Magnetic Resonance Imaging 55 (2019) 81–85

Contents lists available at ScienceDirect

Magnetic Resonance Imaging

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

Original contribution

Accelerated silent echo-planar imaging

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ARTICLE INFO

Keywords:
EPI
Parallel imaging
Non-Cartesian
Iterative reconstruction
Acoustic noise
Interlaced FT

ABSTRACT

Purpose: The standard approach to Echo-Planar Imaging (EPI) is to use trapezoidal readout (RO) gradients with blipped phase-encoding (PE) gradients. Sinusoidal RO gradients with constant PE gradients can reduce acoustic noise. However, this sequence, originally introduced by Mansfield et al., constitutes major challenges for Cartesian parallel imaging techniques. In this study two alternatives to reconstruct a non-blipped EPI are proposed and evaluated.

Theory and methods: The first method separates the acquired k-space data into odd and even echoes and applies Cartesian GRAPPA separately to each partial data set. Afterwards, the resulting reconstructed data sets for each echo are summed in image space. In the second method, an iterative parallel-imaging algorithm is used to reconstruct images from the highly non-Cartesian data samples.

Results: Compared to blipped-EPI, the first method reduces image SNR depending on the acceleration factor between 11% and 60%. For an acceleration factor of 3 folding artefacts appear. The second method produces slight fold-over artefacts although image SNR is on the same level as the blipped approach.

Conclusion: In this study, we have introduced two new approaches to EPI that allow the use of Cartesian parallel imaging in conjunction with continuous data sampling. In addition to providing a reduction in acoustic noise compared to the standard blipped PE EPI sequence, the proposed techniques improve sampling efficiency, resulting in a reduction of the echo-spacing. Of the two methods, the second approach, based on an iterative image reconstruction, provides higher SNR, but requires a longer reconstruction time.

1. Introduction

Since its introduction by Mansfield in 1977, the original echo-planar imaging (EPI) sequence [1] has been adapted to improve image quality and to make use of advanced gradient systems. Its high imaging speed makes it a core methodology for providing high temporal resolution in functional magnetic resonance imaging (fMRI) [2] and for reducing motion-induced image artefacts in diffusion magnetic resonance imaging (dMRI) [3]. The drawback of EPI is a high level of acoustic noise during the examinations of up to 138 dB [4]. Although in a typical setting values of around 100 dB are more common [5]. This noise level is a discomfort to the subject being scanned and can be a severe disruption to fMRI studies, because it impedes communication with the subject; it also contributes a high level of auditory stimulation, which is especially problematic for studies of the auditory system itself [6]. Beside the auditory system, the visual and motor systems can also be influenced by acoustic noise [7].

Several procedures to reducing acoustic noise during fMRI examinations have been proposed, which range from hardware modifications [8–10] and gradient waveform modifications [11–15] to special sampling strategies [16–18]. Today, it is standard practice to perform EPI using trapezoidal readout (RO) gradients and blipped phase-encoding (PE) gradients. Although this is technically convenient on modern scanners, acoustic noise can be reduced by going back to the original form of the EPI sequence introduced by Mansfield; this uses a sinusoidal RO gradient that has a narrow frequency band that allows acoustic resonance frequencies of the gradient system to be effectively avoided [14]. When combined with blipped phase-encoding (PE) gradients, the sinusoidal gradient waveform can be used with Cartesian parallel imaging techniques [15]. This results in a noise reduction of up to 11 dB compared to standard EPI with blipped PE gradients and a trapezoidal RO gradient waveform. However, it has also been shown that blipped PE gradients make a significant contribution to acoustic noise [15].

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https://doi.org/10.1016/j.mri.2018.09.016
Received 4 May 2018; Received in revised form 13 September 2018; Accepted 16 September 2018

Indeed, the quietest EPI sequence is the original one introduced by Mansfield [1] with a constant PE gradient and a noise reduction of 20 dB compared to the standard EPI with blipped phase encoding [14]. However, a straightforward, two dimensional fast Fourier transform (2D-FFT) cannot be used with this data sampling scheme due to the non-Cartesian zigzag-style trajectory. To process data acquired in this way, a different reconstruction procedure, the interlaced Fourier transform (iFT), was introduced by Sekihara in 1987 [19]. It was already shown by Schmitter et al. [14] that this sequence reconstructed with the iFT has a beneficial effect upon fMRI studies. This was more extensively investigated by Pelle et al. [20] who showed that in all areas except for the frontal ones the quiet EPI sequence with a sinusoidal RO and a constant PE gradient is superior to the standard trapezoidal one. Although, as mentioned in this paper, no Cartesian parallel imaging techniques could be applied due to the non-Cartesian trajectory. As a result of the longer RO train, compared to the standard trapezoidal EPI sequence, a significant signal dropout in the frontal areas occurs along with a lower activation level.

In a first approach, we use a slightly modified version of the original EPI sequence by Mansfield to achieve a pure zigzag trajectory without deviations. This makes it possible to apply Cartesian parallel imaging methods by processing odd and even echoes separately. In a second approach, we use the original EPI sequence with a constant PE gradient in combination with non-Cartesian iterative parallel imaging methods, such as ESPIRiT [21]. We also show that we can reconstruct this non-Cartesian trajectory with Cartesian parallel imaging methods. Finally, we compare these two types of reconstruction methods to the iFT.

2. Methods

2.1. Sequence timing

In EPI with blipped PE and sinusoidal RO gradients (see Fig. 1A), the resulting k-space trajectory shows equidistant sampling along the PE direction, but non-equidistant sampling along the RO direction. In this case, a simple one-dimensional regridding of the data is sufficient to align them onto a Cartesian grid. When the blipped PE is replaced by a constant PE gradient, as proposed originally, the resulting k-space trajectory is a sinusoidal zigzag (see Fig. 1B). A true zigzag trajectory without deviations can be realized by using a variable low amplitude gradient waveform that is the modulus of the RO gradient. This sequence is called Zigzag-Aligned-Projections (ZAP) PE EPI [22] (see Fig. 1C). Both of these methods can be combined with either a trapezoidal or sinusoidal RO gradient. However, in this work, only the sinusoidal case is considered.

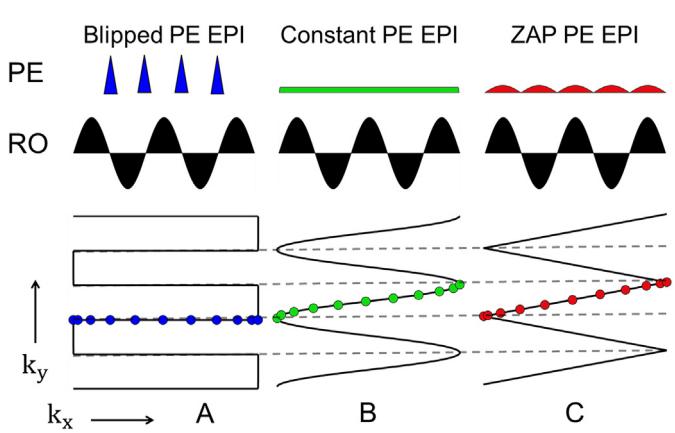

Fig. 1. Sinusoidal EPI with (A) blipped PE, (B) constant PE and (C) ZAP PE. Note, that there is non-equidistant sampling along the RO direction in all three cases.

2.2. Image reconstruction

For the reconstruction of data acquired with zigzag trajectories (constant PE and ZAP PE EPI), some of the standard EPI reconstruction steps can be applied: these include phase correction for the temporal misalignment of odd and even echoes and standard 1D-Kaiser-Bessel-regridding along the RO direction for sinusoidal RO gradients [23]. These steps were performed within the manufacturer's proprietary image calculation environment (ICE, Siemens Healthcare, Erlangen, Germany). However, due to the non-Cartesian nature of these data in two dimensions, it is not possible to use well established Cartesian parallel imaging methods, such as Sensitivity Encoding (SENSE) [24] or Generalized Autocalibrating Partially Parallel Acquisitions (GRAPPA) [25]. This paper is focused on the GRAPPA technique, but the general concepts can be applied to other parallel imaging approaches. To overcome this limitation, the zigzag-sampled data in this study were reconstructed using three alternative approaches: (1) an interlaced Fourier Transform (iFT) algorithm [19], (2) a modified Cartesian GRAPPA procedure, and (3) an iterative reconstruction method using the ESPIRiT method [21]. All approaches were implemented offline in MATLAB (The Mathworks, Natick, MA, USA). The ESPIRiT technique was applied using version 0.4.01 of the BART reconstruction toolbox [26].

2.3. Interlaced Fourier transform

For our implementation of the iFT [19], we use an improved method as described in [27]. Interlacing is performed in the phase-encoding direction using two data sets derived from the odd and even echoes respectively. The trajectories for the odd and even echoes are shifted in the PE direction relative to each other. This means that for a given data column along the PE direction, considering all acquired data for both odd and even echoes, there are two sampling step sizes. One step size fulfills the Nyquist sampling criterion and one does not. According to the general sampling theorem by Papoulis [28], it is possible to reconstruct alias-free images even if the Nyquist criterion is not fulfilled everywhere in k-space, as long as the Nyquist criterion is fulfilled on average. This is the case for the zigzag trajectory, except for the data points at the edges. Due to this, 18% of the data in the RO direction at the edges are skipped and the remaining 82% are used for image reconstruction. This is equivalent to the sampling window used in the standard blipped EPI case. Therefore no difference between constant PE EPI and blipped PE EPI exists concerning the sampling window.

2.4. Reconstruction using modified GRAPPA

After acquisition, the k-space data for odd and even echoes are separated. Cartesian GRAPPA reconstruction is applied to each of the separated k-space data sets resulting in two complete data sets with Nyquist sampling, thereby not affected by aliasing (shown in Fig. 2). The separated data sets have a reduction factor that is twice as large as the acceleration factor. However, only the g-factor induced losses are higher compared to standard blipped PE EPI and Cartesian GRAPPA reconstruction. The resulting two k-space trajectories have opposite slopes, which would result in two images that are tilted with respect to each other. This is corrected by regridding the separated data sets onto a Cartesian grid using Kaiser-Bessel gridding with a kernel width of four. The resulting two magnitude images are summed in image space. Alternatively one could correct the shearing by a linear phase correction according to the Fourier Shift Theorem.

It should be noted that this approach is strictly speaking only valid for ZAP PE EPI. In constant PE EPI there are sinusoidal deviations from a perfect zigzag trajectory (compare Fig. 1). However, these deviations are in general very small and therefore this modified GRAPPA approach can also be applied to constant PE EPI and not only to ZAP PE EPI.

For GRAPPA, the acquisition of a small subset of Nyquist-sampled,