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Wall Morphology, Blood Flow and Wall Shear Stress: MR Findings in Patients with Peripheral Artery Disease

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Abstract

Objectives: To investigate the influence of atherosclerotic plaques on femoral haemodynamics assessed by 2D phase contrast (PC) MRI with three-directional velocity encoding.

Methods: During one year, patients with peripheral artery disease and an ankle brachial index <1.00 were enrolled. After IRB approval and written informed consent, 44 patients (age=70±12 years) underwent common femoral artery MRI. Patients with contraindications for MRI were excluded. Sequences included 2D time-of-flight, proton-density, T1-, and T2-weighted MRI. ECG-gated 2D PC-MRI with 3D velocity encoding was acquired. A radiologist classified images in five categories. Blood flow, velocity, and WSS along the vessel circumference were quantified from the PC-MRI data.

Results: The acquired images were of good quality for interpretation. There were no image quality problems related to poor ECG-gating or slice positioning. Velocities, oscillatory shear stress, and total flow were similar between patients with normal arteries and wall thickening/plaque. Patients with plaques demonstrated regionally increased peak systolic WSS and enhanced WSS eccentricity.

Conclusions: Combined multi-contrast morphological imaging of the peripheral arterial wall with PC-MRI with 3 directional velocity encoding is a feasible technique. Further study is needed to determine whether flow is an appropriate marker for altered endothelial cell function, vascular remodelling, and plaque progression.

Keywords

Phase contrast MRI; plaque; blood flow; wall shear stress; peripheral arterial disease

INTRODUCTION

Lower extremity peripheral arterial disease (PAD) is a widely prevalent syndrome caused by atherosclerosis [1]. There are known risk factors for the development of this disease such as smoking, lack of exercise or diabetes. However, classic risk factors represent global changes

and do not reflect the focal nature of PAD which occurs locally and often near the branching points of arteries [2].

A number of studies have provided evidence that local blood flow characteristics and particularly wall shear stress (WSS), the drag force of blood at the arterial wall, may contribute to the risk of developing PAD. It has been shown that the development of atherosclerosis in adults is associated with complex changes in local wall shear stress (WSS) [3]. Studies in the carotid and coronary arteries have shown that the onset of vessel remodelling and plaque development occurs in arterial regions with low wall shear stress (WSS) and high oscillatory shear index (OSI) [4, 5]. Following plaque development and lumen narrowing, the altered vessel geometry changes the WSS distribution. Increased WSS is found proximal and at the site of the plaque while low WSS moves to regions distal to the atheroma. A number of previous studies based on Doppler ultrasound, flow sensitive MRI, or computational fluid dynamics (CFD) have demonstrated these effects in coronary and carotid vessel segments [3, 4, 6-9].

Wall shear forces, however, are complex, and 3-directional blood flow velocities are thus needed to fully characterize WSS *in-vivo*. In addition, to our knowledge, no systematic analysis of the WSS distribution for plaques in the periphery arteries and its relationship with plaque type and composition has been reported to date. The aim of this study was to combine multi-contrast morphological imaging of the peripheral arterial wall with the analysis of femoral haemodynamics (flow and WSS parameters) based on 2D phase contrast MRI with 3-directional velocity encoding. We hypothesize that presence and type of plaque will be accompanied by altered local haemodynamics at the site of the lesion.

METHODS

Study Population

Participants were identified from the Walking and Leg Circulation Study III (WALCS III), a multi-centre, prospective, observational study designed to establish associations of magnetic resonance imaging (MRI)-measured atherosclerotic plaque characteristics with functional impairment and functional decline in PAD [10, 11]. Although data were collected at one medical centre, WALCS III participants were recruited from four Chicago-area medical centres [11]. For this pilot study, the participants were prospectively recruited between 16 June 2011 and 16 June 2012. Forty-four patients with lower extremity PAD (age = 70.1 ± 12.3 years, 14 female) were included in the study during this time period. Presence of PAD was determined by ankle-brachial index (ABI) measurement as described previously [12]. An ABI < 0.9 was considered diagnostic for PAD. Because ABI measurements are unreliable when the arteries are incompressible (such as in diabetes), care was taken to exclude data from undetectable or incompressible arteries from the ABI calculation. However, no participant had both undetectable dorsalis pedis and posterior tibial pressures in 1 leg, and no potential participants were excluded because of undetectable dorsalis pedis or posterior tibial pressures [11].

Exclusion criteria have been reported and are summarized here briefly [11]. . Nursing home residents, wheelchair-bound patients, and patients with foot or leg amputations were excluded because of their severely impaired functioning. Potential participants who required oxygen therapy or had contraindications to MRI testing were also excluded [11].

This HIPAA-compliant study was approved by our local IRB and informed consent was obtained from all participants.

MR Imaging

All measurements were performed on a 1.5 T MR system (Espree, Siemens Healthcare, Erlangen, Germany). Multi-contrast plaque imaging was performed at the level of the common femoral artery bifurcation. Several consecutive 3-mm axial images were obtained. Four types of 2D images were acquired at this level: time-of-flight (TOF) bright-blood images; and dark blood proton density (PD), T1-, and T2-weighted turbo spin-echo images. For TOF, data acquisition parameters were as follows: TR = 38 ms, TE = 8.67 ms, spatial resolution = $0.469 \times 0.469 \text{ mm}^2$, slice thickness = 3 mm, flip angle = 60° . Proton density, T1-, and T2-weighted images used black-blood saturation to achieve dark blood contrast. For all three techniques, data were acquired using turbo spin-echo sequences with a fat saturation preparation pulse. For PD, data acquisition parameters were as follows: TR = 2,160 ms, TE = 8 ms, slice thickness = 3 mm, spatial resolution = $0.625 \times 0.625 \text{ mm}^2$. The acquisition parameters for T1-weighted images were: TR = 800 ms, TE = 8 ms, slice thickness = 3 mm, spatial resolution = $0.625 \times 0.625 \text{ mm}^2$. The acquisition parameters for T2-weighted images were: TR = 2,160 ms, TE = 48 ms, slice thickness = 3 mm, spatial resolution = $0.625 \times 0.625 \text{ mm}^2$.

Electrocardiogram-gated 2D phase-contrast (PC) MRI with 3-directional velocity encoding was acquired in a 2D slice orthogonal to the femoral artery ($v_{enc} = 120 \text{ cm/s}$ along all directions, temporal resolution = 22.8 ms, slice thickness = 6 mm, spatial resolution = $1.1 \times 1.5 \text{ mm}^2$). The location of the multi-contrast vessel wall images in the femoral artery was copied for data acquisition with 2D PC-MRI to co-register information on the vessel wall and femoral haemodynamics.

Data analysis

Multi-contrast plaque images were visually analyzed by a radiologist (M.S.G., with 2 years of experience reading vascular MRI). A single slice that best matched the PC-MRI image location was used for plaque classification. Based on this slice, the patient's femoral arteries were qualitatively categorized as having no plaque, demonstrating wall thickening, or being abnormal, if a plaque was present at that level. When a plaque was present, it was classified accordingly to its most prominent component: lipid-rich/necrotic core (LR/NC), loose-matrix, or calcification according to the methods previously reported by Cai et al and Saam et al. [13, 14].

Phase contrast data were analyzed using a home built software tool (Matlab, the Mathworks, Natick, MA, USA). After correction for Maxwell terms and eddy currents, the vessel lumen of the femoral artery was manually segmented for all cardiac time-frames. Based on the vessel lumen contours the total flow, and mean peak systolic velocity (i.e. averaged over the vessel lumen) could automatically be quantified. In addition, a cubic b-spline interpolation of the 3-directional velocity data was used to derive the local velocity gradient as a measure of the segmental distribution of the WSS vector along the vessel wall as described previously [13]. Time-averaged absolute WSS, peak systolic WSS, and oscillatory shear index (OSI) were calculated in two ways: (1) averaged over the entire vessel lumen circumference; and (2) in eight angular segments along the vessel wall circumference.

Statistical Analysis

All values are reported as mean $\pm$ standard deviation. Differences between groups were evaluated using a two-sided t-test with a significance level of $P < 0.05$.

RESULTS

Multi-contrast plaque imaging was successfully performed in 44 PAD patients with image quality similar to the examples shown in Fig. 1. The acquired images were of good quality for interpretation. Neither poor ECG-gating or slice positioning rendered images unreadable. Visual analysis of multi-contrast images for all patients revealed $n=15$ femoral arteries with neither wall thickening nor signs of plaque. In the remaining 29 patients, analysis revealed abnormal femoral wall as characterized by wall thickening ($n=9$), loose matrix/necrotic core (LM/NC) plaque ($n=5$), lipid-rich plaque ($n=2$), and calcified plaque ($n=13$). There was no significant difference among the groups regarding age, sex, or ABI (Table 1).

Global flow and WSS

For the quantitative comparison of global flow and wall parameters, patients with normal femoral artery walls at the analyzed level were used for comparison. As summarized in table 2, peak mean systolic blood flow velocities, OSI, and total flow over the cardiac cycle were not significantly different between patients with no femoral wall abnormalities and patients with femoral wall thickening or plaque. Time-averaged WSS was reduced while peak systolic WSS was increased compared to patients with no femoral wall abnormalities but did not reach significance.

Segmental WSS Distribution

A more detailed regional comparison of time-averaged and peak systolic WSS between patients with no femoral wall abnormalities and the different subgroups of patients with femoral wall abnormalities is shown in Fig. 1. Wall thickening alone was not accompanied by altered magnitude and distribution of WSS patterns along the lumen circumference. By comparison, patients with femoral plaques demonstrated considerably increased peak systolic WSS (significant in 3 segments for loose matrix plaques, $P<0.05$) compared to patients without femoral wall abnormalities. In addition, a more eccentric systolic WSS distribution was observed in patients with LR/NC and calcified plaques.

Fig. 2 illustrates differences between time-averaged and systolic WSS for patients with abnormal femoral arteries (plaque or wall thickening) compared to patients with no femoral wall abnormalities. While time-average WSS was similar between groups, regional changes in peak systolic WSS were more pronounced. As shown in Fig. 2A, presence of femoral wall abnormalities (wall thickening, loose matrix/necrotic core, lipid rich, or calcified plaque) was consistently accompanied by increased systolic WSS along the lumen circumference compared to patients with normal femoral artery walls. Further increased and partly significant ($P<0.05$) changes were found in the group of patients with femoral plaques (Fig. 2B, LM/NC, lipid rich, or calcified plaque) compared to patients with no femoral wall abnormalities.

DISCUSSION

To our knowledge, this is the first study investigating femoral wall morphology as well as femoral artery flow, peak velocities and the distribution of regional wall shear stress in a cohort of patients with PAD as defined by ABI. We were able to acquire, in a single MRI test session, both multi-contrast morphological imaging of atherosclerotic plaques and flow imaging at the same arterial location, from which it is possible to calculate several hemodynamic variables. By combining these two techniques in one single study, it is possible to study the relationship between different flow patterns and presence of plaques of several types.

Although atherosclerosis is associated with systemic risk factors, it develops in certain preferential locations within the arterial system. Previous studies have shown that the appearance and development of atherosclerotic plaques is correlated to areas where wall shear stress (WSS) is reduced, a proposed mechanism being an enhanced mass transfer through the arterial endothelium that leads to a gradual accumulation of material in the arterial wall [15]. In fact, our results demonstrate mildly decreased time-averaged WSS in the patients with plaques and wall thickening that did not reach statistical significance. However, systolic peak WSS was substantially increased indicating that time-averaged WSS is less sensitive to changes in femoral shear patterns. We speculate that PAD and femoral plaques are accompanied by altered dynamics of peripheral blood flow with higher systolic velocities and different pulsatile waveform characteristics. As a result, WSS limited to the systolic period can capture these changes while time-averaged WSS is less sensitive to these alterations [16, 17].

When a point-by-point comparison was made between WSS in patients without plaques to WSS in patients with plaques, not including patients with wall thickening, a statistically significant difference between WSS magnitude was found, WSS being higher in patients with plaques. One possible explanation for this finding may be that the lumen is narrowed by the plaque, causing increased flow velocities and WSS; thus, although low WSS precede plaque formation, the presence of an established plaque may by itself disrupt the vessel flow and alter the WSS pattern [18]. In fact, we found more eccentric WSS in plaque patients indicating more deranged flow profiles due to the presence of plaques and asymmetric lumen narrowing.

The fact that the above finding of higher WSS being correlated to the presence of plaque is directly opposed to other studies, point to the fact that the relationship between wall shear stress and atherosclerosis is more complex than initially apparent, and that comparison between studies is difficult due to differences in methodology. Longitudinal studies starting from the healthy state, or the collection of average flow metrics derived from large numbers of healthy vessels, both in conjunction with point-by-point comparisons using appropriate statistical techniques, will be necessary to improve our understanding of the relation between blood flow and atherogenesis.

For the estimation of WSS it is necessary to measure the wall shear rate, which is the blood flow velocity gradient near the vessel wall [19]. Blood flow velocity can be obtained non-invasively by Doppler ultrasound. However, not only ultrasound is limited when there is tissue or bone overlying the vessel being studied, but it also is able to assess flow velocity in only one direction [19]. Wall shear stress patterns are usually complex. Phase-contrast magnetic resonance imaging (PC-MRI) has been increasingly used to assess blood flow velocities, and consequently WSS, in three dimensions. PC-MRI is also not limited by the presence of overlying bone or tissue [20, 21].

Atherosclerosis is a progressive disease, and atherosclerotic plaques can be of many different shapes and composition [22, 23]. Of particular importance is the early detection of the so called “vulnerable plaques”, plaques which are particularly prone to lead to sudden cardiovascular events. The amount of lipid content and the presence of haemorrhage may indicate progression and rupture of the atherosclerotic plaque, while calcification or the presence of loose matrix may indicate healing in subjects with silent rupture [14]. MRI techniques have been shown to accurately assess atherosclerotic plaque composition *in vivo*, with good correlation with histology analysis [14]. In this context, MRI may offer the opportunity to act as a “one-stop shop” for a complete evaluation of PAD, including assessment of its hemodynamic (flow and WSS analysis) and anatomic aspects (plaque composition).

Study Limitations

A limitation of this study is the use of 2D imaging for plaque analysis. The use of a single 2D imaging slice explains why some patients did not have any plaque, although they had PAD as assessed by ABI. However, atherosclerotic plaques are tridimensional and we did not evaluate if the presence of wall abnormalities more proximal or distal to the level where WSS was assessed had any influence on our findings. Further studies based on 3D or multi-slice 2D imaging comparing wall composition and haemodynamic parameters at multiple locations throughout the femoral arteries are needed to provide more information on the relationships between WSS patterns and the presence of atherosclerosis.

It has been shown that lower ABI are associated with smaller arterial lumen area in the proximal superficial femoral artery (SFA) [24]. However, our study did not assess lumen areas, instead concentrating in the composition of the atherosclerotic plaques. There was no significant difference between ABI among the groups. Further studies would be necessary to assess whether the flow analysis is able to differentiate groups of patients that have similar ABI values.

The diameter of the superficial femoral artery in our cohort was 6.7 ± 1.7 mm (mean $\pm$ SD). With an in-plane spatial resolution of 1.5×1.1 mm, 4–6 voxels per lumen were generated by the PC-MRA method. It has been shown that the current spatial-temporal resolution of 2D PC-MRA can underestimate the true WSS magnitude and limit the accuracy of wall parameter calculations [25]. However, the limited resolution in our study does not affect the general WSS distribution or relative regional changes of wall parameters, particularly when the same imaging parameters are used for all patients as in our cohort study.

A drawback of our study is related to the analysis by a single reader. Future studies are needed to investigate observer variability of the WSS analysis. Further drawbacks are related to the absence of haemodynamics analysis proximal and distal to the plaques, the absence of normal healthy controls, the limited spatial resolution of 2D phase contrast MRI, the use of a visual, non-quantitative plaque assessment, and the fact that the findings of this study provide a picture of atherosclerosis in a moment in time when PAD is already present.

Finally, a limitation of this study includes the small patient cohort with heterogeneous wall abnormalities, leading to limited statistical power to detect differences between the subgroups of plaques. However, the aim of this pilot study was to test the feasibility of PC-MRI to detect differences in regional WSS. In addition, the lack of inclusion of participants without PAD prevented us from identifying differences in flow between individuals with and without PAD. Future studies with larger patient cohorts and appropriately matched control subjects are needed to broaden the range of disease severity and further analyze differences between subgroups.

In summary, combined multi-contrast morphological imaging of the peripheral arterial wall with phase-contrast MRI with 3 directional velocity encoding is a feasible technique. Flow analysis may become a marker for altered endothelial cell function and thus vascular remodelling and plaque progression. Further analysis is warranted to co-locate segmental changes in wall shear stress with the position and composition of aortic plaques.

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Abbreviations and acronyms

WSS	wall shear stress
PAD	peripheral arterial disease
OSI	oscillatory shear index
MRI	Magnetic resonance imaging
TOF	time-of-flight
PD	proton density
PC	phase contrast
LR/NC	lipid-rich/necrotic core

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Key points

- Femoral plaques are associated with altered dynamics of peripheral blood flow.
- Multicontrast MRI can investigate the presence and type of atherosclerotic plaques.
- 3D velocity-encoding phase-contrast MRI can investigate flow and wall shear stress.
- Atherosclerotic peripheral arteries demonstrate increased systolic velocities and wall shear stress.

Fig. 1.

Left Example images for multi-contrast plaque characterization for a normal femoral artery (top row) and different types of wall abnormalities. Time-resolved (CINE) 2D phase-contrast MRI with 3-directional velocity encoding at the same anatomic location was used to derive wall shear stress along the femoral artery lumen circumference. **Right:** The polar plots show the segmental distribution of peak systolic wall shear stress for patients with femoral wall abnormalities (wall thickening or plaque, red squares) compared to patients with normal femoral walls (patients with no femoral wall abnormalities, black circles). * = significant difference, $P < 0.05$.

Fig. 2. Comparison of the distribution of time-averaged (left) and peaks systolic WSS (right). **A:** Comparison of segmental WSS for all patients with femoral wall abnormalities (wall thickening, loose matrix, lipid rich, calcified plaque) versus patients with no femoral wall abnormalities. **B:** Comparison of segmental WSS for all patients with femoral plaque versus patients with no femoral wall abnormalities. * = significant difference, $P < 0.05$

Table 1

Acquisition parameters for the four MRI sequences utilized.

	TOF	PDW	T1W	T2W	PC-MRA
Sequence type	Time-of-flight MRA	Spin-echo	Spin-echo	Spin-echo	Phase-contrast MRA
TR [ms]	38	2,160	800	2,160	--
TE [ms]	8.67	8	8	48	--
Flip angle [degrees]	60	90	90	90	--
In-plane spatial resolution [mm × mm]	0.469×0.469	0.625×0.625	0.625×0.625	0.625×0.625	1.1×1.5
Slice thickness [mm]	3	3	3	3	8
Venc [cm/s]	--	--	--	--	120
Temporal resolution [ms]	--	--	--	--	22.8

TOF: time-of-flight; **PDW:** proton-density-weighted; **T1W:** T1-weighted; **T2W:** T2-weighted; **PC-MRA:** phase-contrast magnetic resonance angiography; **TR:** repetition time; **TE:** echo time.

Table 2

Descriptive statistics of the characteristics of the study participants.

	Age [years]	Male sex [%]	ABI
no wall abnormalities at site of PC-MRI (n=15)	65.4 ± 15.4	66.7	0.74 ± 0.14
wall thickening (n=9)	69.4 ± 10.1	55.6	0.64 ± 0.16
plaque (n=20)	73.9 ± 9.5	75.0	0.70 ± 0.22
<i>loose matrix (n=5)</i>	<i>73.1 ± 11.0</i>	<i>80.0</i>	<i>0.70 ± 0.36</i>
<i>lipid rich (n=2)</i>	<i>67.6 ± 4.4</i>	<i>50.0</i>	<i>0.70 ± 0.10</i>
<i>calcified (n=13)</i>	<i>75.1 ± 9.6</i>	<i>76.9</i>	<i>0.70 ± 0.19</i>
total (n=44)	70.1 ± 12.3	68.2	0.70 ± 0.19

Table 3

Descriptive statistics of flow and wall parameters for patients with normal femoral arteries and patients with wall thickening or femoral artery plaque at the location of 2D CINE PC imaging.

	peak mean systolic velocity [m/s]	flow [ml/cycle]	WSS [N/m ²]	peak systolic WSS [N/m ²]	OSI [%]
no wall abnormalities at site of PC-MRI (n=15)	0.34 ± 0.10	2.8 ± 1.1	0.83 ± 0.39	1.29 ± 0.55	23 ± 10
wall thickening (n=9)	0.31 ± 0.22	1.6 ± 1.6	0.73 ± 0.40	1.39 ± 0.77	17 ± 6
plaque (n=20)	0.46 ± 0.21	2.6 ± 1.2	0.67 ± 0.17	1.41 ± 0.55	19 ± 9
loose matrix (n=5)	0.55 ± 0.21	3.1 ± 1.3	0.69 ± 0.11	1.53 ± 0.48	20 ± 7
lipid rich (n=2)	0.50 ± 0.29	2.7 ± 0.6	0.68 ± 0.22	1.58 ± 0.82	15 ± 4
calcified (n=13)	0.42 ± 0.20	2.3 ± 1.3	0.67 ± 0.19	1.34 ± 0.57	19 ± 10