NeuroImage 45 (2009) 749–757

Contents lists available at ScienceDirect

NeuroImage

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

Correction of 3D rigid body motion in fMRI time series by independent estimation of rotational and translational effects in k-space

Mauro Costagli [a,b,*], R. Allen Waggoner [a], Kenichi Ueno [c], Keiji Tanaka [a], Kang Cheng [a,c]

[a] *Laboratory for Cognitive Brain Mapping, RIKEN Brain Science Institute, Japan*
[b] *Laboratory of Clinical Biochemistry and Molecular Biology, University of Pisa, Italy*
[c] *Support Unit for Functional Magnetic Resonance Imaging, RIKEN Brain Science Institute, Japan*

ARTICLE INFO

Article history:
Received 28 August 2008
Revised 18 December 2008
Accepted 23 December 2008
Available online 14 January 2009

Keywords:
fMRI
head motion
3D registration
rotation correction
translational shift
Fourier transform
k-space
IERATIK

ABSTRACT

In functional magnetic resonance imaging (fMRI), even subvoxel motion dramatically corrupts the blood oxygenation level-dependent (BOLD) signal, invalidating the assumption that intensity variation in time is primarily due to neuronal activity. Thus, correction of the subject's head movements is a fundamental step to be performed prior to data analysis. Most motion correction techniques register a series of volumes assuming that rigid body motion, characterized by rotational and translational parameters, occurs. Unlike the most widely used applications for fMRI data processing, which correct motion in the image domain by numerically estimating rotational and translational components simultaneously, the algorithm presented here operates in a three-dimensional k-space, to decouple and correct rotations and translations independently, offering new ways and more flexible procedures to estimate the parameters of interest. We developed an implementation of this method in MATLAB, and tested it on both simulated and experimental data. Its performance was quantified in terms of square differences and center of mass stability across time. Our data show that the algorithm proposed here successfully corrects for rigid-body motion, and its employment in future fMRI studies is feasible and promising.

Introduction

In functional magnetic resonance imaging (fMRI), activated brain regions are detected by analyzing the time course of the images acquired on a voxel by voxel basis. The fundamental assumption in this kind of approach is that the time course of each voxel is primarily a function of physiological changes correlated with the presentation of a stimulus and/or performance of a task. Since even small movements introduce confounding voxel signal changes over time, the correction of the subject's head motion is a fundamental step to be performed prior to statistical analysis.

All the most widely used techniques employed in fMRI assume that all the motion in the data can be described by six parameters, three to define rotations and three for translations (rigid body motion assumption). One class of motion detection techniques proposes to acquire additional "navigator" echoes at every volume acquisition, which provide information for estimating rotational and translational movements. The first method that proposed navigator echoes for motion detection was presented in the late 1980s for the correction of translational displacements (Ehman and Felmlee, 1989), and was eventually followed by more sophisticated techniques, namely orbital navigator echos (ONAV) (Fu et al., 1995) and spherical navigator echoes (SNAV) (Welch et al., 2002), which account for rotation effects as well. The estimated parameters describing rotations and translations can be used to correct motion either prospectively, by adjusting the scanner parameters in real time and let the imaging coordinate system follow the moving subject (Ward et al., 2000), or retrospectively, as an additional post-processing step. Currently, retrospective techniques appear to be more suitable for the registration of fMRI time series. They are performed offline after data acquisition, can take into account the wealth of information contained in the whole scanned volumes, and do not require the acquisition of navigator echoes. The motion correction algorithms typically used in fMRI, such as AIR (Woods et al., 1992, 1998), and the registration tools in SPM (Friston et al., 1994), AFNI (Cox, 1996), Brain Voyager (Brain Innovations, Maastricht, The Netherlands) and FSL (Smith et al., 2004), operate in image-space by minimizing the square difference between volumes. The performance of such registration tools has been reviewed and compared in the literature, but no single algorithm emerged as the optimal one (Oakes et al., 2005). A common drawback of image-space methods is the necessity of estimating at least six parameters all at once, with considerable risk of locking to a local minimum of the cost function. To overcome this problem, the algorithm DART (Maas et al., 1997), devised for correcting in-plane movements only, was proposed to estimate motion in k-space, separating the effects of rotations and translations by exploiting the

* Corresponding author. Laboratory for Cognitive Brain Mapping, RIKEN Brain Science Institute, 2-1 Hirosawa, Wakoshi, Saitama 351-0198, Japan. Fax: +81 48 462 4651.
E-mail address: mauro@brain.riken.jp (M. Costagli).

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doi:10.1016/j.neuroimage.2008.12.067

properties of the Fourier theory. Even though this technique has been used in several fMRI studies targeting a limited number of slices (as is typical in high-resolution experiments, in which it is reasonable to correct only in-plane motion, due to the lack of data in the third spatial dimension), it is not suitable for whole brain studies, where there is sufficient data to make 3D motion correction feasible.

In this work, we propose a retrospective method that addresses 3D rigid body motion by independently estimating rotational and translational effects in the Fourier domain, therefore halving the number of parameters that, in the case of image-space based techniques, must be calculated simultaneously. In the following sections we will briefly review the theoretical framework of motion correction in k-space, then describe the details of our implementation, and finally report the results obtained on both simulations and actual echo planar imaging (EPI) time series.

Methods

Evaluating 3D-rigid body motion requires the estimation of six parameters: three for the rotational effect, and three for translations. In fMRI studies, the brain is contained in a 3D-volume consisting of stacked 2D magnitude images, each representing a brain slice, and obtained by taking the magnitude of the Fourier transform of an EPI acquisition. In order to avoid any ambiguity, magnitude data representing the brain volumes is referred to as “data in the image domain” throughout this article, while complex data obtained by applying the 3D fast Fourier transform (3D-FFT) to the volumes are referred to as “data in the spatial frequency domain” or k-space. Thus, the k-space referred here is not equivalent to the stacked 2D k-space data obtained by EPI acquisitions.

Theoretical background: rigid body motion in 2D k-space

The principles for detecting 3D rigid body motion in k-space can be thought of as an extension of the basic concepts exploited by the in-plane registration algorithm DART (Maas et al., 1997). Here we present an example in two dimensions, in order to introduce the basics that will be eventually extend to the 3D case in the following section.

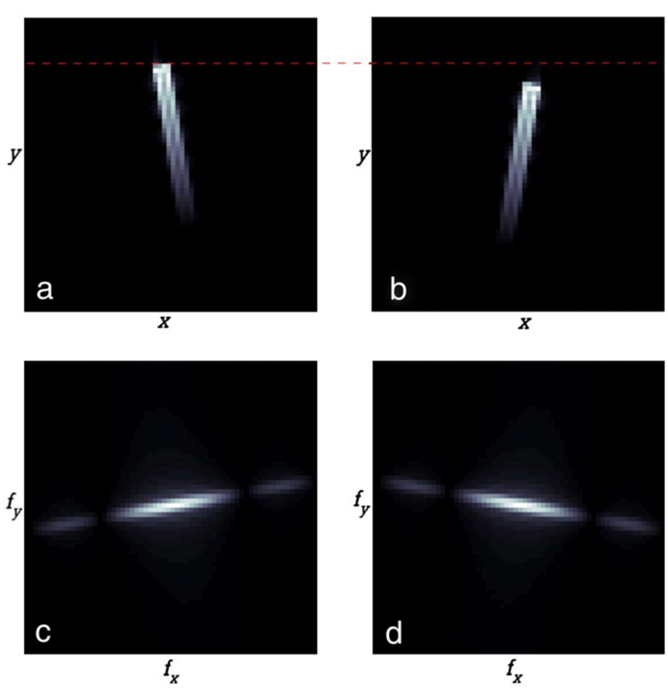

Fig. 1. *Rotations in 2D*. The reference image and a test image affected by rigid body motion are displayed in a and b, respectively. To emphasize the presence of a translational effect between the two images, a red dotted line is superimposed to the two panels. The k-space magnitude data of the two images are represented in c and d, which differ solely by a rotational effect (through the same angle and in the same sense) about the origin of the spatial frequency axes.

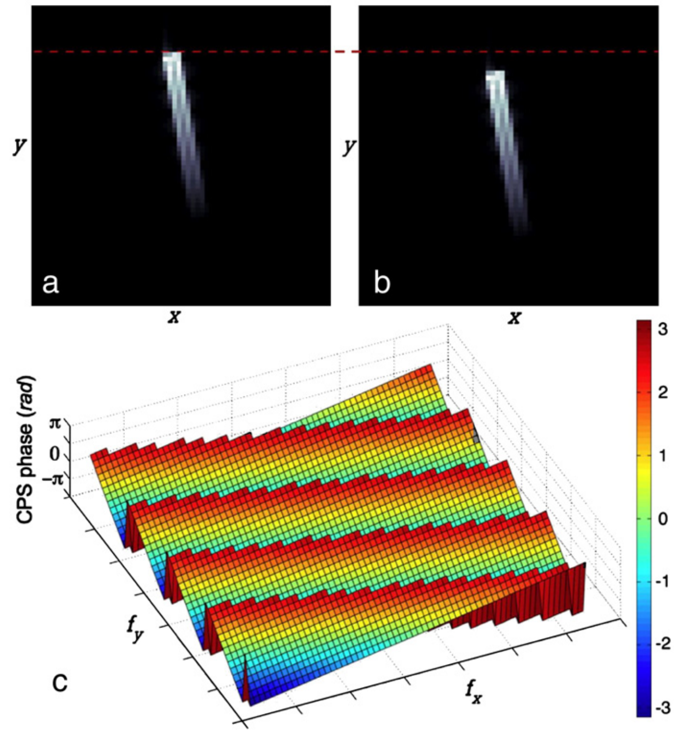

Fig. 2. *Translations in 2D*. After rotation correction, two images affected by rigid body motion differ only by a linear shift. With respect to the reference image (a), the image displayed in b is affected by a 1-pixel translation in the *x* direction, and by a 4-pixel translation in the *y* direction (the shift along the *y* axis is emphasized by the presence of the red broken line). The phase of the Cross-Power-Spectrum of the reference and the translated image is shown in c. In this example, the tilted plane shape of the phase is clearly visible (phase jumps of 2π occur when translations are greater than one voxel).

Given an image affected by rigid motion, our goal is to estimate the rotation angle θ and the shifts s_1 and s_2 along x and y axes, respectively. According to the well-known properties of Fourier's theory (Bracewell, 2000), if an image is rotated and translated from an original image, then the magnitude of its Fourier transform is rotated by the same angle about the origin of the spatial frequency axes, while translations affect exclusively the phase. Therefore, rotations can be estimated independently from translation effects, by analyzing magnitudes of the k-spaces to be aligned, as illustrated in Fig. 1.

Once rotation has been estimated and its effects removed, the two images are assumed to differ only by translational effects. By exploiting the shift theorem of the Fourier transform, which asserts that a translation along any spatial axis introduces a linear phase change along the respective frequency axis, translations in image-space can be addressed by considering the phase of the cross-power spectrum (*CPS*) of the two images to be aligned (Kuglin and Hines, 1975), as conceptually shown in Fig. 2. If we denote the original image by $a(x, y)$ and its Fourier transform $A(f_x, f_y)$, then its shifted version $a_s = a(x - s_1, y - s_2)$ has a Fourier transform represented by $A_s(f_x, f_y) = A(f_x. f_y) \cdot \exp[-j(s_1 f_x + s_2 f_y)]$, where s_1 and s_2 are the shifts along the two axes. It follows that the phase of the CPS can be represented as:

$$\angle\left\{\left(A(f_x, f_y)\right) \cdot \left(A_s(f_x, f_y)\right)^*\right\} = \angle\left\{\left|A(f_x, f_y)\right|^2 \cdot \exp\left[j(s_1 f_x + s_2 f_y)\right]\right\} = s_1 f_x + s_2 f_y,$$

which corresponds to an equation describing a plane. The shift parameters s_1 and s_2 can thus be evaluated by estimating the plane