Phase-Sensitive Image Reconstruction
Sunday March 8 9:38 to 9:50

Session 5: MRV and other applications

E. Mark Haacke, PhD;
Wayne State University
440 E Ferry Street, Unit 2
Detroit, Michigan, 48202
313 758-0065
nmrimaging@aol.com

Take home messages: Phase can be used for a variety of studies in MRI, these include measuring flow, susceptibility, separating water and fat, etc..

Background: Magnetic resonance imaging (MRI) bases its clinical applications mostly on conventional anatomical imaging using spin density, T_1, T_2 and T_2* type contrasts. Phase is not used in many applications, but does have its special roles. Phase information has been used almost since the beginning of MRI in chemical shift imaging experiments especially in water and fat separation techniques(1,2). The phase information has also been utilized in measuring temperature and pH changes in tissue (3,4). And a more recent use of phase is in susceptibility weighted imaging (SWI) (5) and quantitative susceptibility mapping (QSM) (6).

Objectives: There are several objectives in this presentation. The first is to assess the current state-of-the-art processing of phase information for methods such as SWI, QSM and water/fat separation. The second is to show some examples of the clinical applications of phase imaging.

Methods: Phase images generally contain information from a number of sources including but not limited to: static background fields, eddy currents, air/tissue interface fields, chemical shift, local field changes, temperature, pH and motion. Extracting the phase of interest can be difficult and can require special sequences to accomplish the goal of interest. One of the major efforts in obtaining local fields has come from the study of SWI and QSM (6).

The first step in most studies using phase information is to unwrap the phase. Phase unwrapping algorithms can be categorized as spatial domain algorithms and temporal domain algorithms. The former category includes algorithms such as image quality guided phase unwrapping (7), 3D best-path phase unwrapping (8), Laplacian based algorithms (9,10), and optimization based phase unwrapping (11). The selection of the phase unwrapping algorithm is usually a trade-off between robustness and time-efficiency. A thorough review of the phase unwrapping techniques is given in (12). For temporal phase unwrapping, phase images collected with multi-echo sequence are required (13,14), and the phase at short effective TE is utilized, in which the phase aliasing can be largely avoided. This offers pixel-wise phase unwrapping in a time-efficient fashion.

With single echo approaches, special filters have been designed to remove low spatial frequency phase such as a homodyne high pass filter. Apart from high-pass filtering, there are three other methods being used in recent years: geometry dependent artifact correction (15), dipole fitting (16) and methods based on the spherical mean value property of the background field (17,18–21). But there are other means to accomplish this in a more data intensive way and that is fitting the phase to a quadratic function. In the latter approach, the areas with local field variation must be removed from the image and the remaining areas are used as constraints to fit the low spatial frequency field. Then this field is subtracted from the original field to generate local field information (22).

With methods such as three point Dixon (1,2) the added phase from chemical shift can be extracted. Methods to extract flow using the usual flow quantification schemes will be presented. Finally, how to handle phase from multi-coil systems will also be discussed.

Results: Example phase images from both single echo and multi-echo gradient echo data will be presented, both with and without special anti-aliasing and background field removal approaches. The resulting phase images can then potentially be used to quantify things like iron content, flow, and water/fat fractions for example.

Discussion and Conclusion: The use of phase is becoming more and more important. As field strengths increase and signal-to-noise ratio increases, so do the opportunities to use phase information especially when collecting data with higher resolution. Therefore, methods for phase data processing are also taking on a more critical role. New methods are being developed to better handle this need for culling out all the different contributing factors to phase.

References:

1. Haacke EM, Patrick JL, Lenz GW, Parrish T. The separation of water and lipid components in the presence of field inhomogeneities. Rev MagnReson Med. 1986;1(2):123–54.

2. Glover GH, Schneider E. Three-point Dixon technique for true water/fat decomposition with B0 inhomogeneity correction. MagnReson Med. 1991;18(2):371–83.

3. Ishihara Y, Calderon A, Watanabe H, Okamoto K, Suzuki Y, Kuroda K, et al. A precise and fast temperature mapping using water proton chemical shift.MagnReson Med.1995;34(6):814–23.

4. Gillies RJ, Raghunand N, Garcia-Martin ML, Gatenby RA. pH imaging. A review of pH measurement methods and applications in cancers. IEEE Eng Med Biol Mag. 2004;23(5):57–64.

5. Haacke EM, Xu Y, Cheng YN, Reichenbach JR. Susceptibility weighted imaging (SWI). MagnReson Med. 2004;52(3):612-8.

6. Haacke EM, Liu S, Buch S, Zheng W, Wu D, Ye Y. Quantitative susceptibility mapping: current status and future directions.MagnReson Imaging. 2015;33(1):1-25

7. Witoszynskyj S, Rauscher A, Reichenbach JR, Barth M. Phase unwrapping of MR images using ΦUN--a fast and robust region growing algorithm. Med Image Anal. 2009;13(2):257–68.

8. Abdul-Rahman HS, Gdeisat MA, Burton DR, Lalor MJ, Lilley F, Moore CJ. Fast and robust three-dimensional best path phase unwrapping algorithm. Appl Opt. 2007;46(26):6623–35.

9. Ghiglia DC, Romero LA. Robust two-dimensional weighted and unweighted phase unwrapping that uses fast transforms and iterative methods. J Opt Soc Am A.1994;11:107–17.

10. Schofield MA, Zhu Y. Fast phase unwrapping algorithm for interferometric applications. OptLett. 2003;28(14):1194–6.

11. Jenkinson M. Fast, automated, N-dimensional phase-unwrapping algorithm. MagnReson Med. 2003;49(1):193–7.

12. Ghiglia DC, Pritt MD. Two-dimensional phase unwrapping: theory, algorithms, and software. Wiley; 1998.520 p.

13. Feng W, Neelavalli J, Haacke EM. Catalytic multiecho phase unwrapping scheme (CAMPUS) in multiecho gradient echo imaging: removing phase wraps on a voxel-by-voxel basis. MagnReson Med. 2013;70(1):117–26.

14. Robinson S, Schödl H, Trattnig S. A method for unwrapping highly wrapped multi-echo phase images at very high field: UMPIRE. MagnReson Med. 2014;72(1):80-92.

15. Neelavalli J, Cheng YN, Jiang J, Haacke EM. Removing background phase variations in susceptibility-weighted imaging using a fast, forward-field calculation.J MagnReson Imaging. 2009;29(4):937–48.

16. Liu T, Khalidov I, de Rochefort L, Spincemaille P, Liu J, Tsiouris AJ, et al. A novel background field removal method for MRI using projection onto dipole fields (PDF). NMR Biomed. 2011;24(9):1129–36.

17. Schweser F, Deistung A, Lehr BW, Reichenbach JR. Quantitative imaging of intrinsic magnetic tissue properties using MRI signal phase: An approach to in vivo brain iron metabolism? NeuroImage. 2011;54(4):2789–807.

18. Li L, Leigh JS. High-precision mapping of the magnetic field utilizing the harmonic function mean value property. J MagnReson. 2001;148(2):442–8.

19. Li W, Avram AV, Wu B, Xiao X, Liu C. Integrated Laplacian-based phase unwrapping and background phase removal for quantitative susceptibility mapping. NMR Biomed.2014;27(2):219-27.

20. Wen Y, Zhou D, Liu T, Spincemaille P, Wang Y. An iterative spherical mean value method for background field removal in MRI.MagnReson Med. 2014;72(4):1065-71.

21. Zhou D, Liu T, Spincemaille P, Wang Y. Background field removal by solving the Laplacian boundary value problem. NMR Biomed. 2014;27(3):312–9.

22. Zheng W, Nichol H, Liu S, Cheng YC, Haacke EM. Measuring iron in the brain using quantitative susceptibility mapping and X-ray fluorescence imaging.Neuroimage. 2013;78:68-74.

Question 1:

Why is it important to unwrap phase before calculating the magnetic field or susceptibility?

a. An aliased image reveals how bad the field is shimmed.
b. Unwrapping the phase leads to a loss of signal-to-noise and is a bad idea.
c. Reducing T2* signal decay obviates the need for phase unwrapping.
d. Unwrapping the phase leads to the correct local field estimate.

(Answer d)

Question 2:

Phase can be used to quantify or identify:

a. Iron content
b. Flow
c. Water versus fat
d. All of the above
(Answer d)