Radial displacement errors and correction efficiency for streamline visualization in 4D-Flow MRI

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Introduction: 4D Flow MR imaging is a compelling approach for measuring vascular anatomy and hemodynamics. Visualizing the velocity data with streamlines has become an important tool for displaying complex vascular hemodynamics, which are measured as dynamic velocity vector fields. However certain errors can significantly degrade streamline quality and even misrepresent the flow field. One such source of error is displacement artifact due to radial acceleration, which while small on a voxel by voxel basis, can create large errors when integrated over longer streamlines. These errors are more pronounced in non-Cartesian acquisitions due to multi-direction readouts; however they affect all acquisitions to some degree. This work aims to demonstrate and analyze the effectiveness of various potential methods for correcting radial displacement errors with respect to streamline quality.

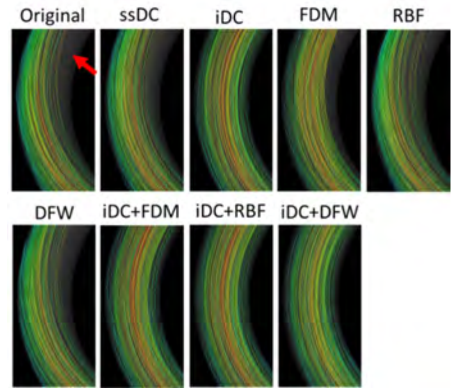

Figure 1. Streamlines in a segment of the circular digital phantom, showing the original dataset in the top left and each of the corrected datasets as labelled. Of particular importance is the tendency of lines to head towards the outside (left) of the vessel, which is the direction the displacement errors move the lines and is pointed out with a red arrow in the top left image.

Corrections: One method of correcting displacement errors is to use streamline based calculations seeded at each imaging voxel to determine an approximate displaced location, and then use those velocity values. This method will be referred to as a single-step displacement correction (ssDC) [1]. Additionally an iterative version of this method (iDC) [2] can be used to find a flow field consistent with the displacement streamline estimates. Displacement artifacts inherently create divergent flow fields, while vascular flow fields should be divergence free. Methods that impose divergence-free flow fields have shown to be very effective for decreasing noise in 4D-flow data, however their effect on coherent divergent errors has not been analyzed. Here we tested finite difference (FDM) [3], radial basis function (RBF) [4], and wavelet (DFW) [5] based methods in the context of correcting for displacement artifacts. In the case of a velocity field perturbed by displacement artifact and noise, a combination of divergence-free methods and displacement corrections might be preferable, so combinations of methods are also tested, where the iDC method is applied and then divergence free methods are used to remove residual errors and noise.

Methods: A digital flow phantom was created depicting laminar flow through a circular vessel. The velocity was displaced by a realistic amount and stochastic noise was added in k-space to reach an SNR = 10. Streamlines were seeded at each voxel in the vessel and allowed to propagate until leaving the vessel or confirmed stable within the vessel. Corrections were applied to this data and then streamline quality was measured as a percentage improvement in length compared to the completely uncorrected case.

Cranial in-vivo flow data were acquired in a patient, following accepted IRB protocols with a 3D radially undersampled phase contrast acquisition (PCVIPR) [6] on clinical 3T scanners (Discovery MR750, GE Healthcare, Waukesha, WI) with a scan time of ~6 minutes and whole brain coverage (TR/TE = 8.2/2.8, venc = 80 cm/s). The displacement time associated with the acquisition was ~3ms and due to the non-Cartesian trajectory, the displacement is in all 3 directions. Streamlines were seeded in both internal carotid arteries in the upper neck and the mean length of the lines was measured. Streamline lengths were also measured after corrections to test for improvements.

Percent improvement in streamline length

	Method	Phantom improve (%)	in-vivo Improve (%)
Streamline Methods	ssDC	16.5%	17.0%
	iDC	131.4%	98.8%
Div-free Methods	FDM	43.8%	48.1%
	RBF	16.5%	8.6%
	DFW	0.3%	33.1%
Combo Methods	iDC+FDM	125.3%	57.0%
	iDC+RBF	137.4%	88.4%
	iDC+DFW	136.1%	111.9%

Table 1. Improvements in mean streamline length as compared to the uncorrected original data set for both digital phantom and in-vivo experiments.

Results: Figure 1 shows a depiction of streamlines in a segment of the digital phantom after each correction. Table 1 shows the improvements in streamline length from both the phantom and in vivo experiment. The largest individual gain is mostly from the iDC method, while combinations of the iDC and DFW give the overall best performance. Figure 2 shows streamlines in the original in-vivo dataset and after correction. Flow rates for all experiments were measured and were never changed by more than 4%.

Conclusion: This work shows the improvements in streamline visualization with the addition of correction methods tailored to displacement artifacts, mainly an iterative streamline based approach. Divergence-free methods had some impact on the displacement errors, though the degree of correction is unclear. Additional work is needed to classify exactly how divergence free methods behave with coherent, divergence causing errors as opposed to incoherent noise. The in vivo example demonstrates how uncorrected streamlines can give fairly inaccurate impressions of the splitting of flow at bifurcations. This misrepresentation is greatly improved with proper correction of the displacement artifacts. Combining displacement corrections and divergence free methods allows for noise and displacement to be accounted for, giving large gains in streamline quality. In future work, this method will be investigated in a larger cohort to fully classify performance gains.

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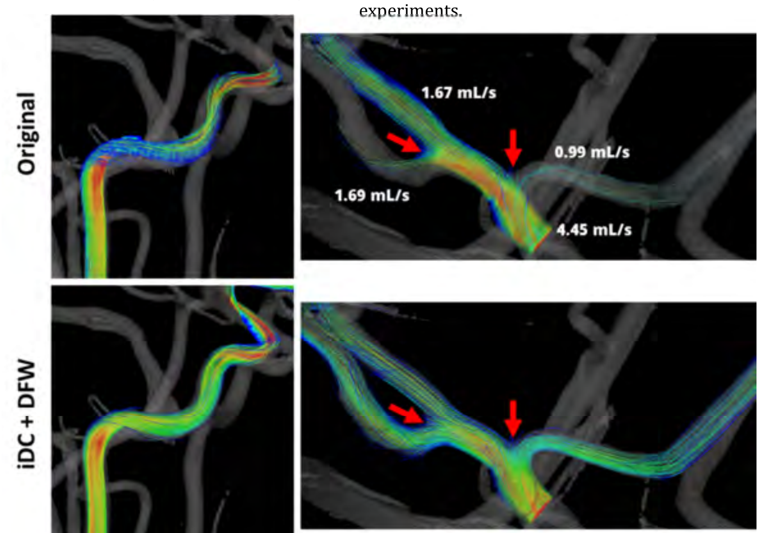

Figure 2. Streamlines in-vivo in the uncorrected and iDC+DFW corrected datasets. In the left column are the measured streamlines in the internal carotid artery, where it can be seen that significantly fewer lines are leaving the vessel at each of the curves when corrected. In the right column are 2 major bifurcations in the circle of Willis, depicted with red arrows. Additionally, flow values are listed for the major vessels. At these points it can be seen that the displacement corrected dataset represents the actual flow distribution much better.

1) Steinman, et al. *JMRI* (1997) *7*(2), 339-346. **2)** Thunberg, et al. *JMRI* (2002) 16(5):591-7. **3)** Song, et al. *JMRI* (1993) 3(4):587-96. **4)** Busch, et al. *MRM* (2013) 69(1):200-10. **5)** Ong, et al. *MRM* (2014) *ahead of print* **6)** Johnson, et al. *MRM* (2008) 60(6), 1329-1336.