase can change significantly. In an interleaved acquisition, the neighboring slices are acquired at different times TR/2 apart, making their phases in respiration quite different. As a critical step in preprocessing the fMRI time series, most motion correction algorithms treat the head as a rigid body. If the neighboring slices are off-phase in respiration, even though the respiration produces considerable spurious motion on each slice, the net effect on the whole image is much smaller and therefore hard to correct.

In this study, we investigated the effect of respiration-induced apparent head motion on the overall image noise at different TRs, and explored the influence of interleaved and sequential slice acquisition order on this effect in two experiments. Compared with sequential acquisition, interleaved slice acquisition order produces less slice cross-talking artifact, but may create more spin history motion artifact. For some applications such as arterial spin labeling, only sequential acquisition order can be used. For sequential acquisition, nearby slices are naturally acquired close in time. This makes it possible to do motion correction on a series of segments of contiguous slices acquired within a small time window. We proposed a new motion correction method for EPI images with sequential acquisition, using a sliding window to select a series of contiguous slices called segments, and applying separate motion correction on each segment. The performance of the new method was compared with that using the conventional motion correction on whole volumes and those using image-based methods for retrospective correction of physiological motion effects (RETROICOR) (Glover et al., 2000) in terms of TSNR. The newly proposed method demonstrated a clear advantage on the superior slices in an oblique transverse acquisition sequence.

2. Methods

2.1. MRI scans

All the scans were performed on a 3 Tesla Siemens TIM Trio scanner using a 32-channel head coil (Siemens healthcare, Erlangen, Germany) at the Imaging Research Facility at Indiana University, Bloomington. All subjects provided written informed consent in a study approved by the Institutional Review Board at Indiana University.

2.1.1. Experiment 1

Six subjects (all female, age = 26.7 ± 2.1 years) were scanned at rest with eyes open and with spontaneous respiration using multi-band EPI (Moeller et al., 2010) in a single imaging run for a total of 590 volumes. The scan parameters were: image matrix = 64 × 64, TR/TE = 675/30 ms, 33 slices, SLT = 3.5 mm without gap, in-plane voxel resolution = 3.4 mm, multi-band acceleration factor = 3. All slices were acquired in oblique orientation approximately 30° with respect to the transverse plane.

2.1.2. Experiment 2

Eight subjects (two males, age = 26.4 ± 3.4 years) were scanned at rest with their eyes open and with spontaneous breathing for two runs of EPI with ascending and interleaved acquisition orders. A total of 150 image volumes were acquired for each run with the following scan parameters: image matrix = 64 × 64, TR/TE = 2500/30 ms, 33 slices, SLT = 3.4 mm without gap, in-plane voxel resolution = 3.4 mm. All slices were acquired in oblique orientation approximately 25° with respect to the transverse plane. The order of the two runs was randomly counterbalanced for the eight subjects. Respiratory data were recorded using a MRI-compatible pneumatic belt mounted on the subjects' abdomen, with a sampling rate of 50 Hz.

2.2. Simulation

The images obtained from Experiment 1 with TR 675 ms were used to simulate scans with an effective TR of 2025 ms. Two approaches were employed in the simulation. The first method extracted one third of the volumes by retaining only the first volume in every three sequentially acquired volumes (Fig. 1). We call the new dataset a 'skipped' fMRI time series. The second method combined every third slice from three consecutive volumes to synthesize a new image volume. The slices are combined in an interleaved fashion for the acquisition order, as illustrated in Fig. 1. We call the new dataset a 'composite' fMRI time series. The adjacent slices in the composite image were all acquired at different TR in the original time series.