Application of Fourier-Based Phase Unwrapping Algorithm for MR-Venography

H. Bagher-Ebadian[1], Q. Jiang[1], J. R. Ewing[1,2]
[1]Neurology, Henry Ford Health System, Detroit, Michigan, United States, [2]Physics, Oakland University, Rochester, Michigan, United States

Introduction: The ability to determine a true phase map from a principal noisy value of a wrapped phase is an important task in many fields of applied physics and medicine, such as laser holography, electron holography and MRI. Many unwrapping techniques are computationally intensive, and some of them suffer in the presence of noise[1]. Thus, a fast, reliable, and robust algorithm for phase unwrapping can be a significant tool in the analysis of MRI data. For instance, venous population and structure plays an important role in evaluating angiogenic mechanisms in the brain tumor and stroke lesions at different stages of recovery. To calculate the value of the unwrapped phase $\varphi(r)$ from its wrapped value $\varphi_w(r)$, an integer coefficient $n(r)$ should be estimated for each location r in Eq 1 using a two-dimensional Laplacian method. Formulating the problem in terms of the Laplace operator offers a distinct advantage (Eq 2) where $\nabla_\perp^2$ and $\nabla_\perp^{-2}$ are the forward and inverse 2D Laplacian operators. Equation 1 can be solved by use of fast Fourier techniques for Laplacian operators as shown by equation 2 and 3 where p and q denote frequency components. Fig 1 shows a flowchart of the technique in 2D space. Susceptibility-weighted imaging (SWI)[2] can be used for high resolution venography. In its usual implementation, low spatial-frequency components originating from static background susceptibility effects are removed by complex division, which essentially subtracts the low-frequency spatial variation from the phase map, leaving only high-frequency components. A phase mask is created from the high-frequency elements of the filtered phase map and applied to the corresponding magnitude map to enhance veins [3], [4]. In our study, our phase unwrapping algorithm was employed to render an unwrapped phase map in one step, after which a high-pass filter isolated those high-spatial-frequency elements used to produce the mask for the venograms.

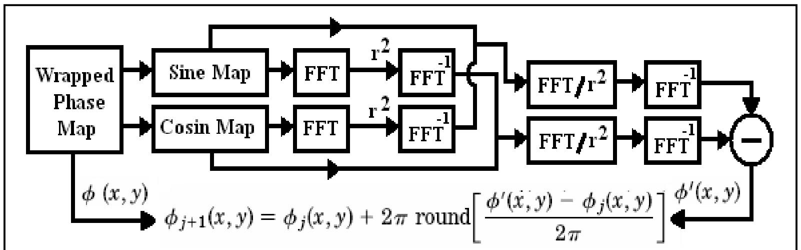

Fig 1

$$\phi(\mathbf{r}) = \phi_w(\mathbf{r}) + 2\pi n(\mathbf{r}) \quad (1)$$

$$n(\mathbf{r}) = \frac{1}{2\pi}\nabla_\perp^{-2}[\nabla_\perp^2\phi(\mathbf{r}) - \nabla_\perp^2\phi_w(\mathbf{r})] \quad (2)$$

$$\nabla_\perp^2 f(x,y) = -\frac{4\pi^2}{N^2}\mathrm{FFT}^{-1}\{(p^2+q^2)\mathrm{FFT}[f(x,y)]\}$$

$$\nabla_\perp^{-2} g(x,y) = -\frac{N^2}{4\pi^2}\mathrm{FFT}^{-1}\left\{\frac{\mathrm{FFT}[g(x,y)]}{(p^2+q^2)}\right\} \quad (3)$$

Materials and Methods: A 7T (25 cm clear bore) Bruker small-animal magnet with gradients of 250 mT/m interfaced to an Avance console running Paravision 2.1.1 was used to acquire a 3D (256x256x64, TE/TR =10/30 ms) brain SWI (Susceptibility Weighted Images) in a male Fisher rat with a 14 days 9L tumor. In human images with even higher resolution, a 3D (512x512x128 TE/TR=20/33) SWI of a human brain was acquired by a GE-3T MRI system. See Fig 1. A Laplacian Fourier-Based algorithm [1], [5] was used to unwrap the reconstructed phase maps. The algorithm consists of 8 FFTs, with computational time of a few seconds. Static magnetic field inhomogenity was corrected by dividing the unwrapped phase map by its filtered version (unitary filter: 11x11and 15x15 for the rat images and human images respectively). As in Haacke et al [2], a linear map was constructed from the resulting high-spatial frequency phase maps and used to multiple the magnitude images of the MRI. Finally a minimum intensity projection indicated the vein structures across typically 8 slices for the animal and 14 slices for the human.

Results: Figures 2 and 3, present the wrapped, unwrapped and venographic images of the animal and human cases respectively. Results demonstrate that venograms using this algorithm produce a good contrast for venous structure in a reasonable computational time. The unwrapped phase images showed excellent image contrast and revealed anatomic structures that were not visible on the wrapped images

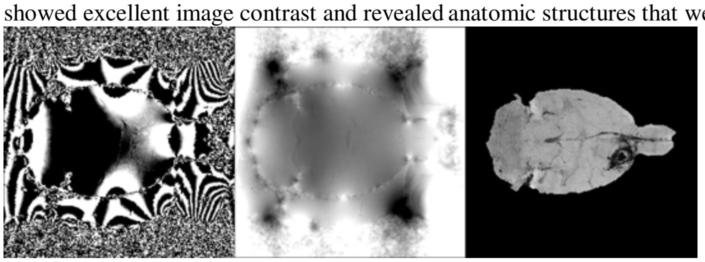
Figure-2

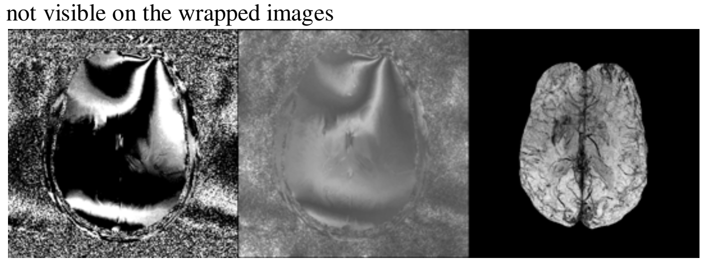
Figure-3

Discussion: A phase unwrapping algorithm was introduced and used for generating the venography maps from SWI data. The algorithm helps to increase the image contrast and reveals venous anatomic structures not visible on the wrapped images. Additionally, the middle images in figures 2 and 3 can be used for correcting the effect of the static magnetic field inhomogeneity.

Acknowledgments: This work was partially supported by NIH grants R01-HL70023 and P01-23393.

References:

[1] Vyacheslav V. et al, *Optics Letters*, Vol. 28, No. 22, pp: 2156-2158, Nov. 2003.
[2] Haacke M.E. et al, *Image Anal Stereol*, Vol. 21, pp: 107-113, 2002.
[3] Rauscher A. et al, *Journal of MRI,* Vol. 18, Issue 2, pp: 175-180, Jul. 2003.
[4] Tratting S. et al, *Topics in Magnetic Resonance Imaging,* Vol. 14, No. 5, pp: 365-375, Oct. 2003.
[5] Marvin A. et al, *Optics Letters*, Vol. 28, No. 14, pp: 1194-1196, Jul. 2003.