The CFD Analysis of Vertebral Artery Stenosis Based on the DSA Data

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Abstract—The incidence of stroke would be decreased if the vertebral artery stenosis could be diagnosed early and therapy effectively. Presently, the Digital Subtraction Angiography (DSA) is a new computer-assisted radiographic procedure to diagnose the vertebral artery stenosis, and can provide clinical information for therapy. In this paper, the hemodynamic characteristics of the vertebral artery stenosis are analysed by the Computational Fluid Dynamic (CFD) method according to the DSA data from a patient with the vertebral artery stenosis in the affiliated hospital of Inner Mongolia university for nationalities, and the study results show that the proposed scheme can provide theoretical basis for diagnosing and treatment.

Index Terms—stroke, vertebral artery stenosis, digital subtraction angiography, Haemodynamics, computational fluid dynamic

I. INTRODUCTION

It is known that 10%-30% patients with vertebral artery stenosis have the risk of ischemic stroke [1]. Vertebral artery stenosis is one of the major causes of ischemic stroke. Therefore, early diagnosing and efficient treating are important to reduce the incidence of ischemic stroke. One ideal method to diagnose vertebral artery stenosis is the Digital Subtraction Angiography (DSA), which can accurately display the lesion location, the length of the narrow and the degree of stenosis [2]-[5].

The DSA technique is playing an important role in diagnosing vertebral artery stenosis. However, the DSA fails to describe the blood flow in detail, which plays a positive role in diagnosing and treating diseases.

The Computational Fluid Dynamics (CFD) can work well in describing the dynamic characteristics of the blood flow [6]. CFD is an alternative that has been used to predict flow patterns in various vascular geometries, including intracranial aneurysms, the thoracic aorta [7], and the carotid bifurcation [8]. The equations describing Newtonian fluid flow are solved numerically for specified boundary and initial condition data. Such approach provides arbitrarily high spatial and temporal resolution, and is in principle capable of estimating flow fields for arbitrarily complex vessel geometries. Absolute hemodynamic parameter estimates can be obtained directly from the high-resolution flow fields produced by CFD, obviating the need for data smoothing.

In this paper, the hemodynamic characteristics were analysed by the CFD method based on the DSA data of a patient with vertebral artery stenosis. The results provide fluid mechanics theoretical guidance for diagnosing and treating vertebral artery stenosis.

Figure 1. The DSA of the vertebral artery stenosis

II. CLINICAL CASE

A 53-year-old male was hospitalized in Inner Mongolia University for Nationalities Affiliated Hospital on June 29, 2013 because of double upper limb numbness over a year, dizziness and trouble with language for seven days. No abnormal signals appeared in nervous and medicine systems testing. Cerebral angiography showed that the beginning part of vertebral artery was stenosis, and the starting port diameter of the right one was approximately 4.1mm. The minimum diameter was 0.9mm. The rate of stenosis reached 78%, as shown in Fig. 1. According to the classification criteria of carotid and vertebral artery stenosis degree made by North American Symptomatic Carotid Endarterectomy Trial (NASCET) [5], three grades are defined: mild (0-29%), medium (30%-69%) and severe (70%-99%). So, the patient’s right side vertebral artery beginning part had severe stenosis, which was 10mm long, and the surface of atheromatous plaque was smooth without anabrosis. The
severe stenosis of the beginning part of vertebral artery would seriously affect cerebral blood supply and cause cerebral infarction or stroke for the reason that the brain stem, cerebellum and bilateral cerebral hemisphere all need adequate blood supply from the vertebral-basilar system.

III. GENERATION OF GEOMETRIC MODEL

The 3D geometric model of the junction of right vertebral artery and subclavian artery is created by using the software GAMBIT2.4.6 according to the data of DSA image that is shown in the Fig. 1. The diameters of the cross-section of the arteria subclavia, the head end and the narrow part of vertebral artery are 14.8mm, 4.1mm and 0.9mm, respectively. The angle between the arteria subclavia and vertebral artery is approximately 84.5 degrees. As shown in Fig. 2, the grid generation made by software GAMBIT2.4.6 was obtained.

IV. CALCULATION METHOD

Assume that blood behaves as a Newtonian fluid [9], therefore, the blood flow is governed by the Navier-Stokes equations:

\[ \nabla \cdot \mathbf{V} = 0 \]  
\[ \frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} = -\nabla P + \mu \nabla^2 \mathbf{V} \]

where \( \rho = 1050 \text{kg/m}^3 \) is the fluid density, \( \mu = 3.5 \times 10^{-3} \text{pa/s} \) is the dynamic viscosity, \( \mathbf{V} \) is the velocity and \( P \) is the pressure. Equation (1) is continuity equation. Equation (2) is momentum equation. In this research, the energy transfer and the weight of fluid were not considered. According to the above equations, the characteristics of the blood flow dynamic were calculated by the Finite Volume Method (FVM) software Fluent6.3.

V. INITIAL AND BOUNDARY CONDITIONS

As an initial condition, a pulsatile waveform based on vivo measurements obtained from hot film anemometry on various animal model [10], is employed at the subclavian artery entrance, as shown in Fig. 3, where \( V_{\text{max}} = 87 \text{cm/s}, T = 0.8 \text{s} \). In order to compare the state of flow field at different speed, three different times were employed, \( t_1 = 0.05T, t_2 = 0.12T, t_3 = 0.21T \). The corresponding speed is \( v_1 = 0.054V_{\text{max}}, v_2 = 0.25V_{\text{max}}, v_3 = V_{\text{max}} \) respectively. The vessel wall is assumed to be rigid, impermeable and stationary, thus a no-slip boundary condition is applied. The outlet of the artery is represented by a traction free boundary condition with a uniform normal pressure, which is good approximation for rigid wall model [9]. The outlet pressure is set to be zero.

VI. RESULTS

The time step is \( T/100 \). Three-dimensional velocity fields, which are distribution near the beginning part of vertebral artery, are presented in Fig. 4. At the time \( t_1 \), the entrance velocity \( v_1 = 0.054V_{\text{max}} \), the blood flow could not pass through the narrow part of vertebral artery because of the tiny blood flow velocity. In the subclavian artery, the blood flow is normal. At the time \( t_2 \), the entrance
velocity $v_2 = 0.25v_{\text{max}}$, the blood flow gets through the vertebral artery, and has a small flow rate. The turbulent flow has appeared in the subclavian artery. At the time $t_3$, the entrance velocity $v_3 = v_{\text{max}}$. Because the inlet velocity increases, the blood flow rate of the vertebral artery significantly increases, the profile map shows there is a large speed at the narrower, as the Fig. 5(a) show, and the flow field of the subclavian artery indicated the turbulent flow is more obvious. The secondary flow vortices of the cross-section I, II, III at the time $t_3$ are shown in the Fig. 4(b) respectively. The secondary flow can obviously indicate transverse flow in the subclavian artery. At time $t_3$, the maximum velocity causes distinct flow vortices in peak systolic.

At the time $t_3$, the distribution of shear stress and pressure on the vessel wall of the subclavian artery and the vertebral artery, whose values of along X axis are relative magnitudes base on the inlet value, are shown in Fig. 5(b, c). The magnitude is a mutation at the stenotic place, which both the shear stress and the pressure have maximum value. The magnitudes of the shear stress and the pressure on other areas are constant.

VII. DISCUSSION

The results show the blood flow could not, or small quantities get through the vertebral artery in the most of time of a cardiac cycle because of the stenosis. The cerebral ischemic attacks would be occurred because the brain is long-term insufficient blood supply. As the blood flow speed increases, the vortex flow appears in the subclavian artery. The secondary flow is obvious. The turbulent flow would not only influence the transportation of blood but also damage the intima of the vessel wall. Specially on the peak systolic velocity, the shear stress and the pressure reach the maximum value at the stenosis location. The high wall shear stress and high pressure damage the intima of the vessel wall.
wall pressure perhaps tear the surface of intima to produce the hyperplasia, and the results will lead to the vertebral artery stenosis increase severity and forms blood clot [11]. So, the local regions of the vertebral artery with stenosis might be associated with the occurrence and development of cerebral stroke [12].

VIII. CONCLUSIONS

The above research results show that the characteristics of hemodynamic, such as the blood flow field, shear stress and pressure, could be described by computational fluid dynamic method to understand the detail of the blood flow via the medical image date. This approach can help the physician to diagnose disease, and further to analyze the disease progresses. Computational fluid dynamic numerical simulation maybe can provide a theoretical basis for the role of hemodynamic factors in occurrence and development of vertebral artery stenosis.

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