Fast, parallelized implementation of a novel temporal phase unwrapping method, and comparison with spatial approaches

Horst Schödl[1], Siegfried Trattnig[1], and Simon Robinson[1]
[1]*Department of Radiology, Medical University Vienna, Vienna, Vienna, Austria*

Introduction: Phase images in MR are used in various applications, including Susceptibility Weighted Imaging (SWI). Raw phase images contain wraps due to the limited (2π) encoding range of phase values. This problem can be solved by using spatial unwrapping methods, which are time consuming and fragile, or temporal approaches, in which there has been a recent resurgence of interest [1]. Such methods work voxel-by-voxel, using information about phase evolution over a number of echo times to unwrap phase images. The limitation with temporal methods to date has been that echoes must be sufficiently closely spaced that no phase wraps occur in the echo spacing period. This is hard to achieve in high-resolution images in high-field MR. One solution is to acquire echoes with unequal echo spacings, and use the phase echo evolution in the time difference between the echo spacings, δTE, which can be selected to be arbitrarily short (so that no wraps occur), to identify and remove wraps in phase difference and ultimately phase images. We call this approach UMPIRE, or Unwrapping Multi-echo Phase Images with iRregular Echo spacings. The aim of this study was to implement UMPIRE in C with parallelization using standard NIfTI libraries [2] and OpenMP [3], a multi-threading API, to make it sufficiently fast and robust to be transferred to the scanner console. UMPIRE was also compared with the region-growing methods PHUN [4] and PRELUDE [5] using a set of simulated phase images and in-vivo multi-echo gradient echo scans.

Methods: Three triple echo gradient-echo scans with a matrix size of 320x320x160 (isometric voxels of 0.65mm side length) were acquired with a 7 T Siemens system with TEs=[3.9, 9.0, 15.1] ms i.e., with an additional delay between the second and the third echo (δTE) of 1.0 ms. PHUN, PRELUDE and UMPIRE were also applied this in-vivo data and simulated data with a matrix size of 128x128x128, which was generated from complicated superposed 3D Gaussian distributions of different widths (Fig. 1).

Results: UMPIRE required 0.507s ± 0.061s to unwrap all three phase images of the simulated data for the difficulty level 4, for which PHUN required 3.695 ± 0.031s and PRELUDE 2D 23m 25s ± 12s (Fig. 1). PRELUDE 3D needed 21h 34m for difficulty 2 and failed on the more complicated shapes and the in-vivo data. For the in-vivo data, the required calculation times were UMPIRE: 7.91 ± 0.29s, PHUN: 28m 59s ± 29s and PRELUDE 2D: 9m 29s ± 1m 50s. Fig. 2 shows the measured unwrapping times for the different methods.

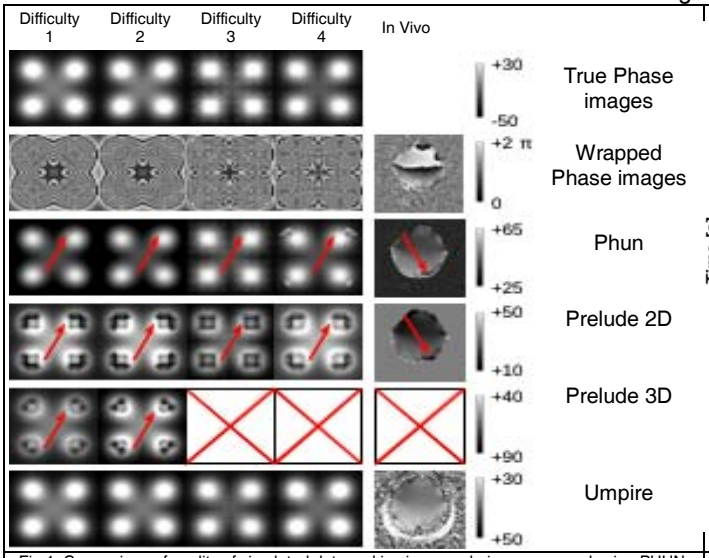

Fig 1: Comparison of quality of simulated data and in-vivo scan being unwrapped using PHUN, PRELUDE (2D/3D) and UMPIRE; Difficulties 3 and 4 and the in-vivo data couldn't be unwrapped with PRELUDE in 3D

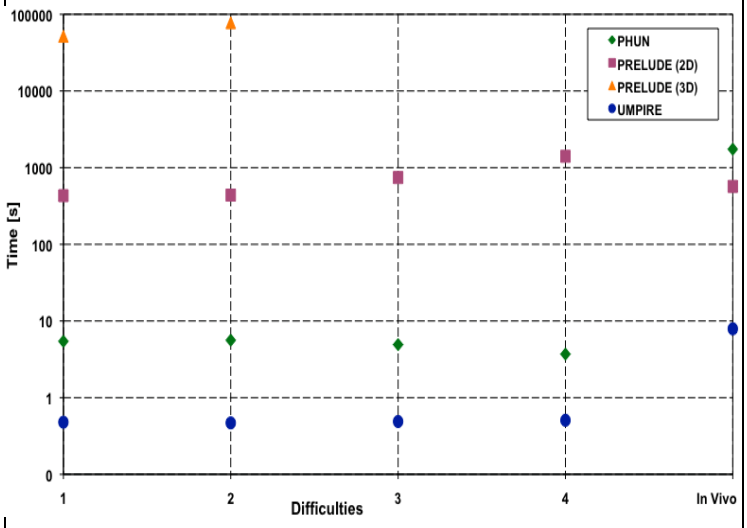

Fig 2: Averaged time for PHUN, PRELUDE (2D/3D) and UMPIRE. There is an increase in calculation time for PRELUDE and PHUN the more complicated the shapes get. UMPIRE needs for all difficulty levels the same amount of time. Error bars are added to the data points but below the visibility.

Discussion and Conclusion: UMPIRE is an extremely fast method for unwrapping phase images, and one in which the processing time is independent of the complexity of the structures in the image. UMPIRE does not need a seed region or connection between regions to be unwrapped, meaning that it works with a number of separate objects, although it is predicated on the difference between phase difference images, meaning it may perform worse than spatial methods in regions of low SNR. The simulation and in-vivo tests here suggest that, despite this caveat, UMPIRE is a fast and robust method, highly suited to implementation on the scanner console.

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