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

A. F. Stalder1, M. F. Russe2, J. Bock1, J. Hennig1, M. Markl1, and A. Frydrychowicz2

1Diagnostic Radiology - Medical Physics, University Hospital Freiburg, Freiburg, Germany, 2Diagnostic 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 transverse 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 (Trios, 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 mm3, 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 mm3, 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, resistence 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. 1B). 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^-3). 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^-3).

Discussion: Results from a study with 11 volunteers indicate the potential of 3D-CINE-3dir.PC MRI (flow sensitive 4D MRI) 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].