Self-calibrated phase-contrast correction of nonlinear background phase in quantitative cardiac imaging

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Target Audience: Radiologists, cardiologists, MR physicists

Purpose: In cardiac phase-contrast (PC)-MRI, pulmonary-systemic flow ratio measurements (Qp/Qs) rely on accurate velocity quantitation. However, residual background phase in PC-MRI introduces velocity errors that result in biased Qp/Qs measurements[1]. While static phantoms have been used to offset this bias[2], improved workflow may be realized if self-calibrated correction is performed by fitting the phase of static tissue from the *in vivo* images[3]. The residual phase, however, can be nonlinear in space and the vessels of interest, e.g. great vessels, are often far from any static tissue in the image. This means that a linear-only fitting[3] can sometimes result in under-fitting, while using higher spatial-orders can lead to over-fitting.

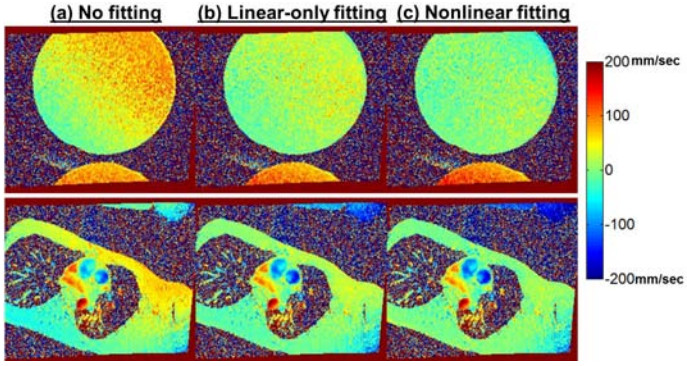

Figure 1: Oblique 2D CINE-PC velocity maps from static phantom (top) and *in vivo* (bottom) scans, with no fitting applied (a), *in-vivo*-derived linear-only fitting (b) and *in-vivo*-derived nonlinear fitting (c). Reduced residual velocity was observed with both linear-only and nonlinear fitting methods, but the residual phase was more uniform with nonlinear fitting.

Methods: We propose a nonlinear self-calibrated phase-contrast (SCPC) method, which assumes a nonlinear shape. This follows observations that the residual phase is similar in shape to that of the concomitant field[4]. Therefore as opposed to linear-only fitting that uses 4 terms (constant + XYZ), the nonlinear-fit has 5 terms that includes the concomitant field. Further steps are taken to improve the fit, which include automated iterative removal of outliers that frequently occur at tissue boundaries, and heavier weighting of velocities from the quiescent cardiac phase to reduce effects from flow artifacts at systole. To prevent over-fitting, the corrected phase is weighted by an assigned value, determined by the probability of the fitted phase exceeding previously proposed velocity specification limits[2] of ±6 mm/sec. In other words, if the fitted phase has only a small effect, no correction is done.

To evaluate the accuracy of the fitted velocities, 12 healthy subjects were imaged at 3T (GE MR750w, MR750) and 1.5T (GE HDx) with 2D CINE-PC (FOV = 30-38 cm, 5 mm slice, TR = 5.5-7.2 msec, TE = 3.3-4.2 msec, VENC = 1200-2000 mm/sec, 4 views per segment, reconstructed CINE phases = 20-30), yielding 31sets of CINE-PC images. Velocities within a 4-cm radius region at isocenter (near the great vessels) with and without correction were compared with ground truth stationary phantom correction[2]. To evaluate the effects on Qp/Qs, 7 patient subjects without cardiac shunt were scanned at 1.5T (GE MR450w) without subsequent scans of a static phantom.

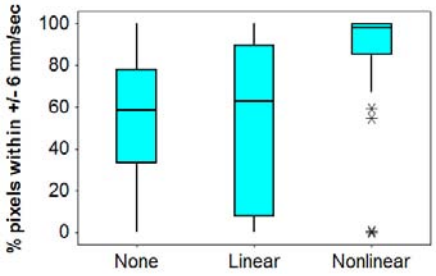

Figure 2: Boxplots of % pixels within ±6 mm/sec velocity limits in 31 CINE phase-contrast images. 27 images were acquired from 11 subjects at 3T and 4 images were acquired from 1 subject at 1.5T. 4/31, 7/31 and 25/31 instances had >90% pixels (within a 4-cm radius at isocenter) within the velocity limits for no fitting, linear-only and nonlinear, respectively.

Results: Figure 1 shows exemplary results obtained using the proposed correction, where the residual phase *in vivo* and in the static phantom with the nonlinear correction were reduced compared to no-fitting and linear-only fitting. The quantitative velocity analysis is shown in Figure 2, where nonlinear was superior to both linear-only fitting and no fitting. 25/31 scans had >90% of pixels within the specified velocity limits. The quantitative results of Table 1 show that in 2 patients the Qp/Qs ratio was improved (closer to 1.0), and no change in Qp/Qs was seen in the other patients.

Table 1. Aortic (Qs) and pulmonary (Qp) flow (in ml/heartbeat) and the Qp/Qs ratios obtained for 10 patients. (*: improvement after SCPC, ^: one case of aortic regurgitation)

#	No correction			SCPC		
	Qs	Qp	Qp/Qs	Qp	Qs	Qp/Qs
1	92	87	0.9	98	84	0.9
2	34	59	1.7^	35	59	1.7^
3	71	80	1.1	71	68	1.0*
4	44	55	1.2	45	53	1.2
5	62	78	1.3	61	81	1.3
6	57	58	1.0	60	58	1.0
7	63	77	1.2	71	68	1.0*

Discussion and Conclusion: The self-calibrated, nonlinear phase-contrast correction provided superior velocity accuracy to linear-only fitting. The SCPC method also provided equal or better results in quantitative Qp/Qs measurements. Residual motion in the static phantom and possible thermal drift may bias phantom results, and are also reasons for favoring self-calibration. The theoretical basis for the nonlinear shape may lie in complex interactions with eddy-currents, which are not accounted for in the standard concomitant field correction. Further work involves validation on more scanners and with quantitative flow phantoms.

References: [1] Gatehouse PD, J Cardiovasc. Magn. Reson. 2010;12:5. [2] Chernobelsky A, J Cardiovasc. Magn. Reson. 2007;9:681-685. [3] Walker PG, JMRI1993;3:521-530. [4] Bernstein MA, Magn. Reson. Med. 1998;39:300-308.