Gradient nonlinearity terms in the concomitant field for quantitative phase contrast correction

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Target Audience: Cardiac MR and physicists interested in quantitative flow measurements.

Purpose: Residual phase errors intrinsic to phase-contrast velocity measurements results in inaccurate flow quantitation. This affects imaging of various cardiac diseases, for example congenital heart disease. These errors are challenging to remedy because (1) there are stringent demands of velocity accuracy, whereby small velocity errors of 0.3% propagate to become 5% flow errors [1]; (2) there is little static tissue near the great vessels one can use to estimate the background phase of the great vessels [2]. The residual, spatially-varying phase errors are attributed to B_0 effects, such as effects of slowly-varying eddy-currents and concomitant fields (CF). The issue of CF has received little attention, because CF are perceived to be low for $B_0 \geq$ 1.5T, and because robust CF corrections (CFC) are already available [3]. However, our preliminary analyses of residual phase errors suggest a strong similarity to the calculated concomitant field (Fig.1), and hence warrant a closer examination of CF effects. Because linear gradient terms were assumed in the original CFC [3], the present work investigates the inclusion of nonlinear gradient terms into the CFC, and the impact of this improved CFC on the estimation of the background, residual phase.

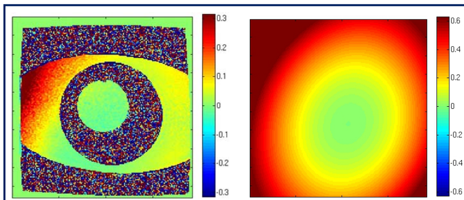

Fig.1. Residual phase (radian) after CFC in an oblique-axial section of a static phantom (left) that shows similarity in shape to the calculated CF (right).

Methods: Spherical harmonics (SH), denoted $H_{n,m}$ were found to be a convenient basis set to describe the concomitant fields B_x and B_y, as they fulfill Laplace's equations and have traditionally been used to characterize the main field (B_z) in gradient warp correction [4]. Using recurrence relations for derivatives of Legendre's polynomials, it can be inferred that the B_x and B_y of transverse gradient coils (X,Y) may be described with m = {0,2} terms (B_z has only m = 1 terms), and for the longitudinal gradient coil (Z) may be described with m = 1 terms (B_z has only m = 0 terms). For the B_x and B_y of each gradient coil, the SH coefficients (from n = 1 to 9) were determined by a linear-least-squares fit to the gradient field maps. The normalized, mean-square-error of the fit was between 0.04% and 0.12%.

In comparison to linear-CFC that groups the spatial cross-terms into four cross-terms [3], the proposed nonlinear-CFC requires a full characterization with six cross-terms. The gradient-waveform integration segment of the pulse sequence was modified to provide all six cross-terms. A 1.5T MRI system with a 55-cm patient bore (GE Healthcare, HDx) was used in the gradient field analysis. Images were also acquired using 2D cine-phase-contrast of a static, bi-compartment (torso and great vessels), copper-sulfate phantom. The tested parameters were oblique-axial or oblique-sagittal prescriptions, VENC = {200,100} cm/sec, and flow-compensation on or off, resulting in eight acquisition permutations. For each acquisition, a quadratic-spatial fit of the residual, static phase from only the torso compartment was used to estimate the residual phase in the great-vessels compartment. Velocities after subtracting the fitting result were compared against a tolerance level of ±6 mm/sec = ±0.3% × 200 cm/sec. A hybrid-fit that combined linear-spatial terms with the calculated CF was also tested, to determine if the calculated CF was a better characterization of the residual phase than a quadratic characterization.

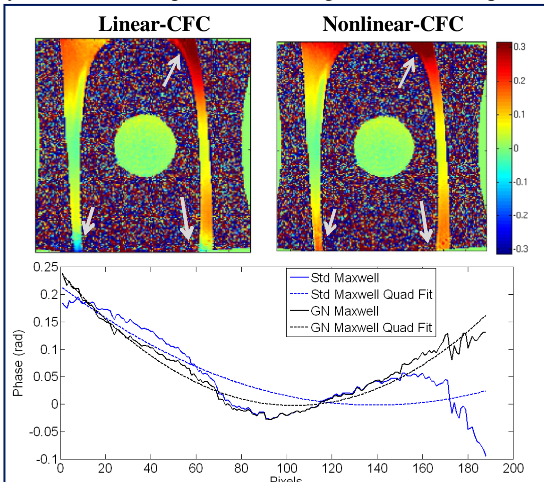

Fig. 2. Residual phase in an oblique-sagittal section of a static phantom after linear-CFC (top left) and nonlinear-CFC (top right). The arrows indicate observed differences in the phase due to nonlinear-CFC. Plots of residual phase in the vertical direction and the resulting quadratic fit are shown (bottom).

Results: Fig. 2 shows that the nonlinear-CFC had an impact on the residual phase in regions far from but not near isocenter where the great vessels typically are found. However, the overall residual phase appeared to be more quadratic in shape after nonlinear-CFC. Table 1 shows results for each combination of CFC and fitting methods, whereby each of the eight acquisition permutations were grouped based on the fraction of pixels in the great vessels that met the acceptable velocity tolerance. Quadratic-fit was worse than no fitting, but the hybrid-fit was superior to no fitting. The hybrid-fit with nonlinear-CFC was superior to the hybrid-fit with linear-CFC, with 6/8 vs. 4/8 of the acquisitions having >90% pixels within the tolerance levels.

Table 1. Residual phase fitting results, showing the number of tested acquisition permutations after linear-CFC or nonlinear-CFC, grouped by the percentage of pixels within the acceptable velocity tolerance.

% Great vessel pixels within ± 6 mm/sec	Linear-CFC			Nonlinear-CFC		
	No fit	**Quad fit**	**Hybrid fit**	**No fit**	**Quad fit**	**Hybrid fit**
< 70%	3	4	3	2	4	0
> 70%, < 90%	2	3	1	3	3	2
>90%	**3**	**1**	**4**	**3**	**1**	**6**
Total	8					

Discussion and Conclusion: The observation of a high degree of similarity between the residual phase from phase-contrast imaging and the concomitant field motivated this investigation into gradient nonlinearity. A nonlinear concomitant characterization resulted in changes only in the shape of the residual phase. But when incorporated into a hybrid-fit method, the nonlinear-CFC provided an improvement over linear-CFC. The proposed hybrid-fitting must be evaluated in several different MRI systems to show robustness. For a fixed imaging field-of-view, the effects of gradient nonlinearity in CFC would be highly dependent on the linearity specifications of the gradient design.

References: [1] Gatehouse PD, Rolf MP, Graves MJ *et al. JCMR* 2010. 12:5. [2] Walker PG, Cranney GB, Scheidegger MB *et al. JMRI* 1993. 3:521-530. [3] Bernstein MA, Zhou XJ, Polzin JA *et al. Magn Res Med* 1998. 39:300-308. [4] Glover GH, Pelc NJ. US Patent 4591789.