Time-resolved magnetic resonance angiography and flow-sensitive 4-dimensional magnetic resonance imaging at 3 Tesla for blood flow and wall shear stress analysis

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Objectives: In light of the ongoing discussion about flow-mediated arterial remodeling, it was the aim of this report to demonstrate the detailed assessment of 3-dimensional vascular hemodynamics by high-field magnetic resonance imaging in healthy volunteers and to illustrate its potential in comparison with results in a patient with stenosis.

Materials and Methods: All examinations consisted of flow-sensitive 4-dimensional magnetic resonance imaging at 3 Tesla. Retrospective blood flow visualization and segmental quantification of wall shear stress and oscillatory shear index were performed. The results from 11 healthy individuals were compared with a 13-year-old patient with aortic stenosis who received a combined protocol with time-resolved 3-dimensional magnetic resonance angiography before and 5 and 9 months after intervention.

Results: Evaluation of normal blood flow characteristics demonstrated predominantly right-handed helical flow in the ascending aorta. Vortex formation was observed in 1 of 11 volunteers. Consistently high segmental wall shear stress was found along the circumference of the ascending aorta (average wall shear stress = 0.191 ± 0.06 N/m^2) and descending aorta (average 0.191 ± 0.06 N/m^2). Compared with volunteers, the patient revealed substantial flow changes proximal and distal to the stenosis. Blood flow alterations in the ascending aorta were also observed associated with changes in velocities and wall shear stress that gradually normalized after intervention.

Conclusion: Flow-sensitive 4-dimensional magnetic resonance imaging at 3 Tesla can provide deeper insights into hemodynamic alterations in the diagnosis and follow-up of aortic pathologies. These findings indicate the potential of the methodology for the evaluation of effects of localized pathologies on the entire vascular system, which will have to be confirmed in future studies.

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The impact of hemodynamic alterations on vessel wall remodeling has gained attention during the past 20 years, and noninvasive methods for the detailed characterization of such changes have recently been adapted for in vivo diagnostics.[1-3] The application of derived parameters such as wall shear stress (WSS) to monitor therapy or find parameters predictive for progression or relapse of an arterial disease could enrich modern diagnostic and therapeutic decision making. In diseases such as aortic stenosis, patients are at a high risk of secondary complications even after successful therapy. Among other concerns, the formation of aneurysms has potentially serious complications. However, the mechanisms associated with aneurysm formation either at the site of stenosis or in the ascending aorta (AAo)[4] are not completely understood, and the association with altered hemodynamics is still hypothetical.

Abbreviations and Acronyms

3D	= 3 dimensional
4D	= 4 dimensional
AAo	= ascending aorta
CE-MRA	= contrast-enhanced magnetic resonance angiography
DAo	= descending aorta
MRI	= magnetic resonance imaging
OSI	= oscillatory shear index
T	= Tesla
WSS	= wall shear stress

Because of its beneficial effects on signal-to-noise ratio,[5] clinical high-field magnetic resonance imaging (MRI) has the potential to enhance the depiction of arterial pathologies and associated functional changes. The combination of methodologically advanced imaging strategies, such as view sharing,[6] parallel imaging,[7] and partial Fourier transform,[8] with fast and functional imaging is currently possible. Thus, high-field imaging at 3 Tesla (T) may contribute to a better understanding of the interaction of alterations in vascular geometry and changes in blood flow and vessel wall characteristics. Previous reports show that the combination of morphologic and functional vascular MRI can reveal comprehensive findings in vascular geometry under physiologic conditions[9] and in the presence of pathologic alterations in vascular geometry.[3,10] To further underline the additional information provided by modern time-resolved contrast-enhanced magnetic resonance angiography (CE-MRA)[11,12] and flow-sensitive 4-dimensional MRI,[13] we compare the collective findings of 11 healthy volunteers with the blood flow and derived vessel wall characteristics in a 13-year-old boy with high-grade descending aortic stenosis. We provide detailed information about the changes in vascular hemodynamics 5 and 9 months after intervention (ie, stent placement and dilatation of the stenosis).

Materials and Methods

Flow experiments were performed in 11 healthy volunteers (22.6 ± 1.4 years, 67.7 ± 9.0 kg, 2 female, 9 male) and a 13-year-old patient before and 5 and 9 months after stent placement and dilatation of a high-grade aortic stenosis. Studies were approved by the local ethics committee and performed after written informed consent on a 3T magnetic resonance system (Magnetom TRIO, Siemens, Germany, maximum gradient strength = 40 mT/m, rise time = 200 μsec, 8-channel receiver coil) using an rf-spoiled gradient echo sequence with interleaved 3-directional velocity encoding during free breathing and prospective electrocardiogram gating. Data were acquired with $\alpha = 15°$, venc = 150 cm/s, spatial resolution (3.2 × 2.1 × 5.0 mm^3 flip angle (FA), echo time (TE) = 3.5ms, repetition time (TR) = 5.6ms, and temporal resolution = 49 ms. To minimize breathing artifacts and image blurring, respiration control was performed on the basis of combined adaptive k-space reordering and navigator gating.[14]

Blood flow quantification and WSS analysis were performed using a homebuilt software tool based on MatLab (The MathWorks Inc, Natick, Mass) that allowed for vessel lumen segmentation of 2-dimensional cutplanes. Freely positioned cutplanes were extracted from the 4-dimensional flow data using a commercially available software package (EnSight, CEI, Apex, NC) that also served to generate time-resolved, color-encoded visualization of flow characteristics.[15] Further visual evaluation of datasets was performed by 2 experienced readers in a consensus reading screening for general hemodynamics, blood flow helicity, development, size and direction of vortices, and degree of physiologic retrograde flow.

For time-resolved 3-dimensional (3D) MRA, an rf-spoiled gradient echo sequence with parallel imaging (k-space based GRAPPA reconstruction[7]) with an acceleration factor of 4 along the phase encoding direction and 32 reference lines, partial Fourier acquisition along the phase and slice encoding direction (for both, partial Fourier factor = 6/8), and view sharing along the temporal domain (TREAT imaging[6]) based on elliptical centric view ordering was used. With the resulting imaging protocol, 20 T1w 3D data volumes were acquired consecutively with a temporal update rate of 2.8 seconds. CE-MRA was performed using gadobenate dimeglumine (Gd-BOPTA chelate, Multihance, Altana Pharma, Konstanz, Germany, molar concentration 0.5 mol/L, single dose = 0.1 mmol/kg body weight, injection rate = 3 mL/s). Further imaging parameters were as follows: flip angle (FA) = 14 degrees, matrix = 224 × 320, field of view 280 × 400 mm^2, TR = 2.12 ms, TE = 0.85 ms, slice thickness = 1.25 mm, effective spatial resolution = 1.96 × 1.25 × 1.25 mm^3, and temporal update rate = 2.82 seconds.

Results

Normal Aortic Hemodynamics and Wall Parameters

Flow-sensitized 4-dimensional (4D) MRI covering the entire thoracic aorta was successfully performed in all healthy volunteers. Subsequent visualization of the measured blood flow velocities and directions included 3D streamline depiction of flow patterns. Figure 1 illustrates the potential of 3D blood flow visualization to analyze global and regional hemodynamics in the thoracic aorta. In healthy subjects, predominantly right-handed helical flow was seen in the AAo and vortices occurred only occasionally (1/11 volunteers). The results of visual 3D flow grading for all 11 volunteers (mean diameter of the AAo = 2.4 ± 0.2 cm) are summarized in Table 1.

With respect to the ongoing discussion of the importance of WSS and its implications for vascular remodeling,[1] a quantification of WSS and flow was conducted in the AAo and descending aorta (DAo) by retrospectively extracting manually positioned 2-dimensional cutplanes from the 3D dataset. Next, segmentation of the aortic wall was interactively performed frame by frame using cubic B-spline smooth contours. Axial WSS was directly derived from the measured 3-directional velocity vector field using a deformation tensor.[16] The oscillatory shear index (OSI) was calculated as the ratio between the area under the WSS time curve of the

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