Probabilistic Streamline Estimation from Accelerated Fourier Velocity Encoded Measurements

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Introduction

Cine phase-contrast flow measurements allow for the non-invasive assessment of blood velocity in the cardiovascular system. Streamline estimation based on three-dimensional velocity vector field data is a common visualization method of blood flow patterns. Velocity encoded phase data are assumed to reflect mean velocity information of voxels superimposed by noise. Partial volume effects, however, distort the intra-voxel velocity distribution near vessel walls and in complex velocity fields, for example. Accordingly, velocity distributions are skewed and no longer follow a normal distribution. To this end, an estimated streamline using phase-contrast data represents one possible realization of the flow field. To consider all possible streamlines, a probabilistic streamline representation has been proposed [1]. This method does, however, assume normal noise distribution. In Fourier velocity encoding [2], spectral velocity distributions of voxels are measured and provide information of the true velocity scattering.

In this work, the combination of k-t PCA [3] accelerated Fourier velocity encoding and probabilistic streamline estimation is proposed. Using computer simulations and in-vivo data acquired in the femoral artery of healthy subjects it is demonstrated that streamline estimation from Fourier velocity encoded data is significantly improved relative to visualizations based on conventional phase-contrast data.

Methods

Three-dimensional Fourier velocity encoding (FVE) was implemented on a 3T Philips Achieva system (Philips Healthcare, Best, The Netherlands). Twelve velocity encoding steps per dimension and a non-encoded reference scan were acquired in the femoral artery of healthy subjects. Five-fold undersampling in k-t space was applied yielding a net scan time reduction of 4.2. Remaining scan parameters were as follows: cardiac triggered segmented gradient echo sequence, number of slices: 15, number of heart phases: 20, spatial resolution: 1.5x1.5x1.5 mm^3, temporal resolution: 41 ms, velocity encoding range: ±180 cm/s, 0.75% partial Fourier sampling along k_y and k_z, T_R: 8.1 ms, T_E: 5.2 ms.

The undersampled data were reconstructed using the k-t PCA method implemented in Matlab (Mathworks, Natick, USA) and run on standard PC hardware yielding time-resolved data in the space-velocity domain (Figure 1a-b).

Velocity spectra for each voxel were interpolated and values below the noise level measured were suppressed (Figure 1c). Streamline estimation was performed using Monte Carlo (MC) simulations with repeated velocity integration (Figure 2a). In each of the total of 1000 iterations, the velocity for every voxel was drawn randomly according to the probability function p(v) derived from the measured velocity distribution S(v). Streamlines were generated in time-reverse direction to avoid split pathways in bifurcating vessels. The final streamline was chosen as the mean of all realizations.

For comparison conventional 4-point phase-difference (PC) data were computed from the Fourier velocity encoded data by selecting the encoding velocity v_{enc} closest to the maximal measured velocity.

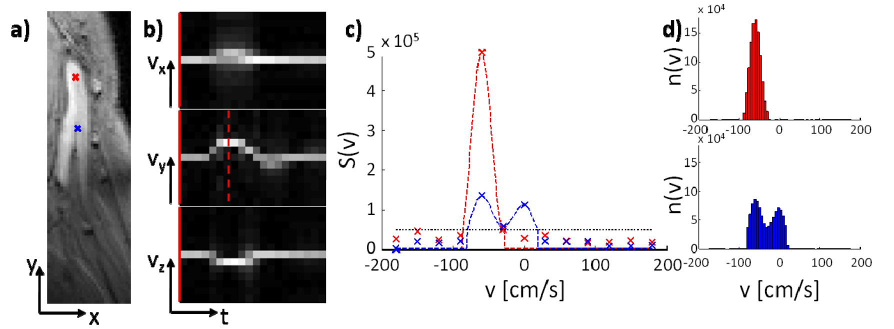

Figure 1: Fourier velocity data measured in the femoral artery (a) resulting in temporally resolved velocity distributions (b) in x, y and z direction for each voxel. The extracted velocity distributions are interpolated and thresholded at noise level (c). For probabilistic streamline estimation random velocities are generated following the measured velocity distribution (d). The voxel marked in red shows a normal velocity distribution whereas the velocity distribution of the voxel in blue is dominated by partial volume effects.

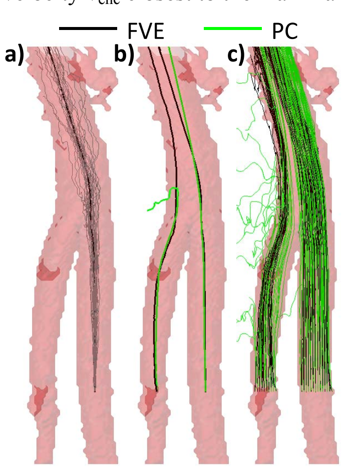

Figure 2: Monte Carlo streamline estimation (gray) from Fourier velocity encoded data (a) results in streamlines inside the vessel (black), whereas conventional streamline estimation (green) based on phase-difference data yields erroneous paths (b-c).

Results

The measured signals show that velocity distributions may deviate considerably from the normal assumption. As an example, the voxel marked in blue in Figure 1a shows partial volume effects resulting in two peaks in the velocity distribution (Figure 1c-d).

Streamlines derived from PC data and MC simulation of the FVE data are shown in Figure 2a-c for a systolic time point. Due to noise and partial volume effects, PC streamlines partly pass the vessel wall (Figure 2b-c). The MC streamline is more probable to stay inside the vessel and follow the vessel wall (Figure 2b-c).

Discussion

A method for streamline visualization based on measured velocity distributions has been presented and compared to traditional streamline estimation based on 4-point phase-difference data. The method takes into account that intra-voxel velocities can deviate considerably from a normal distribution in particular near the vessel walls where partial volume effects can have significant influence. As a result erroneous particle paths near the vessel wall are effectively corrected. In order to address the long scan times associated with Fourier velocity encoding, k-t PCA was employed. At the current point a net acceleration factor of 4.2 was realized which still results in approximately twice the total scan time of Fourier velocity encoding relative to 4-point phase-contrast acquisitions. In future work, this relative drawback will be addressed by exploiting data undersampling in the k_y-k_z-k_v-t domain as previously proposed [4].

References

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