Phase unwrapping using recursive orthogonal referring (PUROR) for susceptibility mapping at 7T

Junmin Liu[1], David A Rudko[1,2], Joseph S Gati[1], Ravi S Menon[1,2], and Maria Drangova[1,2]
[1]*Imaging Research Laboratories, Robarts research Institution, The University of Western Ontario, London, Ontario, Canada,* [2]*Department of Medical Biophysics, The University of Western Ontario, London, Ontario, Canada*

Introduction: Phase images at high magnetic field strengths provide unique contrast compared to magnitude images but require, robust phase unwrapping to visualize these contrasts in the entire brain [1]. Although many unwrapping algorithms have been developed, removing phase aliasing still presents a challenge. In this abstract, we present a new unwrapping algorithm, which uses a recursive orthogonal referring approach (PUROR) to remove streaks that result following conventional 2D phase unwrapping. The performance of the PUROR algorithm is evaluated with a set of volunteer brain images, acquired at 7 T and the results are compared with the commonly used PhiUN [2] and PRELUDE methods [3].

Theory: The PUROR phase unwrapping algorithm starts from two phase images unwrapped using the 1D Itoh algorithm along the row (X) and column (Y) direction, respectively (Fig. 1a). The PUROR algorithm then removes the streaks using the following three procedures: 1) ***intra-image unwrapping***: this is achieved by reducing the phase difference between line-segments and between rows along the X-unwrapping path and between columns along the Y-unwrapping path (Fig. 1b); 2) ***inter-image cross-referring strips***: the widest horizontal and vertical "strips" (*i.e.* error-free bands) are identified from the phase images along the X and Y paths independently, then used to align the phase values of the two orthogonal images (Fig. 1c); 3) ***inter-image cross-referring line-segments***, the mean phase differences of line-segments in the two orthogonal images are used as the "truth" to correct the remaining phase errors (Fig. 1d). Note that line-segments in ***procedures 1*** and ***3*** are defined as a sequence of pixels that have small phase differences ($< \pi$).

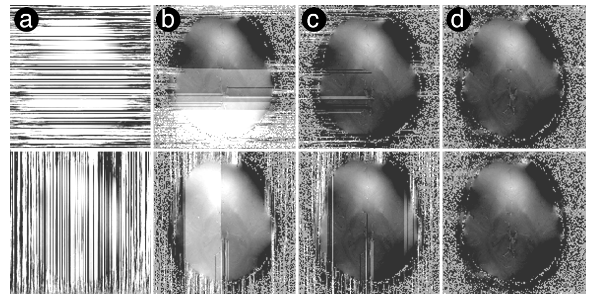

Fig. 1 The steps of the PUROR algorithm are performed along two orthogonal unwrapping paths along the X (top) and Y (bottom) directions. The four steps are detailed in the theory.

Methods: Data for phase image post-processing was acquired on a 7 T MR scanner with 16 independent RF transmit and receive channels. Imaging was performed using a 2D FLASH sequence (TR = 2 s., TE_1 = 4.56 ms, ESP = 4.41 ms, GRAPPA factor = 2, flip angle = 50^o, 6 echoes, 2 mm slice thickness (40 slices), 0.5 mm in-plane resolution and 100 KHz readout bandwidth). For phase image post-processing, the complex images of individual echoes were combined first [4] and then unwrapped using PUROR, PhiUN and PRELUDE. The resulting data was high-pass filtered to remove background fields. Specifically, a 2D Gaussian, high-pass filter with full width at half maximum (FWHM) of 9.4 mm was applied to the Fourier transform of the unwrapped phase data to remove background fields [5]. The relative difference field (RDF - defined as the local Larmor frequency after subtraction of background field contributions) was then calculated using a weighted linear regression to yield the off-resonance frequency at each voxel from all six echoes. Processing of PUROR was performed off-line using MATLAB. The PhiUN software was implemented using compiled MATLAB. The PRELUDE 2D algorithm implemented in C++ as part of the FSL analysis package (Oxford, UK) was used.

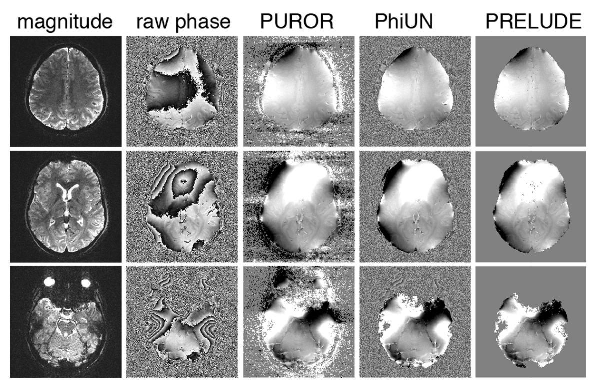

Fig. 2 Example slices comparing the three unwrapping algorithms evaluated. Images from a single echo (all 16 channels) are shown.

Results and Discussion: Figure 2 shows phase maps of the brain unwrapped with all three algorithms. Although all algorithms achieve similar quality in most brain regions, PUROR is the only algorithm that successfully unwrapped the phase in multiple isolated regions (e.g. near the eyes in the bottom row). The computation time for the PRUOR, PhiUN, and PRELUDE algorithms was 1 s, 2, s and 7.2 s per slice. While this is not a direct comparison (since different computers and compilers were used), the PUROR was implemented on the slowest computer with MATLAB, yet resulted in the shortest time. Figure 3 compares the RDF maps calculated from unwrapped phase images using PUROR and PhiUN. (Note that RDF analysis was not applied to the PRELUDE phase maps because of the presence of holes.) Important differences are seen near the brain surface (as highlighted by the arrows) where PUROR unwrapping retains tissue contrast to the edge of the brain surface, which is critical for examining cortical structures. In addition, the PUROR-RDF images are less susceptible to errors near sub cortical structures such as the basal ganglia (bottom row in Fig. 3).

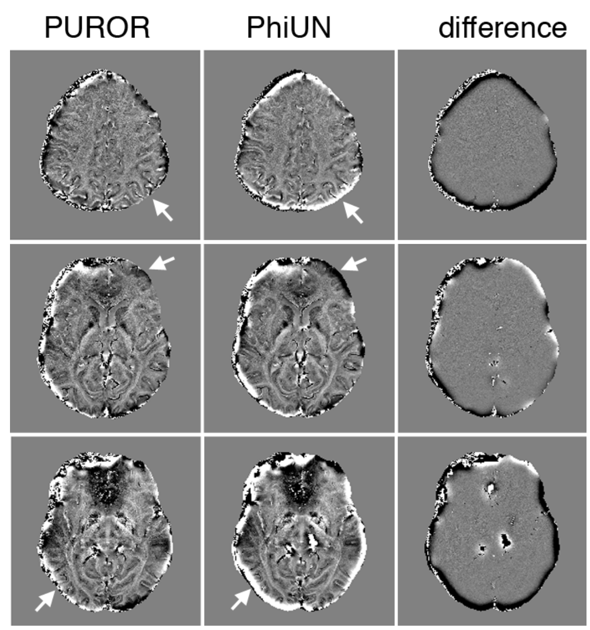

Fig. 3 RDF maps of three images. The difference maps were generated by subtracting the PhiUN from the PUROR map.

Conclusion: The PUROR algorithm represents a robust and rapid phase unwrapping approach for application in high-field and high-resolution brain imaging, allowing improved phase unwrapping at the brain/cortex edge.

References: [1] Duyn et al, PNAS 104:11796-801, 2007. [2] Witoszynskyj, et al., Medical Imaging Analysis 13:257-68, 2009. [3] Jenkinson, MRM 49: 193-7, 2003. [4] Hammond et al., NeuroImage 39: 1683-92, 2008. [5] Rauscher et al, MRI 26: 1145-51, 2008.