# Importance of different correction methods for optimized 3D visualization of 3-directional MR velocity data

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**Introduction:** Phase contrast MRI (PC-MRI) is widely used to assess blood flow. In recent years, the application of 3D PC-MRI with three-directional velocity encoding has gained increased interest for the evaluation of 3D hemodynamics in entire vascular structures [1,2]. In this context, 3D visualization of time resolved 3D phase contrast data plays an important role for the analysis of flow characteristics inside the vessels of interest [3]. Its application in clinical studies therefore implies high accuracy of the calculated 3D streamlines and particle traces which are typically used to visualize the underlying flow information in 3D or 4D. PC-MRI relies on the measurement of changes in the signal phase due to flow or motion in the presence of known linear magnetic gradient fields. It is well know that phase offset errors due to gradient field distortions are caused by three major effects including eddy currents [4], concomitant gradients (aka Maxwell terms) [5], and gradient field non-linearities (non-ideal gradient coil design) [6]. All three effects can severely distort the measured three-directional velocities (Vx, Vy, Vz) and thus result in distortion of streamlines and particle traces which might lead to incorrect flow pattern visualization and subsequently to false conclusions regarding flow characteristics. Although the theory and effect of gradient field distortions are well understood, no detailed analysis of their effect on 3D visualization has been presented to date. In this study correction methods for Eddy currents, Maxwell terms and gradient inhomogeneities were applied to three-directional velocity data to systematically evaluate and quantify their effect on the visualization of streamlines.

**Methods:** For flow experiments a straight tube and a bent tube with an angle of 90° were integrated into a flow circle using a flow pump (MEDOS Medizintechnik AG, Germany) generating constant flow of 5.5 l/min (figure 1). Furthermore, a static phantom was placed next to the tubes. Blood mimicking fluid (60% water, 40% glycerol) was used to imitate blood properties and contrast agent was added to t to increase SNR. All experiments were performed on a 3T MR system (TRIO, Siemens, Germany) using a time resolved phase contrast MRI pulse sequence with three-directional velocity encoding. Imaging parameters for all experiments were: venc: 30m/s, spat. res.: $1.04\times1.04\times1.00\text{mm}^3$, FOV: $300\times300\text{mm}^2$, slices: 88, flip angle: 15°, TE: 3.7ms. Additionally measurements without flow were performed for both experiments. Four different correction methods were applied to the acquired flow data to evaluate the performance on the visualization of streamlines. 1): For first order Eddy current correction a plane was fitted to the static phantom in a least square sense to determine and subtract a linear phase drift and offset from the phase contrast data. 2): For second order Eddy current and Maxwell correction a second order polynomial fit was adapted to the static phantom to subtract the second order phase evolution from the phase data for each slice. 3): As an alternative correction for Eddy currents and Maxwell terms the flow off measurements were subtracted from the flow on measurements. This approach was based on the assumption that eddy current induced phase shifts and Maxwell terms should remain constant for the same imaging parameters. 4) Effects of gradient field inhomogeneities were corrected by calculating the relative field deviations according to vendor specific gradient field model of the three-directions in each voxel. 3D visualization (EnSight, CEI, NC, USA) was used to compare 3D flow characteristics for the different correction methods. A home built tool (Matlab, The Mathworks, USA) was used for lumen contour segmentation and quantification (streamline counts) within the tubes.

**Results:** The subsequent application of all correction methods resulted in an improvement of 3D streamline visualization in comparison to the uncorrected data. The uncorrected data showed strong distortion of streamlines directly after the emitter plane as well as 15 cm up- and downstream from the emitter plane (figure 2a) and 3a)) for the straight and the bent tube. First order eddy current correction clearly improved the streamline visualization at the emitter plane and at the end of the tubes. The second order eddy current correction further enhanced streamline visualization with only small distortion at the end of the tubes. The subtracted data showed best results in terms of correction for Eddy current and Maxwell terms. The remaining distortions of streamlines were partly removed by correcting for gradient field inhomogeneities. The improved visualization related to the application of the correction methods is also summarized in table 1 showing the number of streamlines approximately 15 cm upstream and downstream from the emitter plane. However, even tough the correction of gradient field inhomogeneities showed improved streamline visualisation, the streamline count showed less streamlines than expected.

| | uncorr. | Eddy 1st | Eddy 2nd | sub. | grad corr. |
|---|---|---|---|---|---|
| straight | 75 / 31 | 123 / 33 | 170 / 158 | 169 / 211 | 180 / 194 |
| bent | 129 / 76 | 154 / 96 | 159 / 136 | 194 / 180 | 213 / 136 |

***Table 1:*** *Number of streamlines approx. 15 cm upstream / downstream from the emitter plane (400 emitters) in the middle of the straight and bent tube. The number of streamlines reaching the inflow and outflow plane (dotted white line in figure 2 and 3) increased for each correction method in comparison to the uncorrected data. In general only 50% or less of the emitted streamlines reached the inflow or outflow plane.*

**Discussion:** The results of this study clearly demonstrate the importance of correcting for the three major sources of gradient field distortions for 3D visualization of 3-directional MR velocity data. Although these distortions are well understood, appropriate correction methods are often absent or only partly applied in the present literature. It is important to note that such phase offset errors exhibit a substantial and non-linear increase with increasing distance from the isocenter. 2D phase contrast measurements performed in single vessel segments at or near the isocenter of the magnet are thus relatively insensitive to these errors. For 3D PC-MRI with large anatomic coverage, however, this is not the case. Errors induced by gradient field distortions need to be corrected to ensure accurate visualization as demonstrated in this study. This is of particular importance for typical visualization techniques such as streamlines. Even small systematic inaccuracies can propagate into larger visualization errors with increasing distance from the emitter plane.

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**References:** [1.] Wigstrom L, et al. MRM 1999;41(4):793-799 [2.] Frydrychowicz A, et al. JCAT 2007;31(1):9-15 [3.] Buonocore MH, MRM 1998;40(2):210-226. [4.] Walker PG, et al. JMRI 1993;3(3):521-530 [5.] Bernstein MA, et al. MRM 1998;39(2):300-308 [6.] Markl M, et al. MRM 2003;50(4):791-801

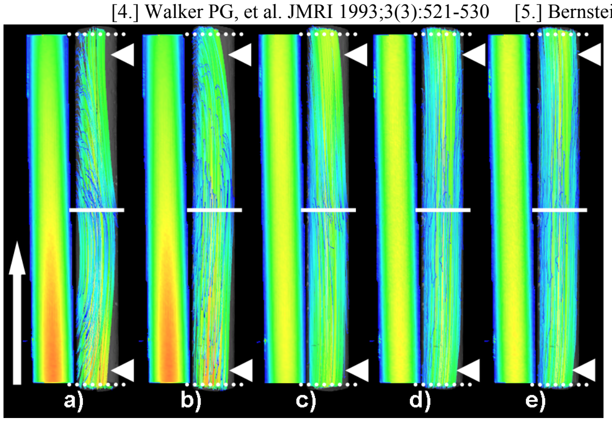


***Figure 2:*** *Streamline visualization inside the straight tube for a) uncorrected data b) first order eddy current correction, c) second order eddy current and Maxwell correction d) subtraction (flow on minus flow off) correction for second order eddy currents and Maxwell and e) Eddy current, Maxwell, and gradient inhomogeneity correction. Streamlines were emitted from the middle of the tube (white line). The dotted white lines indicate the planes for the streamline counts up stream and down stream from the emitter plane.*

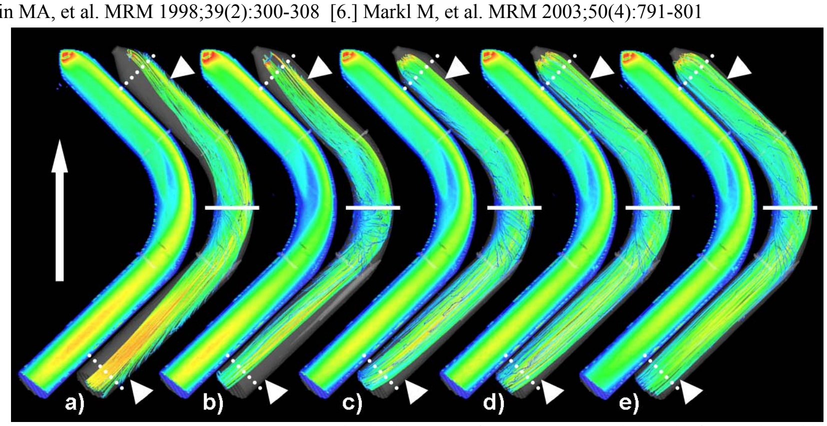


***Figure 3:*** *Streamline visualization inside the bent tube for a) uncorrected data b) first order eddy current correction, c) second order eddy current and Maxwell correction d) subtraction (flow on minus flow off) correction for second order eddy currents and Maxwell and e) Eddy current, Maxwell, and gradient inhomogeneity correction. Streamlines were emitted from the middle of the tube (white line). The dotted white lines indicate the planes for the streamline counts up stream and down stream from the emitter plane.*