Impact of frequency drifts during PROPELLER-EPI measurements

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Introduction

Mechanical vibrations during *echo planar imaging* (EPI) sequences can cause temperature increase in the gradient system of the scanner [1]. Due to the heating of the shim elements a significant shift of the resonance frequency can occur over time. With Cartesian EPI sequences images acquired at the end of a measurement session are typically shifted in phase encoding direction, whereat the shift can reach up to several millimeters for extended *functional magnetic resonance imaging* (fMRI) scans. With *periodically rotated overlapping parallel lines with enhanced reconstruction – echo planar imaging* (PROPELLER-EPI) [2] the phase encoding direction of each blade changes with each blade acquisition, resulting in shifts of single blade images in different directions. If these individual blades are combined the resulting image will exhibit strong blurring which becomes especially severe with higher spatial resolutions. In this work we characterize the impact of frequency drifts on long PROPELLER-EPI measurements and discuss different solutions for measurement and compensation of frequency drifts.

Methods

With PROPELLER-EPI only narrow blades oriented around the center of *k*-space are measured with each RF excitation. The blades are subsequently rotated until the entire *k*-space has been covered. A sequence which uses *N* blades to fill *k*-space thus uses *N* different phase encoding directions. In the presence of frequency shifts the low resolution image of each blade is shifted in different directions, i.e., the phase encoding direction of the individual blade. To demonstrate this effect a time series of PROPELLER-EPI images was obtained *in-vivo* with settings suitable for performing high resolution fMRI experiments: 320×320 matrix size, 220 mm^2 FOV, 2.5 mm slice thickness, 140 kHz acquisition bandwidth, *N*=10 blades, 60 sets of *N* blades, 1000 ms TR, 36 ms TE and 2× GRAPPA acceleration. To correct geometric distortions a multi frequency reconstruction [3] was used on the blade level based on high resolution field maps acquired for each blade. The images for the time series were reconstructed using a sliding-window reconstruction, yielding 591 images with a 1× TR interval. Images were acquired on a Siemens 3T Magnetom Trio with an acquisition time for all images of 10 min.

Compensation of occurring frequency shifts $\Delta\omega(t)$ is possible on a blade level by adding a corresponding linear phase gradient oriented along the phase encoding direction of the *k*-space data $S(k_x, k_y, t)$

$$S'(k_x,k_y,t) = S(k_x,k_y,t)\cdot e^{\frac{-ik_y\cdot\Delta\omega(t)\cdot T}{\Delta k_y}} .$$

T is the time between the acquisition of two consecutive *k*-space lines and $\Delta\omega(t)$ describes the time dependent frequency shift. To estimate the frequency shifts several approaches are conceivable. Before and immediately after the measurement series a calibration scan, which only measures a FID, can be performed to determine the resonance frequency. Alternatively, the shifts can be directly calculated on the blade level by using the data from the central *k*-space line [4] or by performing a center of mass analysis in image space. Another possibility is spatial registration of a complete blade set in image space [2]. By using gradient echo readout it is also possible to observe the frequency shift $\Delta\omega(t)$ as a phase offset $\Delta\phi(t)$ in the image phase:

$$\Delta\omega(t) = \frac{\Delta\phi(t)}{TE} \quad \text{and} \quad \Delta B_0(t) = \frac{\Delta\phi(t)}{\gamma\cdot TE} .$$

To evaluate the effects of possible frequency drifts we visually compared the first and last reconstructed image of the time series. In order to estimate the strength of the shift the low resolution images of blades with the same orientation were analyzed. For simplicity we chose to analyze the image phase in order to extract $\Delta\omega(t)$. To demonstrate the effect of frequency drifts on PROPELLER-EPI images we also reconstructed images with artificial shifts of 1.5×$\Delta\omega$ and 2×$\Delta\omega$ added to the data.

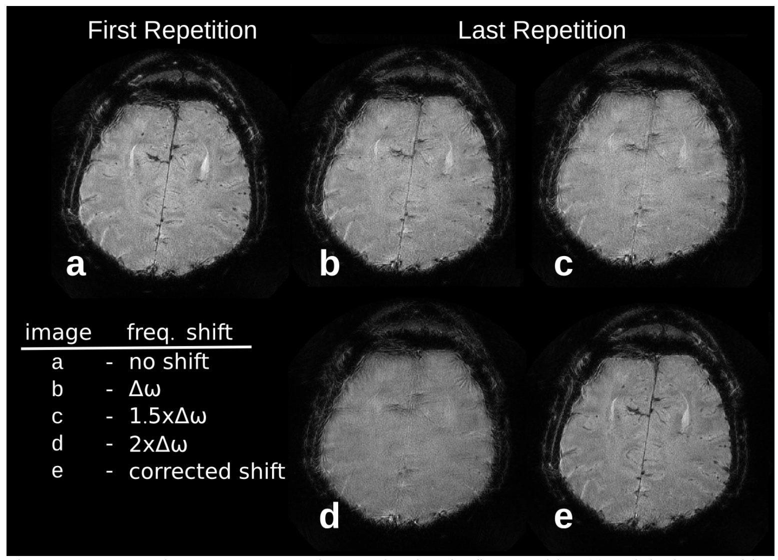

Fig. 1. Reconstructed PROPELLER-EPI images showing the first repetition (a) and the last repetition with the measured frequency shift $\Delta\omega$=44 Hz (b), artificial shifts of 1.5×$\Delta\omega$ (c) and 2×$\Delta\omega$ (d), as well as the corrected image for the last repetition (e).

Results

Over a total measurement time of 10 min a frequency drift $\Delta\omega$ of 44 Hz was observed. This shift caused significant blurring of the high resolution PROPELLER-EPI image (Fig. 1b). Even though some image details are still recognizable, a slightly stronger shift of 1.5×$\Delta\omega$ already removes most of the image structures (Fig. 1c). With a frequency shift of 2×$\Delta\omega$ blurring becomes so severe that no structures are distinguishable anymore (Fig. 1d). If however the frequency shift is known images can be easily corrected, yielding images free of any blurring (Fig. 1e).

Discussion

Our work demonstrates the importance of correcting frequency drifts that may occur during extended PROPELLER-EPI measurements. It is conceivable that such a correction also applies to other applications of PROPELLER-EPI, e.g., long lasting and hardware demanding diffusion weighted sequences. Which correction method should be used depends on sequence parameters, total scan duration and the particular imaging application. For high resolution studies and shorter measurement times the simplest approach of a center of mass analysis will give insufficient results for proper correction since a center of mass analysis is sensitive towards signal fluctuations and subject motion. We have also observed in other experiments that spatial registration can be too imprecise for high resolution imaging or for images which suffer from strong geometric distortions. For measurements with durations short enough so that the frequency drift $\Delta\omega(t)$ can be approximated by a linear model, a simple calibration scan before and after the measurement appears to represent the best choice. Performing a calibration scan directly before starting the actual measurement, but after having acquired all template scans (e.g., phase maps, GRAPPA weights, field maps) also ensures that any additional shift in the resonance frequency occurring after the initial frequency adjustment of the scanner can be detected.

References [1] Foerster BU et al., MRM, 2005, [2] Wang FN et al., MRM 2005, [3] Man LC et al., MRM 1997, [4] Durand E et al., MRM 2001