European Journal of Mechanics B/Fluids 46 (2014) 109–117

Contents lists available at ScienceDirect

European Journal of Mechanics B/Fluids

journal homepage: www.elsevier.com/locate/ejmflu

Fluid-structure interaction investigation of spiral flow in a model of abdominal aortic aneurysm

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HIGHLIGHTS

- Effect of spiral flow on haemodynamic changes in a model of abdominal aortic aneurysm (AAA) is investigated.
- An increase in the intensity of spiral flow results in an increase in the maximum wall shear stress (WSS) and a decrease in the size of regions with low WSS.
- Neglecting the effect of spiral flow in modeling of AAAs can underestimate the magnitude of WSS by up to 30% and overestimate the magnitude of wall stress by up to 11%.
- Spiral nature of blood flow within AAAs reduces the risk of rupture, endothelial dysfunction and the development of atherosclerosis.

ARTICLE INFO

Article history:
Received 16 April 2013
Received in revised form
24 January 2014
Accepted 11 February 2014
Available online 24 February 2014

Keywords:
Spiral flow
AAA
FSI
Wall stress
Wall shear stress

ABSTRACT

The presence of a spiral arterial blood flow pattern in both animals and humans has been widely accepted. The effect of spiral flow on physiological processes associated with abdominal aortic aneurysm (AAA) development and progressions can provide valuable information. The purpose of this study is to investigate the influence of spiral flow on haemodynamic changes in an elastic AAA model by implementing a coupled fluid–structure interaction (FSI) analysis. The results showed that an increase in the intensity of spiral flow resulted in an increase in maximum wall shear stress (WSS) and a decrease in maximum wall stress; however, the spiral flow effect on the WSS was higher than the wall stress. It was also shown that not taking into consideration the effect of spiral flow in modelling of AAA can underestimate the magnitude of WSS by up to 30% and overestimate the magnitude of wall stress by up to 11%. The presence of spiral flow within AAAs is associated with beneficial and detrimental effects. The beneficial effects are to reduce the wall stress and the size of regions with low WSS which in turn reduce the risk of rupture, endothelial dysfunction and the development of atherosclerosis. However, the increase in magnitude of WSS is seen as the detrimental effect of spiral flow.

1. Introduction

Knowledge of blood flow behaviour is essential to identify relationships between flow patterns and disease processes that form in arterial and venous branches. The study of physiological blood flow is quite important and computational simulation is playing a significant role in this field.

Abdominal aortic aneurysm (AAA) is a focal, balloon like irreversible enlargement of descending aorta, and is known as a cause of significant morbidity and mortality throughout the world [1]. Physiological processes associated with AAA development and progressions are worthy of study because they yield insights into diagnosis and treatment of this vascular disease.

Several criteria have been proposed to help clinicians decide whether to intervene surgically in a patient with AAA; among these, the maximum AAA diameter and its expansion rate are the most frequent employed indices [2]. It is reported that an increase in AAA diameter will result in an increase in the possibility of rupture. As an example, for an AAA with maximum diameter greater than 7 cm, the risk of rupture is 64% [3]. However, this criterion cannot be seen as a reliable predictor of rupture as it has previously been shown that small size aneurysms with maximum diameter less than 5 cm can also rupture [4–7]. Therefore, more reliable criteria are needed to be used as a guide for deciding to surgically repair an AAA [6].

The interaction between haemodynamic stresses acting on the abdominal aortic wall and structural changes in the layers of vessel

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http://dx.doi.org/10.1016/j.euromechflu.2014.02.011
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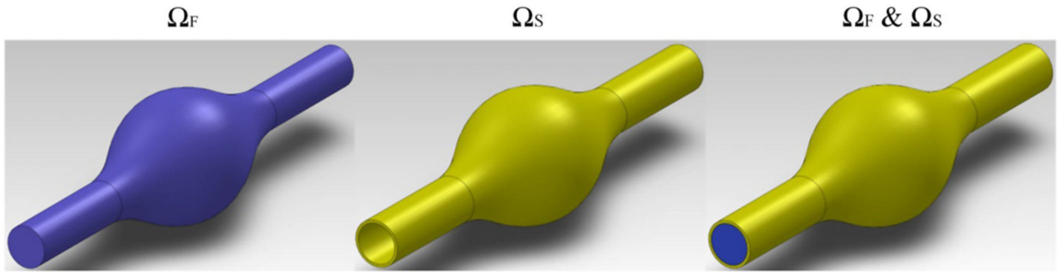

Fig. 1. Fluid domain (Ω_F), solid domain (Ω_S) and integrated fluid and solid domains (Ω_F & Ω_S).

wall is known as a potential cause for aneurysm formation [8]. Any alteration in haemodynamic parameters such as fluid shear stress and pressure may lead to wall inflammation, calcification and thrombus formation [9,10]. Therefore, it is reasonable to assume that interplay between haemodynamic forces and physiological behaviour of vessel wall plays a key role in an aneurysm formation. Fluid-structure interaction (FSI) technique has been shown as a reliable method to model the dynamic interaction of flowing blood with vessel wall in arteries. This technique has been widely used in simulating the blood flow behaviour in patient-specific and idealised models of AAA. Di Martino et al. performed a FSI simulation in a patient-specific AAA and reported that the fluid dynamic field could affect the wall stress [11]. In another study undertaken by Finol et al. [12], the effect of pressure variations was investigated on the wall stress in two patient-specific AAA models. It was found that the pressure gradients affect the wall stress significantly; however, these pressure gradients are dependent on the shape and size of the aneurysm to a great extent and on the blood motion to a less extent. There are other studies [13,14] which explored the effect of shape and size of the realistic aneurysms on the haemodynamic forces such as wall shear stress (WSS) and wall stress. They concluded that the size and shape of the aneurysms dramatically influence the blood flow patterns in AAAs.

The idealised models have made easier the study of different geometric features of aneurysms as in these models; it is possible to change only one geometric parameter while the others are kept constant. Because of this, many studies have utilised the idealised models of AAA in order to simulate the blood flow dynamics. Finol et al. [15], Salsac et al. [16] and Venkatasubramaniam et al. [17] performed computational fluid dynamics (CFD) analysis in idealised models of AAA to study the aneurysm asymmetry. They pointed out that the aneurysm asymmetry results in an increase in the blood flow pressure and WSS. It was also shown that the pressure inside the aorta is non-uniform and pulsatile [18], therefore, in order to account for the non-uniformity of pressure, the interaction between fluid and wall should be taken into consideration. Investigators have also found that use of a static rigid model instead of an elastic model resulted in underestimation of the WSS and wall stress by up to 30% and 12.5%, respectively [19,20].

The presence of a spiral flow pattern has been accepted in both animal and human arteries [21]; in all the aforementioned studies, however, the effect of spiral flow in modelling of AAA is ignored. The first report of a stable spiral laminar flow within human vessels followed angioscopic examination of the luminal surface of arteries, showing a series of spiral folds and spiral flow patterns [22]. This was confirmed with the mapping of flow *in-vivo* using duplex scanning. Stable spiral flow was observed in all subjects, with the direction of rotation varying between sides and individuals [23]. In other studies [24,25], ultrasound and magnetic resonance imaging (MRI) methods were implemented in both dog and human aorta and both studies confirmed the presence of spiral flow. Stonebridge and Brophy [22] and Manosh [26] have shown that the spiral component of blood velocity can have both beneficial and detrimental effects.

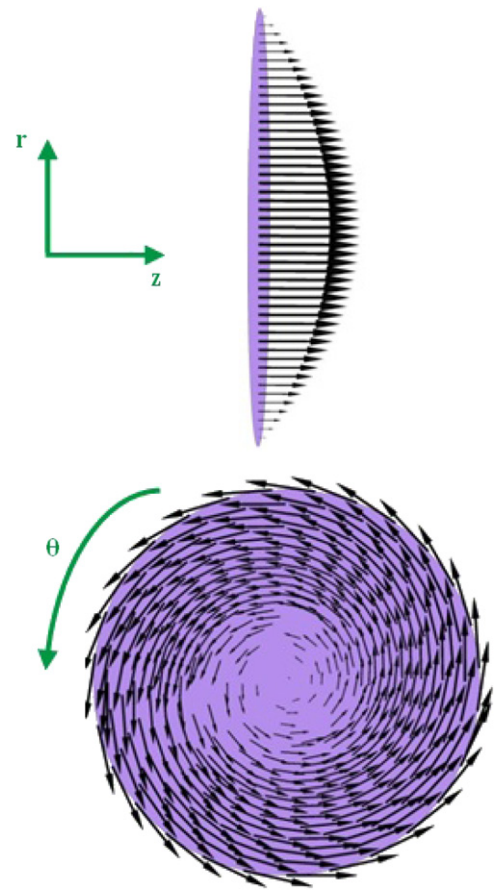

Fig. 2. An interpretation of spiral boundary condition with parabolic flow at inlet of AAA model.

The purpose of this study is to perform FSI analysis in an idealised model of AAA in the presence of spiral flow. In this regard, spiral flows with varying intensities are tested to determine its effect on haemodynamic changes in the AAA model.

2. Methods

2.1. AAA geometry

A computer-generated model of an AAA was created using SolidWorks (Dassault Systems, MA, USA) as previously described [20]. A schema of the model is outlined in Fig. 1, illustrating a fluid domain, Ω_F, representing the aortic lumen and a solid domain, Ω_S, representing the AAA wall.

The geometry of fluid domain is created by making circular cross-sections with undilated diameter of 2 cm and a maximum dilated diameter of 6 cm. The dilated to undilated diameter ratio is 3 which is close to the ratio used in previous studies [20,27,28].