Temporal unwrapping of highly wrapped multi-echo phase images at ultra-high field: UMPIRE

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Introduction: MR phase values outside a 2π range are aliased, causing phase images to contain discontinuities, or "wraps". These can be removed with spatial, region-growing methods (e.g. [1]) which, however well implemented, are computationally intensive and inherently not very robust. Alternatively, the evolution of phase over time can be used to identify wraps on a voxel-by-voxel basis. The rise in use of a number of echoes in Susceptibility Weighted Imaging (SWI) [2] and the desire for unwrapping speed has led to renewed interest in temporal approaches [3]. A limitation of temporal methods to date, however, has been that the phase difference between echoes must be less than 2π [3], a condition which cannot readily be met at very high field. We describe a method which uses unequal spacings between echoes and an assessment of phase evolution in the time difference between the echo spacings to allow a number of wraps between echoes to be resolved. We have called this method UMPIRE, or Unwrapping Multi-echo Phase Images with iRregular Echo spacings.

Materials and Methods: Two data sets were simulated to i) demonstrate the difference between UMPIRE and conventional temporal phase unwrapping and to ii) assess performance in unwrapping complex objects. In simulated data set i) there was a B0 gradient in the x direction and a gradient in receiver offset (Rx, the phase at time=0) in the y direction (Fig. 2(A)). Simulated data set ii) was a complex shape made up of superposed 3D Gaussian distributions of different widths to which the wrapping operator was applied (Fig. 3). High resolution 3D multi-echo (NE=3) gradient-echo scans of a healthy subject were also acquired with a 7 T Siemens system with a matrix size of 320x320x160 (isometric voxels of 0.65 mm side length), monopolar readout, and TE=[3.9,9.0,15.1] ms, i.e., with an additional delay (δTE) of 1 ms between the second and third echo.

Analysis: UMPIRE was implemented in MATLAB (Fig. 1). Phase difference images (PD, Fig.1-B) were calculated between pairs of phase images (P, Fig.1-A). The difference between these phase difference images (DPD) was also calculated (Fig.1-C). DPD is free of wraps if δTE is short. Wraps in PD images were identified by comparison with DPD (Fig.1-D), and removed (Fig.1-E). Receiver phase offsets were calculated [4] and subtracted from phase images (Fig.1-F) and DPD used again to identify wraps (Fig.1-G). These were removed to complete unwrapping (Fig.1-H).

Results: UMPIRE removed wraps in highly wrapped simulated data (Fig. 2), which could not be removed with conventional temporal unwrapping methods [3,5]. It also successfully resolved wraps in complicated simulated shapes which could not be unwrapped with spatial methods PRELUDE [1] and PHUN [6] (Fig. 3). UMPIRE also outperformed spatial methods in unwrapping in-vivo data (Fig. 4). Processing times for in-vivo data were 24m38s ± 21s for PRELUDE, 2m20s ± 91s for PHUN and 1m19 ± 9s for UMPIRE.

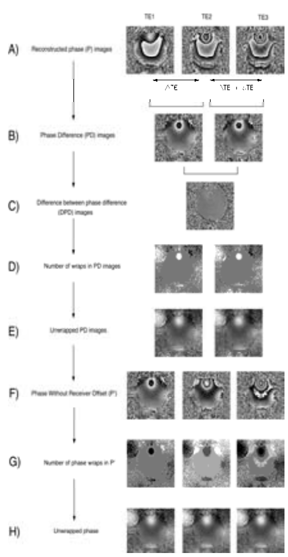

Fig.1: Steps in UMPIRE

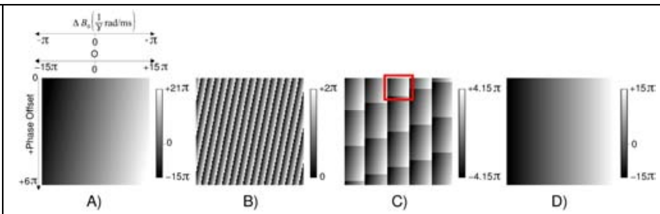

Fig.2: The wrapped phase image from the simulated ΔB0-Rx distribution (A) is shown at the third echo time (B). Phase values unwrapped with conventional temporal phase unwrapping are shown (C, red box) next to the UMPIRE result (D).

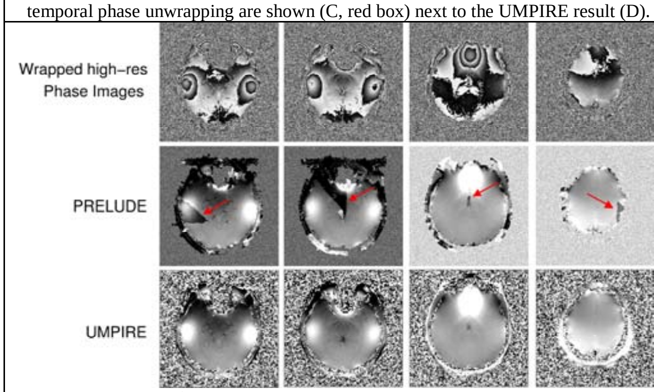

Fig.4: Comparison of unwrapping high resolution 7 Tesla in-vivo phase images with the spatial method PRELUDE compared to the proposed temporal method UMPIRE. Gross errors are marked with red arrows.

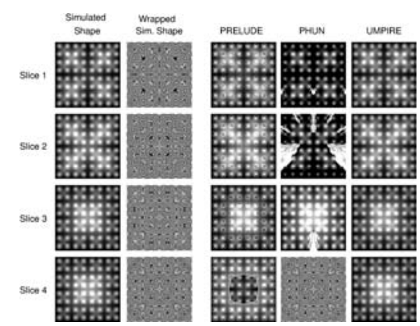

Fig.3: Comparison of quality of unwrapping complex simulated shapes between spatial methods (PRELUDE and PHUN) and UMPIRE.

Discussion and conclusion: UMPIRE unwraps all voxels independently, so does not require image-dependent thresholds and can unwrap phase in disconnected objects. The use of unequal spacings in UMPIRE allows phase images to be unwrapped despite there being a number of wraps between echoes, a feature unique amongst temporal unwrapping approaches. UMPIRE was found to unwrap more effectively where high spatial frequency features (e.g. large veins) were present. This approach is faster than spatial methods, with further speed increase expected with implementation in C.

Acknowledgment: This study was funded by the Austrian Science Fund (KLI 264).

References: [1] Jenkinson, M., MRM, 2003. 49(1) [2] Denk, C., et al., JMRI, 2009. 31(1) [3] Feng, W., et al., MRM, 2012 (epub). [4] Robinson, S., et al., MRM, 2011. 65 [5] Windischberger, C., et al., JMRI, 2004. 20(4) [6] Witoszynskyj, S., et al., Med Image Anal, 2009. 13(2)