Accurate B0 mapping with sparse TE stepping and k-space energy spectrum analysis

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Introduction

Magnetic field mapping (B0 mapping), which contains information pertaining to magnetic field inhomogeneities, has become an important tool for providing robust correction of distorted images in EPI-based studies [1]. Although B0 mapping could be easily achieved by fitting the phase evolution with different echo offsets, the accuracy in areas with prominent field inhomogeneities (and consequent presence of phase aliasing) is strongly dependent on the success of phase unwrapping [2]. The use of multiple TE values with smaller TE spacing favors detection of phase discontinuities, as the phase across successive TEs differing by more than π radians can be unwrapped along the TE-dimension much more reliably as compared with phase-unwrapping along the spatial-dimension. However, many densely-sampled-TE images are required and the lengthened scan time limits its applications. In this study, we proposed an improved approach for B0 mapping through unwrapping the sparsely-sampled multi-TE images. The critical issue of phase unwrapping is overcome by exploiting information from k-space energy spectrum analysis [3]. Experimental results suggest that our approach could be applied to accurately map B0 field inhomogeneities with shorter acquisition time.

Methods

Phase value outside the interval (-π, π) would be aliased to produce a wrapped phase, $\hat{\varphi}(x,y)$, which is related to $\varphi(x,y)$ by $\varphi(x,y)=\hat{\varphi}(x,y)\pm l(x,y)2\pi$ for some integer $l(x,y)$. The goal of phase unwrapping is to restore the actual phase $\varphi(x,y)$ from the wrapped phase $\hat{\varphi}(x,y)$. With sparse TE spacing, restoration of $\varphi(x,y)$ is prone to errors because multiple solutions are possible. The k-space energy spectrum analysis (KESA) is able to provide a coarse estimate of the B0 map, with errors accumulating at larger TEs due to its numerical integration nature [3]. Therefore, we used KESA only for an initial estimation of the phase evolution as a function of TE, which is then compared with $\hat{\varphi}(x,y)$ to find the integer $l(x,y)$ on a pixel-by-pixel basis. Subsequently, $\varphi(x,y)$ is unwrapped by adding or subtracting integer multiples of 2π. The resonance frequency at each pixel is then given by fitting the slope of the phase variations with TE, thereby accomplishing field mapping.

To verify the B0 mapping accuracy of the proposed algorithm, multi-TE EPI data were acquired from a healthy volunteer on a 1.5T MR system (GE Signa, Milwaukee). The imaging parameters included FOV: 240 mm x 240 mm, matrix size: 96 x 96, slice thickness: 4 mm, 8 slices, 37 TE values ranging from 42.3 to 69.4 msec at a 0.752 msec step. The B0 maps obtained from the 37 TE image series were treated as the gold standard. Sparse TE scans were obtained by choosing only 4 echoes with 9 msec TE step instead of the original 0.752 msec step (i.e., the same TE coverage as the 37-TE data). The results were compared with direct TE-unwrapping and the initial KESA based estimation.

Results

Figure 1 shows the wrapped phase values from the sparsely sampled multi-TE scans (red dots), where the red dotted line with crosses directly estimated from phase unwrapping [2] erroneously traced the phase evolution as compared with the gold-standard reference obtained from the densely-sampled 37-TE data (blue line, only the first 10 TEs are shown). The black dotted line represents the slope trend estimated using KESA, which deviated slightly from the gold standard due to the integration error. The magenta dash-dot line with circles represents phase values after unwrapping procedure based on our proposed approach, which closely followed the reference despite that only 4 TE values were used with 9-msec spacing. Figure 2a is the field map obtained as gold standard from densely-sampled data. Figures 2(b,c) are the calculated field maps using only the initial KESA estimations and our proposed approach, respectively. Figures 2(d,e) are the corresponding difference maps between (b,c) and the gold standard. Our proposed method showed an excellent agreement with the densely-sampled field map and with improved performance compared with using solely the KESA estimates within the cerebral parenchyma.

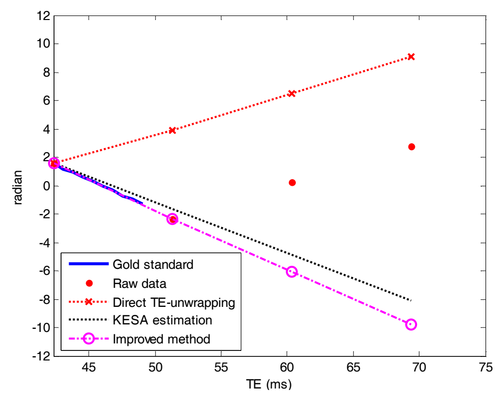

Fig. 1 Phase evolution plotted vs. TE

Discussion and Conclusion

Results from our study showed that B0 mapping using sparsely-sampled multi-TE data may cause failure during the TE-dimension phase unwrapping procedure [2], In contrast, the phase evolution at different echo offsets could be obtained correctly by applying our proposed approach with taking KESA initial estimation. The excellent consistency between the gold standard calculated from 37 TE values and the estimated B0 values using our approach suggests that the accurate B0 mapping with sparse TE stepping is feasible. One important pre-requisite for the validity of this method is that there should be no pixels with signal dropout due to echo-shifting effect (i.e., where the field inhomogeneity is so severe that the entire echo is shifted out of the entire k-space) [3]. The proposed method is not restricted to EPI applications, but can generally be used for gradient-echo and asymmetric spin-echo imaging as well. Furthermore, the inclusion of TEs with large stepping suggests that it may also be used for accurate T2* measurements.

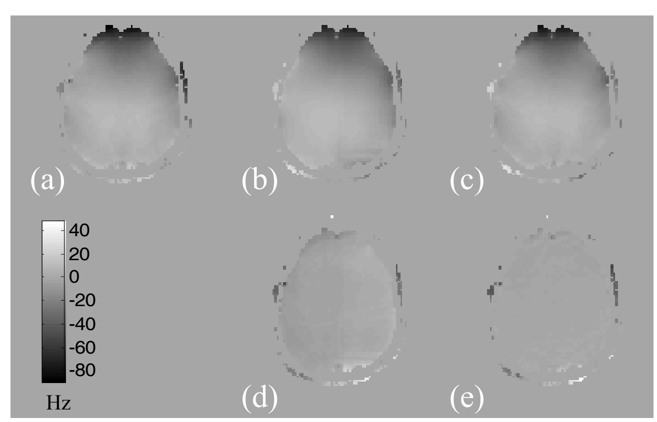

Fig. 2 Field maps. (a) Gold standard. (b) KESA estimate. (c) Proposed method. (d) Difference between a and b. (e) Difference between a and c.

References

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