Computational fluid dynamics simulation of the right subclavian artery cannulation

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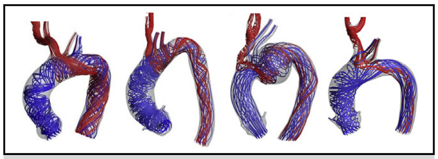
ABSTRACT

Objective: The purpose of this study was to evaluate the efficacy of right subclavian artery cannulation using computational fluid dynamics.

Methods: Patient-specific models of the aortic arch were made with 4 patterns (1: normal aorta, 2: ascending aorta aneurysm, 3: distal arch aneurysm, 4: bovine arch) based on the computed tomography images. Right subclavian artery and ascending aorta cannulation models were created to simulate the physiologic pulsatile flow. Perfusion flow through the arterial cannula was set to 2.50 L/min (50% flow), 3.75 L/min (75% flow), and 5.0 L/min (100%), respectively, and a 3-dimensional movie was made of 1 cardiac cycle to evaluate the blood flow.

Results: In both 50% and 75% flow simulation with right subclavian artery cannulation, the blood streamline from the right subclavian artery produced retrograde flow of the brachiocephalic artery and antegrade flow of the right common carotid artery throughout the cardiac cycle in all cases. Right subclavian artery flow deflected ascending aorta flow to the descending aorta. Left-side supra-aortic branches were perfused by blood flow from both the right subclavian artery cannula and the aortic valve. The ascending aortic cannulation model showed that blood flow from the aortic valve reached all 3 supra-aortic vessels in systole.

Conclusions: Right subclavian artery cannulation was cerebroprotective, especially on the right side. (J Thorac Cardiovasc Surg 2017;154:480-7)



Computer simulation of rSCA cannulation of 4 different anatomies.

Central Message

rSCA cannulation was simulated by CFD, which showed that cannulation produced a protective effect on the brain, especially on the right side.

Perspective

The brain protection effect of rSCA cannulation is well known; however, the mechanism is not well understood. Blood flow streamline can be visualized by computer stimulation, and now we can understand how rSCA cannulation influences systemic blood circulation. Our results may change the arterial cannulation strategy significantly.

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Preoperative and intraoperative evaluations of the aorta with computed tomography, transesophageal echocardiography, and epiaortic ultrasound are mandatory in patients with systemic atherosclerosis. To prevent embolization during cardiopulmonary bypass, it is essential to choose the best arterial cannulation site. The right subclavian artery (rSCA) is easy to expose, and it is sufficient for arterial cannulation. Acute aortic dissection rarely extends to the rSCA.[1,2] Many reports have shown the positive clinical impacts of rSCA cannulation.[3-7] However, the mechanism of how perfusion of the rSCA prevents cerebral embolism has not been established. Blood flow analysis by computational fluid dynamics (CFD) has become more popular. CFD can evaluate the flow streamline, flow velocity, wall shear stress, helicity index, and other fluid dynamic parameters.[8-10] CFD also enables visualization of blood flow. We describe our experience with visualizing blood flow from the aortic root to the descending aorta with rSCA cannulation and ascending aorta (AscAo) cannulation during cardiopulmonary bypass.

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Abbreviations and Acronyms

AscAo = ascending aorta
CFD = computational fluid dynamics
MRI = magnetic resonance imaging
rSCA = right subclavian artery
3D = 3-dimensional

MATERIALS AND METHODS

Study Design for Computational Analysis

We evaluated rSCA and AscAo cannulation by using CFD in 4 patients. Perfusion flow through the rSCA or AscAo cannula was set to 2.50 L/min (50% flow), 3.75 L/min (75% flow), and 5.0 L/min (100%) at a constant, steady flow. In addition, a 3-dimensional (3D) movie was made for 1 cardiac cycle to evaluate the streamline of the blood flow and velocity.

Patient Profiles for Computational Analysis

We chose 4 patients with different aortic arch pathologies: patient 1, with a normal size aortic arch; patient 2, with an ascending aortic aneurysm with a unicuspid aortic valve; patient 3, with a distal arch aneurysm; and patient 4, with a bovine aortic arch with a normal-sized aorta. Patient 1 was a 76-year-old man who underwent coronary artery bypass grafting for stable angina. Preoperatively, he underwent evaluation of the thoracic aorta, which was normal in size; therefore, we used his data for a control. Patient 2 was a 72-year-old man who had severe aortic valve stenosis and elongation of the AscAo with dilatation (diameter, 45 mm). AscAo and aortic valve replacement were performed. Patient 3 was an 80-year-old man who underwent total arch replacement for a distal arch aneurysm (maximum diameter, 60 mm). Patient 4 was a 79-year-old woman who underwent coronary artery bypass grafting. The postoperative computed tomography scan showed a bovine aortic arch, and the right and left common carotid arteries arose from the common trunk. The study was approved by the institutional review board of Kyoto Prefectural University of Medicine, and written informed consent was obtained from all participating patients.

Computational Simulation

The methods of our computational analysis have been described.[8,9] Data for the analyses were acquired by thin-slice, early-phase, enhanced multidetector-row computed tomography imaging. Image data in a Digital Imaging and Communications in Medicine format were transferred into 3D patient-specific geometries by using Osirix, a medical open source imaging software (Osirix Foundation, Geneva, Switzerland). The images were modified by 3D-Coat, a 3D computer graphics software program (PIGWAY, Kiev, Ukraine). For rSCA cannulation, end-to-side anastomosis between the rSCA and an 8-mm prosthetic graft was simulated. For AscAo cannulation, the insertion of an 8-mm AscAo cannula into the AscAo was simulated. Computational meshes were created with ANSYS-ICEM CFD 16.0 (ANSYS, Japan, Tokyo, Japan). More than 2,000,000 cells with tetrahedral meshes and 3 boundary-fitted prism layers were generated at the boundaries of the rSCA and AscAo.

Boundary Conditions

To simulate the flow around the valve leaflets, inlet boundaries for the AscAo and cannulation site were extruded to 5 times their diameters to develop the velocity profiles. The inlet boundary conditions in the AscAo were set as the mass flow boundary conditions with a pulsatile wave, and those in the subclavian and AscAo perfusion cannulas were set as the constant steady flow rate conditions. Cardiac outputs were set at 5.0 L/min. Pressure waveforms in 1 case during cardiopulmonary bypass of 50% and 75% pump flow were measured. Then, on the basis of the measured pressure waveform, the boundary pressure conditions were derived to realize reflection wave and vascular inertance, and were given at the extended boundary mesh. The outlet boundaries for the supra-aortic branches, descending aorta, and both coronary arteries were extended to 50 times the diameter of each vessel to obtain a stable flow split to the branches, based on our previous validation study on aortic CFD modeling.[10] The outlet boundary conditions were used as the pressure boundary conditions, which represented the external forces from outside of the analysis domain. One of the main external forces from the peripheral tissue is a reflection wave; thus, to determine the reflection, the following formula was used:

$$P_{measured} - Z_0 Q_{inlet}$$

where $P_{measured}$ is the measured pressure wave, Q_{inlet} is the total inlet flow, and Z_0 is the characteristic impedance of the aorta. To determine the inertial properties of the vessel wall, we set the inertial term with inductance L to maintain the intravessel pressure with the flow change as follows:

$$-L\frac{dQ_{inlet}}{dt}$$

In addition, the aortic flow is typically regulated by the autonomous system, such as the vasovagal reflex, to prevent flow voids from the neck vessels or excessive current to the lower half body, which can occur when the flow decreases in the late systolic phase. To simulate vascular bed constriction or dilatation according to the abnormal flow split, we added peripheral tonus regulation term for flow split modulation as follows:

$$R_{peripheral} \times H\left(Q_{descending} - Q_{inlet}\right)$$

where $R_{peripheral}$ is the peripheral arterial resistance (constant) and xH is the Heaviside function. Outlet boundaries in the coronary arteries were set as the mass flow boundary conditions with pulsatility, and 2.5% of the total aortic flow was released into the right and left coronary arteries. The vessel walls, including the extended boundary walls, were considered rigid (Figure 1).

Turbulent Pulsatile Flow Simulations

The finite volume solver package ANSYS-FLUENT 15.0 or 16.0 (ANSYS, Japan) was used to solve the Navier–Stokes equation of incompressible transient Newtonian fluid. The blood properties were set as follows: 1060 kg/m^3 for density and 0.004 kg/m/s for viscosity. Because the Reynolds number was approximately 4000 in the peak systolic phase, we analyzed the turbulent flow simulation by using Renormalization Group k-ε models. In the transient flow simulation, each time step was set to 10^{-5} seconds to reduce the Courant number to the sufficient level. The convergence criteria were set to 10^{-5} times the residual for all degrees of the parameters at each time step.

RESULTS

Right Subclavian Artery Cannulation

We classified flow distribution of the supra-aortic branches into 4 different subsets: grade 4, totally perfused by cannulation flow; grade 3, greater than 50% perfused by cannulation flow; grade 2, partially perfused by cannulation flow; and grade 1, no perfusion from cannulation flow (Table 1).

In all rSCA cannulation models, the right common carotid artery was a grade 4 in systole and diastole with 50% and 75% flow (Table 1), indicating that the right common carotid artery was perfused by blood flow from the rSCA cannula during the entire cardiac cycle regardless of cardiopulmonary bypass flow (Figure 2, Video 1).