CAMPUS: A Catalytic Multiecho Phase Unwrapping Scheme

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INTRODUCTION

Susceptibility weighted imaging (SWI) [1] uses phase information at long echo time (*TE*). However, due to long *TE*, phase aliasing inevitably occurs. For SWI, phase wraps can be removed by region growing unwrapping methods or homodyne highpass filtering. Recently, a multiecho SWI approach has been proposed [2], in which 5 echoes were collected. The phase images of all the five echoes were homodyne filtered with adjusted filter sizes to suppress the more severe phase wraps at longer TE, which were then used to form a multiecho SWI image. However, the increased filter sizes at longer echoes could introduce undesired artifacts. In this abstract we propose a new pixel-wise catalytic multiecho phase unwrapping scheme (CAMPUS) that is suited for multiecho gradient echo imaging with short inter-echo spacing.

METHODS

A total of 11 echoes were collected at 3T. The first echo is flow compensated in all 3 directions and the rest of the odd echoes are flow compensated in the readout direction only. The even echoes are not flow compensated. Other scanning parameters are: field-of-view (FOV) = 25.6 cm x 19.2 cm, in-plane resolution = 0.5 mm x 0.5 mm, slice thickness = 2 mm, flip angle = 15°, first echo at TE_1 = 5.68 ms, inter-echo spacing ΔTE= 2.57 ms, last echo at TE_{11} = 31.38 ms, repetition time *TR* = 37 ms, bandwidth (BW) = 465 Hz/pixel and an acquisition matrix of 512×384×64 with 64 slices. Ignoring flow-induced components for now, the phase at voxel location **r** at the *i*th echo TE_i can be written as

$$\varphi(\mathbf{r}, TE_i) = \varphi_0 - \gamma\Delta B(\mathbf{r})TE_i + \theta_{l(i)}(x) \qquad (1)$$

where φ_0 is the initial phase shift, γ is the gyromagnetic ratio, x is the coordinate of the voxel along the readout direction, $\Delta B(\mathbf{r})$ is local field variation caused by susceptibility effects, $\theta_{l(i)}(x)$ is the linear phase along the readout direction caused by eddy currents and gradient delays, $l(i)$= 1, when i is odd and $l(i)$=2, when i is even. It is assumed that the eddy current behavior reaches a steady state such that the all the positive (negative) gradients induce the same linear phase [3]. Inter-echo phase advancements are computed with complex division of the adjacent complex echo images. Taking into account the flow-induced component, the phase advancements from positive echo to negative echo ($\Delta\varphi_{np}$) and from negative echo to positive echo ($\Delta\varphi_{pn}$) can be written as,

$$\begin{cases}\Delta\varphi_{np}(\mathbf{r},\Delta TE) = -\gamma\Delta B(\mathbf{r})\Delta TE - \gamma v M_1 + (\theta_2(x) - \theta_1(x)) \\ \Delta\varphi_{pn}(\mathbf{r},\Delta TE) = -\gamma\Delta B(\mathbf{r})\Delta TE + \gamma v M_1 - (\theta_2(x) - \theta_1(x))\end{cases} \qquad (2)$$

where M_1 is the first moment of the gradient at even echoes and $-\gamma v M_1$ is the flow-induced phase advancement at even echoes assuming constant velocity. The eddy current induced terms in Eq. (2) can be modeled as a linear phase along the readout direction and removed from the phase advancement images. The flow induced phase term $-\gamma v M_1$ can be estimated by subtraction of $\Delta\varphi_{np}(\mathbf{r},\Delta TE)$ and $\Delta\varphi_{pn}(\mathbf{r}, \Delta TE)$. Note for ΔTE short enough, after removal of the eddy current induced terms and assuming slow flow, the inter-echo phase advancement induced by local field variation is small enough that there is no phase aliasing. Addition of $\Delta\varphi_{pn}(\mathbf{r}, \Delta TE)$ and $\Delta\varphi_{np}(\mathbf{r}, \Delta TE)$ removes the flow induced term to give

$$\Delta\varphi_{i+2,i}(\mathbf{r}, 2\Delta TE) = -\gamma\Delta B(\mathbf{r})2\Delta TE \qquad (3)$$

The local field variation $\Delta B(\mathbf{r})$ can be estimated from Eq. (3). Then inter-echo phase advancements $\Delta\varphi_{21}$ and $\Delta\varphi_{32}$ can be unwrapped using Eq. (2) to get $\Delta\varphi_{21}^{un}$ and $\Delta\varphi_{32}^{un}$. The other inter-echo phase advancements can be unwrapped by,

$$\begin{cases}\Delta\varphi_{43}^{un} = \Delta\varphi_{43} + 2\pi R_d\left((\Delta\varphi_{21}^{un} - \Delta\varphi_{43})/(2\pi)\right) \\ \Delta\varphi_{i,i-2}^{un} = \Delta\varphi_{i,i-2} + 2\pi R_d\left((\Delta\varphi_{i-2,i-4}^{un} - \Delta\varphi_{i,i-2})/(2\pi)\right), \quad i=5,6,\ldots,11\end{cases} \qquad (4)$$

where R_d is the rounding operator. Notice that in Eq. (4), the unwrapping of the odd echoes with respect to echo one is achieved using only previously unwrapped odd echoes, and unwrapping of the even echoes is done using only the previously unwrapped even echoes. This is designed to reduce the effect of the flow-induced variations in phase in the readout direction because the odd echoes are flow-compensated in the readout direction, while the even echoes are not. Finally, the initial phase φ_0 is estimated by projecting the phase using Eq. (1) back to t=0. After CAMPUS processing, the phase images for echoes 7 to 11 are highpass filtered and then used to generate single echo SWI images, which are then averaged to form a multiecho SWI image. Note that a regular highpass filter, instead of the highpass filter based on complex division in *k*-space is used to unwrap the phase images, which introduces no phase wrapping.

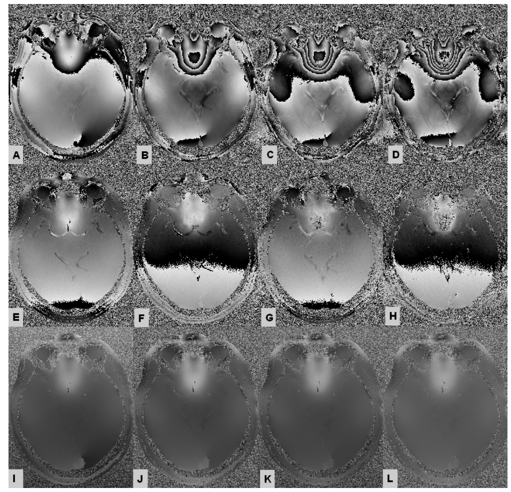

Fig. 1. Phase images of a mid-brain slice of a normal volunteer during CAMPUS unwrapping process. 1st row: original phase at echoes 1 (A), 4 (B), 7 (C) and 10 (D); 2nd row: $\Delta\varphi_{i+1,i}(\mathbf{r},\Delta TE)$, i=1,4,7,10, from complex division of echo pairs; 3rd row: unwrapped phase images corresponding to the 1st row. Note all unwrapped phase images are scaled to the full gray scale range for viewing.

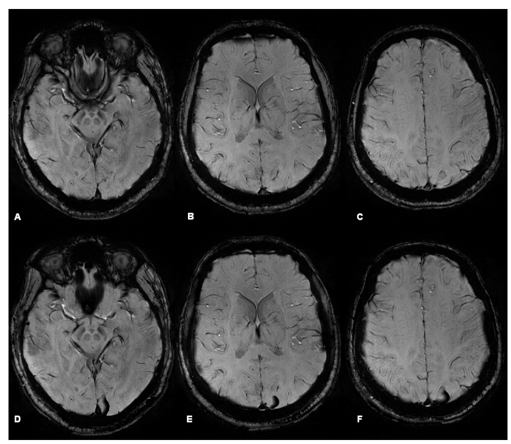

Fig. 2. Multiecho SWI images in the mid-brain, thalamostriate, and upper-brain generated with conventional homodyne filtering of the phase images (A,B,C) and regular highpass filtering on CAMPUS-unwrapped phase images (D,E,F).

RESULTS AND DISCUSSION

Figure 1 shows phase images during CAMPUS unwrapping process. The eddy current induced linear phase along the readout direction is evident and is seen to be consistent with the steady state assumption. The unwrapped phase images show that the true phase values were recovered except for a few pixels in the major arteries, where the slow flow assumption is violated. Figure 2 shows multiecho SWI images reconstructed using conventional homodyne filtering of the original phase images and using CAMPUS-unwrapped phase images. Figure 2(D) shows that the CAMPUS based SWI image is free of severe wraps in the orbitofrontal area caused by phase aliasing in conventional SWI approach as seen in Fig. 2(A). Notice the phase artifact at the posterior of the brain, which is present in the original phase images (Fig. 1) as well. It is generated by the reconstruction algorithm for multi-coil phased array acquisition from the scanner (we are working to resolve this issue).

CONCLUSION

A novel pixel-wise catalytic multiecho phase unwrapping scheme is proposed that can recover the true phase for multiecho images with short echo spacing. CAMPUS requires no filtering of the phase data and is not based on the conventional region growing approach. It exploits the fact that short echo spacing induces small inter-echo phase advancements, which is free of aliasing after correction of the eddy current and flow induced phase components. This technique lays the foundation for further phase related processing, such as forming multiecho SWI images and performing susceptibility mapping. The multiecho SWI images generated with the CAMPUS-unwrapped phase show significant improvement in reducing phase aliasing induced artifacts.

REFERENCES

[1] Reichenbach et al., *Radiology*, 204:1, pp. 272-277, 1997; [2] Denk and Rauscher., *JMRI*, 31:1, pp. 185-191, 2010; [3] Yu et al., *JMRI*, 31:5, pp. 1264-1271, 2010.