Fast conjugate phase image reconstruction based on a Chebyshev approximation to correct for B0 field inhomogeneity and concomitant gradients

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Introduction: Off-resonance effects can cause image blurring or artifacts in a number of fast imaging methods. Concomitant gradient (Maxwell) fields [1] and B0 inhomogeneity, including main field inhomogeneity and susceptibility-induced field variations, are two common sources of off-resonance effects. When B0 inhomogeneity and concomitant gradients are both present, correction of only one of them is insufficient and sometimes can increase blurring artifacts in some parts of the image. Since both B0 field inhomogeneity and concomitant gradients typically vary slowly in space, we could use conjugate phase reconstruction (CPR) [2] to correct them simultaneously. However, conjugate phase reconstruction is computationally prohibitive. In this abstract, we present a fast CPR method based on a Chebyshev approximation for simultaneous B0 inhomogeneity and concomitant gradient field correction. We apply the algorithm to off-resonance correction for spiral scanning. The method can be extended to other pulse sequences.

Theory: The presence of B0 field inhomogeneity and concomitant gradients results in an off-resonance phase term $\phi(\mathbf{r},t)$ that varies in both space and time. Chebyshev approximation can be used to approximate an arbitrary off-resonance phase term:

$$e^{i\phi(\mathbf{r},t)} = \sum_{k=0}^{N-1}\left[h_k(\mathbf{r})T_k(t)\right], \qquad [1]$$

where we separate the off-resonance phase term into a spatial function $h_k(\mathbf{r})$ (Chebyshev polynomial coefficients) and a time function $T_k(t)$ (Chebyshev polynomials in time). This is a different approximation than a Chebyshev approximation reported previously for B0 inhomogeneity correction [3]. Based on this separation, the final image $m(\mathbf{r})$ can be reconstructed rapidly using CPR:

$$m(\mathbf{r}) = \sum_{k=0}^{N-1}\left[c_k(\mathbf{r})p_k(\mathbf{r})\right], \qquad [2]$$

where $c_k(\mathbf{r})$ are spatial interpolation coefficients and $p_k(\mathbf{r})$ are base images that can be reconstructed by gridding. For spiral scanning, based on the theory developed by King et al [4], $c_k(\mathbf{r})$ depends only on the value of B0 inhomogeneity and concomitant gradient fields. Therefore, $c_k(\mathbf{r})$ can be pre-calculated for a range of B0 inhomogeneity and concomitant gradient field values and used later for reconstruction of any data sets acquired using same spiral readout length. The number of base images required in Eq [2] is proportional to the range of off-resonance phase accrual. We incorporate linear concomitant gradient correction [5] and center and/or linear B0 inhomogeneity correction [6] into CPR to reduce the off-resonance range.

The concomitant gradient field map can be calculated from the applied gradient. The correction of B0 inhomogeneity, however, requires the knowledge of an accurate B0 map. Semi-automatic correction [7] has been proposed to reduce this problem. Semi-automatic correction requires calculating the value of individual pixels at an arbitrary constant frequency without reconstructing the whole image at the same frequency. Chebyshev approximation is well suited for this purpose and therefore it can be used for combined semi-automatic off-resonance and concomitant field correction.

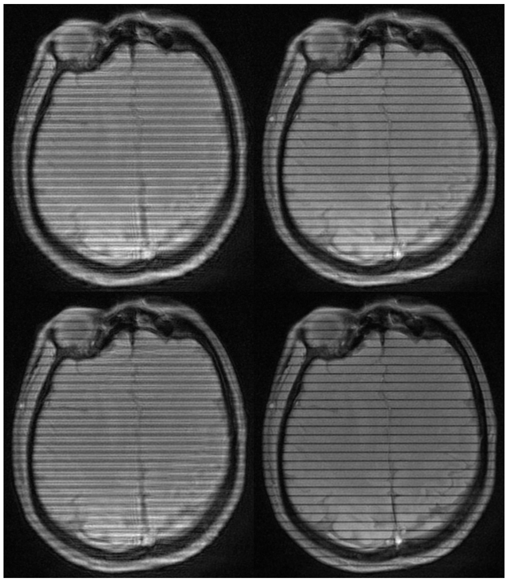

Figure 1: a) No correction; b) Maxwell field correction using Chebyshev approximation; c) Semi-automatic off-resonance correction; d) Combined correction using Chebyshev approximation

Methods and Results: We applied the proposed algorithm to both phantom and in vivo data sets acquired from a 1.5 T Siemens Avanto scanner using spiral sequences. We used the following parameters for the spiral scanning: 14 interleaves with 8192 samples and 2 microseconds ADC dwell time per interleaf, 5 mm slice thickness and 512 by 512 reconstructed image matrix. A low resolution field map was acquired using two single-shot spirals with a 1 ms echo delay. Figure 1 shows a double oblique spiral scan of a normal volunteer. Tagging lines are created to make the off-resonance effects more prominent [8]. The imaging slice is 8.4 cm off isocenter along the transverse direction, 2.6 cm off isocenter along the sagittal direction, and 4.8 cm off isocenter along the coronal direction. The imaging plane is tilted 30 degrees from transverse to coronal and then tilted 15 degrees from coronal toward sagittal. The combined correction can achieve more accurate off-resonance correction than either B0 or concomitant field correction alone for spiral scanning.

Discussion: The proposed method is computationally efficient for combined off-resonance correction in spiral scanning. The only computational difference compared to that of fast CPR methods applied for B0 inhomogeneity or concomitant gradient field correction alone is the increased number of base images resulting from the increased total off-resonance phase accrual. This added computation can be significantly reduced by incorporating linear concomitant gradient correction and center and/or linear B0 inhomogeneity correction. It can be further reduced by interchanging the sequence of gridding and demodulation [9].

Chebyshev approximation is an efficient and effective method to approximate an arbitrary phase term. Therefore, it can be a useful tool in the correction of concomitant gradient fields arising from non-spiral gradients. It can be used to correct for other complicated phase terms such as eddy currents, in addition to off-resonance phase. In addition to conjugate phase reconstruction, phase approximation using Chebyshev polynomials can also be combined with other image reconstruction methods such as SPHERE [10] to achieve fast computation.

The off-resonance phase arising from concomitant gradients varies non-linearly in time; however, it can be roughly approximated by an off-resonance phase with a linear time variation. Interestingly, semi-automatic correction using conventional fast CPR corrects somewhat for simultaneous B0 inhomogeneity and concomitant gradients, because the automatic step detects the concomitant gradients. When the concomitant gradient fields become large or the non-linearity becomes significant, semi-automatic correction is insufficient for combined off-resonance correction and the proposed combined correction becomes necessary.

The concomitant gradient fields are proportional to the distance from isocenter. Gradient non-linearity becomes more pronounced when the imaging plane is far from isocenter. We have not observed obvious effects from gradient non-linearity on the Maxwell field correction alone or the combined correction on the data sets we tested.

References: [1] Norris et al. Proc., 4th SMRM, 1037 (1985) [2] Macovski MRM 2: 29 (1985) [3] Schomberg IEEE Trans Med Imaging 18: 481(1999) [4] King et al. MRM 41: 103 (1999) [5] Sica et al, Proc., 11th ISMRM, 480 (2003) [6] Irarrazabal et al, MRM 35: 278 (1996) [7] Chen et al, Proc., 15th ISMRM 3435 (2007) [8] Wang et al, MRM 58:190 (2007) [9] Man et al, MRM 37: 785 (1997) [10] Kadah et al MRM 38: 615 (1997)