Advanced Quantitative Flow and Wall Shear Stress Analysis at 3T: 2D vs 3D time-resolved MR Velocity Mapping

A. F. Stalder[1], M. F. Russe[2], J. Bock[1], J. Hennig[1], M. Markl[1], and A. Frydrychowicz[2]

[1]Diagnostic Radiology - Medical Physics, University Hospital Freiburg, Freiburg, Germany, [2]Diagnostic Radiology, University Hospital Freiburg, Freiburg, Germany

Introduction: Time-resolved (CINE) phase contrast (PC) MRI permits the assessment of blood flow within entire 3D vascular structures [1, 2]. The resulting high-dimensional datasets (3 spatial dimensions, 3 velocity directions, and time) require new visualization and quantification methods to derive reliable clinical parameters. In this context, an advanced flow quantification tool was developed based on detailed planar analysis of measured three-directional velocity fields [2]. State of the art interpolation and numerical methods were employed to provide optimal quantitative assessment of flow and derived vessel wall parameters such as wall shear stress (WSS). The aim of this study was to evaluate the accuracy of in vivo blood flow and vessel wall parameters determined from transversal planes retrospectively defined on 3D CINE PC data with 3-directional velocity encoding (*3D-CINE-3dir.PC*) by comparison after registration to conventional 2D CINE PC data with 3-directional velocity encoding (*2D-CINE-3dir.PC*). Specifically, the influence of spatial and temporal resolution, in several planes along the thoracic aorta was investigated in a volunteer study.

Materials and Methods: All experiments were performed on a 3T MR-system (Trio, Siemens, Germany) using a respiration controlled ECG gated rf-spoiled gradient echo sequence with three-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=1.5 m/s) and 3D (*3D-CINE-3dir.PC:* spatial resolution: 2.71-2.93 x 1.58-1.69 x 2.60-3.0 mm^3, temporal resolution: 48.8 ms, venc=1.5 m/s) [1]. 11 healthy volunteers were studied (mean age 23.6 years). For *3D-CINE-3dir.PC*, data was acquired in a 3D volume covering the complete thoracic aorta. Additionally, eight *2D-CINE-3dir.PC* scans positioned at precise landmarks of the thoracic aorta (Fig. 1B) were performed for every volunteer. Data preprocessing included eddy current correction and optionally velocity aliasing correction. After registration of the 2D imaging planes within the 3D volume, analysis planes at the exact locations of the *2D-CINE-3dir.PC* imaging planes were extracted from the *3D-CINE-3dir.PC* data using a 3D visualization software (Ensight, CEI, USA) and exported into an in-house tool based on Matlab (MathWorks, USA). Next, interactive frame-wise segmentation of the vessel lumen with smooth contours was performed for both *2D and 3D-CINE-3dir.PC* data. Flow and derived vessel wall parameters are then automatically derived using an optimal combination of Green's theorem with spatio-temporal cubic B-spline interpolation. The combined knowledge of vessel contour and three-directional velocity field permitted the extraction of several flow and wall parameters: geometrical information (time-resolved: area, perimeter, equivalent diameter), flow (time-resolved flow, flow acceleration, flow per cardiac cycle, regurgitant flow ratio, resistance index, pulsatility index), Reynold number, kinetic energy and WSS (vectorial WSS and oscillatory shear index (OSI)). Vectorial WSS was derived from the slope of the measured 3-directional velocity field at the vessel wall. Additionally, the OSI represents the degree of oscillation of WSS.

Results: Due to the large amount of quantified data quantified (e.g. for axial WSS: 11 volunteers x 8 planes x 13-40 time frames x 12 WSS vectors spatially resolved x 2 imaging modalities ≈ 50000 values), only a limited number of the evaluated flow parameters can be presented here. Examples for flow, WSS and OSI being of particular interest, are illustrated in Fig. 1B for a plane in the ascending aorta of a volunteer. At this location, WSS is relatively homogeneous and exhibits only minor oscillations (OSI values, Fig.1 B3-B4) due to early diastolic regurgitant flow (Fig.1 B1). A comparison of estimated mean axial WSS and axial OSI for all evaluated slices along the aorta is represented in Fig. 2. Close agreement between *2D* and *3D-CINE-3dir.PC* MRI can be observed and inter-individual WSS variations are interestingly low, supporting a potential for *3D-CINE-3dir.PC* MRI for WSS assessment. A systematic comparison between *2D* and *3D-CINE-3dir.PC* acquisition of important flow and wall parameters is summarized in Table 1. All parameters revealed limited differences and significant correlation (p-value < 0.05). Generally, parameters derived from the *3D-CINE-3dir.PC* data tend to be underestimated (visible on Fig.1 B1-B2 as well). Volumetric flow parameters (total flow, peak flow, time to peak flow) as well as the lumen area compare very well between both methods (rel. error < 15 %, a > 0.72; p-value < 10^{-15}). In contrast, due to the limited temporal resolution, parameters such as regurgitant flow and OSI are underestimated in the 3D measurements (rel. error: 77.4% and 53.7%). The spatial mean axial WSS compare well between *2D* and *3D-CINE-3dir.PC* (rel. error< 20%, a = 0.54; p-value < 10^{-12}).

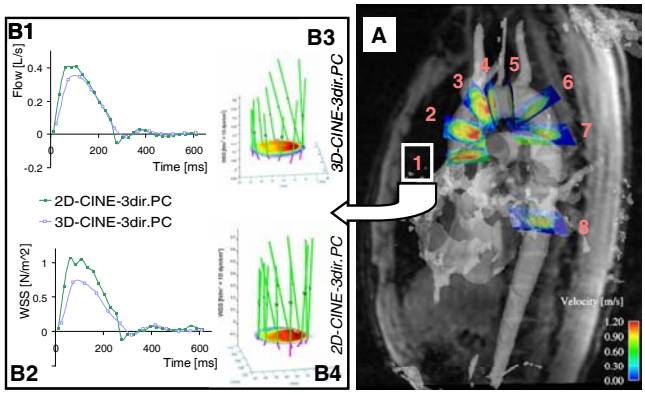

Fig. 1 Flow analysis in the thoracic aorta of a volunteer. **A:** Plane definition for 3*D-CINE-3dir.PC* MRI data. **B:** Analysis from 2*D* and 3*D-CINE-3dir.PC* data at plane1 in the ascending aorta. **B1-B2:** time-resolved flow and mean axial WSS, **B3-B4:** local vectorial WSS averaged over the cardiac cycle (green) and OSI (purple)

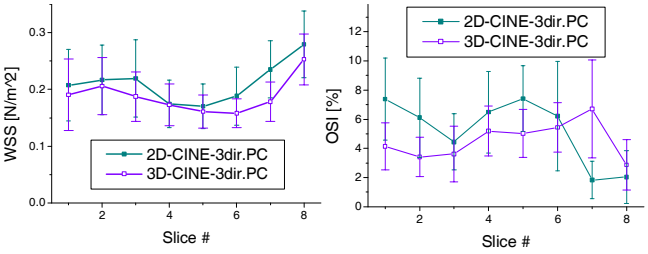

Fig. 2 Comparison of the evolution of wall shear stress (WSS) and oscillatory shear index (OSI) along the thoracic aorta derived from 2*D* and 3*D-CINE-3dir.PC* MRI data. Refer to Fig. 1A for slice positions. Error bars represent inter-individual variation.

	Total flow	Regurgitant flow	Axial WSS	Axial OSI	Peak flow	Time to peak flow	Mean Area
	[L/cycle]	[%]	[N/m^2]	[%]	[L/s]	[ms]	[mm^2]
Mean 2D-CINE-3dir.PC	0.059	3.7	0.211	5.2	0.303	131.5	388.6
std dev. - slices	0.011	3.1	0.044	2.9	0.067	39.2	82.2
std dev. - volunteers	0.014	2.5	0.054	2.4	0.070	18.1	81.3
Mean 3D-CINE-3dir.PC	0.055	1.7	0.188	4.5	0.271	143.5	375.5
std dev. - slices	0.012	1.0	0.038	2.0	0.066	31.5	81.1
std dev. - volunteers	0.013	1.5	0.041	1.9	0.065	20.4	67.4
Mean rel. error*	14.6%	77.4%	19.4%	53.7%	12.9%	14.0%	9.2%
a*	0.81	0.16	0.54	0.15	0.89	0.72	0.82
b	0.007	1.1	0.074	3.8	0.003	48.3	57.0
R^{2*}	0.644	0.133	0.460	0.047	0.849	0.721	0.839
p-value*	$<10^{-15}$	4.8E-04	3.9E-13	4.3E-02	$<10^{-15}$	$<10^{-15}$	$<10^{-15}$

Table 1 Flow and wall parameters determined from 2*D* and 3*D-CINE-3dir.PC* MR-acquisitions. Mean values over all slices as well as inter-slice and inter-individual variations (std dev.) are reported. Mean rel. error corresponds to the mean of the absolute difference between 2*D* and 3*D-CINE-3dir.PC* for each slice and volunteer and is normalized to the mean of the 2D measurements. Results of correlation analysis are listed in the lower rows: a (linearity), b (systematic difference), R^2 (coefficient of determination) and p-value. * designates dimensionless elements.

Discussion: Results from a study with 11 volunteers indicate the potential of 3*D-CINE-3dir.PC* MRI (flow sensitive 4D MRI [1]) for reliable quantitative assessment of flow and wall parameters within the entire thoracic aorta. Spatially integrated flow parameters such as flow and area compared very well between *2D* and *3D-CINE-3dir.PC* acquisitions. However, parameters representing time-varying aspects such as regurgitant flow and OSI are slightly underestimated by *3D-CINE-3dir.PC* acquisitions due to reduced temporal and spatial temporal resolution. Mean spatial WSS, although slightly underestimated for *3D-CINE-3dir.PC* MRI compared pretty well to the measurements from 2D. Our WSS measurements are in good agreement with published results in the abdominal aorta derived from phase-contrast MRI [3-5] which delivered similar average WSS values over the course of the cardiac cycle (0.18 to 0.95 N/m2). Further similar WSS values were also reported in a recent study of WSS in different segments of the descending thoracic aorta [6].

References: [1] Markl M. et al, J Magn Reson Im, in press (2006) [2] Stalder A. F. et al, Proc. ISMRM Workshop on Flow and Motion, NYC (2006) [3] Moore JE Jr. et al, Atherosclerosis 110:225– 40 (1994) [4] Pedersen EM et al, Eur J Vasc Endovasc Surg 18:328 –33 (1999) [5] Oyre S. et al, J Am Coll Cardiol 32:128 –34 (1998) [6] Wentzel J.J. et al, J Am Coll Cardiol. 45:846-54 (2005)