Accurate B0 mapping with an adaptive algorithm integrating KESA, PRELUDE, and time-domain phase unwrapping

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Introduction

Mapping of the B0 field could be achieved through acquisition of two sets of gradient-echo MRI data with different echo times (TEs) [1]. Although the phase difference map calculated from the corresponding data can, in theory, be directly converted to the B0 field map, the choice of the phase accumulation time (ΔTE) exhibits an obvious trade-off. A small ΔTE is prone to noise influences in the entire imaging area due to the smaller phase accumulation, leading to low-SNR B0 maps. On the other hand, a widened TE coverage results in pronounced phase wrap-around effects due to a larger frequency offset. In addition for large ΔTE, the susceptibility-induced intravoxel signal loss, which is a common phenomenon in T2*-weighted imaging data at long TE, may also degrade the regional SNR of the produced B0 field maps in local areas having heterogeneous B0 distribution. In this study, we propose an improved phase unwrapping algorithm that provides accurate B0 field mapping for dual-TE MRI data with a large TE coverage, taking into account the intravoxel signal loss at long TE. The phase unwrapping for phase accumulation map is accomplished by exploiting information from k-space energy spectrum analysis (KESA) [2]. We further provide experimental results in comparison with two other methods based on the PRELUDE algorithm [3] and the Laplacian operator [4] to demonstrate the superiority at different TE coverages.

Methods

Our algorithm utilizes the phase accumulation map derived from KESA-based field mapping as an initial estimation (i.e., the coarse phase $\varphi_{KESA}(x,y)$). Two image-domain masks were created from the two magnitude images at different TEs to first identify regions with sufficient SNR. Then for KESA procedure, the integration from background gradient to B0 map was started from a reference voxel with sufficiently high SNR chosen according to the generated masks to ensure reliable starting values, followed by integration toward low-SNR voxels. Note that this action alone leads to improved field mapping performance in regions prone to susceptibility-induced signal loss, because the phase estimation relies on contiguous integration from "neighboring" voxels rather than relying on its own uncertain phase estimation. A reference map from PRELUDE, a fine-tuned phase map $\varphi_{actual}(x,y)$ but with presence of phase wrap-around [3], was further applied to minimize the constant offset of the KESA field map resulting from the integration estimation. Finally, phase unwrapping was achieved in the time domain based on equation 1 to obtain $\varphi_{true}(x,y)$ by adding or subtracting integer multiples of 2π on a pixel-by-pixel basis:

$$\varphi_{true} = \varphi_{actual} + 2\pi \cdot round\,(\frac{\varphi_{KESA} - \varphi_{actual}}{2\pi}) \qquad (1)$$

Subsequently, an accurate B0 field map was calculated via division of the estimated phase accumulation map by ΔTE.

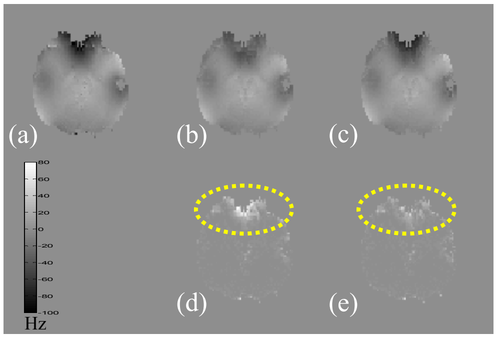

Fig. 1 Field maps. (a) Gold standard. (b) PRELUDE estimate. (c) Proposed method. (d) Difference between a and b. (e) Difference between a and c.

To verify the B0 mapping accuracy in vivo, multi-TE EPI data were acquired from a healthy volunteer on a 1.5T MR system (GE Signa, Milwaukee). The imaging parameters included FOV: 24 cm, matrix size: 96×96, slice thickness: 4 mm, echo spacing time: 0.752 msec, 8 slices, 96 TE values ranging from 42.3 to 113.74 msec at a 0.752 msec step. The B0 map derived from the first 20 TE image series was treated as the gold standard. To investigate field mapping accuracy at different ΔTE, 95 datasets of dual-TE acquisition were generated with TE spacing from 0.752 to 71.44 msec. The results from the proposed field mapping approach were then compared with the gold standard and against two other methods, one based solely on PRELUDE and the other using the Laplacian operator. Residual sum-of-square errors for B0 maps were calculated within the brain region for quantitative evaluation.

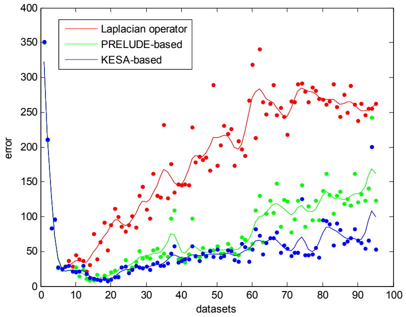

Fig. 2 Error vs. TE coverage

Results

Figure 1a is the field map obtained as gold standard from densely-sampled data. Figures 1(b,c) are the calculated field maps, where TE spacing of the dual-TE data is 59.408 msec, using the only-PRELUDE-based method and our proposed approach, respectively. Figures 1(d,e) are the corresponding difference maps between (b,c) and the gold standard. Our proposed method showed excellent agreement with the densely-sampled field map and with improved performance compared with the method using solely PRELUDE, especially in areas with pronounced susceptibility induced signal loss (yellow dotted circles). Figure 2 shows the quantitative comparison of the residual sum-of-square errors for each dataset, where dots represent the measured errors and the solid lines are the fitting curves based on cubic spline smoothing with factor 0.4, respectively. The estimates from the methods using Laplacian operator, PRELUDE and the proposed approach are represented as red, green and blue colors, respectively. Results in the figure show that at ΔTE > 8 msec, the error in B0 estimation increases with the increasing ΔTE for the brain regions investigated in this study. In addition, our algorithm demonstrates the best performance, with advantage for accurate B0 mapping particularly evident at larger TE coverage.

Discussion and Conclusion

Results from our study showed that the phase wrap-around effects in B0 mapping using large phase accumulation time in dual-TE data can be reliably unwrapped using the time-domain approach. Although the long TE used may cause B0 mapping inaccuracy in areas with pronounced susceptibility-induced signal loss, an appropriate use of the mask in the initial KESA estimation can overcome this difficulty. In conclusion, our improved approach integrating KESA and PRELUDE could provide benefits to studies requiring a high quantitative accuracy in B0 mapping.

References

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