Rapid Cardiac-Output Measurement with Ungated Spiral Phase-Contrast

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Introduction: Cardiac output (CO) can be a key indicator for assessing patients with cardiovascular diseases and can be an essential factor in monitoring the post-surgical or -medicated condition of the patients. Previously, it was shown that ungated spiral phase-contrast (USPC) can rapidly and reproducibly measure accurate time-averaged flow rates with relatively high spatial resolution in the femoral and renal arteries [1]. However, the high pulsatility and speed of flow in the ascending aorta (AA), and the anatomy around the AA, pose a greater challenge for measuring CO with USPC. In this study, we successfully modified and validated USPC for measuring CO in 5 seconds, whose preliminary protocol was presented in [2]. We measured CO in the AAs of nine normal subjects and one patient. We also measured abnormal CO in normal subjects undergoing valsalva maneuvering and exercise. Continuous scanning was performed to show that USPC can temporally resolve physiological changes of CO.

Method: USPC is a non-cardiac-synchronized phase-contrast (PC) technique that uses interleaved spiral k-space trajectories [1]. The two flow-encodings (FEs) in the through-plane direction are alternated every excitation, and the spiral readouts are rotated every odd excitation. In USPC, interleaved spiral k-space trajectories provide significant flow-artifact suppression [1]. Moreover, a pseudo-randomized interleave ordering and a minimum-first-moment FE scheme further reduce flow artifacts [1]. To measure CO, it was necessary to modify the original USPC [1], as summarized in Table 1. Major modifications were (a) smaller imaging-matrix size, (b) thinner slice and lower flip angle, (c) shorter TE by using a short RF pulse of 480 us, and (d) higher V_{enc} (maximum-velocity encoded) of 250 cm/s. Modifications (a) and (b) reduced flow artifacts and in-flow signal enhancement, respectively, which are likely to increase in the AA. Modification (c) minimized the second-order moment, reducing the error caused by flow acceleration. Modification (d) provided adequate balance between reduced systematic [1] and random phase errors in USPC. In addition, axial imaging slice (i.e., FE lobes on the physical Z-gradient) were used, which significantly reduced phase errors caused by eddy-current-induced and concomitant fields from FE gradients, which is hard to post-correct due to the lack of static material nearby. A dead-time of 0.8 ms before the readout further reduced eddy-current effects by preventing the temporal overlap of the readout gradients and the eddy-current-induced fields. For comparison, we used a triggered real-time SSFP imaging (TRT) to indirectly calculate CO by measuring LV volumes with multiple slices [3,4]. TRT images a slice and then advances to the next slice at each cardiac trigger to obtain 8-10 slices fully covering the LV.

Results: USPC and TRT showed good agreement in all normal subjects as the difference between the mean values of USPC (breath-hold) and TRT was 0.12±0.68 L/min (Fig. 1). USPC measurements with free-breathing also showed good agreement. With the patent ductus arteriosus (PDA) patient, the USPC measurement agreed well with the invasive cardiac-catheterized Fick measurement, but the TRT measurement showed 18% overestimation possibly due to regurgitant flow at the aortic valve. USPC magnitude images showed almost no flow artifacts (Fig. 2). As expected, CO dropped about 20-30% with valsalva-maneuvered breath-holding compared to normal breath-holding (Fig. 3-a). The continuous 28-second maneuvering experiment showed that USPC can temporally resolve physiological changes (Fig. 3-b). Finally, CO increased about 100% after 5-minute running exercise as expected and gradually decreased while the subject rested inside the scanner (Fig. 4).

Discussion: Both USPC and a real-time PC technique involve an ungated acquisition with a short TR. However, USPC uses more interleaves to achieve sufficient spatial resolution for less spatial partial-volume effects, compared to a typical real-time method [5], but at the cost of a longer full scan time. Despite the longer full scan time, which typically increases motion artifacts, the spiral k-space trajectory offers significant resistance to such artifacts, leading to accurate time-averaged measurements.

Conclusion: This study showed that accurate in vivo CO can be non-invasively, reproducibly, and rapidly measured without cardiac-synchronization by using USPC. As suggested by the results from continuous USPC scanning in the valsalva and stress studies, the sensitivity and high temporal resolution of USPC to physiological CO changes may provide insights into the patho-physiology and response to therapy for a diverse set of patients.

References: [1] Park JB, et al., MRM, 49:322-28, 2003, [2] Park JB, et al., Proceedings of ISMRM 2004, p.2585, [3] Nayak KS, et al., MRM, 49:188-92, 2003, [4] Narayan G, et al., Proceedings of ISMRM 2004, p.1954, [5] Korperich H, et al., Circulation, 109:1987-93, 2004, [6] Pelc NJ, et al., MRQ, 10:125-47, 1994

	N	TR	FOV	Δx	slice	θ	TE_{min}	Slice	V_{enc}
CO	12	11.8ms	24cm	2mm	3mm	10°	2.2ms	Axial	250cm/s
PA	40	15ms	30cm	1mm	10mm	30°	3.5ms	Oblique	100cm/s

Table 1: USPC Scan Parameters for CO compared with those for peripheral-artery flow (PA)

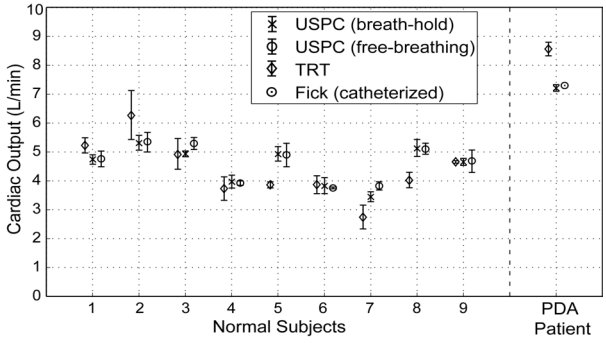

Fig. 1: CO Measurements using USPC. The scan time for each USPC measurement was 5 seconds.

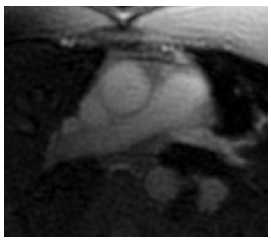

Fig. 2: USPC Magnitude Image

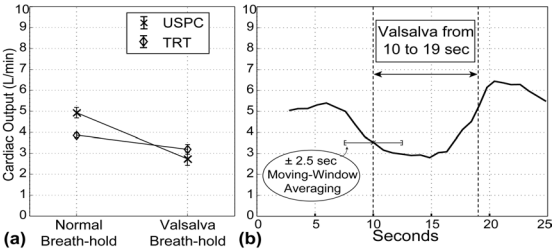

Fig. 3: Valsalva Results

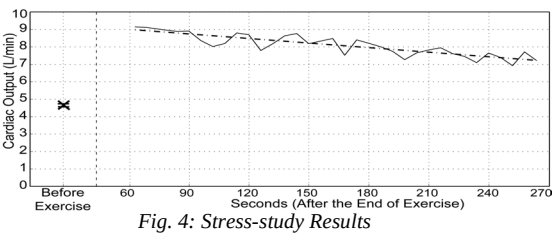

Fig. 4: Stress-study Results