Quantitative 2D and 3D Phase Contrast MRI: Optimized Analysis of Blood Flow and Vessel Wall Parameters

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Introduction: Quantification of CINE phase contrast (PC)-MRI data is challenging because of the limited spatio-temporal resolution and SNR. The method presented here combines "Green's theorem" and B-spline interpolation of velocity and its local derivatives to provide optimized quantification of blood flow and vessel wall parameters. As a result, spatial and temporal variation of vectorial Wall Shear Stress (WSS) and Oscillatory Shear Index (OSI) could be calculated from the data in addition to blood flow parameters such as flow volume or lumen area. Functional diagnosis of the cardiovascular system is continuously gaining interest (1) and in this context, WSS is an important determinant of endothelial cell function (2-4). Flow and wall parameter quantification were evaluated in a study with 19 healthy volunteers in 8 planes distributed along the entire thoracic aorta obtained using both high resolution planar 2D and lower resolution volumetric 3D CINE PC-MRI with 3-directional velocity encoding. Synthetic flow data, inter-modality variability and inter-observer variability were used to evaluate the accuracy of the method. To our knowledge, these results constitute the first report of in-vivo analysis of blood flow parameters and vectorial WSS over complete arterial sections.

Methods: All experiments were performed at 3T (Trio, Siemens, Germany) using a respiration controlled and ECG gated rf-spoiled gradient echo sequence with 3-directional velocity encoding in 2D (*2D-CINE-3dir.PC*: spatial resolution: 1.24-1.82 x 1.25-1.82 x 5 mm^3, temporal resolution: 24.4 ms, venc=150 cm/s) and 3D (*3D-CINE-3dir.PC*: spatial resolution: 2.71-2.93 x 1.58-1.69 x 2.60-3.5 mm^3, temporal resolution: 48.8 ms, venc=150 cm/s) (5). Flow and wall analysis was performed at 8 planes distributed along the thoracic aorta (Fig. 3, right) using *2D-CINE-3dir.PC* and *3D-CINE-3dir.PC* for comparison as illustrated in Fig. 1. Data analysis and segmentation was integrated in an in-house analysis tool (6) based on Matlab (MathWorks, USA). For each CINE time-frame, the vessel lumen was segmented using B-spline contours (Fig.1, mid). Subsequent cubic B-spline interpolation (7) of the velocity data provided interpolated velocity and their local derivatives at the vessel contour (Fig.1, bottom). Based on the analytical vessel lumen contour, "Green's theorem" and B-spline interpolation, area and flow were efficiently and accurately computed from single integrals. WSS vectors were derived from the deformation tensor at the vessel wall (8) by assuming a transverse analysis plane and no flow through the vessel wall. The flow quantification tool has been evaluated on synthetic parabolic flow data with various resolutions and in 19 healthy volunteers.

Results: The effect of systematically varied spatial resolution showed that WSS was more strongly affected while the total flow remained relatively constant (Fig. 2, left). Quantification of flow, mean WSS and percentage of circumferential WSS is given in the table.

	Plane:	1	2	3	4	5	6	7	8
2D-CINE-3dir.PC	Flow [mL/cycle]	74.4 (16)	70.2 (15)	70.7 (18)	51.8 (11)	48.7 (10)	50 (11)	61.6 (13)	63.8 (11)
	Mean WSS [N/m^2]	0.431 (0.082)	0.447 (0.067)	0.444 (0.091)	0.385 (0.082)	0.414 (0.072)	0.466 (0.089)	0.53 (0.085)	0.564 (0.08)
	Circ. WSS [%]	11.8 (11)	15.7 (11)	16.2 (9.9)	19.4 (8.1)	18.6 (4.8)	10.9 (6.8)	12.1 (6.9)	14.4 (6.7)
3D-CINE3dir.PC	Flow [mL/cycle]	73.9 (19)	67 (14)	63.8 (14)	50.8 (12)	48.4 (10)	44.2 (9.6)	45.4 (12)	48.5 (9.2)
	Mean WSS [N/m^2]	0.294 (0.072)	0.309 (0.067)	0.306 (0.056)	0.311 (0.066)	0.308 (0.049)	0.308 (0.053)	0.317 (0.044)	0.384 (0.077)
	Circ. WSS [%]	24.4 (7.8)	24.9 (9.3)	23.9 (8)	25.4 (7)	25.1 (6.8)	25.8 (6.9)	20.1 (8.6)	17.4 (7.1)

Various spatio-temporal resolution between 2D and 3D-CINE-PC, resulted in relative differences of flow and area under 18% but higher relative errors for WSS and OSI at 45 and 65% (Fig. 2, right). To illustrate the potential of our method for detailed evaluation of the spatial distribution of WSS, Fig. 3 shows WSS vectors and OSI for one volunteer based on 2D and 3D data. In the ascending aorta (slice 1) and in the aortic arch (slice 3), the WSS vectors present a substantial right-handed circumferential component similar to the helical flow pattern in the aorta.

Discussion: The method presented here aimed at quantifying blood flow and vessel wall parameters by using Green's theorem and cubic B-spline interpolation. In contrast to other approaches assuming blood flow models (e.g. paraboloid (9) or numerical flow simulations (10)), our approach was not based on restrictive assumptions regarding the flow profile. Simple parameters such as the flow volume could be accurately quantified even for low resolution data while derived parameters such as WSS were more limited by the spatio-temporal resolution. Although WSS values were systematically underestimated in *3D-CINE-3dir.PC*, the high consistency between volunteers indicate the potential WSS estimation for the analysis of relative pathological WSS alterations as demonstrated in initial patient results. Our WSS measurements are in good agreement with published results in the descending and abdominal aorta derived from phase-contrast MRI (3, 11-13) which delivered similar average WSS values over the course of the cardiac cycle (0.18 to 0.95 N/m^2). Analysis of WSS along the aorta revealed the presence of a relevant circumferential component of WSS of 10 - 20%, indicating that the vector nature of WSS has to be taken into account to fully characterize wall shear forces in the aorta.

References: (1) Y. Richter and E.R. Edelman, Circulation 113:2679-2682 (2006) (2) Cheng C. et al, Circulation 113(23):2744-2753 (2006) (3) Wentzel J.J. et al, J Am Coll Cardiol. 45:846-54 (2005) (4) Davies PF, Physiol. Rev. 75: 519-560 (1995) (5) Markl M. et al, J Magn Reson Im. 25:824-831 (2007). (6) Stalder A. F. et al, Proc. ISMRM Workshop on Flow and Motion, NYC (2006) (7) Unser M., IEEE Signal Process. Mag. 16 22–38 (1999) (8) Papathanasopoulou P. et al, J. Magn. Reson. Im. 17(2):153-162 (2003) (9) Oyre S. et al, Magn. Reson. Med. 40:645-655 (1998) (10) Shojima et al, Stroke 35:2500-2505 (2004) (11) Moore JE Jr. et al, Atherosclerosis 110:225– 40 (1994) (12) Pedersen EM et al, Eur J Vasc Endovasc Surg 18:328 –33 (1999) (13) Oyre S. et al, J Am Coll Cardiol 32:128 –34

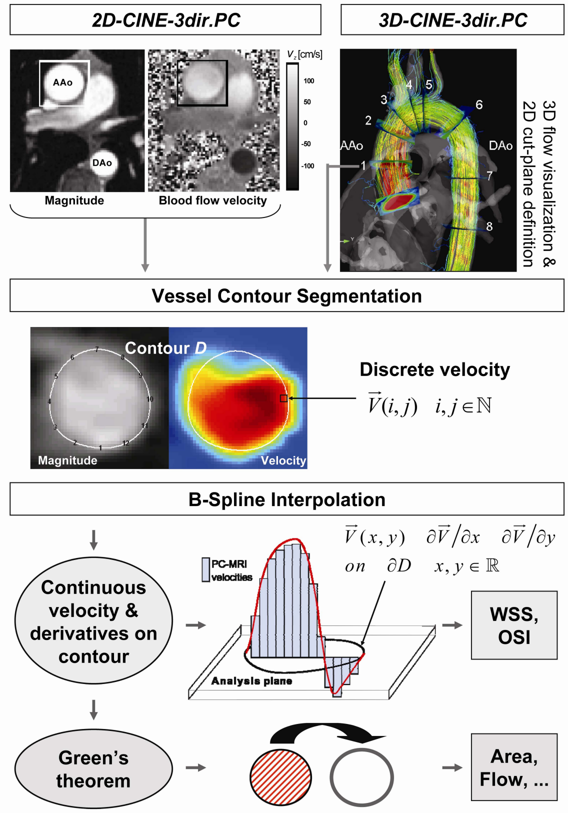

Fig. 1: Flow and wall parameter quantification strategy. **Top:** Planar PC-MRI data was directly measured (*2D-CINE-PC-3dir*) or extracted from volumetric data (*3D-CINE-PC-3dir*). **Mid:** Manual segmentation of the lumen contour ∂D. **Bottom:** B-spline interpolation was used to derive continuous flow velocities and derivatives along ∂D as required for WSS. Flow parameters were subsequently calculated by single integration along ∂D using "Green's theorem".

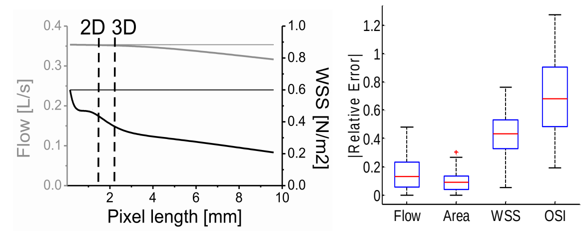

Fig. 2: **Left:** Effect of pixel size on flow and WSS for a synthetic flow profile.Honrizontal lines = theoretical flow and WSS. Vertical lines = settings used in the volunteer study. **Right:** Inter-modality (2D vs 3D) relative error for flow and wall parameters.

Fig. 3: Segmental distribution of WSS vectors and OSI in the ascending aorta of a volunteer. All WSS vectors illustrate the vectorial nature of WSS that include a circumferential component.