Evidence across CMR sites and systems of phase-contrast background velocity offsets requiring correction for accurate regurgitant or shunt flow

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Purpose: To assess velocity offsets in the background of phase-contrast acquisitions across CMR sites and systems.

Introduction: Phase-contrast CMR potentially provides accurate measurements of aortic or pulmonary regurgitation, cardiac output and shunt flow. Among several well-known errors we examined one: a 2cm/s velocity offset (i.e. around 1% of a typical VENC) can cause >20% error in cardiac output (1,2) with larger consequences for regurgitation and shunt flow, particularly in dilated vessels. As a collaborative group, we measured velocity offsets across sites and scanner types, an initiative backed by the European Society of Cardiology CMR Working Group.

Method: To eliminate flow, 10-15 litre uniform gelatine phantoms were used, containing 5 millimoles/litre Gd-DTPA for SNR. We used similar phase-contrast sequence parameters at each site, measuring the same 45^{o} oblique 'aortic' (Ao) and two 'main pulmonary artery' (MPA) planes at each site, repeating each plane at 5 head-foot shifts of 0, +/-25, +/-50mm. The Ao plane used ant-posterior phase-encode, whereas the MPA plane was repeated with ant-posterior and left-right phase-encoding. Constant sequence parameters were: concomitant gradient correction (3), retro-gated cine, through-plane Venc=150cm/s, SLT=6mm, FOV= 320x320mm, uninterpolated pixels 1.25(FE)x2.5(PE)mm, bandwidth 355Hz/pixel, 6 rawdata lines per cardiac cycle, no cine data-sharing or parallel imaging. Unless stated, velocity encoding was asymmetric (i.e. phase-subtraction of compensated and velocity-encoded). The gradient-echo was asymmetric (early for short TE); Philips applied partial-echo sampling which may explain its shorter TR. Slower machines were excluded because fast gradient performance was necessary. Three 1.5T scanner types were compared, and tests were reproduced exactly at the 4 sites of each scanner type by protocol file transfer: GE (4 sites) Signa Excite 14M5. Symmetric velocity-encoding (compulsory), flow analysis on, flow optimization off, TR5.9-6.0ms, TE2.9-3.0ms (image orientation dependent). Philips (4 sites) Achieva R2.53. TR5.5ms, TE2.8ms, asymmetric RF pulse (late centre), LPC off. Siemens (4 sites) Avanto VB15 TR6.6ms, TE2.8ms. All velocity images were reconstructed without offset correction (which performed unrealistically well in the large uniform phantom). The largest mean velocity offset in cm/s (over 300mm^2 ROI) anywhere within 50mm in-plane from the magnet z-axis was recorded for each plane (i.e. covering the region where cardiac outflow ROIs are usually placed). All images were measured independently at two separate institutions, where errors from cine frame variations were also estimated.

Results Table: For the three plane orientations described above, the first value in each table cell is the largest velocity offset (cm/s) found as stated in Methods for the plane with 0mm head-foot shift. The values in brackets are (min max) of the velocity offsets found in all 5 shifted planes (-50,-25,0,25,50mm head-foot shift) using the same method. The four rows per plane are from the four sites using each scanner type. The column order is not specified, i.e. scanner types are not identified. All results are the average from the two image analysis centres, ±0.4cm/s worst-case error between them. (* = off-isocentre shifted slice results invalid for the protocol used on this scanner type, to be reacquired before ISMRM).

Plane	Site	Scanner type 1	Scanner type 2	Scanner type 3
Aorta	**1**	**2.2 (*)**	**2.3 (1.6 3.9)**	**1.1 (1.0 1.5)**
	2	**2.8 (*)**	**1.2 (1.2 1.6)**	**1.6 (1.2 2.3)**
	3	**0.6 (*)**	**1.6 (1.4 2.1)**	**0.9 (0.7 1.2)**
	4	**1.3 (*)**	**2.8 (2.8 3.2)**	**1.1 (0.6 2.2)**
MPA(HF phase-enc)	**1**	**2.0 (*)**	**3.3 (1.8 5.5)**	**0.4 (0.4 1.1)**
	2	**1.6 (*)**	**3.7 (3.7 4.4)**	**0.9 (0.8 1.5)**
	3	**1.5 (*)**	**3.7 (3.0 5.3)**	**1.3 (1.0 1.3)**
	4	**1.7 (*)**	**4.8 (4.7 5.4)**	**1.3 (1.3 2.7)**
MPA(LR phase-enc)	**1**	**2.7 (*)**	**5.3 (4.8 5.8)**	**0.4 (0.4 0.5)**
	2	**2.8 (*)**	**3.1 (2.9 3.9)**	**1.4 (0.9 1.9)**
	3	**1.9 (*)**	**3.6 (3.4 3.9)**	**1.6 (1.2 2.0)**
	4	**2.0 (*)**	**4.8 (4.7 5.4)**	**1.5 (1.5 3.8)**
For the isocenter planes only:				
Average	**All**	**1.9**	**3.4**	**1.1**
Maximum	**All**	**2.8**	**5.3**	**1.6**

Discussion and Conclusion: The results are believed reliable because: 1) cine images were stable without ghosting, 2) similar values in nearest parallel shifted slices, 3) most of the independent image analysis results agreed within estimated error limits. As available using couch move options, imaging with zero slice-shift reduced some extreme velocity offsets, but did not always minimise them, see (min,max) values in Table 1. No scanner had sufficiently small uncorrected error in all three planes (even at zero slice-shift) for reliable accuracy in the sensitive clinical purposes described above. Comparison of hardware is prevented by remaining differences between sequences; we emphasise that small sequence changes may completely alter velocity offsets. An offset of 1% of Venc (π/100 radians) is impressive engineering, representing a residual gradient ≈0.02% (for approx. TE/2, 50mm from isocentre) of typical velocity-encoding gradients! This great sensitivity to adjustments such as pre-emphasis may explain variations between nominally identical sites. Various automatic offset corrections are routinely installed. However, this study intentionally omitted them as their accuracy may depend on application. Offset correction uses stationary tissue pixels which can be identified automatically based on their smaller temporal variation (1), or identified by users during postprocessing. This approach is sometimes limited by insufficient stationary tissue, its low SNR in flow images, and possible spatial non-linearity. A more time-consuming approach repeats identical flow acquisitions on a static phantom, subtracting the corresponding apparent phantom velocities from the clinical acquisition (2). For the cardiac applications above, there is a need for (if possible) optimized acquisition protocols, further improvements in system engineering and reliable correction methods to minimise velocity offsets. We conclude that most systems require velocity offset correction of flow images for these most sensitive cardiac applications.

Acknowledgements: Drs Jason Polzin (GE), Marc Kouwenhoven (Philips), Andreas Greiser (Siemens).

References: 1) Lankhaar, Hofman et al JMRI2005 2) Chernobelsky, Shubayev et al JCMR2007 3) Bernstein, Zhou et al MRM 1998