Surgical strategy for aortic arch reconstruction after the Norwood procedure based on numerical flow analysis†

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Abstract

OBJECTIVES: Inefficient aortic flow after the Norwood procedure is known to lead to the deterioration of ventricular function due to an increased cardiac workload. To prevent the progression of aortic arch obstruction, arch reconstruction concomitant with second-stage surgery is recommended. The aim of this study was to determine the indications for reconstruction based on numerical simulation and to reveal the morphology that affects the haemodynamic parameters.

METHODS: Fifteen patients who underwent the Norwood procedure or arch repair and Damus–Kaye–Stansel anastomosis were enrolled. The pressure gradient in aortic arch was 1.6 ± 3.9 mmHg (ranged from 0 to 12 mmHg) on catheter examination. Six patients who had prominent turbulent flow accompanied with a large flow energy loss index greater than 40 mW/m² and high wall shear stress greater than 100 Pa underwent arch reconstruction.

RESULTS: After arch reconstruction, the energy loss index significantly decreased from 88.5 ± 50.0 mW/m² to 23.1 ± 10.4 mW/m² (P = 0.026) and wall shear stress significantly decreased from 194.5 ± 87.4 Pa to 60.3 ± 40.5 Pa (P = 0.0062). There were 3 late deaths due to heart failure caused by progressive atrioventricular valve regurgitation during the follow-up period (60 months). The systemic ventricular function was preserved in the remaining patients without any pressure gradients in the arch.

CONCLUSIONS: Determining the surgical strategy for arch reconstruction based on numerical flow analysis may effectively reduce the ventricular load even if no stenosis or pressure gradients are observed on catheter examination or echocardiography.

Keywords: Norwood procedure • Arch reconstruction • Numerical analysis • Energy loss • Wall shear stress

INTRODUCTION

The Norwood procedure for the hypoplastic left heart syndrome is one of the most technically challenging and high-risk surgical procedures. The early outcomes have improved by the refinement of surgical technique and postoperative management. However, the long-term outcomes have not always been satisfactory, partially because of the reconstructed arch obstruction. Even the inefficient blood flow in the reconstructed arch with or without pressure gradient and/or flow acceleration [1] and the stiffened arch deteriorates long-term ventricular function, because they cause an increase in ventricular afterload [2]. To prevent the progression of an aortic arch obstruction, or to eliminate the inefficient turbulent flow inside the arch, arch reconstruction concomitant with a second-stage surgery is beneficial. However, the indication of reconstruction for patients without any pressure gradient or flow acceleration remains to be determined.

Computational fluid dynamics (CFD) is a practical tool to evaluate physical phenomena that involve fluid flow. CFD is also a powerful tool to reveal the details of the blood flow for the improvement of the surgical techniques in congenital cardiac surgery [3]. It can assess flow energy loss (EL) and wall shear stress (WSS). Flow EL is an important parameter in considering efficiency of oxygen delivery in congenital heart disease [4]. Flow EL represents the load to the single ventricle and is used to evaluate

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the Fontan circulation [5]. WSS is another important parameter used to assess the risk of intimal thickening, resulting in an increase of flow EL. Previous studies have shown that using CFD, the geometric configuration of the reconstructed aorta is important to realize efficient flow and reduce the flow EL and/or WSS to the vessel wall [6].

The objective of this study was to demonstrate the clinical utility of numerical simulation in the preoperative planning of an aortic reconstruction after the Norwood procedure.

METHODS

Patient demographics

Between April 2007 and March 2013, 15 patients who underwent the Norwood procedure or arch repair and Damus–Kaye–Stansel anastomosis in Kitasato University Hospital were enrolled in this study. The diagnoses included the following: hypoplastic left heart syndrome, 10 patients; coarctation of aorta (CoA), hypoplastic arch, aortic stenosis and ventricular septal defect, 3 patients and single ventricle with CoA, hypoplastic arch and subaortic stenosis, 2 patients. The Norwood procedure was performed in 13 patients and arch repair and Damus–Kaye–Stansel anastomosis in 2 patients with single ventricle, CoA and subaortic stenosis. The mean body weight and age at the Norwood procedure or arch repair were 2.9 ± 0.5 kg and 24 ± 39 days, respectively. The cardiac catheterization and the 3D computed tomography (CT) were performed in all the patients before the second stage or the Rastelli operation. The mean age at catheterization was 5.3 ± 2.1 months. The pressure gradient between the ascending aorta and descending aorta was 2.1 ± 3.9 mmHg (range 0–12 mmHg), and 9 patients had no pressure gradient at all. The echocardiography revealed that no patients had an accelerated blood flow of more than 2.0 m/s at the aortic arch.

The Institutional Review Board in Kitasato University Hospital approved this study.

Computational simulation methods

Computational analysis methods were based on our previous studies [6]. The postoperative data were acquired using thin-slice early-phase enhanced multidetector row CT. The image data in a Digital Imaging and Communications in Medicine format were translated into 3D patient-specific polygon using the medical imaging software OsiriX (The OsiriX Foundation, Geneva, Switzerland). The threshold value for segmentation from CT was defined to maximize the gradient of the CT value at the wall boundary. The polygon smoothing was conducted using 3D computer graphics software Blender (The Blender Foundation, Amsterdam, Netherlands). The geometry was manually smoothed to avoid the change of the diameter and the shape.

Computational meshes were created using the commercial meshing software ANSYS ICEM 14.0 (ANSYS Japan, Tokyo, Japan). The mesh creation parameters were determined based on our previously reported mesh refinement study [7]. Over 1,000,000 tetrahedral cells and 5 boundary-fitted prism cells were generated for each to calculate accurate EL and WSS values. To imitate the flow around valve leaflets, inlet boundaries for the pulmonary and aortic valves were extended 5 times their original diameters to develop the velocity profiles. The outlet boundaries for the arch branches, the descending aorta and the bilateral coronary arteries were extended 50 times of each vessel’s diameter to stabilize the flow between them, to imitate reflex waves from the peripheral portions and to ensure sufficient pressure recoveries [6].

Mass flow corrected by the body surface area of each patient was given as the inlet boundary condition. Cardiac outputs were set at 4.3 l/min/m². Pulsatile flow profiles through the pulmonary and aortic valves from our previously reported studies were used. Pressure boundary conditions realizing the reflection wave and vessel inertertance was given for all outlets including arch branches and the descending aorta [8]. The following formula was used to determine the distal external forces outside of the analysis domain mainly caused by the reflection wave:

\[ P_{measured} - Z_0 Q_{inlet}, \]  

where \( P_{measured} \) was the measured pressure wave in the aortic arch, and \( Q_{inlet} \) was the total inlet flow rate. \( Z_0 \) was the characteristic impedance of the aorta. To determine the inertial properties of the vessel wall, the inertial term with inductance \( L \) to maintain the intravessel pressure with the flow change was added to equation (1) [9].

\[ -L \frac{dQ_{inlet}}{dt}. \]  

As coronary boundary condition, time-dependent mass flow was given to maintain 2.5% of total cardiac output to the right and left coronary arteries. The vessel walls, including the extended boundary walls, were assumed to be rigid walls.

The commercial finite volume solver ANSYS Fluent 14 (ANSYS Japan, Tokyo, Japan) was used to solve the Navier–Stokes equations for incompressible transient Newtonian fluid. The blood properties were set as follows: density, 1060 kg/m³ and viscosity, 0.004 Pa-s. The turbulence model of the renormalization group k-epsilon model was used to compute the flow. Standard wall function was used for the near-wall treatment with the turbulence model.

The numerical results were visualized and analysed using the CFD postprocessing software, CFD Post (ANSYS Japan). Maximum WSS and EL were calculated. To correct the EL based on patient’s body size, EL index (ELI) was defined as follows.

\[ EL = \sum_{inlet} (\text{Total pressure} \times \text{flow rate}) \]  

\[ - \sum_{outlet} (\text{total pressure} \times \text{flow rate}), \]  

\[ EL \times \text{body surface area}. \]  

Aortic arch geometry evaluation

The geometry of the reconstructed arch is evaluated by the maximum curvature of the arch and the distal arch/descending (arch/DAO) aorta area ratio. The curvature of the arch was calculated from a streamline in systolic peak phase.
Study protocol

The surgical strategy is shown in the flowchart (Fig. 1). The surgical plans were determined based on the above numerical simulation. The criteria for the arch reconstruction were defined as WSS >100 Pa and ELI >40 mW/m². We performed a numerical analysis using the same analytical method on 5 patients with aortic arch repair for CoA (body surface area = 0.25 ± 0.07 m²). The mean maximum WSS was 97.5 ± 27.3 Pa, and the mean ELI was 42.2 ± 16.8 mW/m². On the basis of these results, we determined the criteria of the ELI and WSS for an arch reconstruction.

If the turbulent flow was prominent with both a flow ELI greater than 40 mW/m² and a high WSS greater than 100 Pa, the aortic arch reconstruction using a patch augmentation was performed at the second-stage procedure. In patients who underwent an aortic arch reconstruction, numerical flow simulation was performed again, before the third stage or at 6 months after a biventricular repair. The follow-up cardiac catheterization was performed in surviving patients at 1 year and 5 years after completion of the Fontan or Rastelli operation, to evaluate the aortic arch flow and the systemic ventricular function.

Statistical analysis

Statistical tests were performed with the statistical software EZR (Saitama Medical Centre, Jichi Medical University) [10]. We tested for data normalcy using the Shapiro–Wilk test. EL, ELI and maximum WSS were compared between the unreconstructed and after reconstruction groups, and between before and after reconstruction using the Mann–Whitney test and the Wilcoxon signed-rank test, respectively.

RESULTS

Aortic arch geometry evaluation

Figure 2 shows the relationship between arch/dAo area ratio versus WSS, arch/dAo area ratio versus ELI, maximum curvature versus WSS and maximum curvature versus ELI. There were strong correlations between maximum curvature and WSS and between maximum curvature and ELI, respectively ($R = 0.81$, $P < 0.01$ and $R = 0.61$, $P = 0.02$, respectively). There were negative correlations between arch/dAo area ratio and WSS and between arch/dAo area ratio and ELI, respectively ($R = 0.54$, $P = 0.04$ $R = 0.31$, $P = 0.25$, respectively). The geometries of the aortic arch of the 15 patients are shown in Fig. 3.

Patients without arch reconstruction

Nine patients had no turbulent flow and underwent the second stage without arch reconstruction. As shown in Fig. 4, the patients had a smoothly curved aortic arch without a drastic diameter change. There was neither notable acceleration nor disturbance of blood flow in the aortic arch. The mean ELI was 35.2 ± 21.8 mW/m² that ranged from 11.9 to 78.1 mW/m². The mean max WSS was 51.6 ± 32.1 Pa that ranged from 19 to 107 Pa. Two patients had high ELI, 60.3 and 78.1 mW/m²; however, their WSS was low, 60 and 34 Pa. These patients including the aforementioned 2 patients underwent a second-stage operation or a Rastelli operation without arch reconstruction.
Arch reconstruction

Six patients who had prominent turbulent flow with both a flow ELI greater than 40 mW/m² and a high WSS greater than 100 Pa, with swirling vortex and flow detachment underwent aortic arch reconstruction. In 2 patients, a high ELI was discovered in the middle portion of the aortic arch (Fig. 5). Flow detachment with a high total pressure drop was observed in the descending aorta. An expanded polytetrafluoroethylene graft patch augmentation in the middle of the aortic arch was performed at the second stage. The discrepancy of the diameter and steep curvature was improved and flow detachment with the high ELI disappeared.

Also in 4 patients, discrepancy of the diameter and steep curvature in the anastomosis site caused a disturbed flow with acceleration. An expanded polytetrafluoroethylene graft patch augmentation in the anastomosis site was performed. The discrepancy of the diameter and steep curvature was improved by widening the lesser curvature of the anastomosis site. Helical flow in the descending aorta disappeared after the reconstruction.

After arch reconstruction, the ELI significantly decreased from 88.5 ± 51.0 to 23.1 ± 10.4 mW/m² (P = 0.026), and the WSS significantly decreased from 194.5 ± 87.4 to 60.3 ± 40.5 Pa (P = 0.0062). The WSS and ELI before and after the reconstruction are listed in Table 1. The changes of the WSS and ELI before and after reconstruction are shown in Fig. 7.

Finally, the flow acceleration and flow turbulence disappeared and a laminar flow was realized in all the patients.

Follow-up

The mean follow-up period after the second stage or Rastelli operation with or without arch reconstruction was 60 months. Twelve patients completed the Fontan procedure or the Rastelli...
operation. Two patients died before the Fontan procedure due to heart failure caused by progressive atrioventricular valve regurgitation. Another patient died at 1 month after the Fontan procedure due to sepsis. The remaining patient is currently waiting for a Fontan procedure.

A follow-up catheter examination was performed at 1 year after the Stage 2 or Rastelli operation in 12 surviving patients and at 5 years in 5 other patients. At the last follow-up catheterization, the pressure gradients between the ascending aorta and descending aorta was 1.3 ± 2.3 mmHg (range 0–9 mmHg), and 9 patients had no pressure gradients. The systemic ventricular ejection fraction was 0.62 ± 0.13 (range 0.5–0.88). The systemic ventricular end-diastolic volume index was 110 ± 25% of normal (range 84–152%). The end-diastolic pressure was 6.5 ± 1.6 mmHg (range 4–9 mmHg). The systemic ventricular function was preserved in all the surviving patients during the follow-up period.

**DISCUSSION**

To enhance long-term outcomes, achieving optimal blood flow dynamics is believed to be important. Some previous flow analytical studies have shown that maintaining WSS in normal range accelerates the intimal proliferation, which leads to the growth of lumen diameter [11–14].

Energetic performance of blood flow in the neoaorta is also an important factor for risk assessment. It is used for various numerical studies including the Fontan circulation and the Norwood procedure to evaluate the cardiac workload to single ventricle [15–17]. WSS and ELI quantitatively evaluate the geometrical feature of the neoaorta. Figure 2 shows the relationship between WSS, ELI, arch/dAo area ratio and curvature of the reconstructed arch of the patients in this study. Figure 3 shows the geometry of the aortic arch of 15 patients. Nine cases that did not require arch revision had gradual tapering in calibre of the aortic arch, whereas 6 cases that needed arch adjustment had the abrupt change in calibre. There were some differences in surgical techniques between the groups. According to our previous study, longitudinal incision of the descending aorta in the patients with AA and the combination of arch repair and Damus–Kaye–Stansel in
Figure 6: This case had a steeply curved, narrow anastomosis site in the distal aortic arch, where the disturbed flow caused a high energy loss index (100 mW/m) and a high WSS (257 Pa). Patch augmentation of lesser curvature reduced the energy loss index to 38.4 mW/m² and the WSS to 21 Pa. WSS: wall shear stress.

Figure 7: The energy loss index and wall shear stress of the unreconstructed group and the group before and after reconstruction are shown.

Table 1: The comparison between before and after reconstruction

<table>
<thead>
<tr>
<th></th>
<th>Non-reconstructed</th>
<th>Reconstructed (before reconstruction)</th>
<th>Reconstructed (after reconstruction)</th>
<th>P-value (non-reconstructed vs after reconstruction)</th>
<th>P-value (before vs after reconstruction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td></td>
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</tr>
<tr>
<td>EL</td>
<td>12.2 ± 11.4</td>
<td>18.9 ± 11.1</td>
<td>7.2 ± 2.5</td>
<td>0.953</td>
<td>0.031</td>
</tr>
<tr>
<td>ELI</td>
<td>35.2 ± 21.8</td>
<td>88.5 ± 51.0</td>
<td>23.1 ± 10.4</td>
<td>0.262</td>
<td>0.026</td>
</tr>
<tr>
<td>Max WSS</td>
<td>51.6 ± 32.1</td>
<td>194.5 ± 87.4</td>
<td>60.3 ± 40.5</td>
<td>0.689</td>
<td>0.006</td>
</tr>
</tbody>
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EL: energy loss; ELI: energy loss index; WSS: wall shear stress.
the single anastomosis in the patient with AS were effective to ensure sufficient anastomotic space, which prevents flow collisions from the ascending aorta and pulmonary artery and reduce WSS and EL in the Norwood procedure. Large ELI and large WSS are associated with the steep curvature of the arch and low arch/ dAo area ratio. Hasegawa et al. [18] reported that using glutaraldehyde-treated autologous pericardium patch at the anastomosis site created smooth arch curvature and high coarctation index, and it diminished the incidence of postoperative recoarctation, bronchial compression and branch pulmonary artery compression. It is also reported that coarctation index, which can be expressed by the square root of arch/dAo area ratio in this study, is associated with ventricular function deterioration. Larrazabal et al. [2] reported that there is a significant correlation between lower coarctation index and lower right ventricular fractional area change. Thus, the high ELI and high WSS could be the risk factor of reintervention, and it is feasible to use these parameters as criteria for arch reconstruction.

Currently, blood flow without a pressure gradient or flow acceleration in the neoaorta is considered to be a criterion for a successful reconstruction after the Norwood procedure, and the technical performance of the Norwood procedure is measured based on cardiac catheterization and echocardiography [1]. However, the EL and wall stiffening caused by inadequate blood flow after aortic arch repair are known to affect cardiac function [2, 16]; therefore, a detailed flow assessment is needed. The CFD is one of the most potential tools to analyse in vivo blood flow in congenital heart disease. One of the most important advantages of the CFD is that it enables patient-specific analysis with deep insight of prognosis prediction by calculating ELI and WSS. Measuring energetic efficiencies in the reconstructed arch is difficult in the clinical setting, because the pressure in the vessel wall cannot be measured with an invasive catheter in an exact manner. In addition, the CFD is the only way to accurately measure the distribution of the WSS, because the WSS calculation requires a precise distribution of blood flow near the wall with high spatial resolution. 3D distribution of flow velocity and pressure enables one to elucidate the mechanism of acceleration, collision and flow detachment, which may increase the WSS and ELI in the complex reconstructed arch in each patient. In this study, effective workload of blood flow delivery affecting a long-term deterioration of systemic ventricle and vascular wall stress causing a long-term vascular stiffening were estimated with the ELI and WSS, respectively. As previously reported, the small anastomosis site and steep angle in the aortic arch were the 2 main causes that increased the WSS and ELI [3]. In each case, the specific cause of the high ELI and WSS were identified and resolved at the second-stage procedure, providing the requisite indication for an aortic arch repair.

It is considered that the blood flow evaluation using CFD will be the primary tool for congenital heart disease. CFD can be performed from CT image that is acquired in ordinary practice, and no additional invasive measurement is required. It can acquire large information about blood flow and has a possibility of substituting invasive measurement such as oxygen saturation measurement by computing diffusion or pressure measurement by calculating EL.

In addition, virtual surgery can be performed using CFD and enables prediction of postoperative blood flow by modifying the preoperative aortic arch geometry. This helps surgical planning for each patient and is one of the most important roles of the CFD simulation.

**Limitations**

There are a few limitations in this study. First, to our knowledge, there are no studies on the relationship between long-term outcomes, EL and WSS. Accumulated flow analysis data with investigations into patient prognosis are warranted to determine the criteria for reconstruction.

Second, we applied a fixed boundary condition for the vessel wall. It has been reported that WSS is overestimated using a rigid wall [19]; therefore, a wall motion with elastic properties should be included to increase the accuracy. However, estimation of the elastic property distribution in a postoperative aortic arch is quite difficult. Therefore, in this study, we avoided using the fluid-structure interaction method, because providing an inaccurate wall property would not increase the accuracy of the flow simulation and because the arch vessel wall after the repeated operation would be considerably hard.

Third, sample size was small, which limited the statistical power of this study. Thresholds of 100 Pa of WSS and 40 mW/m³ of ELI worked well, and none of the patients had deterioration of the ventricular function arise from the aortic arch flow inefficiency. However, for the practical use of CFD on clinical practice, we will need additional investigations in a larger cohort to evaluate the relationship between the haemodynamic parameters and the clinical outcomes.

Finally, the CFD results are not clinically measured data but calculated data. It is calculated on simplified models including the rigid wall model, the Newtonian fluid model and the turbulent model. One of these models must be suited to each case, and all the patients cannot be analysed by CFD. On the other hand, 3D cine (time-resolved) phase-contrast magnetic resonance imaging (4D flow magnetic resonance imaging) [20] and Doppler-based echocardiographic vector flow mapping [21] are other potential methods to evaluate in vivo blood flow including haemodynamic parameters such as WSS and ELI based on actual measurements. However, these measurements have less spatial and temporal resolution, which affect the accuracy and precision of WSS and ELI evaluation. In future studies, both actual measurements and simulations should be properly used to assure the best affordable results.

**CONCLUSIONS**

In conclusion, the gradual tapering in calibre of the aortic arch reduced WSS and EL. Even if those were not achieved in the first surgery, reconstruction of the aortic arch during an interstage procedure could correct the steep curvature and prevent drastic change in the diameter in the aortic arch and successfully reduce WSS and ELI in patients with the WSS >100 Pa and the ELI >40 mW/m³. Determining the surgical strategy for arch reconstruction based on numerical flow analysis may effectively reduce the ventricular load even if no stenosis or pressure gradients are observed on catheter examination or echocardiography.
Conflict of interest: Shohei Miyazaki is an employee at the maker of the blood flow analysis tools: Cardio Flow Design Inc. (Tokyo, Japan). Keiichi Itatani is an equity shareholder and founder of the vendor for the blood flow analysis tool: Cardio Flow Design Inc. (Tokyo, Japan). He was an endowed chair of Kitasato University, financially supported by Hitachi Aloka Medical (Tokyo, Japan) between 2012 and 2015 and is an endowed chair of Kyoto Prefectural University of Medicine, financially supported by Medtronic Japan (Tokyo, Japan). Kagami Miyaji was an endowed chair of Kitasato University, financially supported by Hitachi Aloka Medical (Tokyo, Japan) between 2012 and 2015.

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