Navigator-Free Dynamic Phase Correction for Echo-Planar Imaging Based Functional MRI

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INTRODUCTION

In dynamic echo-planar imaging (EPI), such as functional MRI, where a time series of EPI images are collected, there is additional modulation along echo readout due to changes in hardware states (e.g., temperature) that the standard reference scan based phase correction methods [1-3] cannot account for, thereby resulting in an increase of ghost level over time. To address this problem, non-phase-encoded navigator echoes can be collected at each temporal frame to calibrate the additional modulation between odd and even echoes [4]. The per-temporal-frame modulation is then corrected in image reconstruction in addition to the static modulation measured from the reference scan. However, the navigator-based method assumes that the additional modulation that the center echoes (corresponding to echoes covering the center of the *k*-space) experience is the same as that predicted by the first few navigator echoes. When this assumption is not true (e.g., when there is additional modulation building up across the echo train), the modulation of the center echoes would not be well corrected, thereby still leading to significant ghost drift. We propose a new, navigator-free method to use scan data itself for estimating the additional per-temporal-frame modulation. This method can estimate the modulation more faithfully than the navigator-based method, thus significantly reduced ghost drift.

PROPOSED METHOD

The phase $\theta(n,t)$ of the *k*-space data at time *t* after taking a Fourier transform along the readout can be written as:

$$\theta(n,t) = \theta_{PE}(n) + (-1)^n \theta_{static} + (-1)^n \theta_{dynamic}(t), \quad (1)$$

where *n* denotes the phase encoding index, $\theta_{PE}(n)$ is the phase term due to phase encoding (independent of time), θ_{static} is the static phase modulation that exists in all temporal frames, $\theta_{dynamic}(t)$ is the phase due to the additional per-temporal-frame modulation, and $(-1)^n$ is due to time reversal of every other echo in EPI.

To estimate $\theta_{dynamic}(t)$ from imaging data itself, the data of time *t* is first normalized over the data of the first temporal frame (i.e., time 0). Specifically, magnitude of the two data frames are multiplied before being square rooted and the phase of the first frame is subtracted from the current frame. This operation removes the $\theta_{PE}(n)$ term in Eq. (1) from the imaging data. The θ_{static} term can be removed from the standard EPI reference scan. The phase of the resulting data contains only the $\theta_{dynamic}(t)$ term. We then polynomial fit (weighted by the magnitude data) $\theta_{dynamic}$ to obtain three coefficients, a constant coefficient and a linear coefficient along the readout direction and a B_0 coefficient (linear ramp) along the phase encoding direction. These coefficients, in addition to the static phase correction coefficients, are applied to the imaging data to remove Nyquist ghost in image reconstruction.

RESULTS

Static phase correction, dynamic phase correction with navigators (several non-phase-encoded echoes at the beginning of the echo train), and the proposed navigator-free dynamic phase correction methods are compared using gradient-echo based dynamic EPI data from a spherical phantom. The scan time was 6 min 40 s.

In Fig. 1, the differences in ghost appearance between first and last temporal frames reconstructed by the three phase correction methods are compared. The static phase correction method produces very significant ghost drift (indicated by the red arrow), which is reduced by the navigator-based dynamic phase correction. However, compared to a), noticeable ghost drift (indicated by the green arrow) still exists in c). The proposed method generates negligible ghost drift as indicated by the very similar ghost appearance in a) and d). Note that the edge ghosting visible in all figures is due to the use of ramped *k*-space sampling during readout.

Ghost intensity is measured as the mean intensity of a 4×4-pixel window near one corner of the edge ghosting area (outside the phantom boundary). The percentage ghost level (calculated as the ghost intensity divided by the signal intensity) is plotted in Fig. 2 for the abovementioned methods. The static phase correction reduces Nyquist ghost to about 1% for the first image of the final image series. However, it fails to track the changes of modulation along time, thereby leading to ghost drift from 1% to 9% over 6 min and 40 s scan. The navigator-based phase correction is capable of capturing part of the dynamic changes of modulation and therefore outperforms the static phase correction method. However, changes in the navigators (first several echoes in echo train) significantly deviate from that in the center echoes in this experiment. Therefore, Nyquist ghost still drifts from 1% to 6.3%. The proposed navigator-free method derives phase correction coefficients from scan data itself. These correction coefficients represent the actual changes near the center of *k*-space due to the magnitude weighting used in the phase fitting algorithm, therefore leading to an almost flat Nyquist ghost level over the entire 6 min and 40 s scan time.

Conclusion

Nyquist ghost drift in dynamic EPI (e.g., fMRI) due to change of system parameters can be reduced by per-temporal-frame phase correction. The proposed navigator-free dynamic phase correction provides an effective and faithful estimation of the per-temporal-frame correction coefficients based on imaging data itself.

REFERENCES

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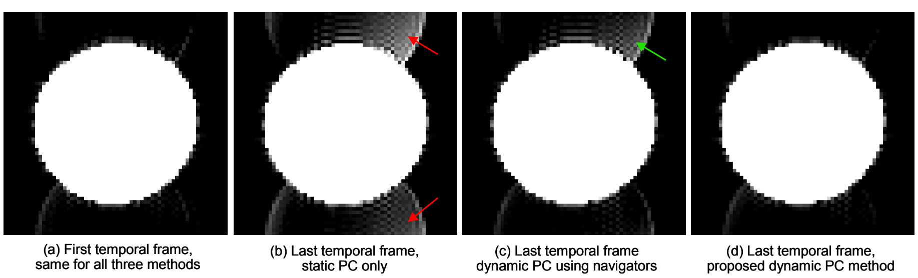

Fig. 1. Gradient-echo EPI images reconstructed by three different phase correction methods: Static phase correction only, dynamic phase correction using navigator echoes, and the proposed navigator-free dynamic phase correction method. All three methods have the same ghost appearance for the first temporal frame, whereas the proposed method has the lowest ghost for the last temporal frame (after 6 min 40 s of scan time), which is the closest to the first frame as well.

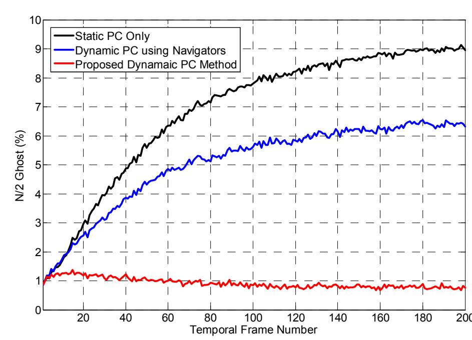

Fig. 2. Nyquist ghost level comparison of the EPI image series in Fig. 1. Ghost intensity is measured as the mean intensity of a 4×4-pixel window near one corner of the edge ghosting area.