Computational Fluid Dynamic Simulation of a Giant Basilar Tip Aneurysm with Eventual Rupture After Hunterian Ligation

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Key words
- Cerebral aneurysm
- Computer simulation
- Flow alteration
- Flow diversion
- Flow dynamics
- Hunterian ligation

Abbreviations and Acronyms
BA: Basilar artery
CFD: Computational fluid dynamic
CT: Computed tomography
PCA: Posterior cerebral artery
Pcom: Posterior communicating artery
WSS: Wall shear stress

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■ BACKGROUND: **Hunterian ligation is performed to reduce and to change the flow of an aneurysm; it is a surgical option for a complex aneurysm that cannot be managed by either clipping or coiling. However, it may be associated with adverse effects. This study was carried out to analyze how Hunterian ligation changed the flow dynamics of a particular cerebral aneurysm.**

■ METHODS: **A case of giant basilar tip aneurysm, in which Hunterian ligation resulted in rupture 6 months later, was subjected to computational fluid dynamic simulation. Among the simulations with various boundary conditions, the flow dynamic parameters of streamlines, velocities, and wall shear stresses were compared and analyzed qualitatively and quantitatively.**

■ RESULTS: **Hunterian ligation switched the parent artery from the basilar artery to the left posterior communicating artery. The changes in the direction and the diameter of the parent arteries resulted in the focal elevation of the shear magnitude and the high shear gradient on the posterior wall of the aneurysm after the ligation. These hemodynamic changes might have been associated with the eventual rupture of the aneurysm.**

■ CONCLUSIONS: **Hunterian ligation is a useful flow diversion surgery, but it might worsen the flow dynamics in specific cases.**

INTRODUCTION

Giant basilar artery (BA) aneurysms are prone to recanalization even after adequate coiling; these types of aneurysms are also difficult to obliterate by surgical clipping because of the surrounding perforating arteries. Hunterian ligation, which reduces and changes the aneurysm flow by obliterating the parent artery, is a simple and useful option for the management of giant BA aneurysms when there are sufficient collateral circulations. According to Steinberg et al. (17), Hunterian ligation achieved successful thrombosis in two thirds of upper BA aneurysms. However, when the thrombosis was incomplete, one fifth of the aneurysms ruptured even after Hunterian ligation. The incomplete thrombosis is supposedly associated with the aneurysm flow dynamics after the ligation. Chang and Roach (2) suggested that the larger differences in the diameter of both posterior communicating arteries result in the larger flow into the aneurysm cavity and prevent successful thrombosis.

In the present report, we describe a patient with a giant basilar tip aneurysm who underwent Hunterian ligation who subsequently experienced aneurysm rupture. Retrospective analysis of the flow dynamic change before and after the ligation was conducted via computational fluid dynamic (CFD) simulation to investigate how the hemodynamic changes in the aneurysm contributed to the eventual rupture.

METHODS

Case Presentation

A 74-year-old woman presented with a 1-year history of progressing headache and cognitive dysfunction. Computed tomography (CT) revealed a giant aneurysm (26 mm) at the tip of the BA (Figure 1). The patient had an abdominal aortic aneurysm, and surgical treatment was preferred over endovascular treatment. However, clipping was considered to be too difficult because of the large size and the broad neck of the aneurysm. This patient had a sufficient posterior communicating artery (Pcom) on the left side to supply the posterior circulation. Hunterian ligation was performed just below the origin of superior cerebellar arteries (SCAs) via the right subtemporal approach. The patient abruptly became comatose 6 months after the surgery and died. Brain CT showed massive intraventricular hematoma and subarachnoid hemorrhage, which was considered to be from the aneurysm. No autopsy was performed.

CFD Simulation

To investigate the mechanism of the aneurysm rupture after Hunterian ligation, flow dynamics before and after Hunterian ligation were analyzed on computer simulation. Three-dimensional constant blood flow was modeled with a finite volume solver (SC/Tetra; Software Cradle,

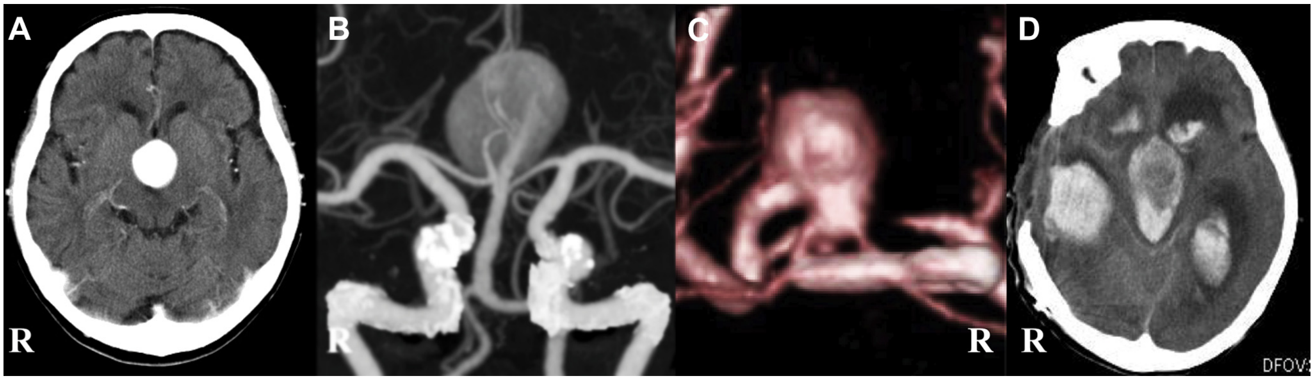

Figure 1. (**A** and **B**) Contrast-enhanced computed tomography (CT) and three-dimensional CT angiography at presentation. A giant basilar tip aneurysm extends into the third ventricle and compresses the surrounding brain. (**C**) Three-dimensional CT angiography obtained 5 months after ligation viewed posteriorly. Most of the aneurysm is thrombosed except the posterior part of the aneurysm. (**D**) CT obtained after the aneurysm rupture. R, right.

Osaka, Japan) under the governing equation of mass conservation and Navier-Stokes as was described previously (13-16).

Vessel and Aneurysm Modeling. The aneurysm and the adjacent vessels were segmented from three-dimensional CT angiography obtained before surgery to create a three-dimensional surface using Avizo (VSG, Burlington, Massachusetts, USA). The three-dimensional surface was converted to a computational mesh consisting of 1,303,297 tetrahedral and prism elements using SC/Tetra. The average resolution of the computational mesh was 0.35 mm. The region of analysis encompassed from the bottom of the BA to its major outflow branches. The model had 6 orifices: BA, left and right SCAs, right and left posterior cerebral arteries (PCAs) and left Pcom. A cross-sectional plane was also determined at the proximal portion of the left PCA as P1 for the purposes of simulation (**Figure 2**).

Boundary Modeling. Blood was assumed to be an incompressible Newtonian fluid with a specific gravity of 1053 kg/m^3 and a viscosity of 4.0×10^{-3} Pa · seconds (14). The vessel wall was assumed to be rigid in this study. The pulsatile change of blood flow during a cardiac cycle was not incorporated, and the flow was simulated in steady-state conditions. The boundary conditions of inlets and outlets were applied as described subsequently and as summarized in **Table 1**.

For simulation 1, the control (before surgery) simulation, the orifices of the BA and left Pcom were inlet ports, and the other orifices were outlet ports. The flow volume of the BA was determined to be 260.0 mL/minute according to the literature (5, 12), whereas the mean flow velocity of BA was 0.3 m/second. This value was applied to the orifice of the BA with Poiseuille velocity profile. The contribution of the left Pcom to the posterior circulation was unknown in this particular case, and it was estimated according to the assumption that the flow would be divided in proportion to the vessel area at a branching point (2, 3, 21). To stabilize the calculation, zero surface pressure was applied to the orifice of the left Pcom as the boundary condition.

In simulation 2, the Hunterian ligation simulation, in which the orifice of BA was closed, the left P1 served as a parent artery of the aneurysm and supplied the right PCA and both SCAs. The perfusion demands of the right PCA and both SCAs were deemed unchanged after the ligation, suggesting that their flow volume was likely to be preserved (simulation 2-1) (**Table 1**); this held true on one important condition that there was sufficient collateral flow from the left P1. We added 2 simulations where the flow volume of the right PCA and both SCAs was not maintained (25% reduction in simulation 2-2; 50% reduction in simulation 2-3) (**Table 1**).

Visualizations and Measurements. The streamline and the velocity distribution in the aneurysm cavity and the shear stress distribution on the aneurysm wall were visualized in each simulation and compared before and after Hunterian ligation using SC/Tetra and Avizo. The range of colored contour of wall shear stress (WSS) was set at 0–2 Pa to enhance the shear distribution on the aneurysm wall, where the shear magnitude is markedly lower than the physiological range (1–7 Pa) (8). The BA and its branches with physiologic WSS were scaled out and visualized in red color. The

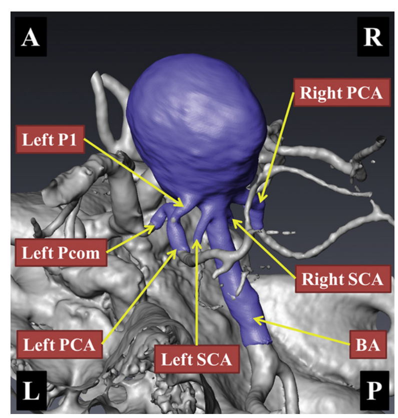

Figure 2. Region of fluid dynamic analysis (*blue*), segmented from three-dimensional computed tomography angiography (*gray*), is viewed from left-rear side. A, anterior; P, posterior; L, left; R, right; PCA, posterior cerebral artery; SCA, superior cerebellar artery; BA, basilar artery; P1, proximal part of posterior cerebral artery.