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Multidirectional WSS disturbances in stenotic turbulent flows: A pre- and post-intervention study in an aortic coarctation

Magnus Andersson [a,*], Jonas Lantz [b,c], Tino Ebbers [b,c], Matts Karlsson [a,c]

[a] Department of Management and Engineering (IEI), Linköping University, Linköping, Sweden
[b] Department of Medical and Health Sciences (IMH), Linköping University, Linköping, Sweden
[c] Center for Medical Image Science and Visualization (CMIV), Linköping University, Linköping, Sweden

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ABSTRACT

Wall shear stress (WSS) disturbances are commonly expressed at sites of abnormal flow obstructions and may play an essential role in the pathogenesis of various vascular diseases. In laminar flows these disturbances have recently been assessed by the transverse wall shear stress (transWSS), which accounts for the WSS multidirectionality. Site-specific estimations of WSS disturbances in pulsatile transitional and turbulent type of flows are more challenging due to continuous and unpredictable changes in WSS behavior. In these complex flow settings, the transWSS may serve as a more comprehensive descriptor for assessing WSS disturbances of general nature compared to commonly used parameters. In this study large eddy simulations (LES) were used to investigate the transWSS properties in flows subjected to different pathological turbulent flow conditions, governed by a patient-specific model of an aortic coarctation pre and post balloon angioplasty. Results showed that regions of strong near-wall turbulence were collocated with regions of elevated transWSS and turbulent WSS, while in more transitional-like near-wall flow regions a closer resemblance was found between transWSS and low, and oscillatory WSS. Within the frame of this study, the transWSS parameter demonstrated a more multi-featured picture of WSS disturbances when exposed to different types of flow regimes, characteristics which were not depicted by the other parameters alone.

1. Introduction

Disturbed blood flow promotes a complex environment of wall shear stress (WSS) on the endothelial surface, which has been associated to atherosclerosis (Caro et al., 1971), vascular remodeling, and other pathological events (Cecchi et al., 2011; Chiu and Chien, 2011; Dolan et al., 2013; Kwak et al., 2014b; Meng et al., 2014). Much attention has been directed towards estimating WSS at different vascular sites using computational fluid dynamics (CFD) simulations (Browne et al., 2015; Caballero and Laín, 2013; Lee et al., 2014; Peiffer et al., 2013b), where time-average wall shear stress (TAWSS) and oscillatory shear index (OSI) have been some of the most common parameters. The shortcomings of both these metrics in assessing disturbed WSS have recently been highlighted (Peiffer et al., 2013a, 2013b) and complemented by a new parameter, transverse wall shear stress (transWSS), which accounts for the multidirectional properties of WSS disturbances. Elevated transWSS has been shown to collocate with plaque prevalence in the vicinity of branch ostia in rabbits (Mohamied et al., 2015; Peiffer et al., 2013a) and intracoronary stents in minipigs (Pedrigi et al., 2015), but not at typical locations in human carotid bifurcations (Gallo et al., 2016). These studies were performed in unsteady but laminar flow regions, whereas less focus has been directed towards the multidirectional WSS response in turbulent flows. Two recent arteriovenous fistula studies (Bozzetto et al., 2015; Ene-Iordache et al., 2015) demonstrated modest-to-high transWSS close to transitional flow instabilities along the proximal part of the venous side branching, a region associated to wall remodeling.

Turbulent hemodynamics are accompanying a wide spectrum of WSS disturbances, typically found in relation to aortic valvular disease and malformations of larger arteries, such as coarctation of the aorta (CoA) and aneurysms (Dyverfeldt et al., 2008; Nichols et al., 2011). These flow disturbances are rarely fully developed turbulent, due to the re-laminarization nature in pulsatile flows, but rather a mix of laminar or turbulent dominating states. The level of WSS disturbances associated with only turbulent instabilities, the turbulent wall shear stress (turbWSS), can be estimated by statistical measures using e.g. the root mean square

* Correspondence to: Department of Management and Engineering, Linköping University, SE-581 83, Linköping, Sweden. Fax: +46 13149403.
E-mail address: magnus.andersson@liu.se (M. Andersson).

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(RMS) on the transient WSS components (Gårdhagen et al., 2010; Lantz et al., 2012). As defined, the turbWSS parameter inherently fails to detect WSS disturbances driven by laminar oscillations. This is unlike the OSI, which is not constrained to whether the flow is predominantly laminar or turbulent, but instead is insensitive to the magnitude of the oscillations. The transWSS, however, may serve as a more representative parameter for general disturbed WSS assessments in complex flows, as it, in theory, only is incapable of estimating the magnitude of WSS disturbances associated to pure unidirectional fluctuations. Multidirectional WSS in cardiovascular disease has only been investigated by a handful of studies limited to laminar or transitional-like flow disturbances.

The aim of this study was to investigate the transWSS properties in flows dominated by turbulent characteristics. Scale-resolving numerical simulations were performed on a patient-specific CoA model before and after intervention. TransWSS properties were compared to both local hemodynamics and common WSS parameters.

2. Method

The study was performed on a 63 year old female, who was treated for a residual coarctation in the descending aorta using a balloon angiography. Before and 2 years after intervention, the patient was examined on a 1.5T Philips Achieva MRI system (Philips Health Care, Best, The Netherlands). Both investigations included a contrast-enhanced magnetic resonance angiography (CE-MRA) using a Steady-State Free Precision (SSFP) gradient-echo sequence and a retrospective cardiac gated 2D through-plane phase-contrast MRI (PC-MRI) in the ascending aorta to measure supracoronary aortic blood flow. Proper consent was obtained from the patient and local ethics committee.

2.1. Computational model

The computational domains were reconstructed from the CE-MRA and include the major vessels surrounding the CoA region (Fig. 1). Segmentations were performed by a 3D level set technique using a freely available software (Heiberg et al., 2010) (http://segment.heiberg.se). Before intervention the degree of stenosis was 65% based on the cross-sectional area and at follow-up reduced to 50%, while the trans-stenotic pressure drops were 22 mmHg and 8 mmHg, respectively.

The inlet of the ascending aorta was set by the 2D PC-MRI blood flow measurement, whereas a square law governed the vessels in the aortic arch. The wall was assumed to be rigid and blood rheology non-Newtonian following the Carreau model. Large eddy simulation (LES) was used in order to resolve the most energy containing structures in the turbulent field, while the WALE subgrid model managed the unresolved part. The equations were solved in ANSYS CFX using a central-difference and second-order backward Euler scheme for the spatial and temporal gradients. The CFD models were discretized by hexahedral elements and an adaptive timestep marching approach was adopted; with appropriated spatio-temporal resolution according to a previous study (Andersson et al., 2015). In this work 40 cardiac cycles (omitting the initial 5) were used to guarantee sufficient WSS statistics, as twice the amount of cycles only resulted in minor differences (see Supplementary materials). Further details regarding the CFD method and MRI acquisition are provided in (Andersson et al., 2015) and Supplementary materials.

2.2. WSS parameters

In periodic pulsatile flows the WSS vector ($\boldsymbol{\tau}$) can be divided into phase-average ($\langle\boldsymbol{\tau}\rangle$) and fluctuating component ($\boldsymbol{\tau}'$):

$$\boldsymbol{\tau}(\boldsymbol{x},t) \quad = \langle\boldsymbol{\tau}\rangle(\boldsymbol{x},t)+\boldsymbol{\tau}'(\boldsymbol{x},t) \tag{1}$$

The phase-average WSS was estimated by ensemble averaging the instantaneous WSS over the range of available cardiac cycles N according to:

$$\langle\boldsymbol{\tau}\rangle(\boldsymbol{x},t) \quad = \frac{1}{N}\sum_{n=0}^{N-1}\boldsymbol{\tau}(\boldsymbol{x},t+nT) \tag{2}$$

where $(t+nT)$ represents a specific cardiac timestep over the constant cardiac time length T. The fluctuating part of the WSS vector was estimated by the RMS difference between the instantaneous and phase-average WSS components:

$$\boldsymbol{\tau}_{rms}(\boldsymbol{x},t) \quad = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1}[\boldsymbol{\tau}(\boldsymbol{x},t+nT)-\langle\boldsymbol{\tau}\rangle(\boldsymbol{x},t)]^2} \tag{3}$$

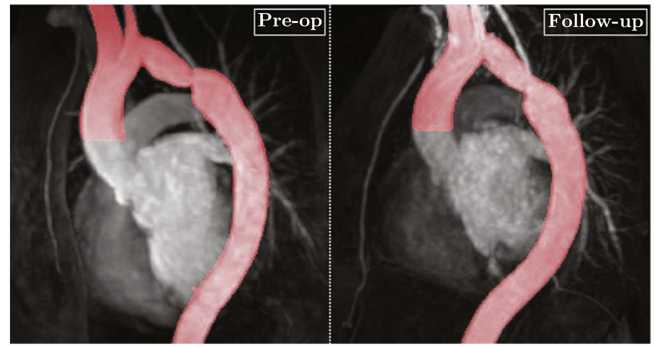

Fig. 1. Angiogram with imposed segmentation region (red) before (Pre-op) and after intervention (Follow-up).(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

The turbWSS, TAWSS, time-average WSS vector ($\boldsymbol{\tau}_m$) and OSI (Ku et al., 1985) were defined as:

$$\text{turbWSS} = \frac{1}{T}\int_0^T \|\boldsymbol{\tau}_{rms}\|\text{d}t \tag{4}$$

$$\text{TAWSS} = \frac{1}{T}\int_0^T \|\langle\boldsymbol{\tau}\rangle\|\text{d}t \tag{5}$$

$$\boldsymbol{\tau}_m = \frac{1}{T}\int_0^T \langle\boldsymbol{\tau}\rangle\text{d}t \tag{6}$$

$$\text{OSI} = \frac{1}{2}\left(1-\frac{\|\boldsymbol{\tau}_m\|}{\text{TAWSS}}\right) \tag{7}$$

The OSI will yield a non-zero value as long as the WSS vector $\langle\boldsymbol{\tau}\rangle$ departs from the $\boldsymbol{\tau}_m$ direction during any instant of the cardiac cycle. The transWSS (Peiffer et al., 2013a) was defined as:

$$\text{transWSS} = \frac{1}{T}\int_0^T |\langle\boldsymbol{\tau}\rangle\cdot(\boldsymbol{e}_n\times\boldsymbol{e}_m)|\text{d}t \tag{8}$$

where the unit vectors $\boldsymbol{e}_n$ and $\boldsymbol{e}_m = \boldsymbol{\tau}_m/\|\boldsymbol{\tau}_m\|$ represent the wall normal and time-average WSS direction respectively. The cross-product between these vectors gives the transverse direction, thus the transWSS represents the WSS portion acting perpendicular to $\boldsymbol{\tau}_m$.

Inconclusive evidence relating high OSI to sites of vascular disease has previously been reported (Peiffer et al., 2013b) questioning the bearing of the low-oscillatory WSS theory. A drawback with the OSI is its inability to differentiate between multidirectional and unidirectional flow oscillations, and lack of magnitude information. Therefore alternative descriptions of this oscillatory part were introduced, governed by the transWSS and turbWSS parameters:

$$\text{OSItr} = \frac{\text{transWSS}}{\text{TAWSS}} \tag{9}$$

$$\text{OSItu} = \frac{\text{turbWSS}}{\text{TAWSS}} \tag{10}$$

The OSItr and OSItu defines regions exposed to low-transverse WSS and low-turbulent WSS respectively. The alignment between $\langle\boldsymbol{\tau}\rangle$ and $\boldsymbol{\tau}_m$ was estimated by the time-averaged atan2 angle:

$$\text{WSSang} = \frac{1}{T}\int_0^T |\text{atan2}(\|\boldsymbol{\tau}_m\times\langle\boldsymbol{\tau}\rangle\|, \boldsymbol{\tau}_m\cdot\langle\boldsymbol{\tau}\rangle)|\text{d}t \tag{11}$$

where 0° indicated that all $\langle\boldsymbol{\tau}\rangle$ are pointing in the $\boldsymbol{\tau}_m$ direction while 180° in the reversed direction. This formulation avoids accuracy problems for nearly parallel vectors.

2.3. Data assessment

Quantitative comparisons between WSS parameters were performed using surface integral values and percentile surface area distributions. The flow was characterized by three hemodynamic parameters: kinetic energy (KE), turbulent kinetic energy (TKE) and turbulence intensity (TI), see Supplementary materials. Spearman's rank was used to assess the relationship between the WSS parameters themselves and against the near-wall hemodynamics. The directional dynamics of the WSS vector was evaluated by rose diagrams at specific locations. This study primarily focused on results in the post-stenotic region.

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