A New Iterative Phase Correction Method for Segmented EPI to Reduce Image Distortion

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Introduction: Segmented interleaved echo planar imaging offers a fast approach for high resolution volumetric magnetic resonance imaging such as Susceptibility Weighted Imaging (SWI). Echo Time Shift (ETS) technique effectively smoothes the phase discontinuities between segments and creates ghost free magnitude image. However, phase evolution in the phase encoding direction with the linear k_y dependence of the ETS technique puts back the large distortion seen on single shot EPI. In this work, we demonstrate that with a center out k-space trajectory coupled with a phase map, phase discontinuities can be eliminated iteratively. At the end the phase error is eliminated in the phase encoding direction so that the image distortion is effectively reduced.

Materials and methods: In this work, only even echoes are sampled to ensure flow compensation in the readout direction. This also makes it possible to focus on the phase error caused by the static off-resonance effects including: B_0 field inhomogeneity $\Delta B(x, y)$ and chemical shift. The phase error $\varphi(k_x, k_y)$ of the *jth* segment originating from $\Delta B(x, y)$ and chemical shift f is

$$\varphi(k_x, k_y) = -\gamma\,(\Delta B(x, y) + 2\pi f/\gamma)\;\;(k_x/G_x + TE(j)) \qquad (1)$$

where TE(j) is the echo time of the *jth* echo in the echo train and G_x is the readout gradient. The discontinuity of the phase error $\Delta\varphi(k_x,k_y)$ for two adjacent segments is

$$\Delta\varphi(k_x,k_y) = -\;\gamma\,(\Delta B(x, y)\; + 2\pi f/\gamma)\; T_{es} \qquad (2)$$

where T_{es} is the echo spacing. We collect a calibration echo first to remove the unwanted phase effects between echoes (see Fig. 1). There is no phase encoding between the calibration echo and the first data echo. The low frequency version of the phase map can be calculated simply via complex division of the two complex images from these two echoes. The resulting phase is none other than that in Eq.(2). Fig. 2 is a sketch of the center out k-space trajectory. The phase discontinuity between region 1 and 2 can be eliminated by doing the following: first replace all data points in k-space in regions other than 1 with zero. Then Fourier transform zero filled k-space to the image domain to get a complex image $\rho(x,y)$. Next multiply $\rho(x,y)$ with $\exp(i\varphi(x, y))$ to get $\rho'(x,y)$. Then Fourier transform $\rho'(x,y)$ back to k-space and replace back all data points in k-space other than region 1 with the original acquired data points. This has now corrected the phase for echo one as if it were collected at the time of echo two hence removing the phase discontinuities. Now the central region of 1 and 2 in k-space are properly matched and we call this new central region 2'. The same procedure can now be applied to phase corrected region 2' to eliminate the phase discontinuity between region 2' and region 3. This process is repeated again until all echoes have been corrected and all phase discontinuities removed.

Results and discussions: Fig.3a and 3b are two phantom images reconstructed without and with proposed phase correction. The largest resolution circle is reasonably well delineated with the central k-space alone. The phase discontinuities on higher k-space between segments cause sever ghosting and blurring for those small resolution circles (Fig. 3a). Ghosting and blurring are mostly gone in Fig. 3b, which indicates successfully reduce of phase discontinuities. However, the correction is not perfect for the smallest resolution circles. There are residual ripples that are the result of missing high frequency information in the phase map. Obviously there is a trade off between the increase in speed and the accuracy of the phase map. One can also use an extra reference scan to get an accurate phase map if time is not an issue. For high resolution 3D imaging like SWI which demands 0.5 x 0.5 mm resolution, a smaller number of echoes suffices so that a much larger central k-space and more accurate phase is available. In summary, the proposed method has the potential to reduce scan times for high resolution 3D imaging methods such as SWI or MRA.

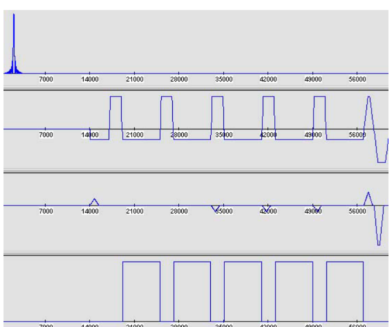

Figure 1

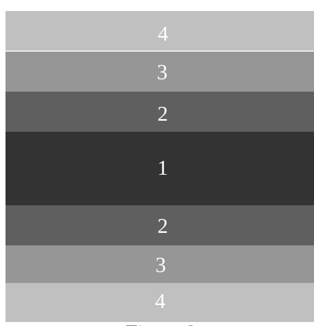

Figure 2

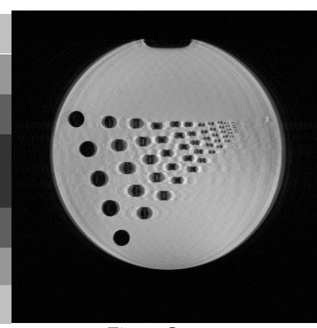

Figure 3a

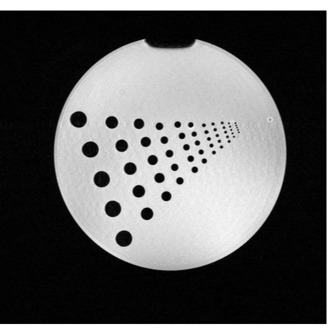

Figure 3b

Fig. 1 Simulated sequence diagram. Fig. 2 sketch of center out k-space trajectory. Fig. 3a and 3b magnitude images without and with iterative phase correction.

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