Reliable phase gradient mapping and phase unwrapping for low-SNR images: A novel procedure based on k-space energy peak quantification

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Purpose:

It is well known that MRI phase mapping is difficult because of the phase wrap-around. Many phase unwrapping procedures have therefore been implemented; [1,2] however, their performance may degrade significantly when being applied to phase images of low SNR. Although the SNR can be improved by image smoothing in post-processing (e.g., kernel convolution in image-space), existing procedures that are suitable for smoothing the magnitude images may actually distort the phase information, particularly in regions affected by pronounced susceptibility field gradients of gradient-echo MRI data.

To address the above mentioned challenges, here we 1) report a novel procedure for mapping the phase gradients of low-SNR images through quantifying the k-space energy peak displacement, and 2) develop a robust phase unwrapping method that incorporates the phase gradient information derived from the k-space analysis. Our preliminary results indicate that the developed methods can reliably measure the phase gradient values and successfully achieve phase unwrapping for images with low SNR.

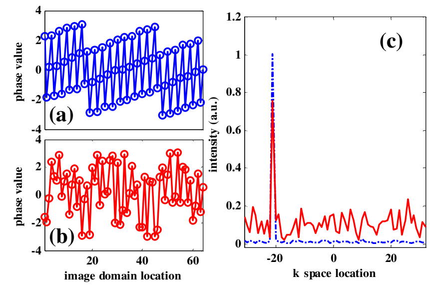

Fig. 1 Illustration of relationship between phase evolution and k energy peak

Methods:

According to the Fourier transform theory, [3] phase gradients in image-domain can be quantified through measuring the k-space energy peak displacement. Furthermore, it should be noted that detecting energy peaks in k-space is more robust and has a better tolerance to noises, as compared with mapping the phase gradients in image-domain. As illustrated by 1D simulation (Fig.1), image-domain phase gradient patterns (Fig 1a) and k-energy peak displacement (blue dashed line in Fig 1c) can both be reliably detected for data of high-SNR. However, for low-SNR data, phase gradient patterns cannot be easily resolved in image-domain (Fig. 1b), while the k-space energy peak displacement remains detectable (red line in Fig. 1c).

To reliably quantify the image-domain phase gradients through k-space analysis, we developed a moving image-domain patch, and examined the k-space energy pattern when using the patch as a mask to crop images. The echo shifts in each direction (kx and ky) were then mapped out in a patch-by-patch fashion, and subsequently, the image-domain phase gradient can be mapped.

A numerical phantom was produced with variable field gradients. By varying the amplitude of image-domain signals (e.g., red circle in Fig. 2a), the impact of SNR on the developed phase mapping procedure were assessed. An image-domain 1D phase unwrapping algorithm provided by MATLAB (MathWorks, Natick, MA) was also used for comparison.

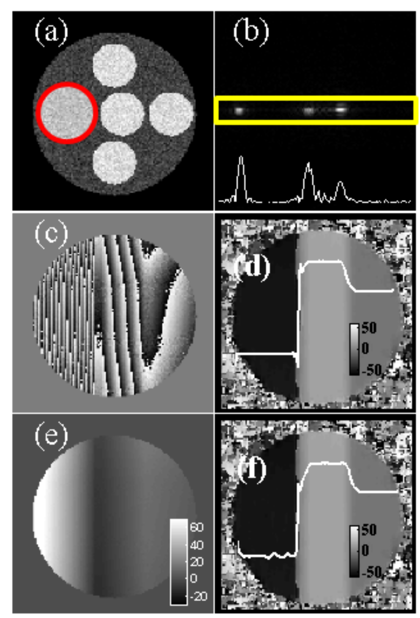

Fig. 2 Mathematical simulation

Results:

Figures 2a and 2b show the input image of our mathematical simulation and the corresponding k-space signals, respectively. The three k-space energy peaks in Figure 2b originate from 3 levels of phase gradients along the horizontal direction in the input phase image (Fig. 2c). The rapid phase wrap-around in the left part of FOV makes it difficult to measure phase gradients, especially for images with low SNR. Using the developed moving image-patch based k-space analysis, the estimated the kx displacement (Fig. 2d, with white line indicating the echo shifts of voxels along the central row) and ky displacement (not shown) can be quantified, which can be further used to guide image-domain phase unwrapping (Fig. 2e). When the SNR was lowered in our simulation, the image-domain phase patterns became very complicated, while the kx displacement could still be reliably quantified (Fig. 2f). Figures 3a and 3c show the phase values of a specified row of red circle in Figure 2a, with two different noise levels. For higher SNR data, phase unwrapping can be reliably performed with conventional phase unwrapping method and the proposed approach (Fig. 3b). In contrast, for low SNR data, the phase unwrapping can only be successfully achieved with our approach (red line in Fig. 3d) but not the conventional method (black dots in Fig. 3d). Figure 3e shows the L1 norm of the developed method (solid line) and the conventional phase unwrapping method (dashed line) corresponding to 5 different SNR levels, indicating that the proposed method has much better tolerance to noises than conventional phase unwrapping methods.

Discussion and Conclusion:

In this study, a novel approach is developed to reliably measure the phase gradient and unwrap phase values for images with low SNR. Specifically, the moving patch algorithm facilitates the identification of k-space energy peak, and the local phase gradients can thus be quantified and used to resolve the ambiguities in phase unwrapping. The preliminary results show the superior performance of the developed method for low-SNR images.

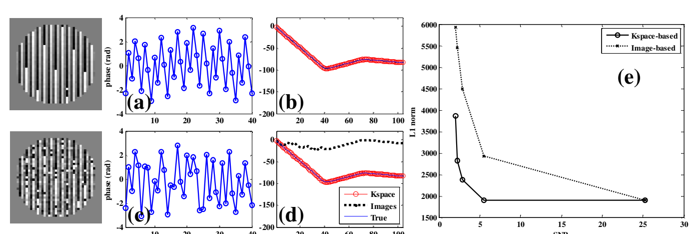

Fig. 3 The wrapped (a, c), unwrapped (b, d) phase values with high/low SNR, and L1 norm (e).

References

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