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Blood flow patterns and pressure loss in the ascending aorta: A comparative study on physiological and aneurysmal conditions

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A B S T R A C T

An aortic aneurysm is defined as a balloon-shaped bulging of all three histologic components of the aortic vessel walls (intima, media and adventitia). This dilation results from vessel weakening owing to remodeling, i.e. due to cystic degeneration of the Tunica media (Marfan), progression of atherosclerosis or presence of a bicuspid aortic valve. The growth rate of the aortic diameter varies from patient to patient and may progress until the aneurysm ultimately ruptures. The role of hemodynamics, i.e. blood flow patterns, and shear stresses that are supposed to intensify during aneurysm growth are not yet fully understood, but thought to play a key role in the enlargement process. The aim of this study is to characterize the aortic blood flow in a silicone model of a pathological aorta with ascending aneurysm, to analyze the differences in the blood flow pattern compared to a healthy aortic model, and to single out possible blood flow characteristics measurable using phase contrast magnetic resonance imaging (MRI) that could serve as indicators for aneurysm severity. MRI simulations were performed under physiological, pulsatile flow conditions using data obtained from optical three dimensional particle tracking measurements. In comparison to the healthy geometry, elevated turbulence intensity and pressure loss are measured in the diseased aorta, which we propose as a complimentary indicator for assessing the aneurysmal severity. Our results shed a light on the interplay between the blood flow dynamics and their contribution to the pathophysiology and possible role for future risk assessment of ascending aortic aneurysms.

1. Introduction

An aortic aneurysm is a balloon-shaped bulging in the aortic vessel walls, which can form in any location of the aorta. It is defined by a diameter that is more than 50% larger than the normal aortic diameter (Hope et al., 2007; Saliba and Sia, 2015). The formation of an aneurysm is believed to be a multi-factorial and predominantly degenerative process resulting from a complex interplay between biological processes in the artery walls (i.e., vascular endothelium response), and hemodynamic factors (i.e., disturbed or turbulent blood flow and elevated wall shear stresses) (Lasheras, 2007). The fluid-mechanical forces acting on the vessel wall after developing the aneurysm lead to further weakening of the wall tissue, which may result in an expansion of the vessel. The growth rate of the aortic diameter is approximately constant in time but varies from patient to patient. Although many parameters may influence the enlargement of the vessel, such as age, genetics, environmental factors, hemodynamic stresses, there is no consensus on the most critical physical factors causing the expansion. The most important criterion for intervention is based on the aneurysm size and its growth rate and does not directly consider disturbed blood flow (Hiratzka et al., 2010; Erbel et al., 2014).

Turbulent flow in the cardiovascular system can be utilized to detect abnormalities in the function of the human heart (Gülan et al., 2014; Gülan et al., 2017). Although there have been studies on the blood flow patterns in the aorta, little is known about complex flow characteristics and possible effects of turbulent flow in diseased aortas. Les et al. (2010) demonstrated that physical exercise may provoke moderate turbulence in abdominal aortic aneurysm (AAA) leading to higher fluid shear stresses on the aneurysmal wall which may accelerate aneurysmal growth (Les et al., 2010; Khanafer et al., 2007). Ge and Kassab (2010) showed that the flow may become turbulent if the dilatation is sufficiently large, which enhances the interactions with the endothelium, i.e. elevated shear stress and increased turnover rate, that may cause deterioration of the walls of the aorta. However, turbulence is usually not considered when

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assessing the severity of the disease and rupture risk associated with aortic aneurysms in clinical practice. A possible reason may be that up to recently it was difficult to assess turbulent blood flow in vivo. Recent progress in magnetic resonance imaging (MRI) technology makes it possible to quantify space-time resolved blood flow velocity, including turbulent kinetic energy (Dyverfeldt et al., 2006). Although there have been clinical studies on the ascending aortic aneurysms, all of them have focused on the phase averaged flow field (Hope et al., 2007; Barker et al., 2012). So far, the potential of addressing disturbed blood flow in aortic aneurysms and extracting relevant turbulence characteristics for risk assessment based on MRI has not been investigated.

The rationale of this study is to investigate the differences in the hemodynamics of phase-averaged and fluctuating velocity fields and associated kinetic energies, between a healthy and an aneurysmal ascending aorta and to propose possible blood flow characteristics measurable using phase contrast (PC-) MRI, which could be useful for the assessment of the severity of the disease and rupture risk in aneurysms. Three dimensional particle tracking velocimetry (3D-PTV) and subsequent PC-MRI simulations were performed to assess the quantities that are measurable via MRI in two different compliant silicone models under pulsating flow conditions. Our findings reveal alterations in the aortic blood flow, kinetic energy and energy losses, which could be used as complementary parameters for rupture risk assessment of aortic aneurysms.

2. Materials and methods

2.1. Experimental setup

In this study, 3D-PTV was performed in two compliant, silicone aortic models under physiological flow conditions. We have used time-of-flight magnetic resonance angiograms (TOF-MRA) with a spatial resolution of 1.17 mm × 1.17 mm × 2.6 mm in the oblique superior-inferior, anterior-posterior and right-left directions, respectively to produce an anatomically correct physical replica of an aorta of a healthy and an aneurysmal patient (Fig. 1b). Using the reconstructed 3D geometry of the models in stereolithography (STL) file format, optically transparent flexible silicone phantoms were produced from DOW Chemicals (Sylgard 184) by Elastrat Sarl (Geneva, Switzerland). To avoid large irregularities in the wall thickness the surface of the wax positive was repeatedly brushed and the layer was cured to the elastic state from the initially liquid state.

The tensile strength of the models is 6.7 MPa and the tear strength is 27 N/mm. The diameter of the healthy aorta was 21 mm, similar to the one of the diseased aorta prior to the development of the aneurysm. The aneurysm model had a diameter of 50 mm and the patient was recommended for surgery because of a high rupture risk. The investigation domain for both cases covered the ascending aorta. To derive the flow along the silicone phantom, a VAD (Berlin Heart, Germany) was used (Fig. 1a). The stroke volume of the VAD was 54 ml. An electro-pneumatic pump (Medos, Germany) was used to provide the suction and driving pressures, which moved the membrane between the air and liquid chambers of the VAD. For both model cases, resting conditions at a heart rate of 55 bpm were studied. The time variation of normalized inlet velocity profile is shown in Fig. 1c. In our setup, the aorta was connected to a circular pipe with the same diameter and a length of 8 cm. This development length is not sufficient to reach fully developed pipe flow (i.e. Poiseuille), but the profile resembles a rather plug-flow like shape. The outflows are measured. The brachiocephalic branch has 32%, left common carotid artery and left subclavian artery have 11% of the flow. The main flow passes through the descending aorta is 46% of the flow.

3D-PTV is an optical measurement technique and the main components are a high speed camera, an image splitter, and a

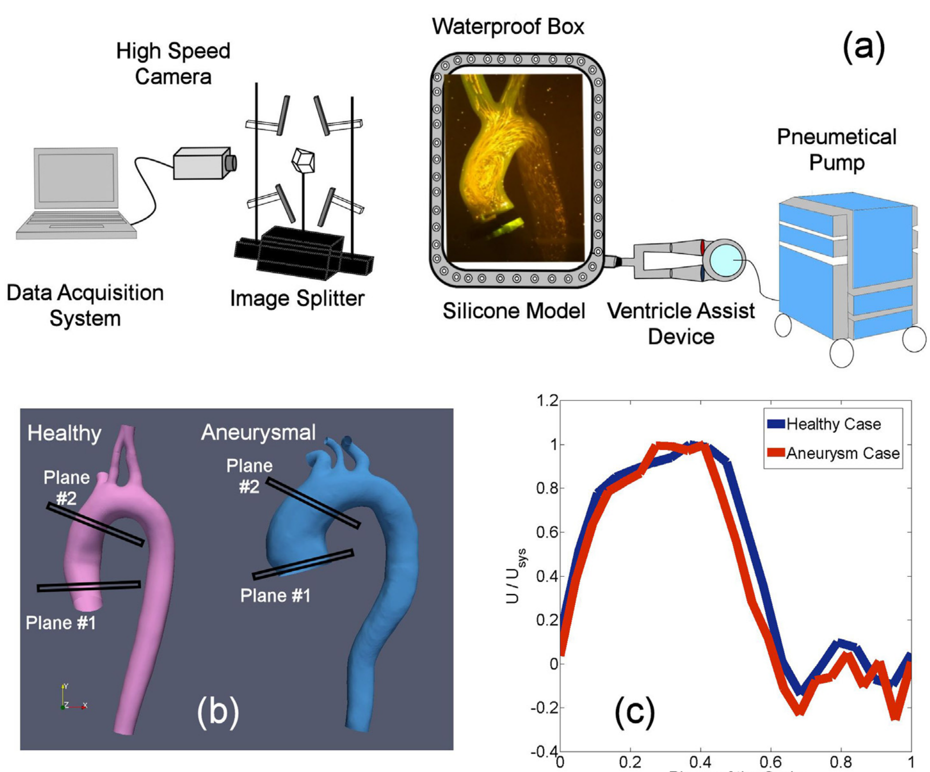

Fig. 1. Schematic view of the experimental setup including the data acquisition system, high-speed camera, image splitter, silicone phantom, ventricular assist device and waveform generator (a), schematic illustration of aortic geometry for the healthy and aneurysmal models (two different planes which are used for cross sectional analysis in the results section are depicted) (b), time evolution of normalized inlet velocity profile (c).