Improved Velocity-to-Noise Ratio in Time-resolved 3D Blood Flow Measurements for Cardiac Imaging

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Introduction

Time-resolved phase-contrast (PC) imaging permits the assessment of volumetric, multi-directional blood flow velocities [1]. The resulting vector field data can be visualized in different ways using streamlines, arrows, and particle traces [2]. These visualization modes allow for an accurate and intuitive analysis of blood flow characteristics in normal and pathological cases [3]. Despite the advantages of the method, wide-spread acceptance in a clinical setting has been hampered by the long scan durations. In order to reduce the long measurement times, parallel imaging [4] may be employed. Noise amplification from parallel imaging can partly be compensated for by conducting the measurements at high field. Since the velocity-to-noise ratio (VNR) is not only dependent on base signal-to-noise but also scales inversely with the encoding velocity (Venc), lowering Venc may be considered an alternative approach to improving VNR. If Venc is chosen smaller than the actual blood velocities, phase aliasing arises and needs to be corrected. Phase unwrapping is a well studied field and has been extensively discussed for two [5] and more dimensions [6].

It was the objective of the present work to improve VNR by using low Venc phase-contrast imaging in conjunction with an automatic phase unwrapping algorithm suited for time-resolved 3D blood flow measurements. The gain in VNR is then used to compensate for SNR loss in accelerated scans using parallel imaging and concurrently increase spatial resolution.

Methods

Data acquisition: Time-resolved 3D PC data covering the left-ventricular outflow tract, ascending and descending aorta were acquired on a Philips 3T Achieva system (Philips Medical Systems, Best, The Netherlands). Scan parameters of the navigated and retrospectively triggered fast gradient-echo sequence of a first set of scans were: FOV = 320x260x51mm^3, matrix = 128x128x17, T_R = 3.05-3.94ms, flip angle = 5°, cardiac phases = 25, resulting scan resolution = 2.5x2.5x3mm^3. A second set of scans was acquired using parallel imaging to reduce the scan time while concurrently increasing the scan resolution: FOV = 320x256x46mm^3, matrix = 160x160x20, SENSE reduction factor = 2, resolution = 2.3x2.3x2.3mm^3. Healthy subjects were scanned twice with $Venc_{1x,y}$ = 200cm/s, $Venc_{1z}$ = 100cm/s avoiding phase wraps and $Venc_{2x,y}$ = 100cm/s, $Venc_{2z}$ = 50cm/s intentionally accepting phase wraps. A 75 years old patient with a dilated ascending aorta (4.8 cm diameter) was scanned with the following parameters: FOV = 350x280x75mm^3, matrix = 176x176x30, T_R = 4.10ms, flip angle = 5°, cardiac phases = 20, $Venc_{x,z}$ = 50cm/s, $Venc_y$ = 60cm/s.

Phase unwrapping: The phase unwrapping algorithm was designed to take into account appropriate prior knowledge about the phase evolution during one heart cycle as shown in Figure 1: a) absence of phase wraps was assumed for the first heart phase; b) phase wraps can only occur between two mate extremes of the first derivative v'(t); and c) the intermediate curvature given by the second derivative v"(t) must fit the remainder of the velocity curve. Multiple phase wraps are corrected by consecutive runs of the algorithm. To correct residual aliases a 5x5 median filter was applied, correcting single misjudged voxels with respect to the 2π level of the median.

Data evaluation: After unwrapping, the VNR of all data series were calculated for multiple regions-of-interests in the ascending aorta. Velocity noise was determined from the phase noise in static tissue as automatically identified using temporal statistics of the velocity data. VNR values of both the normal and accelerated scans were normalized by dividing the absolute VNR value by the voxel volume and the square root of the total number of measurements to allow for comparison. Unwrapped subject and patient data were then used to calculate traces for particles interspersed in the aortic arch during early systole.

Results

The phase algorithm was able to correct for the aliasing in the low Venc acquisition of all healthy subjects, but showed some deficits in unwrapping less regular flow in the pathologically dilated aorta. Those deficits were corrected manually. Figure 2 displays images of the data series acquired without parallel imaging with high and low Venc, as well as the absolute VNR curves for the three velocity encoding directions over time. Comparing relative VNR of the normal and accelerated acquisitions normalized to unit voxel volume and unit measurement time resulted in a ratio of 2.06±0.17 being in good accordance with the theoretical prediction of a factor of two.

Particle traces of the patient data are shown in Figure 3, depicting the dilated ascending aortic volume (a) and flow patterns occurring in the aortic outflow tract at different time points during systole. The overall flow velocities are low compared to healthy subjects as can be seen by the color encoded particle traces. The flow shows a vortex pattern with the onset of systolic ejection (b) that is then swirling upwards (c) and accompanied by significant retrograde flow (d) in mid systole.

Discussion

It has been shown that lowering the encoding velocity with subsequent phase unwrapping is a feasible method to improve VNR in time-resolved PC. The gain in VNR facilitates application of parallel imaging by compensating for its inherent loss of SNR. Lowering the encoding velocity by a factor of two results in doubling of the VNR, whereas using a reduction factor of two in parallel imaging results in an SNR and VNR decrease of a square root of two assuming an ideal geometry factor. The remaining yield in VNR was invested to achieve an isotropic scan resolution of 2.3mm as compared to the previously used voxel size of 2.5x2.5x3mm^3 without increasing the effective acquisition time.

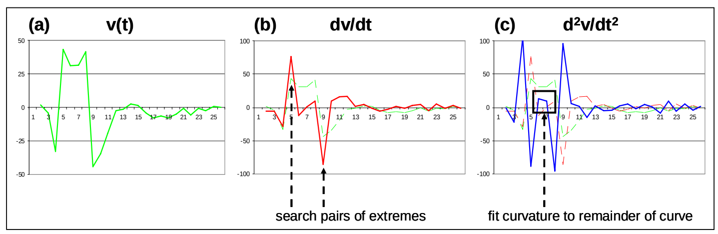

Figure 1: The first graph depicts the evolution of velocity values (Venc: 50cm/s) over time with a phase wrap in mid systole (a), the potential location of which is determined by analyzing the first derivative with respect to time (b). Since not all phase wraps result in two mate extremes with a step size greater than π, the intermediate part of the second derivative is examined (c) to reassure whether to unwrap the values.

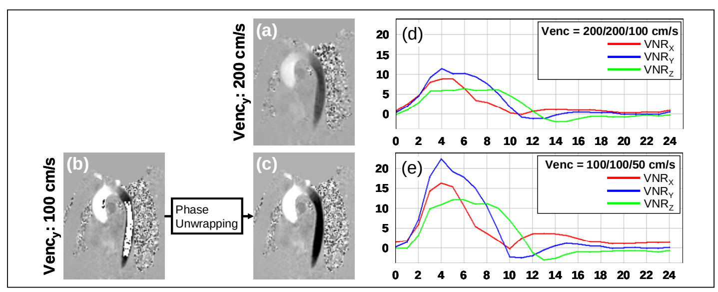

Figure 2: Lowering the encoding velocity from 200cm/s (a) to 100cm/s results in phase wraps due to higher velocities occurring in the aortic arch (b). Unwrapping such values yields correct velocity data (c) with approximately doubled absolute velocity-to-noise ratio (d, e).

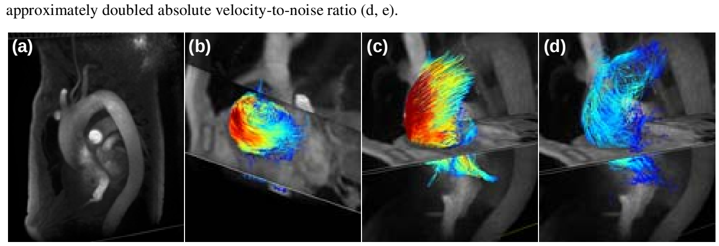

Figure 3: The pictures show the dilated aortic volume of a 75 years old patient (a) and particle traces of the swirling flow in the aortic outflow tract (b, c), accompanied by significant retrograde flow (d) in mid systole.

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