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Signal fluctuations in fMRI data acquired with 2D-EPI and 3D-EPI at 7 Tesla

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Abstract

Segmented three-dimensional echo planar imaging (3D-EPI) provides higher image signal-to-noise ratio (SNR) than standard single-shot two-dimensional echo planar imaging (2D-EPI), but is more sensitive to physiological noise. The aim of this study was to compare physiological noise removal efficiency in single-shot 2D-EPI and segmented 3D-EPI acquired at 7 Tesla. Two approaches were investigated based either on physiological regressors (PR) derived from cardiac and respiratory phases, or on principal component analysis (PCA) using additional resting-state data. Results show that, prior to physiological noise removal, 2D-EPI data had higher temporal SNR (tSNR), while spatial SNR was higher in 3D-EPI. Blood oxygen level dependent (BOLD) sensitivity was similar for both methods. The PR-based approach allowed characterization of relative contributions from different noise sources, confirming significant increases in physiological noise from 2D to 3D prior to correction. Both physiological noise removal approaches produced significant increases in tSNR and BOLD sensitivity, and these increases were larger for 3D-EPI, resulting in higher BOLD sensitivity in the 3D-EPI than in the 2D-EPI data. The PCA-based approach was the most effective correction method, yielding higher tSNR values for 3D-EPI than for 2D-EPI postcorrection.

Keywords: Signal fluctuations; Physiological noise; Segmented 3D-EPI; BOLD fMRI; Ultra-high field

1. Introduction

High-field magnetic resonance imaging (MRI) provides considerable improvements in image signal-to-noise ratio (SNR) [1], potentially allowing for higher sensitivity and spatial resolution in blood oxygen level dependent (BOLD) functional MRI (fMRI). However, the increase of noise from non-thermal sources, including physiological processes as well as spontaneous neural activity and subject motion, imposes an asymptotic limit on the achievable temporal SNR (tSNR) [2–4]. Great effort has therefore been dedicated to the characterization and correction of physiological noise [5–11]. Several types of physiological signal fluctuations have been identified: (a) quasi-periodic signal oscillations due to the pulsatility of blood flow in the brain and magnetic field changes induced by respiratory motion [5]; (b) nonperiodic fluctuations due to low-frequency drifts in end-tidal CO_2 (a potent vasodilator), caused by subtle, naturally occurring changes in breathing rate and depth [6]; (c) nonperiodic fluctuations due to cross-beat changes in heart rate (affecting cerebral hemodynamics, namely, oxyhemoglobin concentration), which may occur in several frequency bands [7].

Besides the field strength, B_0, the noise characteristics of fMRI can be affected by imaging parameters such as the echo time (TE), the flip angle [4], the voxel volume [12] or the imaging sequence.

Commonly used two-dimensional echo planar imaging (2D-EPI) techniques tend to present increasingly longer single volume acquisition times at higher fields, as a result of the possibility of achieving higher spatial resolution. This is further encouraged by studies showing that physiological noise contributions can be minimized by reducing voxel size [13]. Furthermore, thinner slices have the advantage of reduced signal loss due to through-slice dephasing, but result in higher numbers of slices per volume for adequate coverage. Segmented three-dimensional EPI (3D-EPI) has recently been

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proposed as a promising technique for high-resolution fMRI at ultra-high fields, in which one *k*-space plane is acquired after each excitation pulse [14]. When optimizing the signal using the Ernst angle, 3D-EPI offers superior image SNR relative to standard 2D-EPI due to the whole-volume radio-frequency (RF) excitations [14], which can be traded for higher spatial resolution and offer lower specific absorption rate (SAR) levels due to the smaller optimal flip angle [15]. More importantly, it allows parallel imaging acceleration in two spatial dimensions, significantly reducing total volume acquisition times. In 2D-EPI, acceleration in the slice-encoding direction can be achieved either by time multiplexing, in which case signals from different slices are refocused at different times within an EPI echo train [16], or by multislice simultaneous excitation, in which case the different slices are separated thanks to the varying coil profiles [17,18]. The first method has a penalty in terms of increased distortion artifacts (arising from the longer echo train needed), and as both methods rely on the excitation of an increased number of slices per unit of time, they have an SAR penalty that can make their use prohibitive at high field strengths. Despite the 3D-EPI advantages in terms of spatial SNR (sSNR), physiological noise contributions appear to increase in functional data, thus compromising potential tSNR increases [14,15,19]. This disadvantage becomes more important at ultra-high fields, given the above-mentioned dependence of physiological noise contributions on B_0 [2–4]. Several physiological noise removal strategies have been developed. One group relies on inclusion of physiological information in the general linear model (GLM), depending on assumptions regarding the influence of physiological processes on BOLD signals and requiring physiological data acquisition simultaneously with fMRI [5–7,9]. These methods are applicable to resting-state data as well as task-driven fMRI, and allow the characterization of physiological signal contributions. All three physiological noise components mentioned in the first paragraph can be separately modeled and removed with this methodology. Another powerful approach for task-driven fMRI involves the identification of physiological signal fluctuations with the aid of a separately acquired resting-state data set [10]. Here, all correlated signal fluctuations unrelated to the external stimulus are addressed simultaneously, including spontaneous signal fluctuations.

The present work aims to compare physiological noise characteristics in standard 2D-EPI and 3D-EPI data, acquired at 7 Tesla, and test physiological noise correction methods for BOLD fMRI. A physiological regressor (PR)-based approach [9] and a principal component analysis (PCA)-based approach [10] were applied to both data types.

2. Materials and methods

2.1. Data acquisition

Ten healthy subjects (aged 26±4 years, four males, six females) were studied, with approval from the institutional review board of the local ethics committee, and provided written informed consent. One subject was excluded from PR-based analyses due to corrupted physiological recordings, and a second subject was excluded from both PR-based and PCA-based analyses due to a lack of significant activation in 2D data.

Each subject underwent four fMRI runs, counterbalanced across subjects: rest with eyes closed (*Rest*), visual localizer paradigm (*Loc*) acquired with a 2D-EPI or a 3D-EPI sequence. The localizer paradigm consisted of the visual presentation of faces (*F*), houses (*H*), objects (*O*) and scrambled objects (*S*), separated by fixation periods, in a block design of 18s blocks [20,21].

MRI data were acquired using a 7 Tesla/680-mm scanner (Siemens Medical Solutions, Erlangen, Germany), with an eight-channel head array coil (RAPID Biomedical GmbH, Germany). For each fMRI run, 112 volumes were acquired from a region covering the primary and ventral visual cortex. Multislice single-shot 2D-EPI volumes consisted of 40 interleaved 2mm thick slices with a volume acquisition time of 3.2s (TR_{2D}/α_{2D}=3200ms/63°–65°). In segmented 3D-EPI, a seven-lobe *sinc* pulse was used to obtain a good slab selection profile; 40 *k*-space planes were sequentially encoded, with a single *k*-space segment measured after each RF excitation, followed by application of a crusher gradient, with a volume acquisition time of 3.2s (TR_{3D}/α_{3D}=80ms/18°). Although spurious echo formation is not a problem at TR=80ms [15], RF spoiling was also applied to avoid instability of the transverse steady-state magnetization [19]. The TE (25ms), parallel imaging acceleration factor (GeneRalized Autocalibrating Partially Parallel Acquisitions (GRAPPA)=2 for the in-plane phase-encoding direction), matrix size (104×104), field of view (210×210mm^2) and resolution (2mm isotropic) were kept the same for both techniques.

Whole-brain structural images for anatomical reference were acquired using the MP2RAGE sequence, a modified magnetization-prepared rapid gradient-echo (MPRAGE) sequence that generates two image sets at different inversion times for bias field compensation [22], with 1×1×1mm^3 spatial resolution. Single-volume whole-brain 2D-EPI images (104×104×80 voxels, 2×2×2mm^3 spatial resolution, TE=25ms, α_{2D}=65°) were acquired to aid spatial co-registration, providing more coverage and thus anatomical landmarks than the fMRI data sets.

Respiratory amplitude and pulse oximetry levels were recorded at a 50Hz sampling rate simultaneously with the fMRI acquisition, utilizing the respiratory belt and pulse oximeter provided with the MRI scanner.

2.2. MRI data analysis

Data analysis was performed with the FMRIB Software Library (FSL 4.1.2, http://www.fmrib.ox.ac.uk/fsl) and routines implemented in Matlab for the optimization steps (http://www.mathworks.com). Following a set of common preprocessing steps, two analysis approaches were employed for physiological noise characterization and correction: a PR-based [9] and a PCA-based [10] approach.