SY3-2-1-3

Modeling of Integrated Fluid Dynamics of Cerebral Circulation and Cerebrospinal Fluid Flow

Shigeki Yamada (1) (2), Marie Oshima (2), Changyoung Yuhn (2), Hirotaka Ito (3), Yoshiyuki Watanabe (4), Shusaku Maeda (5), Naoki Takeish (5), Tomohito Otani (5), Shigeo Wada (5) and Kazuhiko Nozaki (1)

(1) Department of Neurosurgery, Shiga University of Medical Science
(2) Interfaculty Initiative in Information Studies / Institute of Industrial Science, The University of Tokyo
(3) Medical System Research & Development Center, FUJIFILM Corporation
(4) Department of Radiology, Shiga University of Medical Science
(5) Department of Mechanical Science and Bioengineering, Graduate School of Engineering Science, Osaka University

Abstract

Objectives: In the fluid dynamics of cerebral circulation and cerebrospinal fluid (CSF) motion, the computational simulation model has not been established. We conducted the multi-scale simulation in the cerebral circulation model. Therefore, we would like to integrate these two different fluid dynamics models. *Methods & Results*: Using the 3 tesla MRI and 3D workstation, the flow volumes of blood and CSF were measured in the 20 healthy volunteers. In addition, the 3D structures and movements of the brain, intracranial CSF spaces and major arteries were reconstructed for computational fluid dynamics. *Conclusions*: The CSF movements synchronized with a heartbeat were driven by the pulsation of large intracranial arteries and brain. In the current concepts of the cerebral circulation and fluid exchange of CSF and interstitial fluid, i.e., glymphatic system, the simulation model of the brain fluid dynamic is extremely complicated. There are many black boxes in this field.

Keywords cerebral circulation; cerebrospinal fluid dynamics; 4D Flow MRI; computational fluid dynamics

1. Introduction

Cerebrospinal fluid (CSF) moves pulsatile to smooth cerebral circulation in the closed space skull. Recent developments in magnetic resonance imaging (MRI) technology have made it possible to visualize the CSF dynamics, denying the traditional classical bulk flow theory for the CSF dynamics. However, it is difficult to accurately reproduce the CSF dynamics in the complicated 3D structure of ventricle and subarachnoid spaces. Because a computational fluid dynamics (CFD) modeling that combines cerebral circulation and CSF dynamics requires a huge amount of calculation, it has not yet been established. We developed a multi-scale simulation that combines cerebral circulation and systemic circulation using the integrated 3D-1D-0D CFD model.[1-3] In this multi-scale simulation, cerebral circulation around the circle of Willis was created in a 3D model, distal circulation to the circle of Willis was calculated in a 1D model considering pulse wave transmission elements based on simplified Navier-Stokes equations, and capillary circulation was calculated in a 0D model based on the Windkessel effect in fractal distal flow. In addition, we succeeded in reproducing the whole cerebral circulation using a large scale of a 3D CFD model.[4] To develop a mathematical model that integrates complex cerebral circulation and CSF dynamics, the 3D flow volumes of CSF and cerebral arteries synchronized with a heartbeat were measured on 4D Flow MRI which can be visualized complex flow patterns based on the acquired velocity vectors in all three spatial dimensions.

2. Materials and Methods

The MRI examination was performed using the 3T MRI scanners (SIGNA™ Architect, GE Healthcare Japan, Tokyo, Japan) with a 64-channel head coil in 19 healthy volunteers and 37 patients diagnosed with chronic adult hydrocephalus. The time-resolved 3D velocity encoding data obtained from 4D Flow MRI sequence with 120 cm/s of velocity encoding for the measurement of arterial velocity and with 5 cm/s of velocity encoding for the measurement of CSF velocity, voxel size with a side of 1.0 mm, synchronising the peripheral pulse rate measured from the finger. To increase the accuracy of fine anatomical information, the time-of-flight MRA sequence with the voxel size of 0.4 mm for cerebral arteries and the fast spin eco isotropic 3D T2 CUBE sequence with the voxel size of 0.8 mm for CSF spaces (Fig.1) were superimposed on 3D flow data using the 4D flow application in the 3D volume analyzer workstation (SYNAPSE 3D; FUJIFILM Corporation, Tokyo, Japan). The surface mesh of CSF spaces was generated by increasing the image resolution and applying maximum smoothing, with an interpolation of 1/4 interval and decimation rate of 50%.

Fig. 1. Cerebral artery and Cerebrospinal fluid

3. Results

As shown in Fig. 2, the 3D flow of cerebral arteries including the circle of Willis and the CSF movements were observed on 4D Flow MRI.

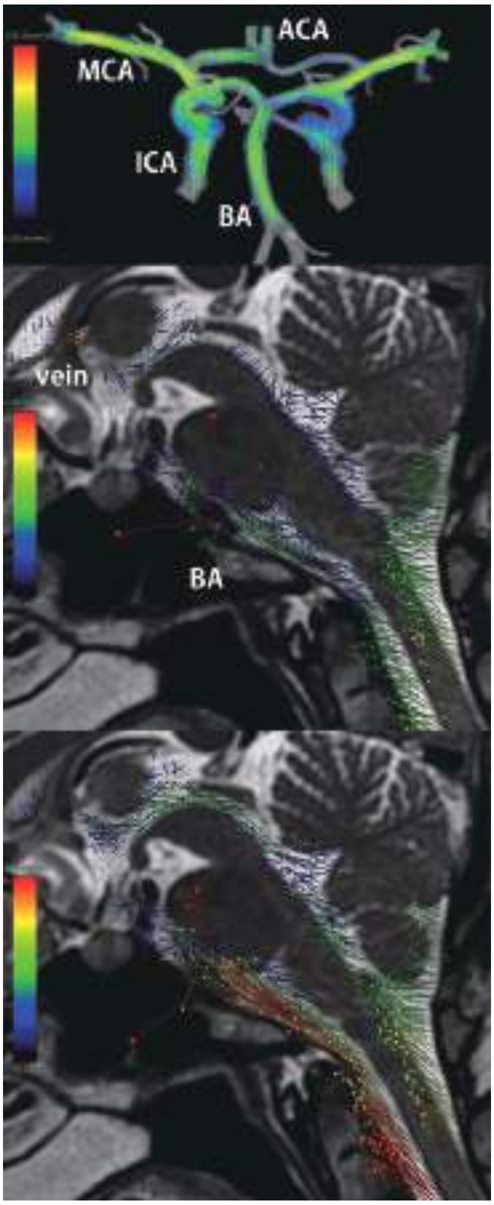

Fig. 2. 4D Flow MRI

The peak of pulsatile blood flow in the left and right internal carotid arteries (ICAs) and the basilar artery (BA) does not always coincide exactly. Therefore, the flow pattern of the anterior and posterior communicating arteries that form the circle of Willis are often bidirectional rather than unidirectional. During one cardiac cycle, synchronized with the inflow and outflow of cerebral circulation, the CSF moved periodically in the directions of craniocaudal (outward from the cranium) and caudocranial (inward) in the foramen magnum and subarachnoid spaces in front of the brain stem. Cerebral circulation and CSF pulsatile movements were not always coherent. However, there is no doubt that cerebrospinal fluid does not always flow from the ventricles into the subarachnoid space. Normally, the CSF movements in the ventricular systems were very small, but increased as the volume of ventricles increased due to chronic hydrocephalus.[5-7]

4. Discussion

The CSF movements synchronized with a heartbeat were driven by the pulsation of large intracranial arteries and brain. However, the relationship between the cerebral circulation and CSF pulsatile movements on 4D Flow MRI has a complexity that cannot be proved by the CFD model. On the contrary, 4D Flow MRI still has many limitations and is not suitable for measuring the flow of small intracranial arteries and complex slow movements of CSF.[5-7] Therefore, the flow velocities measured by the 4D Flow MRI should be verified and supplemented by CFD. Furthermore, in the current concepts of the cerebral circulation, lymphatic CSF drainage, and fluid exchange of CSF and interstitial fluid, i.e., glymphatic system, the simulation model of the neurofluid dynamic is extremely complicated. Since there are many black boxes in this field, it is expected that research will develop in the future.

References

[1] Yamada S, Kobayashi M, Watanabe Y, et al. (2014) Quantitative measurement of blood flow volume in the major intracranial arteries by using 123i-iodoamphetamine SPECT. Clin Nucl Med. 39(10) 868-873.

[2] Zhang H, Fujiwara N, Kobayashi M, et al. (2016) Development of a Numerical Method for Patient-Specific Cerebral Circulation Using 1D-0D Simulation of the Entire Cardiovascular System with SPECT Data. Ann Biomed Eng. 44(8) 2351-2363.

[3] Kobayashi M, Hoshina K, Nemoto Y, et al. (2020) A penalized spline fitting method to optimize geometric parameters of arterial centerlines extracted from medical images. Comput Med Imaging Graph. 84101746.

[4] Ii S, Kitade H, Ishida S, et al. (2020) Multiscale modeling of human cerebrovasculature: A hybrid approach using image-based geometry and a mathematical algorithm. PLoS Comput Biol. 16(6) e1007943.

[5] Yamada S, Ishikawa M, Ito H, et al. (2020) Cerebrospinal fluid dynamics in idiopathic normal pressure hydrocephalus on four-dimensional flow imaging. Eur Radiol. 30(8) 4454-4465.

[6] Yamada S, Ito H, Ishikawa M, et al. (2021) Quantification of Oscillatory Shear Stress from Reciprocating CSF Motion on 4D Flow Imaging. AJNR Am J Neuroradiol. 42(3) 479-486.

[7] Yamada S, Ishikawa M, Nozaki K. (*in press*) Exploring mechanisms of ventricular enlargement in idiopathic normal pressure hydrocephalus: A role of cerebrospinal fluid dynamics and motile cilia. Fluids Barriers CNS.

Corresponding Author:
Shigeki Yamada: shigekiyamada39@gmail.com