Optimal bipolar gradient design to reduce velocity offsets.

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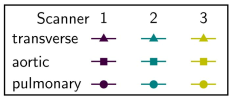
Introduction: Phase-contrast velocity quantification is a valuable tool in cardiac magnetic resonance imaging. However, eddy-currents cause additional signal phases, which result in offsets in the velocity measurements. Even a relative small offset (>0.6 cm/s) can result in significant errors in clinical parameters [1]. Gatehouse et al. [2] showed that for a typical breath-hold flow protocol none of several commercial MR scanners had sufficiently small offsets for reliable accuracy in cardiac volume flow measurements. Optimal sequence design by slowing down the sequence, by timing or gradients, might reduce the offsets due to eddy currents [3]. Furthermore, the effect of asymmetric versus symmetric velocity encoding is largely unknown. With an adapted sequence these concepts were tested in a setting comparable to a clinical set-up.

Method: A standard flow quantification sequence (retrogated phase-contrast spoiled gradient echo sequence) on a 1.5T scanner (Magnetom Avanto, Siemens, Erlangen, Germany) was adapted to obtain full control over the velocity encoding gradients. The adjusted sequence had parameters for: 1. setting a time delay between velocity encoding and signal read-out (*Td*), 2. variation of the amplitude and slew rate of the velocity encoding gradients, and 3. the option to switch from the standard asymmetric (velocity encoded - velocity compensated) to symmetric (positive - negative velocity encoded) velocity encoding. Measurements were performed on three different sites. A large uniform phantom was used. The phantom fluid was allowed to settle down for at least 5 minutes before the first measurement was started. The basic breath-hold flow quantification protocol was derived from the one used by Gatehouse et al. [2]: TR 8.3 ms, TE 4.0 ms (no overlap of the bipolar pulse with slice selection gradients), concomitant gradient correction, retro-gated cine, through plane Venc 150 cm/s, asymmetric encoding, SLT 6 mm, FOV 320x320 mm, uninterpolated pixels 1.25(FE)x2.5(PE) mm, bandwidth 355 Hz/pixel, 6 raw data lines per cardiac cycle, no cine data-sharing or parallel imaging. The timing delay Td, encoding strategy (asymmetric or symmetric) and gradient amplitude and slew rate were varied to identify their effects on velocity offset. All measurements were performed in three orientations: transverse, aortic (T>S -45°), and pulmonary vessel orientation (T>C 45°).

All velocity images were reconstructed without further offset correction. The largest absolute mean velocity offset in cm/s (over a 30 mm diameter ROI) anywhere within 50 mm (for transverse and aortic) or 70 mm (for pulmonary) in-plane from the magnet iso-center was recorded for each scan (i.e. covering the region where cardiac outflow ROIs are usually placed). This approach results in the "worst-case" offset relevant for a typical cardiac output measurement. Relationships were tested by linear regression analysis.



Results: Velocity offsets showed a great sensitivity to time delay Td and varied from scanner to scanner. Figure 1 shows the offset as a function of Td for three different scanners. No correlation of the velocity offsets with time delay Td was found. Symmetric encoding gave significantly lower offsets (-0.4 cm/s, P<0.01) (Fig. 2). Reduced gradient amplitude (Fig. 3) and slew rate of the bipolar gradients did consistently reduce offsets. Detailed results of the multiple regression analysis are given in Table 1.

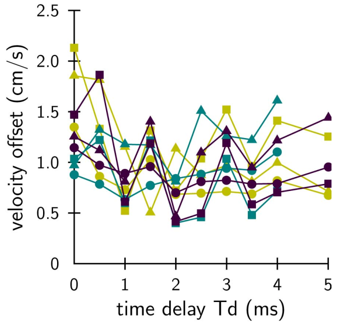


Figure 1: Velocity offset as a function of time delay Td. Variable and marked sensitivity to timing was found.

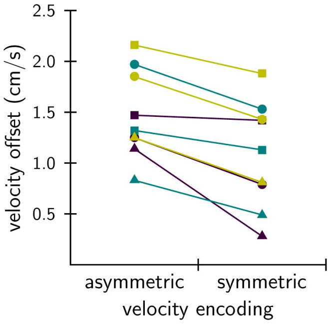


Figure 2: Velocity offset with asymmetric and symmetric velocity encoding. Symmetric encoding was significantly lower.

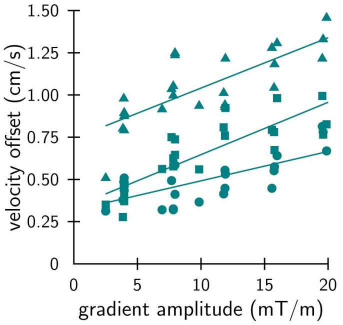


Figure 3: Velocity offset as a function of bipolar gradient amplitude with varying slew rate. Lines represent linear fits to the data.

Table 1: Results from multiple regression of gradient amplitude and slew rate on velocity offset.

	scanner 1			scanner 2			scanner 3			average		
	transv	aortic	pulm	transv	aortic	pulm	transv	aortic	pulm	transv	aortic	pulm
grad ampl (cm/s per mT/m)	0.02	0.05	0.04	0.01	0.03	0.03	0.04	0.11	0.07	0.02	0.06	0.05
slew rate (cm/s per mT/m/s)	2.28	0.85	-0.86	2.23	1.23	0.14	0.85	-0.34	0.30	1.79	0.58	-0.14
correlation coefficient r^2	0.57	0.49	0.47	0.66	0.73	0.61	0.81	0.89	0.81	0.68	0.70	0.63

Discussion: Velocity offsets were very sensitive to small variations in timing, no correlations with timing delay Td were found and offsets differed considerably between the systems. These effects depend on the characteristic time of the dominant eddy currents in the velocity offset. For eddy currents with a time constant in the order of ms (~TE), small changes in timing are expected to cause changes in offsets. Offsets induced by eddy currents with short (<TE) or long (>TR) time constants are much less time dependent [4]. With symmetric encoding velocity offsets were significantly lower than with asymmetric encoding. This can be understood by the more efficient internal cancellation of the symmetric approach. Velocity offsets decreased with reducing velocity encoding gradient amplitude and slew rate, as was expected from theory. The correlations found were highly significant, but generally not very strong and with varied considerably from scanner to scanner. This was probably also due to the timing; when the gradients change, the timing changes also. This explains why general protocol settings often show inconsistent effects.

Current protocol options should be extended with symmetric encoding and additional gradient modes for the bipolar gradient. With these options it will be possible to reduce velocity offsets down to an acceptable level (<0.6 cm/s) for volume flow quantification in transverse and aortic orientations. However, the slower velocity encoding gradients are usually incompatible with the time constraints of a breath-hold protocol and users should always be aware of the sensitivity to minor changes in the protocol and differences between scanners. Pulmonary volume flow quantification will remain a challenge as the region of interest is generally further away from the isocenter. In those cases offset correction in postprocessing has to be performed.

References: [1] Kilner et al. JCMR;9:723, [2] Gatehouse et al. ISMRM '09;325, [3] Bieri et al. MRM;54:129, [4] Zhou et al. ISMRM '04;552.