35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Assessment of Flow and Hemodynamics in the Carotid Artery Using a Reduced TE 4D Flow Spiral Phase-Contrast MRI

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Abstract— **4D flow MRI is a powerful technique for quantitative flow assessment and visualization of complex flow patterns and hemodynamics of cardiovascular flows. This technique results in more anatomical information and comprehensive assessment of blood flow. However, conventional 4D PC MRI suffers from a few obstacles for clinical applications. The total scan time is long, especially in large volumes with high spatial resolutions. Inaccuracy of conventional Cartesian PC MRI in the setting of atherosclerosis and in general, disturbed and turbulent blood flow is another important challenge. This inaccuracy is the consequence of signal loss, intravoxel dephasing and flow-related artifact in the presence of disturbed and turbulent flow. Spiral k-space trajectory has valuable attributes which can help overcome some of the problems with 4D flow Cartesian acquisitions. Spiral trajectory benefits from shorter TE and reduces the flow-related artifacts. In addition, short spiral readouts with spiral interleaves can significantly reduce the total scan time, reducing the chances of patient motion which may also corrupt the data in the form of motion artifacts.**

In this paper, the accuracy of flow assessment and flow visualization with reduced TE 4D Spiral PC was investigated and good agreement was observed between the spiral and conventional technique. The systolic mean velocity, peak flow and the average flow in CCA and ICA of normal volunteers using 4D spiral PC MRI showed errors less than 10% compared to conventional 4D PC MRI. In addition, the scan time using spiral sequence was 3:31 min which is half of the time using conventional sequence.

I. INTRODUCTION

Conventional 2-D PC MRI is based on flow quantification in a slice of interest in a 2-D image. Although it is possible to acquire 3 components of velocities in a 2D slice, by extending the imaging volume to 3-D, 3 components of flow can be determined in 3D. 4-D flow imaging is based on flow quantification in three directions in subsequent TR's in a 3-D volume. 4-D flow MRI has been widely investigated to quantify and visualize the global and local blood flow in arteries with complex flow patterns [1-8]. In addition to providing comprehensive anatomical and flow information in both in-plane and through-plane directions, 4D flow imaging results in shorter total scan time compared to 3-D flow imaging or multiple 2D slice imaging to cover a volume; in either case, a separate scan for each of the 3 flow directions is required.

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Although conventional 4D PC-MRI based on Cartesian trajectory is more scan efficient than three alternative 3D scans with separate flow encodings, it can still result in relatively long scans and is prohibitive for some clinical applications. Spiral trajectory has several desirable characteristics compared to Cartesian trajectory and has been previously been employed for several clinical studies [9-10]. The readout echo time (TE) in spiral trajectory is shorter due to removing the rephasing part of readout gradient leading to shorter scan time. In addition, signal to noise ratio (SNR) is higher and it benefits from desirable flow characteristic [11].

In addition to longer acquisition times, atherosclerotic disease and vascular occlusions cause challenges to conventional PC acquisitions due to intravoxel dephasing secondary to disturbed blood flow and turbulence distal to narrowing, often resulting in signal loss and flow-related artifacts [10,12-13]. Several approaches have been developed to mitigate the signal loss and flow-related artifacts in PC-MRI [14-16]. However, a reliable flow measurement technique in the presence of turbulence has remained elusive. One important approach that has revealed significant impact in correction of the signal loss involves reduction of the echo time (TE) and gradient duration [17-18]. Reducing the TE decreases the impact of turbulent fluctuation velocity, intravoxel dephasing and the subsequent signal loss. The approach results in higher signal to noise ratio and more reliable estimation of disturbed and jet flows since a shorter TE will ameliorate the effect of intravoxel dephasing caused by random fluid mixing. In addition to it scan efficiency, spiral acquisitions with shorter TE have the potential to reduce the signal loss and flow-related artifacts and improve the accuracy of flow quantification.

Previously, Sigfridsson et al. [19] proposed a 4D Spiral flow sequence and used their method for imaging and visualization of flow through the aorta. In this paper, a 4D spiral flow MRI technique was designed which through combination of bipolar and slice select gradient further reduces the TE in comparison to Sigfridsson et al.'s implementation. Carotid artery was selected for study due to irregular geometry of this vessel at carotid bifurcation which results in disturbed blood flow. Flow assessment using conventional 4D PC MRI can yield inaccurate results in the presence of atherosclerostic disease in carotid bifurcation and internal carotid artery (ICA). The purpose of this study was to validate 4D flow spiral MRI with conventional 4D flow Cartesian MRI in normal volunteers. 4D flow spiral MRI has the advantage of having a shorter TE and total scan time when compared with conventional 4D flow acquisitions.

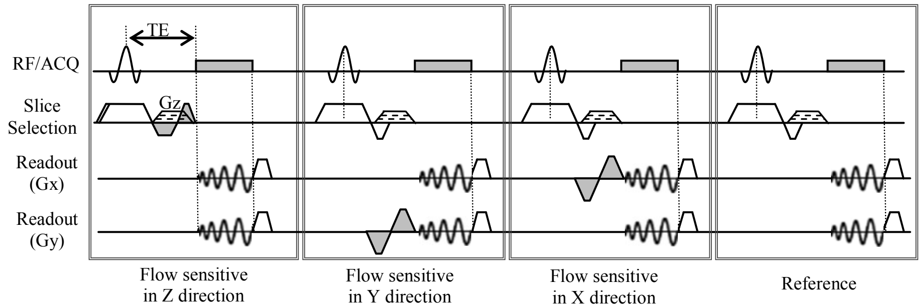


Figure 1. A schematic of reduced TE 4D spiral PC MRI sequence with for consecutive scans including 3 flow sensitive scans in three flow directions and one reference scan. Subtraction of each phase image of flow sensitive scan from phase image of the reference scan results in PC velocities for the corresponding flow direction. Gradient G_z is applied to acquire multiple slices in a volume using stack of star strategy.

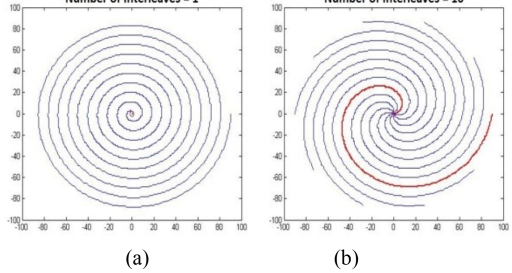
II. Material and Method

A. Pulse sequence

Figure 1 shows the proposed sequence based on the four-point acquisition technique where flow encoding gradients are applied in all three directions in subsequent TR's [20]. For each time frame, three separate flow encoded scan (each of which with flow encoding only in one of x, y, and z direction) and one flow compensated (reference) is acquired. The flow velocity volumes are determined by subtraction of each flow encoded volume from the flow compensated volume.

In contrast to Cartesian acquisition where k-space is acquired using parallel horizontal lines, spiral acquisition collects the k-space data using a spiral trajectory (figure 2), significantly reducing the total scan time. The single shot spiral acquisition technique covers the entire k-space in one readout resulting in longer TR, but with the potential drawback of off-resonance artifact due to T_2 effects. Multi-shot or interleaved spiral acquires multiple spiral shots in each TR (figure 2 (b)). As a result, the whole k-space is collected using multiple but shorter spiral arms.

In Cartesian PC sequences, slice excitation, rephasing, and velocity encoding gradients need to be applied during TE. These gradients prolong TE and may lead to phase errors and velocity miscalculation. In addition to reduced acquisition times, spiral trajectory benefits from shorter TE due to removal of the phase encoding gradient and the rephasing portion of the readout gradient. The TE in spiral acquisition is the time from the center of RF pulse to the beginning of spiral readout gradient.



(a) (b)

Figure 2. Demonstration of (left) conventional single shot spiral acquisition with 10 rotations and (right) interleaved spiral acquisition with 10 interleaves.

Figure 1 displays the proposed 4D spiral flow sequence, designed using a 3D stack of spirals trajectory. A stack of spirals trajectory was also adopted in [19]; however, as shown in figure 1, the TE is now further shortened through combination of the flow encoding/compensated gradient with the refocusing portion of slice select gradient. Further reduction in TE is possible using higher values of Velocity encoding (Venc).

B. Imaging strategy

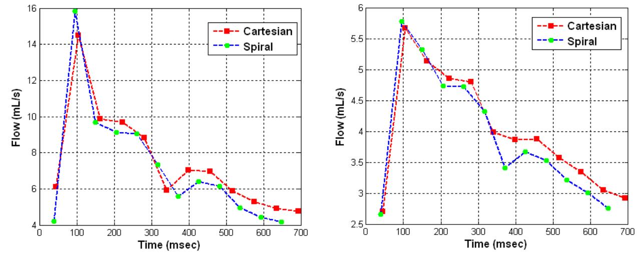
Imaging was performed on a Philips Achieva 1.5T scanner (Philips Healthcare, Best, NL) using a combined 16-element SENSE Neurovascular coil capable of imaging carotid vessels from the aortic arch to circle of willis. Four normal volunteers with a mean age of 27±4 years were scanned using standard 4D flow Cartesian PC sequences as well as the proposed 4D flow spiral PC sequence. Flow assessment was performed in the carotid arteries in an axial 3D volume with 10 slices and a 3D slab thickness of 5 mm for each slice. The acquired volume started at 15 mm proximal to the bifurcation and ended at 35 mm distal to the bifurcation.

Phase errors due to eddy current and hardware imperfections were corrected using a static phantom which was scanned with identical parameters prior to the main scan. The phase error in static phantom MR image was assumed to be only due to eddy current and hardware imperfection and was subtracted from the in-vivo scan.

The scan parameters for two sequences were TE/TR = 4.4/7.7 ms (for Cartesian trajectory), TE/TR = 2.1/9.3 ms (for spiral trajectory), FOV= 160*160*50 mm, Venc= 150 in all three flow directions, flip angle= 10, spatial resolution= 1.5*1.5*5.0 mm, and 12 cine frames in each cardiac cycle. For the spiral trajectory, various combinations of spiral interleaves (20,30,50,60) and readout duration (2,3,5,10, msec) were examined and it was determined that number of interleaves=30 and readout duration=5 msec resulted in a good compromise between flow measurement fidelity and total scan time. The scan time for the 4D Cartesian flow was 6:16 minutes while the scan time for the proposed 4D spiral flow was 3:31 minutes. The TE (2.1 msec) and scan time (3:31 minutes) in spiral sequence shows significant improvement relative to Cartesian sequence and with the scan time reduced by half.

Table I. Comparison of 4D Cartesian flow and 4D spiral flow in 12 slices in right and left CCA and 20 slices in right and left ICA in four volunteers. The quantities are percentage of discrepancy in spiral technique relative to Cartesian technique

	Peak Systolic flow discrepancy	Systolic mean velocity discrepancy	Average flow discrepancy
Right CCA	3.7	3.8	6.3
Right ICA	4.5	4.9	6.8
Left CCA	5.7	5.9	9.5
Left ICA	9.2	8.4	9.7



(a) (b)

Figure 3: Flow waveform for Right CCA (a) averaged in 12 slices proximal to bifurcation and for Right ICA (b) in 20 slices distal to bifurcation using Cartesian (red cruve) and spiral (blue curve) PC MRI in four volunteers.

III. RESULTS AND DISCUSSIONS

Flow assessment was carried out in right and left CCA for three slices located proximal to bifurcation as well as five slices distal to bifurcation in the right and left ICA in 4 volunteers. The difference in heart rate in all volunteers was taken care of by interpolating the measured flow quantities in the last three volunteers to match their cardiac frame time with the cardiac frame time in the first volunteer. Figure 3 demonstrates the flow waveforms in right CCA averaged in 12 and right ICA averaged in 20 slices in 4 volunteers. The resulting flow waveforms for conventional 4D flow and proposed 4D spiral flow reveal good agreement in flow quantification during the entire cardiac cycle. The results of blood velocity and flow evaluation in right and left CCA in 12 slices proximal to bifurcation and right and left ICA in 20 slices distal to the bifurcation using 4D Cartesian flow 4D spiral flow are summarized in table I. The values represent the difference of measured quantities between conventional and spiral flow. In order to quantitatively compare results between 4D spiral flow with the conventional technique, the normalized root mean square error (RMSE) is calculated. The normalized root mean square error can be expressed as:

$$Error = \sqrt{\frac{1}{N}\left(\frac{Q_{cart} - Q_{SP}}{Q_{cart}}\right)^2}$$

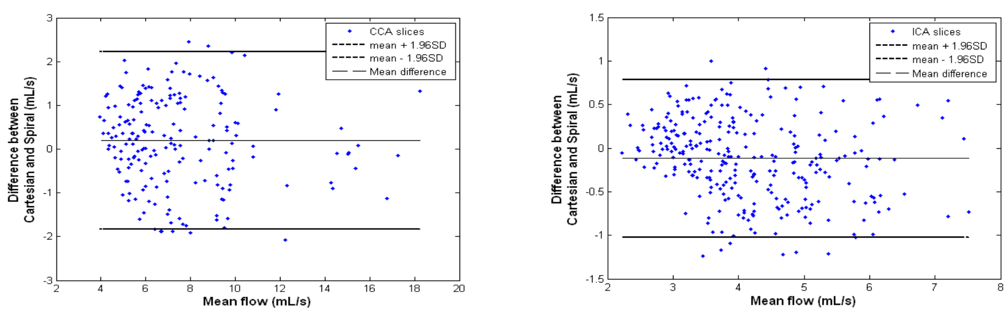
where Q_{cart} and Q_{SP} are measured flow using Conventional and spiral techniques and N is the number of time points in a cardiac cycle where data is collected (i.e. number of cardiac phases). The velocity and flow measurements between the two show less than 10% difference for both the CCA and the ICA. The discrepancy for left and right CCA shows a reasonable accuracy with 4D spiral flow while the discrepancies for the right and left ICA are slightly higher -- most likely due to smaller size of these arteries and more sensitivity to artifacts.

Figure 4 demonstrates the Bland-Altman plot representing the mean difference of flow measured using 4D Cartesian flow and 4D spiral flow. Mean flow in each slice and in each cardiac phase in 4 volunteers generated 144 data points in CCA and 240 data points in ICA. The Bland-Altman plot reveals a reasonable accuracy for 4D spiral flow with mean difference and confidence range in right CCA as 0.02 and [-1.84,2.12] and for left CCA as 0.01 and [-1.04,0.78].

Figure 5 shows blood velocity profiles in 10 slices along the right carotid artery in the systolic cardiac phase in a normal volunteer. The color-coded velocity and shape of velocity profile in 4D spiral flow reveals good agreement with conventional 4D flow. Figure 6 displays zoomed flow pathlines in carotid bifurcation, right ICA, and ECA. Good correspondence between flow pathlines from 4D spiral and 4D Cartesian flow can be observed. 4D spiral flow shows slight erroneous pathlines in the ICA.

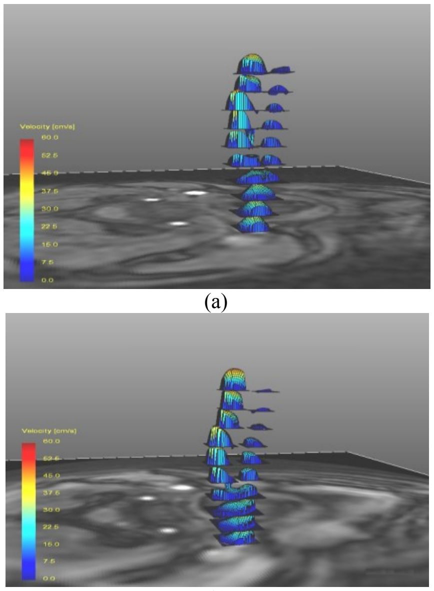
IV. CONCLUSIONS

A reduced TE 4D spiral flow technique was implemented with the goal of reducing the scan time compared to conventional 4D PC MRI while resulting in reduced TE compared to previously published techniques. In



(a) (b)

Figure 4: Bland-Altman plot in each cardiac phase in four normal volunteers demonstrating the mean flow difference between 4D conventional and 4D spiral flowin (a)RCCA and (b) LCCA. The blue dots are all measured flow values from 4 volunteers in all cardiac frames. Having 4 volunteers, 3 CCA slices in each volunteer, and 12 cardiac frames in each CCA results in 4*3*12=144 data points (a). For ICA 5 slices are available distal to bifurcation in each volunteer and the number of data points is 4*5*12 = 240 (b). The abscissa is the mean flow values from 4D conventional flow calculated over 12 slices during the cardiac cycle.



(a)

(b)

Figure 5: Velocity profile for 10 slices along right carotid artery using 4D Cartesian flow (a) and 4D spiral flow (b) in a normal volunteer during systolic phase of the cardiac cycle.

comparison to conventional 4D Cartesian flow, the total scan time was reduced by half. The accuracy of flow quantification and characterization with the spiral acquisition revealed a good agreement with the conventional technique.

ACKNOWLEDGMENTS

This work was supported in part by the National Science Foundation under Grant 0730467 and by an innovative grant from the Clinical and Translational Research Program of the University of Louisville to A. Amini.

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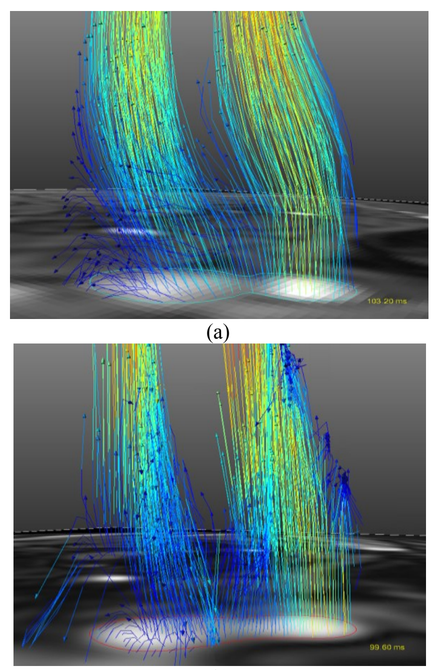

(a)

(b)

Figure 6: Flow pathlines systolic cardiac phase in right carotid artery acquired using (a) conventional 4D Cartesian PC MRI and (b) 4D spiral PC MRI