International Journal of Heat and Fluid Flow 31 (2010) 1032–1039

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Combining magnetic resonance measurements with numerical simulations – Extracting blood flow physiology information relevant to the investigation of intracranial aneurysms in the circle of Willis

Dorothea I. Zuleger [a,b,*], Dimos Poulikakos [a], Anton Valavanis [b], Spyros S. Kollias [b]

[a] Laboratory of Thermodynamics in Emerging Technologies, Department of Mechanical and Process Engineering, ETH Zurich, Zurich, Switzerland
[b] Institute of Neuroradiology, University Hospital Zurich, Zurich, Switzerland

ARTICLE INFO

Article history:
Received 11 December 2009
Received in revised form 2 July 2010
Accepted 6 July 2010
Available online 9 August 2010

Keywords:
Computational fluid dynamics (CFD)
Hemodynamics
Cerebral aneurysms
Phase-contrast magnetic resonance angiography (PC-MRA)
Oscillatory shear index (*OSI*)
Wall shear stress gradient (*WSSG*)

ABSTRACT

Cerebral aneurysms in the region of the circle of Willis have an incidence of 3–6% in western populations and involve the risk of rupture with subsequent subarachnoidal bleeding. The patient specific blood flow patterns are of substantial importance for understanding the pathogenesis of the lesions and may eventually contribute to deciding on the most efficient treatment procedure for a specific patient.

A non-invasive method for performing *in vivo* measurements on blood velocity is 4D phase-contrast magnetic resonance angiography (PC-MRA), on the basis of which a flow field with all its parameters can be simulated. We are using this approach to investigate the hemodynamic parameters in the circle of Willis and, by analyzing the values at common locations of aneurysms, trying to find potential parameters to predict the development of aneurysms. Methodologically, we are acquiring the artery geometry with 3D-time-of-flight magnetic resonance (TOF) measurements and the blood velocity in the feeding arteries with 4D PC-MRA measurements in a healthy volunteer. These measurements are combined with computational fluid dynamics (CFD) to describe detailed hemodynamic patterns within the circle of Willis.

1. Introduction

The incidence of intracranial aneurysms in humans is between 3% and 6% as reported in angiographic studies, although autopsy studies suggest a slightly lower occurrence (Chen et al., 2004; King, 1997). Aneurysms rupture with a yearly rate of approximately 2% (Rinkel et al., 1998) in which case they are usually treated on an emergency basis. Treatment of incidentally detected, unruptured aneurysms is considered to prevent future rupture. Treatment options of both ruptured and unruptured aneurysms are either endovascular coiling or neurosurgical clipping, which are invasive procedures with recognized risks of morbidity and mortality (Tummala et al., 2005). Preoperative imaging information is of importance for enhancing the safety and effectiveness of treatment for both the symptomatic and silent lesions. Today, only morphological properties of the aneurysms provide the basis of pre-treatment assessment, without reference to the associated hemodynamic abnormalities (Wiebers et al., 1998), although the natural history of aneurysms as well as the outcome of the treatment may be influenced by hemodynamic factors (Chatziprodromou et al., 2007; Resnick et al., 2003). Detailed hemodynamic information in cerebral arteries and within cerebral aneurysms is therefore gaining importance for both understanding the pathophysiology of aneurismal formation and rupture and for its potential clinical implications in treatment planning.

A widely available, non-invasive, and adaptable method for performing *in vivo* blood velocity measurements is PC-MRA velocity mapping, which can be used for both angiographic and quantitative applications (Bryant et al., 1984; Firmin et al., 1990; Redpath et al., 1984; Walker et al., 1988). Four-dimensional maps of the blood velocity field in the arteries can be obtained by applying cardiac triggering to the image acquisition. We have previously shown that velocities obtained with 4D PC-MRA velocity mapping measurements in a realistic arterial aneurysm model provide good results in the larger straight arteries around an aneurysm, as long as the measurement plane is perpendicular to the main flow direction. However, measurements performed inside the aneurysm were less reliable (Hollnagel et al., 2007, 2009).

Apart from the velocity field itself, other properties such as the wall shear stresses, are also very important for describing the hemodynamic effects of the flow around and within an aneurysm. As it is impossible to measure these characteristics non-invasively,

* Corresponding author. Address: Laboratory of Thermodynamics in Emerging Technologies, Department of Mechanical and Process Engineering, ETH Zurich. Sonneggstrasse 3, 8092 Zurich, Switzerland. Tel.: +41 44 632 3170; fax: +41 44 632 1176.
E-mail address: zuleger@ltnt.iet.mavt.ethz.ch (D.I. Zuleger).

0142-727X/$ - see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.ijheatfluidflow.2010.07.003

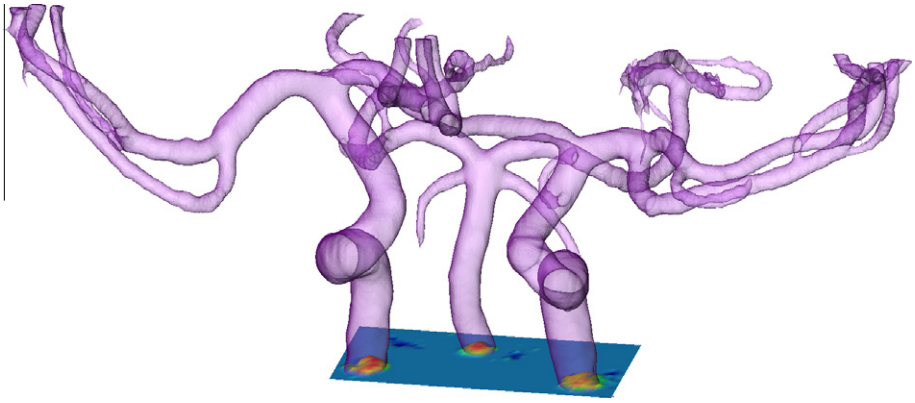

Fig. 1. PC-MRA velocities on a slice below the circle of Willis. The slice was placed as perpendicular to the main flow axis of the arteries as possible to obtain the best possible results.

two possibilities exist for obtaining descriptors of the hemodynamic forces based on the non-invasive PC-MRA measurements: either deriving them directly from the measured velocity field (Frayne and Rutt, 1995; Meckel et al., 2008; Urchuk and Plewes, 1994), or by using the velocity field measurements as patient-specific inlet conditions in a numerical simulation that calculates the flow field with all its parameters and flow characteristics (Acevedo-Bolton et al., 2006; Cebral et al., 2003; Jou et al., 2003; Rayz et al., 2008; Steinman et al., 2003; Zhao et al., 2003). We are using the second approach by performing accurate PC-MRA measurements in areas with simpler arterial geometry below the circle of Willis (i.e., in the internal carotid arteries). This flow information is combined with 3D-TOF geometry measurements of the entire circle of Willis, which are used to simulate the flow field within the entire geometry. This opens the opportunity to investigate flow characteristics, like wall shear stress, wall shear stress gradients, and oscillating shear index, as they really occur in healthy and pathologic conditions.

2. Methods

We acquired the arterial geometry of the circle of Willis in a 27 years old healthy male human volunteer by measuring 80 slices of 0.5 mm thickness with a 3D-TOF MR sequence. The in-plane resolution was 0.4 mm $\times$ 0.4 mm, the repetition time (TR) and the echo time (TE) were 16 ms and 3.45 ms, respectively, and the flip angle was 19°. In the same scanning session, 4D PC-MRA velocity mapping of the through-plane velocities was performed on a cross

Fig. 2. Geometry segmentation from 3D-TOF slices.

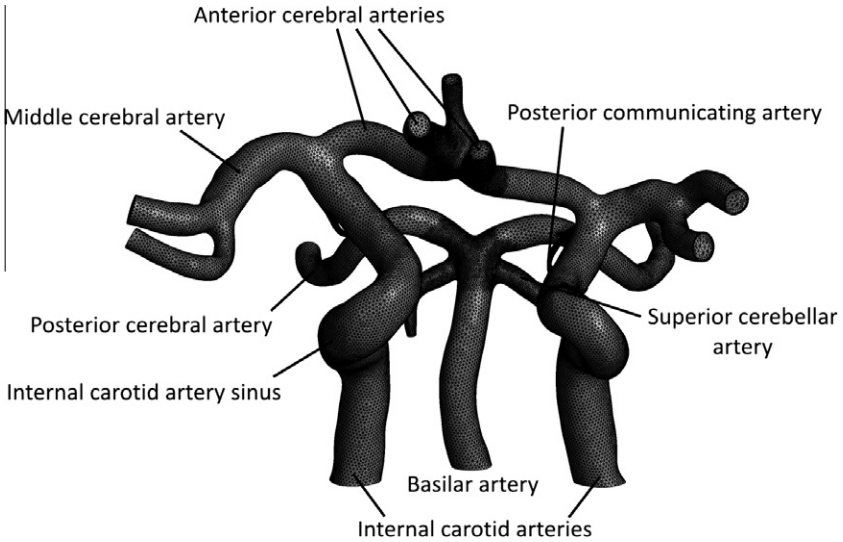

Fig. 3. Cleaned geometry with the fine mesh.