Fast PC Flow Measurements Using Undersampled PR: *in vitro* Validation and Preliminary Results *in vivo*

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INTRODUCTION

Schoenberg *et al.* [1] showed that MR flow measurement techniques could be used to identify the hemodynamic significance of stenoses. However, a great amount of temporal resolution is needed for accurate flow measurements, and as Tang *et al.* showed [2], accurate flow measurements also depend on voxel dimensions. Higher levels of spatial or temporal resolution require longer scan times. In scanning those regions of the body that shift during respiration, the scan must be performed during a breath hold in order to prevent motion-induced artifacts and blurring. Since scans in these regions are limited to the duration of a patient's breath hold, either spatial or temporal resolution must be sacrificed, which may lead to inaccurate flow measurements. Using undersampled projection reconstruction (PR), phase contrast (PC) data can be acquired with higher spatial resolution per unit time than with spin-warp encoding [3]. Whereas spatial resolution is dependent on scan time in Fourier acquisitions, it is independent of scan time in undersampled PR. Thus, for a given scan time, the Fourier method can be replaced with undersampled PR to achieve images with better spatial and/or temporal resolution. Alternatively, undersampled PR can be used to reduce the scan time without decreasing the spatial resolution. The purpose of this study was to validate an undersampled PR PC acquisition method *in vitro* by evaluating the accuracy of flow measurements obtained from scans that were acquired in the time of an average breath hold and to determine the feasibility of *in vivo* undersampled projection reconstruction.

MATERIALS AND METHODS

An undersampled projection reconstruction PC imaging technique was implemented on a 1.5 T MR scanner (Signa Excite, GE Healthcare, Milwaukee, WI) and used to image the tubing of a flow pump (R.G. Shelley LTD., Toronto, Canada) that was accurate to ± 0.01 mL/sec. A four-element phased array torso coil (GE Medical Systems, Milwaukee, WI) was employed. The following parameters were used: TR/TE = 6.4/3.0 ms, RBW = ± 31.25 kHz, FOV = 24-34 cm, slice thickness = 5 mm, and frequency encoding values = 256. Scans were performed with 256, 128, 64, 32, 16, and 8 projections for flow rates of 1 – 10 mL/s in 1 mL/s intervals. These scans were performed with constant flow and sinusoidal flow, the former triggered using a waveform generator (Fogg System Company, Inc., Denver, Colorado) and the latter triggered using the pump itself at 60 bpm. Images were analyzed with CV Flow (Medis, Netherlands). Data were summarized with Bland-Altman analysis [4].

Preliminary *in vivo* tests were performed on a single normal male with parameters similar to those above. Images were acquired during breath hold intervals as high as 25 seconds (64 projections) and as low as 4 seconds (8 projections) at locations orthogonal to the flow in the aorta and iliac arteries. Scans were performed with 64, 32, 16, and 8 projections using 1 and 2 views per segment (vps). Images were also acquired with a traditional cardiac-gated, segmented Fourier acquisition with TR/TE = 9.9/4.4 ms, 2 vps, 23 seconds per scan using 64 phase encoding values, and a ½ FOV.

RESULTS AND DISCUSSION

Seventeen-second scans acquired using 32 projections produced images with flow measurements averaging a difference of -0.057 mL/s from the actual flow rate of the pump in constant flow scans and flow measurements averaging a difference of +0.046 mL/s from the actual flow rate of the pump in pulsatile flow scans (Figure 1, dashed line). Linear regression of the same scans acquired using 32 projections with pulsatile flow yielded an R^2 value of 0.9998. Eight-second scans acquired using 16 projections produced a difference of -0.26 mL/s in constant flow scans and +0.19 mL/s in pulsatile flow scans. While accuracy deteriorated in images acquired with fewer than 32 projections, the errors were acceptable in images acquired with 16 projections.

In *in vivo* results, 13 second scans acquired with the undersampled PR method using 32 projections and 2 views per segment provided an average flow rate of 9.9 mL/s in the aorta and 4.6 and 6.2 mL/s in the left and right iliac arteries, respectively. The Fourier method acquired using 2 views per segment provided an average flow rate of 11.7 mL/s in the aorta and 6.3 and 9.4 mL/s in the left and right iliac arteries, respectively. Assuming the sum of the flow rates in the iliac arteries should be equal to the flow rate in the aorta, undersampled projection reconstruction provided more convincing results. In addition, the undersampled PR PC method provided a faster scan time and more phases throughout the cardiac cycle. The average flow rates determined for the aorta and iliac arteries for both the Fourier and undersampled PR methods are summarized in Table 1. Twenty-five-second scans acquired with the undersampled PR method using 32 projections and 1 view per segment were collected to evaluate the potential benefits of improved temporal resolution. Using these scans, the average flow rate was 12.2 mL/s in the aorta and 4.9 and 6.1 mL/s in the left and right iliac arteries, respectively. These averages were calculated using 45 phases acquired during the RR interval. The scan time of the Fourier acquisition with 1 view per segment was prohibitively long, and therefore, not attempted.

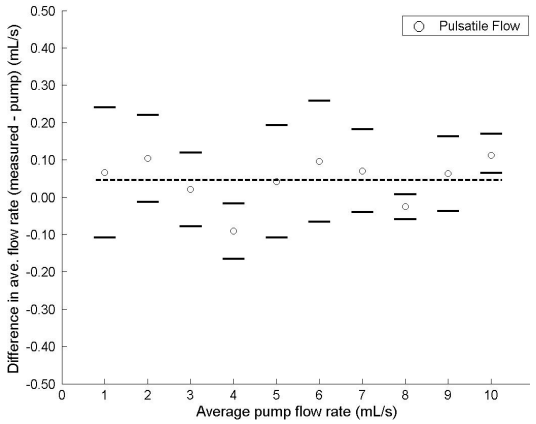

Figure 1. Bland-Altman analysis of 32-projection scans. The differences between the measured average flow rates calculated using CV Flow and the pump's average flow rate are shown on the ordinate while the pump's average flow rates are on the abscissa. With three scans at each flow rate, the average difference across all flow rates was +0.046 mL/s for pulsatile flow (dashed line). Error bars are shown (mean ± 2 s.d.).

	PR 2 vps (mL/s)	Fourier 2 vps (mL/s)	PR 1 vps (mL/s)
aorta	9.9	11.7	12.2
left iliac	4.6	6.3	4.9
right iliac	6.2	9.4	6.1
sum of iliacs	10.8	15.7	11.0

Table 1. Average flow rates in the aorta and right and left iliac arteries as measured in undersampled projection reconstruction scans with 1 and 2 views per segment (vps), along with the measurements obtained using a cardiac-gated Fourier acquisition with 2 vps. The sum of the average flow rates in the iliacs is shown for comparison to the average flow rate in the aorta.

CONCLUSIONS

PC undersampled projection reconstruction provides accurate flow measurements *in vitro* in scan times less than an average breath hold. Depending on the ability of a patient to perform a breath hold, undersampled projection reconstruction can be used to adjust scan time without compromising the accuracy of flow measurements. It was demonstrated that PC undersampled projection reconstruction provides the ability to optimize temporal and spatial resolution, therefore creating the possibility for accurate flow measurements at reduced scan times. Ultimately these results may lead to improved assessment of the hemodynamic significance of stenoses.

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