these shunts and the ventricular assist device can be inadequate for support of impaired patients with an RV-PA shunt. Therefore, we have never used a ventricular assist device as a circulatory aid.

Study limitations

This study has several limitations. First, this study has its retrospective nature and the small number of patients. Second, it was evaluated by only a univariate analysis. Third, this study assessed the cases over 12 years and the bias such as the induction of bilateral pulmonary artery banding may have affected the results.

CONCLUSIONS

The institution of ECMO after cardiac collapse was thus found to be a significant factor predictive of a poor outcome. It is not always easy to predict a circulatory collapse. However, when signs of hemodynamic instability are rising in impaired patients, early initiation of ECMO should be considered to avoid circulatory collapse and fatal conditions following stage 1 Norwood procedures.

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Transfusion-Free Neonatal Cardiopulmonary Bypass Using a TinyPump

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Background. We devised a miniaturized circuit incorporating a TinyPump in the venous line to amplify the venous return. We compared this system to the conventional blood-primed circuit and investigated whether this circuit could maintain hematocrit levels without blood transfusion and reduce coagulation and inflammatory cascades.

Methods. Thirteen 1-week-old piglets (3.7 ± 0.2 kg) were divided into group M (miniaturized circuits with TinyPump-assisted venous drainage without blood, n = 7) and group C (conventional circuits with blood priming, n = 6). Cardiopulmonary bypass (CPB) was performed at 150 to 180 mL · kg^{-1} · min^{-1} for 2 hours, including 60 minutes of cardioplegic cardiac arrest. Modified ultrafiltration (MUF) was subsequently performed. Data were acquired before CPB and after the end of MUF.

Results. The priming volume including the hemofilter circuit of the main circuit required 152 mL in group M and 300 mL in group C. The mean hematocrit values in group M and group C were not significantly different during CPB (21.5% ± 2.0% versus 23.2% ± 1.3%) or after MUF (30.7% ± 2.1% versus 32.9% ± 4.0%). After MUF, group M had lower thrombin-antithrombin complex levels (16.7 ± 5.0 ng/mL versus 28.4 ± 8.4 ng/mL, $p < 0.01$) and interleukin-8 levels (2,867 ± 758 pg/mL versus 13,730 ± 5,220 pg/mL, $p < 0.01$) than group C. The pulmonary vascular resistance index was lower in group M after MUF (4,105 ± 862 dynes · cm^{-5} · kg^{-1} versus 6,304 ± 1,477 dynes · cm^{-5} · kg^{-1}, $p < 0.01$). The lung water content was also better in group M (83.7% ± 0.5% versus 84.9% ± 0.5%, $p < 0.01$).

Conclusions. The minicircuit with TinyPump-assisted venous drainage successfully maintained acceptable hematocrit levels and the cardiopulmonary function in neonatal piglets. Employing this technique may attenuate blood requirements and inflammatory responses, thereby improving the clinical outcomes of neonatal open-heart surgery.

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Evidence is gathering to suggest that cardiopulmonary bypass (CPB) and blood products during CPB have adverse effects on clinical outcomes through inflammatory responses [1–6]. Neonatal CPB is still in a difficult situation in terms of these several points. The disparity between the circuit volume and neonates' blood volume necessitates the relatively large circuit and the use of allogeneic blood to prevent unacceptable hemodilution and maintain adequate oxygen delivery. Moreover, neonates are more vulnerable to damaging effects after CPB owing to their higher metabolic demands, reactive pulmonary vasculature, and immature organ function [5–8]. Although CPB remains challenging without blood products at present, the miniaturization of the CPB circuit is the mainstay of strategies to diminish hemodilution, artificial surface area, and blood transfusion requirements.

The centrifugal pump-assisted venous return technique was originally developed to establish femorofemoral bypass for cardiac decompression in repeat cases and to facilitate minimally invasive cardiac surgery in adults. This technique enables the amplification of venous drainage through smaller cannulas and the downsizing of the CPB circuit [8–11]. However, there are no suitable centrifugal pumps for the pediatric body size, and miniaturization of the circuit has only provided minimal advantages over other venous augmentation techniques.

We developed a seal-less, ultraminiature rotary centrifugal blood pump, which we call the TinyPump, with a priming volume of 5 mL [12, 13]. We designed a miniature CPB circuit incorporating the TinyPump on the venous line to amplify venous return through downsized tubing for small infants. The purposes of this study were to evaluate the feasibility of TinyPump-assisted venous drainage and to investigate whether this miniaturized circuit without blood transfusion could maintain acceptable hematocrit levels and reduce inflammatory cascades and CPB-induced side effects in comparison to the conventional blood-primed CPB circuit in neonatal pigs.

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Material and Methods

Animal Groups and Preparation

All experimental animals were cared for in accordance with institutional guidelines and the "Guide for the Care and Use of Laboratory Animals" prepared by the National Academy of Science and published by the National Institutes of Health (NIH Publication 86-23, revised 1985). The experimental protocol was approved by the Okayama University School of Medicine Experimental Animals Committee. Thirteen 1-week-old piglets with a mean body weight of 3.7 ± 0.2 kg were used for the experiments. Animals were divided into two groups based on the CPB circuit and priming components. Group M (n = 7) underwent surgery with the miniaturized circuits with TinyPump-assisted venous drainage without blood prime; and group C (n = 6) underwent surgery using conventional larger circuits with gravity drainage and blood priming. Donor pigs weighing 20 to 30 kg were used to harvest blood for blood priming 1 week before the experiments. After animals were anesthetized, blood was obtained by sterile technique through the right carotid artery and stored at 4°C in citrate phosphate dextrose adenine solution (CPDA Blood Bag; Terumo, Kanagawa, Japan).

The animals were given methylprednisolone (30 mg/kg) 2 hours before surgery and premedicated with intramuscular ketamine hydrochloride (20 mg/kg) and acepromazine (1 mg/kg). After induction of anesthesia with pentobarbital (25 mg/kg) and pancuronium (0.2 mg/kg), the animals were mechanically ventilated with a tidal volume of 10 mL/kg and a peak end-expiratory pressure of 5 cm H_2O. Isoflurane inhalation (1% to 2%) and intermittent infusion of pentobarbital (10 mg/kg) were used to maintain anesthesia. The ventilator settings were adjusted to maintain an arterial PCO_2 of 35 to 45 mm Hg. Rectal temperature was continuously monitored. For pressure monitoring and blood gas sampling, 22G catheters were placed in the left carotid artery and in the left internal jugular vein. A micromanometer was inserted into the left atrium for pressure monitoring, and a 7F Swan-Ganz catheter (Arrow, Reading, PA) was inserted into the main pulmonary artery.

Cardiopulmonary Bypass Circuits

The layout of the CPB circuits in both group are shown in Figure 1. An arterial roller pump (CAPS; Stöckert, Sorin, Germany) and a hollow fiber membrane oxygenator with a hard-shell reservoir (Capiox RX 05; Terumo) were used in both groups. Group M had an arterial line of 3/16-inch internal diameter and 55-cm length, a venous line of 3/16-inch internal diameter and 55-cm length, and a line for the roller pump head (1/4-inch internal diameter). Group C had standard arterial and venous line diameters and lengths: arterial line (3/16-inch internal diameter and 160-cm length), venous line (1/4-inch internal diameter and 160-cm length).

In group M, the venous line was bifurcated and the TinyPump was incorporated in one of the bifurcations to enable the selection of either gravity drainage or TinyPump-assisted venous drainage by clamping one of the two lines. The negative pressure of the venous line was monitored at its inlet site. A flow probe (Transonic System, Ithaca, NY) was placed on the venous line between bifurcated lines and the inlet of the reservoir. The hemofilter (Capiox Hemocentrator HC05; Terumo) was connected between the outlet and one of the inlets of the reservoir. The CPB circuit was placed as close to the operation table as possible, and the roof of the venous reservoir was set 10 cm lower than the position of the table.

The volume in the reservoir was kept as low as possible (about 15 mL) in group M. In group C, the aggressive perfusion attempt was not used, and the volume level in the reservoir was maintained at the level of approximately 100 mL. The circuit in group M was primed with 25% albumin (50 mL), sodium bicarbonate (4 mL/kg), mannitol (4 mL/kg), methylprednisolone (30 mg/kg), heparin sodium (2000 U), and lactated Ringer's solution. In group C, the stored blood (250 mL) was added to the circuit and ultrafiltrated before CPB with lactated Ringer's solution (1,500 mL) for "washing," and the same amount of filtrate was removed. The same drugs and solutions as above were subsequently added into the circuit.

Cardiopulmonary Bypass

Anticoagulation was induced with heparin sodium (300 U/kg) to maintain an activated clotting time more than 480 s. The CPB was established by cannulation to the aortic root (2.6 mm [Stöckert]) and to the right atrium (DLP, 16F [Medtronic, Minneapolis, MN]). The CPB was conducted at flow rates of 150 to 180 mL · kg^{-1} · min^{-1}. If

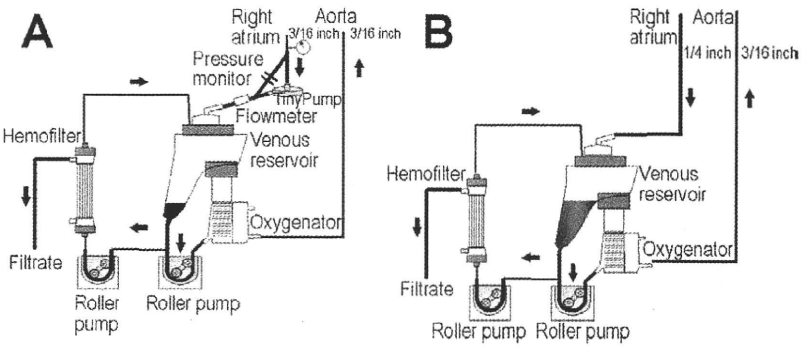

Fig 1. (A) The miniature cardiopulmonary bypass circuit with TinyPump-assisted venous drainage. (B) The conventional circuits.

additional volume was required, lactated Ringer's solution was added to the reservoir. Animals were cooled to 28°C in 30 minutes, the ascending aorta was clamped, and cardiac arrest was achieved with crystalloid cardioplegia at a dose of 20 mL/kg. During cardiac arrest, the left ventricle was vented through the left atrium appendage. Crystalloid cardioplegia at a dose of 10 mL/kg was added 30 minutes after cardiac arrest. The cardioplegic volume returned in the reservoir was removed with ultrafiltration. After 60 minutes of cardiac arrest, the ascending aorta was declamped and the animals were rewarmed to 36°C in 30 minutes. After 2 hours of bypass, the animals were weaned from CPB without inotropic support, and standard arteriovenous modified ultrafiltration (MUF) was performed for about 10 minutes until all the blood in the main circuit was returned. If the animals were unable to be weaned from CPB or tolerate MUF because of hemodynamic instability, epinephrine was administered at a dose of 0.05 $\mu g \cdot min^{-1} \cdot kg^{-1}$. After MUF, the aortic cannula was clamped, an arterial line for MUF was opened, and all the primed blood of the hemofilter circuit was returned to the animal through the right atrium. At the end of each experiment, the animal was sacrificed by the intravenous injection of potassium chloride.

Flow Rates of Venous Return

The flow rates of venous return were initially assessed in group M by clamping the TinyPump line and measuring venous return with gravity drainage alone. Thereafter, the flow rates of TinyPump-assisted venous drainage were evaluated by clamping the other venous line. The ratio of flow rate to the desired value (%) was calculated by dividing by 180 ($ml \cdot min^{-1} \cdot kg^{-1}$) and the animal's body weight (kg) and multiplying by 100.

Hemodynamics

Hemodynamic variables, including heart rate, mean arterial pressure, mean pulmonary artery pressure, central venous pressure, and left atrial pressure, were continuously monitored. Ten minutes before CPB and 10 minutes after the end of MUF, the cardiac output was measured by the thermodilution technique and airway pressure was assessed to calculate static pulmonary compliance. Both the cardiac output and pulmonary vascular resistance were indexed by dividing by the animal's weight.

Blood Sampling

Hematocrit was collected 10 minutes before CPB, 60 minutes after the initiation of CPB, and 10 minutes after the termination of MUF. Free hemoglobin levels, blood gases, thrombin-antithrombin complex (TAT), and plasma interleukin-8 (IL-8) levels were collected before CPB and 10 minutes after the termination of MUF. These samples were centrifuged for 10 minutes, and the plasma was stored at −70°C. Plasma free hemoglobin levels were measured by spectrophotometry. Thrombin antithrombin complex levels were measured using an enzyme immunoassay kit (SRL, Tokyo, Japan). The IL-8 levels were measured by an enzyme-linked immunosorbent assay kit (BioSource International, Camarillo, CA).

Interleukins in Airway Lavage Fluid

After the abovementioned parameters had been measured, 10 mL saline was administered to the animal's airway from the tracheal tube. After ventilating the animals several times, the airway lavage fluid was sucked from the distal airway and collected. The IL-8 levels in the airway lavage fluid were measured.

Heart and Lung Water Gain

The free wall of the right ventricle and a peripheral lung specimen were obtained immediately after death. The specimens were weighed, desiccated in a warming oven at 80°C for 24 hours, and then reweighed to determine the water content.

Statistical Analysis

Normally distributed values between groups were compared with the unpaired t test. Abnormally distributed data between groups were compared using the Mann-Whitney U test. Intragroup comparisons were performed with the Wilcoxon signed rank test. All data were expressed as the mean ± SD. A p value less than 0.05 was considered to be statistically significant.

Results

The priming volume of the circuit including the hemofilter line of the main circuit in group M was 152 mL, whereas the priming volume was 300 mL in group C, reducing 148 mL in the priming volume in group M. Decrease in the priming volume came from reduction in the arterial and venous line lengths by applying TinyPump-assisted venous drainage by 48 mL, and from reduction in the reservoir level at the initiation CPB. The miniaturized circuit of group M had a flow rate of 531 ± 20 mL/min (80.9% ± 6.8%) with only gravity drainage (without the TinyPump). However, use of the TinyPump significantly augmented the venous return to 710 ± 72 mL/min (107.3% ± 5.9%, $p < 0.01$) at a pump speed of 1,531 ± 178 rpm. Similarly, the TinyPump amplified the negative pressure of the venous line from −27.5 ± 3.0 mm Hg to −37.8 ± 5.6 mm Hg ($p < 0.01$). Group M had no differences in plasma free hemoglobin levels before CPB as compared with group C (6.9 ± 4.1 mg/dL versus 9.2 ± 4.4 mg/dL, $p = 0.475$). However, plasma free hemoglobin levels after MUF were significantly lower in group M than in group C (24.1 ± 11.6 mg/dL versus 90.3 ± 68.5 mg/dL, $p < 0.01$). No pump-related problems occurred, and a visual inspection confirmed no thrombus formation inside the TinyPump in any experiment.

Hematocrit

The hematocrit dropped after the initiation of CPB in both groups, and there was no significant difference between the groups at 60 minutes after CPB (21.5% ± 2.0% versus 23.2% ± 1.3%, $p = 0.109$) or after the end of MUF (30.7% ± 2.1% versus 32.9% ± 4.0%, $p = 0.215$)

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without additional transfusion of blood during CPB (Fig 2).

Hemodynamic Profiles and Blood Gas Analyses

All animals in both groups were weaned from CPB without inotropic support; however, 2 of the 6 piglets in group C required epinephrine infusion during MUF because of hemodynamic instability. There were no differences in hemodynamic profiles between the groups before CPB, whereas the mean pulmonary artery pressure, central venous pressure, and left atrial pressure were elevated in both groups after MUF (Table 1). The mean pulmonary artery pressure and central venous pressure after MUF were significantly lower in group M than in group C. The pH levels and PaO_2 decreased in both groups after MUF, but there were no significant differences between the two groups (Table 2). The venous oxygen saturation (SvO_2) levels were lower in group C after MUF, although no significant difference was observed between the two groups.

Cardiopulmonary Function and Water Content

There was no difference in cardiac index before CPB and after MUF between the groups (Table 3). The pulmonary vascular resistance index increased after MUF in both groups, although lower values were noted in group M than in group C. Static pulmonary compliance decreased in group C after MUF, but there were no significant differences between the two groups. Myocardial and lung water contents after the experiment were significantly lower in group M than in group C.

Thrombin Antithrombin Complex and Interleukins

The TAT levels increased during CPB in both groups; however, group M had lower levels than group C after MUF (Table 4). Plasma IL-8 was not detectable before CPB in both groups, but increased during CPB. Group M had lower levels of plasma IL-8 than group C after MUF. The level of IL-8 in the airway lavage fluid after MUF was also lower in group M than in group C.

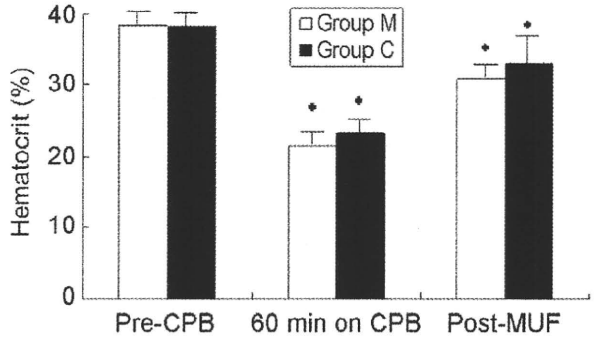

*Fig 2. Hematocrit before, during, and after cardiopulmonary bypass (CPB). *p < 0.05 after CPB versus before CPB. (MUF = modified ultrafiltration; black bars = group C [CPB]; white bars = group M [MUF].)*

Table 1. Hemodynamic Variables Before Cardiopulmonary Bypass (CPB) and After Modified Ultrafiltration (MUF)

	Pre-CPB		Post-MUF	
	Group M	Group C	Group M	Group C
HR, L/min	143 ± 8	143 ± 13	128 ± 15[a]	120 ± 9[b]
MAP, mm Hg	45 ± 4	47 ± 4	41 ± 4	40 ± 9
MPAP, mm Hg	16 ± 3	13 ± 5	21 ± 3[b,c]	28 ± 5[b]
CVP, mm Hg	3 ± 1	3 ± 1	4 ± 1[a,d]	8 ± 2[b]
LAP, mm Hg	3 ± 1	3 ± 2	5 ± 1[a]	7 ± 2[b]

[a] $p < 0.05$ post-MUF versus pre-CPB. [b] $p < 0.01$ post-MUF versus pre-CPB. [c] $p < 0.05$ group M versus group C. [d] $p < 0.01$ group M versus group C.

CVP = central venous pressure; HR = heart rate; LAP = left atrial pressure; MAP = mean arterial pressure; MPAP = mean pulmonary arterial pressure.

Comment

In the present study, we assessed the efficacy of a TinyPump in the venous line and investigated the effect of this miniaturized circuit without blood transfusion on hemodynamics and inflammatory responses in neonatal piglets. Our key findings were as follows: (1) the TinyPump amplified venous return through a smaller venous line to obtain adequate venous flow rates; (2) the miniaturized circuit could maintain acceptable hematocrit levels without blood transfusion; (3) the miniaturized CPB had lower thrombin formation and cytokine activation after MUF than the circuit with blood ultrafiltration before CPB; and (4) employing a downsized circuit and avoiding blood transfusion prevented cardiac damage and minimized myocardial and pulmonary edema.

Significance of TinyPump-Assisted Venous Drainage

Neonates undergoing CPB face the challenge of hemodilution and subsequent blood transfusion. Cardiopulmonary bypass also exposes a patient's blood to the artificial surface of the bypass circuit. These issues are associated with the deleterious effects of CPB such as the activation of inflammation and coagulation. Matching the volume between neonates and the CPB circuits is one of the most

Table 2. Blood Gas Analysis Before Cardiopulmonary Bypass (CPB) and After Modified Ultrafiltration (MUF)

	Pre-CPB		Post-MUF	
	Group M	Group C	Group M	Group C
pH	7.37 ± 0.05	7.38 ± 0.08	7.23 ± 0.04[a]	7.25 ± 0.05[b]
PCO_2, mm Hg	40 ± 8	39 ± 9	37 ± 4	39 ± 3
PO_2, mm Hg	543 ± 71	528 ± 55	413 ± 111[a]	340 ± 190[b]
SVO_2, %	84 ± 3	85 ± 5	78 ± 13	71 ± 13.6[b]

[a] $p < 0.01$ post-MUF versus pre-CPB. [b] $p < 0.05$ post-MUF versus pre-CPB.

PCO_2 = partial pressure of carbon dioxide; PO_2 = partial pressure of oxygen; SVO_2 = mixed venous oxygen saturation.

Table 3. Cardiopulmonary Function and Water Content Before Cardiopulmonary Bypass (CPB) and After Modified Ultrafiltration (MUF)

	Pre-CPB		Post-MUF	
	Group M	Group C	Group M	Group C
Cardiac index, L/min/kg	0.301 ± 0.039	0.295 ± 0.051	0.280 ± 0.037	0.291 ± 0.081
PVRI, dynes/cm^5/kg	2,911 ± 690	2,550 ± 992	4,105 ± 862[a,b]	6,304 ± 1,477[a]
C stat, mL/cm H_2O	6.4 ± 1.3	6.1 ± 1.3	5.4 ± 1.9	3.8 ± 0.8[c]
Myocardial water content, %			78.4 ± 1.4[b]	80.9 ± 1.8
Lung water content, %			83.7 ± 0.5[b]	84.9 ± 0.5

[a] $p < 0.01$ post-MUF versus pre-CPB. [b] $p < 0.01$ group M versus group C. [c] $p < 0.05$ post-MUF versus pre-CPB.

C stat = static pulmonary compliance; PVRI = pulmonary vascular resistance index.

practical way to overcome CPB-related adverse effects. Augmented venous return techniques are crucial to downsize the CPB and to fulfill demands of high-flow perfusion in small patients. The TinyPump has a very low priming volume of 5 mL, which is suitable for the mini-CPB circuit. We previously had created the miniaturized circuit with a TinyPump [13], but this tricky semiclosed system could not be suitable for a wide clinical application. Consequently, we developed a unique CPB circuit with a TinyPump-assisted venous drainage technique and open-reservoir system.

In the current study, the TinyPump could reduce the priming volume of 48 mL in the arterial and venous lines as compared with group M by downsizing tubings, which was noteworthy to keep acceptable hematocrit levels in neonates. The priming volume of our novel circuit requires only 152 mL (including a hemofilter circuit), and this size is comparable to other minicircuits reported in the literature [14–16]. Our results demonstrated that the TinyPump augmented a sufficient venous return and kept the circulation at approximately 700 mL/min under mild pump support in the neonatal piglet model without pump problems. We also revealed that our mini-CPB circuit could maintain satisfactory hematocrit levels as a result of less hemodilution. This technique could also be utilized for selective caval cannulation and miniaturization of CPB systems for infants and larger children.

TinyPump-Assisted Drainage Versus Vacuum-Assisted Drainage

The biggest advantage of our system incorporating TinyPump in the venous drainage is to facilitate the venous drainage by creating a negative pressure in the venous system, which is essentially the same as the vacuum-assisted venous drainage system. The subsequent advantages of these systems are to attain effective drainage with relatively small venous cannulas and to reduce CPB circuit lengths and subsequent priming volume. Despite the potential advantages, the vacuum-assisted system is not universally used because of the concerns over increased risk of gaseous microemboli, especially in the setting of a high negative pressure [17] and possible overpressurization of venous reservoir. The TinyPump created a moderate negative pressure ranging from −27 to −38 mm Hg in the venous system and seemed to have a less traumatic profile to the blood, characterized by acceptable hemolysis. In addition, there is no concern to have overpressurization in the TinyPump-assisted system. There were no data on gaseous microemboli with TinyPump-assisted venous drainage system. It is of great interest to investigate the impacts of two different drainage system, namely, TinyPump-assisted versus vacuum-assisted on safety (airlock, gaseous microemboli, overpressurization of the venous reservoir), degree of hemolysis and inflammatory response, and the impact of two techniques in miniaturization of the circuit.

Side Effects of Blood Priming

Blood transfusion to avoid extreme hemodilution has been identified as a major risk factor for post-CPB multiorgan failure [1, 2, 5, 15]. The plasma from stored blood cells directly primes neutrophils for cytotoxicity and prompts release of lytic enzymes, which activate inflammatory responses [18]. Recent studies have demonstrated that using downsized circuits and avoiding blood product administration mitigated hemodynamic deterioration,

Table 4. Laboratory Data Before Cardiopulmonary Bypass (CPB) and After Modified Ultrafiltration (MUF)

	Pre-CPB		Post-MUF	
	Group M	Group C	Group M	Group C
TAT, ng/mL	4.4 ± 2.9	3.9 ± 0.4	16.7 ± 5.0[a,b]	28.4 ± 8.4[a]
Plasma IL-8, pg/mL	<31.2	<31.2	2,867 ± 758[a,b]	13,730 ± 5,220[a]
ALF IL-8, pg/mL			405 ± 175[c]	1,249 ± 733

[a] $p < 0.01$ post-MUF versus pre-CPB. [b] $p < 0.05$ group M versus group C. [c] $p < 0.01$ group M versus group C.

ALF = airway lavage fluid; IL = interleukin; TAT = thrombin-antithrombin complex.

activation of inflammatory responses to CPB, and myocardial and pulmonary injuries [2, 5, 6, 14]. However, there have been no reports comparing clear primed fluid with primed blood after ultrafiltration before CPB. This technique has the potential to reduce inflammatory responses associated with blood transfusion [3, 4]. In the current study, the miniature CPB circuit without blood was more advantageous owing to lower levels of inflammatory mediators and better cardiopulmonary function in comparison with the larger circuit with "washed" blood priming.

Interleukin-8 in Plasma and Airway Lavage Fluid

Cardiopulmonary bypass provokes proinflammatory cytokines such as tumor necrosis factor-α, IL-6, and IL-8, which are produced by monocytes, macrophages, lymphocytes, and endothelial cells and correlate with myocardial and lung injuries [1, 2, 5, 6, 8, 19]. Interleukin-8 is a potent polymorphonuclear and T-lymphocyte chemotactic factor that amplifies endothelial cell to neutrophil interaction, which subsequently induces degranulation [14]. It is also involved in neutrophil-induced endothelial injury and may be related to post-CPB capillary leak syndrome [5, 6]. The IL-8 concentration in bronchoalveolar lavage fluid correlates with neutrophil influx to the airway and following elastase release; furthermore, these increases are associated with pulmonary dysfunction after CPB [20]. Neutrophils migrate to the distal airway after CPB, and elastase stimulates the release of IL-8 from neutrophils, which attracts additional neutrophils and forms a vicious cycle. The present study showed that lower levels of IL-8 in the plasma and airway lavage fluid in the downsized circuit may have resulted from less blood-synthetic interaction and no blood transfusion.

CPB-Induced Cardiopulmonary Dysfunction

Cardiac and pulmonary dysfunction resulting from CPB is a significant cause of postoperative morbidity. Inflammatory mediators induced by CPB have been implicated in depressed cardiac contractile activity, the need for inotropic support, impaired gas exchange, increased pulmonary vascular resistance, decreased pulmonary mechanics, and tissue edema [1, 2, 5, 6]. These conditions could lead to right ventricular dysfunction and elevated central venous pressure, which can induce fluid accumulation [1, 2, 5, 8]. In the present study, the miniaturized CPB group maintained better hemodynamic stability and did not need inotropic support; furthermore, this group experienced lower pulmonary artery pressure and central venous pressure, lower pulmonary vascular resistance, and less tissue water gain. These results are attributed to decreased inflammatory responses. Preservation of cardiopulmonary function is vital for postoperative management and results in decreased intensive care unit and hospital stays.

CPB-Related Coagulopathy

Precise management of blood coagulation is of critical importance during repair of congenital heart diseases in neonates, given the immaturity of the neonatal coagulation system that increases the risk of postoperative bleeding [19]. Cardiopulmonary bypass and subsequent inflammatory mediators activate extrinsic pathway of coagulation [4, 19]. Thrombin production induces the increased expression of P-selectin on endothelial cells, which leads to neutrophil adherence and activation. The activation of thrombin receptors on leukocytes can also induce the release of inflammatory cytokines. The lower TAT levels after MUF in the miniaturized circuit indicated decreased thrombin formation and less activation of coagulation cascades, which resulted from lower inflammatory load associated with miniaturized circuits without blood. Furthermore, thrombin itself plays a role of the inflammatory mediator and, therefore, lower levels of TAT could also be associated with the better preservation of the cardiopulmonary function in the mini-CPB group. Finally, the miniaturized group maintained hematocrit levels after MUF similar to those of the conventional group with blood priming. Modified ultrafiltration can concentrate hematocrit values of the patient by returning the blood in the circuit, but the concentration depends on the bleeding in the operative field. Although TAT levels describe only parts of the whole coagulation process, this result also may suggest less hemostatic failure in the miniaturized group without blood.

Study Limitations

This study has certain limitations. First, we could not determine whether the lower inflammatory responses in the miniaturized circuit resulted from downsizing of the circuit or employment of the TinyPump. However, we at least demonstrated that the use of the TinyPump was appropriate for downsizing the circuit. Second, we did not incorporate an arterial filter in the miniature circuit to simplify the circuit. The efficacy of the arterial filter has been controversial, and in some institutions, it has not been used for CPB miniaturization [7]. Third, we incorporated the hemofilter circuit and performed MUF. Although this additional circuit requires more volume in the line, it facilitates control of the fluid level in the venous reservoir and enables the conduction of conventional or modified ultrafiltration. Fourth, MUF removes some inflammatory mediators but also has a potential to initiate inflammatory response. It would have been ideal to collect data at the termination of CPB and after MUF, which would allow us to assess the direct impact of miniaturized circuits on inflammatory markers. Fifth, bronchoalveolar lavage has recently been utilized to diagnose respiratory disorders; however, the distal airways of the neonatal piglets were too small to collect lavage fluid through bronchoscopy. We, therefore, substituted bronchoalveolar lavage fluid for fluid from the airways after the administration of saline. Sixth, the stored blood we used in group C may have been older than ideal, which may exaggerate the negative results of the control animals. Seventh, although there were no fatal problems such as acidosis and low blood pressure, blood used for priming in group C had not undergone blood typing test and radiation, and that may have had an impact on inflammatory responses. Eighth, similar

cytokine profiles are evident after normothermic CPB, suggesting common underlying mechanisms that are independent of temperature [21]; although this study focused on moderate hypothermia, inflammation related to normothermic bypass or hypothermic arrest may also be reduced with a strategy of circuit miniaturization. Ninth, our test of coagulation function was only assessed by TAT levels. Thromboelastogram may have indicated more purely the coagulopathy. Finally, our study had only acute changes 10 minutes after CPB. The short duration of follow-up was compulsory because the poor cardiopulmonary function in those animals receiving blood transfusion precluded the use of a chronic preparation.

In conclusion, the use of the TinyPump in the venous line could augment venous return in the miniaturized CPB circuit, and this technique enabled the performance of transfusion-free CPB in a neonatal piglet model. Employing the downsized circuit as well as avoiding blood transfusion resulted in inhibition of coagulation and inflammatory cascades, thereby alleviating cardiac and pulmonary damages. We believe that the TinyPump-assisted venous drainage technique has the potential to facilitate the miniaturization of the CPB circuit safely and to improve the outcomes of neonates undergoing CPB for the correction of congenital heart defects.

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Double-barrel Damus–Kaye–Stansel operation is better than end-to-side Damus–Kaye–Stansel operation for preserving the pulmonary valve function: The importance of preserving the shape of the pulmonary sinus

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Objective: The Damus–Kaye–Stansel operation sometimes results in deteriorating semilunar valve insufficiency. We verified the semilunar valve function after the Damus–Kaye–Stansel operation and compared the end-to-side Damus–Kaye–Stansel with the double-barrel Damus–Kaye–Stansel.

Methods: Forty-seven patients who underwent the Damus–Kaye–Stansel operation between June 1993 and August 2008 were retrospectively reviewed. Any patient who underwent a Norwood-type operation was excluded. The median age at operation was 19 months (range, 0–276 months). Forty-five patients were Fontan candidates. Thirty-nine patients underwent pulmonary artery banding before the Damus–Kaye–Stansel operation. Twenty-two patients had undergone an arch repair previously. The semilunar valve function was evaluated by echocardiography.

Results: Thirteen patients underwent the end-to-side Damus–Kaye–Stansel operation, and 34 patients underwent the double-barrel Damus–Kaye–Stansel operation. The mean follow-up period was 71 ± 50 months (range, 1–188 months). Although there were 4 deaths, no death was related to the Damus–Kaye–Stansel procedure. Two of the patients with early death could not undergo a postoperative evaluation of the semilunar valves. The semilunar valve regurgitation mildly deteriorated in 7 patients (pulmonary regurgitation in 5 patients and aortic regurgitation in 2 patients). Pulmonary regurgitation deteriorated from none to mild in 1 patient, none to trivial in 2 patients, and trivial to mild in 2 patients. Both deteriorations in aortic regurgitation ranged from none to trivial. Semilunar valve regurgitation did not affect patients' circulatory condition. The end-to-side Damus–Kaye–Stansel operation more frequently caused a deterioration in pulmonary regurgitation than the double-barrel Damus–Kaye–Stansel operation (4/11 vs 1/34, $P = .001$). No surgical intervention for a systemic ventricular outflow obstruction was observed in the follow-up period.

Conclusions: The double-barrel Damus–Kaye–Stansel operation was found to be superior to the end-to-side Damus–Kaye–Stansel operation for the prevention of postoperative pulmonary regurgitation. (J Thorac Cardiovasc Surg 2011;141:193-9)

The Damus–Kaye–Stansel (DKS) operation contributes to an improved clinical outcome of the Fontan operation in patients with systemic ventricular outflow obstruction (SVOO). The DKS operation is aggressively performed for Fontan candidates who have an SVOO or the anatomic potential for SVOO, such as a double-inlet ventricle with transposition of the great arteries and tricuspid atresia with transposition of the great arteries.

Damus,[1] Kaye,[2] and Stansel[3] originally described an end-to-side anastomosis between the main pulmonary artery and the ascending aorta (end-to-side DKS) to achieve a biventricular repair in patients with dextro-transposition of the great arteries. Waldman and colleagues[4] reported a technical modification of the DKS operation in which the ascending aorta was sutured to a new bivalve single aorta, known as the "double-barrel method" (double-barrel DKS). The double-barrel DKS is the first choice for the DKS operation in the Okayama University Hospital because it is simpler and technically easier than the end-to-side DKS and no patch material is needed. The influence of the DKS operation on the semilunar valves, especially for the pulmonary valve, remains controversial. Past studies have observed mild or moderate postoperative pulmonary regurgitation (PR) in patients who underwent end-to-side DKS.[5-7] However, there have been few reports describing the pulmonary valve function after double-barrel DKS and which DKS operation is superior for pulmonary valve function has not been

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Abbreviations and Acronyms
AR = aortic regurgitation
DKS = Damus–Kaye–Stansel
PAB = pulmonary artery banding
PR = pulmonary regurgitation
SVOO = systemic ventricular outflow obstruction
TCPC = total cavopulmonary connection

elucidated. The purpose of this study was to investigate the mid- to long-term outcome of patients who underwent the DKS operation and describe the effect on the semilunar valve function.

PATIENTS AND METHODS

Study Subjects

The medical and surgical records of patients with congenital heart disease who underwent the DKS operation in Okayama University Hospital between June 1993 and August 2008 were retrospectively reviewed. Any patients who underwent a Norwood-type operation were excluded.

Data Collection and Measurements

This study was approved by the institutional research ethics board at the Okayama University Hospital, and patient consent was waived. The data collected from medical record review included patient demographics, cardiac diagnosis, clinical condition, previous procedures, operative information, and postoperative and follow-up clinical status, including catheter and echocardiographic data. A significant SVOO was determined to be a systemic ventricular outflow tract Doppler flow velocity of greater than 2.0 ms of systemic ventricular outflow as confirmed by preoperative echocardiography or more than 5 mm Hg of pressure gradient between the systemic ventricle and the ascending aorta verified by preoperative catheter examination. The semilunar valve function was evaluated using echocardiography by independent cardiac pediatricians who were all trained at Okayama University Hospital. However, the preoperative and postoperative pulmonary valve functions were not always evaluated by a pediatrician. The semilunar valve regurgitation was graded as none, trivial, mild, moderate, or severe. Thereafter, a "deterioration of the semilunar valve function" was diagnosed when the postoperative semilunar valve regurgitation was worse than the preoperative one.

Selection of the Method of Damus–Kaye–Stansel Operation

The double-barrel and end-to-side DKS operations were performed equally until 2001; however, the double-barrel DKS has been the first choice of treatment since 2002. The end-to-side DKS has been performed only in patients with an ascending aorta of insufficient diameter for the double-barrel DKS. An almost equal diameter of the ascending aorta to the that of the pulmonary trunk was considered to be a good indication for the double-barrel DKS. All DKS operations were performed by only 1 surgeon.

Surgical Procedures

The DKS operation was performed using a conventional continuous flow cardiopulmonary bypass with mild to moderate hypothermia (24°C–34°C) or circulatory arrest under deep hypothermia. The DKS anastomosis was created using polypropylene running sutures. The DKS operation without any patch material was the first choice. Figure 1 shows the types of DKS operation that were used. All of the semilunar valves were examined at the time of operation.

Data Analysis

To determine the effect of the DKS operation on the semilunar valve, these patients were divided into 2 groups according to the type of the DKS operation (the end-to-side DKS group and the double-barrel DKS group), and these groups were then compared statistically. Binary data were analyzed using Pearson's chi-square test. The Student t test or Mann–Whitney U test was used for comparisons of continuous data as appropriate. A multiple logistic regression analysis was used to compare the postoperative incidence of deterioration in PR. Odds ratios and confidence intervals were calculated as appropriate. Data are expressed as the mean ± standard deviation or median and range as appropriate.

RESULTS

Patient Characteristics

Forty-seven patients with complex congenital heart disease underwent the DKS operation during the study period. The preoperative cardiac anatomic characteristics of these patients are summarized in Table 1. Forty-five patients were candidates for a Fontan operation, and 2 patients were candidates for a biventricular repair. The median age at the time of the operation was 19 months (range, 0–276 months), and the median body weight was 8.5 kg (range, 2.6–45 kg). Thirty-three patients had a bulboventricular foramen in the systemic ventricular outflow tract. Twenty-two patients had arch anomalies, which included coarctation of the aorta in 15 patients and interruption of the aortic arch in 7 patients. Thirty-nine patients had undergone pulmonary artery banding (PAB) previously, and the median duration from the PAB to the DKS operation was 18 months (range, 3–108 months). Twenty-nine patients had a significant SVOO. The average preoperative blood flow velocity across the systemic ventricular outflow tract was 1.91 ± 0.86 ms (range, 0.80–3.54 ms) with echocardiography. There was no preoperative instance of PR in 17 patients, whereas it was trivial in 29 patients and mild in 1 patient. Preoperative aortic regurgitation (AR) was not seen in 31 patients, was trivial in 15 patients, and was mild in 1 patient, as determined by echocardiography.

Surgical Data

The DKS operation was performed during a bidirectional Glenn procedure in 34 patients, before a bidirectional Glenn procedure in 4 patients, during a total cavopulmonary connection (TCPC) in 6 patients, during a TCPC takedown in 1 patient, and during a biventricular repair (repair of interruption of the aortic arch, closure of ventricular septal defect, and right ventricular outflow tract reconstruction) in 2 patients. Thirteen of the 47 patients underwent an end-to-side DKS, and an expanded polytetrafluoroethylene patch augmentation was used in 1 patient to prevent kinking of the anastomosis. Thirty-four patients underwent a double-barrel DKS with no prosthetic materials. Five of the 47 patients underwent circulatory arrest with deep hypothermia. The other associated procedures were the enlargement of an atrial septal defect in 12 patients, reconstruction of the

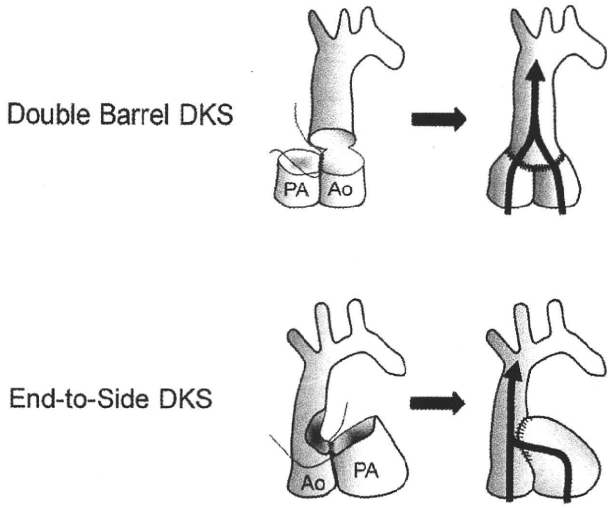

FIGURE 1. DKS types. When the double-barrel DKS is created, the posterior wall of the ascending aorta is uncut if possible to prevent bleeding after the anastomosis. The double-barrel DKS seems to have a smoother systemic ventricular outflow tract than the end-to-side DKS. *DKS*, Damus–Kaye–Stansel; *PA*, pulmonary artery; *Ao*, aorta.

pulmonary artery in 2 patients, resection of subaortic stenosis in 2 patients, a modified Blalock–Taussig shunt in 4 patients, tricuspid valve repair in 2 patients, and exchange of a pacemaker generator in 1 patient. The mean aortic cross-clamp time was 60 ± 23 minutes (range, 23–122 minutes), and the mean cardiopulmonary bypass time was 126 ± 60 minutes (range, 67–419 minutes). All of the semilunar valves were found to have a normal appearance.

Postoperative Outcomes

There were 2 early deaths. One of these patients was a 5-month-old female with tricuspid atresia and transposition of the great arteries who had previously undergone PAB. She underwent a semi-emergency bidirectional Glenn operation and the DKS operation because of heart failure with acidosis, severe hypoxia, and subaortic stenosis (2.0 ms by echocardiography). She had necrosis of the intestine and died 18 days after the operation. The other patient was a 52-month-old female with a double-inlet left ventricle (situs solitus, L-loop, L-transposition). Although she initially underwent a TCPC without a DKS operation, low-output syndrome occurred as the result of SVOO, which deteriorated after the TCPC. As a result, an emergency DKS operation and TCPC takedown were performed on the first postoperative day; however, extracorporeal membranous oxygenation support was required because hypoxia and low left ventricular function did not improve. The patient died of sepsis and multiorgan dysfunction. There were 2 late deaths, and the mean follow-up time of the 45 early survivors was 75 ± 49 months (range, 6–188 months). Both of the patients with late death underwent the DKS operation with a bidirectional Glenn operation and a subsequent Fontan completion. However, they died of mediastinitis and pneumonia after the Fontan completion. There were no deaths related to the DKS operation. There were no re-do DKS operations or surgical interventions for SVOO. No obstruction of the left pulmonary artery caused by compression of the bulbous pulmonary trunk after DKS was observed. Forty-two of the 45 Fontan candidates underwent a Fontan completion. Postoperative PR was not observed in 13 patients, was trivial in 28 patients, and was mild in 4 patients. Postoperative AR was not seen in 27 patients, was trivial in 17 patients, and was mild in 1 patient. AR and PR were not evaluated postoperatively in the 2 patients who died early. A mild deterioration

TABLE 1. Summary of cardiac anatomic diagnoses

Functional single ventricle (n = 45)	
SLV	15
SLV (SLL)	7
SLV (SDD)	5
Others	3
TA + TGA	3
SRV	4
SRV (SDL)	1
Others	2
MA or severe MS with hypoplastic LV	5
MA + DORV	4
MS + DORV	1
DORV	13
DORV (SDN) + straddling MV	1
DORV (SDN) + CAVC + Swiss cheese-like muscular VSD	1
DORV (SDN) + CAVC + hypoplastic LV	1
DORV (SDN) + inlet VSD	1
DORV (SDN) + multiple VSDs	1
DORV (SDD) + CAVC	1
DORV (SDD) + CCH	1
DORV (SDD) + straddling MV	1
DORV (SLD) + hypoplastic LV	1
DORV (SLD) + PS	1
DORV (SLD) + CCH + straddling of MV	1
DORV (IDL) + CAVC	1
TBH + straddling of MV	1
TGA	4
d-TGA + VSD + straddling of MV	2
d-TGA + Swiss cheese-like muscular VSD	1
l-TGA + VSD + PS	1
AS + MS + VSD	1
Two ventricular heart (n = 2)	
IAA + VSD	1
IAA + DORV	1

AVSD, Atrioventricular septal defect; *AS*, aortic stenosis; *CCH*, crisscross heart; *DORV*, double outlet right ventricle; *IAA*, interruption of the aortic arch; *IDL*, situs inversus, D-loop, L-transposition; *LV*, left ventricle; *MA*, mitral atresia; *MS*, mitral stenosis; *MV*, mitral valve; *PS*, pulmonary stenosis; *SDD*, situs solitus, D-loop, D-transposition; *SDL*, situs solitus, D-loop, L-transposition; *SDN*, situs solitus, D-loop, Normal position; *SLD*, situs solitus, L-loop, D-transposition; *SLL*, situs solitus, L-loop, L-transposition; *SLV*, single left ventricle; *SRV*, single right ventricle; *TA*, tricuspid atresia; *TBH*, Taussig–Bing heart; *TGA*, transposition of the great arteries; *VSD*, ventricular septal defect.

CHD

TABLE 2. Comparison of the two techniques for the Damus–Kaye–Stansel anastomosis

	End-to-side DKS (n = 13)		Double-barrel DKS (n = 34)		Univariate		Multivariate		
					P	OR	*P*	OR	CI
Age at DKS (mo)	12 (0–112)		22 (1–276)		.644				
Period	June 1993 to January 2008		March 1996 to August 2008						
Previous PAB	10/13		29/34		.495				
Duration from the previous PAB (mo)	13 (3–51)		21 (3–108)		.422				
Significant SVOO	10/13		19/34		.184				
Arch anomaly	8/13 (CoA 5, IAA 3)		14/34 (CoA 10, IAA 4)		.211				
Preoperative AR	none:	9	none:	22	.908				
	trivial:	3	trivial:	12					
	mild:	1							
Preoperative PR	none:	7	none:	10	.110				
	trivial:	6	trivial:	23					
			mild:	1					
Anomaly of PV	0		0						
CPBT (min)	144 ± 93 (75–419)		118 ± 42 (67–239)		.348				
ACCT (min)	60 ± 21 (27–104)		60 ± 25 (23–122)		.886				
Follow-up (mo)	75 ± 56 (0.6–188)		70 ± 48 (6–161)		.740				
Postoperative AR	none:	7	none:	20	.969				
	trivial:	3	trivial:	14					
	mild:	1							
Postoperative PR	none:	4	none:	9	.687				
	trivial:	4	trivial:	24					
	mild:	3	mild:	1					
Deterioration of AR	0/11		2/34		.048				
			none → trivial:	2					
Deterioration of PR	4/11		1/34		.001	0.073	.023	0.068	0.007-0.688
	none → trivial:	1	none → trivial:	1					
	none → mild:	2							
	trivial → mild:	1							

DKS, Damus–Kaye–Stansel; *ACCT*, aortic crossclamp time; *AR*, aortic regurgitation; *CI*, confidence interval; *CoA*, coarctation of the aorta; *CPBT*, cardiopulmonary bypass time, IAA; interruption of the aortic arch, *OR*, odds ratio; *PAB*, pulmonary artery banding; *PR*, pulmonary regurgitation; *PV*, pulmonary valve; *SVOO*, systemic ventricular outflow obstruction.

in PR was observed in 5 patients. Four of the 5 patients underwent PAB before the DKS operation. However, PAB was not found to be a significant risk factor for PR deterioration ($P = .799$). A mild deterioration in AR was found in 2 patients.

End-to-Side Damus–Kaye–Stansel Versus Double-Barrel Damus–Kaye–Stansel

Table 2 shows a comparison of the characteristics between the patients who underwent an end-to-side DKS and the patients who underwent a double-barrel DKS. There was no significant difference in age at the DKS operation, the number of patients who had undergone a PAB before the DKS operation, the duration from the PAB to the DKS operation, the number of patients who had significant SVOO or arch anomalies, aortic crossclamp time, cardiopulmonary bypass time, preoperative AR, or preoperative PR. Postoperative deterioration in AR, which ranged from none to trivial, occurred in 2 patients in the double-barrel DKS group and was more frequent in the double-barrel DKS group ($P = .048$). Deterioration in PR was found in 4 patients in the end-to-side DKS group and in 1 patient in the double-barrel DKS group ($P = .001$). The degree of PR deterioration ranged from none to mild in 1 patient, none to trivial in 2 patients, and trivial to mild in 2 patients. All instances of a deterioration of the semilunar valve regurgitations were observed at the first echocardiographic examination after the operation, and no further deterioration was observed in the late follow-up period. A multiple logistic regression analysis showed the double-barrel DKS to be superior to the end-to-side DKS for preventing the deterioration of postoperative PR (odds ratio 0.068; confidence interval, 0.007–0.688; $P = .023$).

DISCUSSION

Although some reports have described the outcome of the pulmonary valve subjected to systemic circulation after an arterial switch operation or a Ross operation, few studies have attempted to describe the pulmonary valve function after the DKS operation. However, some reported the development of mild or moderate insufficiency of the pulmonary

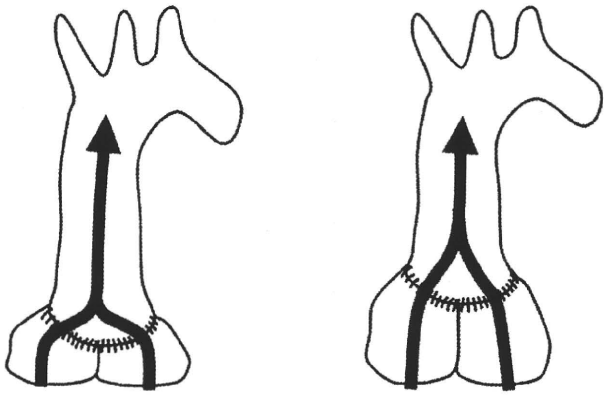

FIGURE 2. The effect of the length of the main pulmonary artery. The length of the main pulmonary artery is important to make a smooth systemic ventricular outflow tract.

valve function after the DKS operation. These reports mainly included patients undergoing the end-to-side DKS, and no reports have elucidated the pulmonary valve function after the double-barrel DKS. The incidence of deteriorated pulmonary valve function after the end-to-side DKS ranged from 4% to 55%.[8-11] Thirty-one percent of the patients who underwent the end-to-side DKS in the current series had mildly deteriorated pulmonary valve insufficiency after the DKS operation. On the other hand, the incidence of deteriorated pulmonary valve insufficiency in patients with the double-barrel DKS was 2.9%. The double-barrel DKS seems to be superior to the end-to-side DKS for pulmonary valve function. All instances of PR deterioration were observed during the early postoperative period. Therefore, the main cause of the impaired pulmonary valve function was thought to be a deformation of the pulmonary valve resulting from the DKS operation. The double-barrel DKS has been regarded as the first choice of treatment since 2002. The double-barrel DKS has a more smooth blood flow of the left ventricular outflow tract than the end-to-side DKS, thus inducing less energy loss and stress on the pulmonary valve, and there seems to be less potential for pulmonary valve deformation (Figure 1). Deterioration of the pulmonary valve function was more common in the patients with the end-to-side DKS in this study than with the double-barrel DKS. Although this change in the pulmonary valve function was mild, the pulmonary valve function should be carefully followed because the long-term results are unknown. On the other hand, the deterioration of AR was more frequent in the double-barrel DKS group than in the end-to-side DKS group probably because the end-to-side DKS achieves a smoother blood flow of the ascending aorta and less tension of the aortic sinus than the double-barrel DKS (Figure 1). However, the degree of AR and PR deterioration was small and not thought to affect patients' circulatory conditions. There was no postoperative PR that was more than mild and no postoperative AR that was more than trivial. These results indicate the superiority of our careful consideration for the management strategy of semilunar valve functions in DKS candidates.

No patch materials were used for the DKS operation except for 1 patient who underwent the end-to-side DKS. The advantage of the double-barrel DKS is that a high-quality DKS anastomosis can be created to establish smooth systemic blood flow with no deformation of the pulmonary sinus without using patch materials. The double-barrel DKS is thought to be meaningful for the creation of the DKS anastomosis because homograft material is still not allowed for use in Japan. The length of the main pulmonary artery is important to create a smooth systemic ventricular outflow tract in the DKS operation (Figure 2). Therefore, PAB should be performed at a position as far from the pulmonary valve as possible to obtain a sufficient length of the main pulmonary artery for the DKS operation and avoid any deformation or degeneration of the pulmonary valve. The PAB is usually performed via a median sternotomy, not via a thoracotomy, if the patient is thought to require the DKS operation afterward because accurate positioning of the PAB is often more difficult via a thoracotomy than via a median sternotomy. The preservation of good pulmonary valve function and a sufficient length of the pulmonary trunk are important factors for achieving an excellent outcome when performing the DKS operation.

The double-barrel DKS cannot be performed in a patient who has a narrow ascending aorta. In this case, an end-to-side DKS or a Norwood-type aortopulmonary anastomosis should be selected. The Norwood-type aortopulmonary anastomosis has been the first choice for such patients since 2002. Therefore, the end-to-side DKS has been performed only in patients with a long pulmonary trunk. It is important to avoid a deformation of the pulmonary valve when performing an end-to-side DKS in a patient with an insufficiently long pulmonary trunk. Patch material may be needed to maintain a smooth and optimal shape of pulmonary sinus for the end-to-side DKS (Figure 3).

If such patients have either pulmonary stenosis or PR that is deemed to be more than moderate, a DKS cannot be performed even if a patient requires it. However, in our experience, when patients have a pulmonary stenosis, they usually have a large bulboventricular foramen and subaortic space. Therefore, the number of patients who underwent SVOO release, except for DKS, in the Okayama University Hospital was small. One patient underwent a subaortic muscle resection before the Fontan operation. In addition, 4 patients underwent subaortic muscle resection or subaortic ridge resection at the Fontan operation. There were no Fontan candidates who underwent an enlargement of the bulboventricular foramen or a palliative arterial switch in the Okayama University Hospital.

Although there were 4 deaths in this study, no death was related to the DKS operation itself. On the other hand, 2 patients with SVOO died during the early postoperative period.

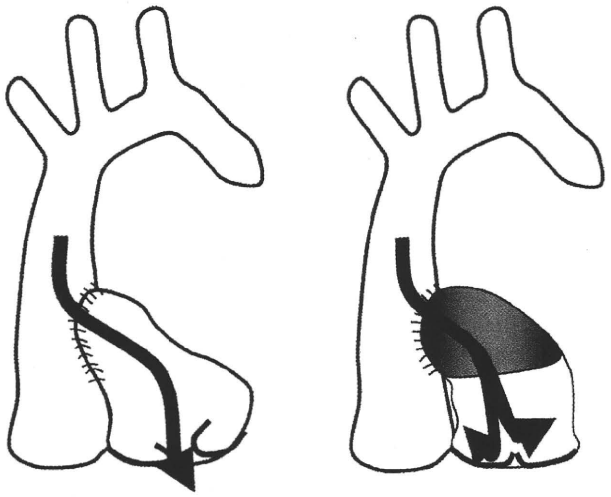

FIGURE 3. End-to-side DKS with a patch material. Some kind of a patch material may be needed to create a smooth and optimal shape for the end-to-side DKS.

One early death was due to postoperative necrosis of the intestine. This patient had mild subaortic stenosis, heart failure, acidosis, and severe hypoxia preoperatively. Subaortic stenosis may have been underestimated because of the low output state; therefore, it was difficult to determine how the degree the subaortic stenosis contributed to the heart failure. This patient's condition did not improve, and acidosis persisted even after the operation. The preoperative SVOO might have contributed to the poor preoperative condition of this patient and thereby affected the results; therefore, the DKS should have been performed earlier in this case. Another early death occurred because of low output syndrome caused by SVOO immediately after a TCPC without a DKS operation. This patient could have survived if the DKS operation had been performed concomitantly with the TCPC initially. The DKS operation should be performed before or during the Fontan operation in patients with a potential for systemic ventricular outflow tract obstruction, such as tricuspid atresia with transposition of the great arteries and double-inlet left ventricle with transposition of the great arteries[12] because SVOO is an independent risk factor for an early death after a Fontan operation and sometimes progresses significantly after a Fontan operation.[13]

Study Limitations

There are some limitations to this study. First, this study was conducted retrospectively and the selection of the DKS method was not randomized. Second, the number of patients was not significantly large and only 5 patients exhibited a deteriorated postoperative pulmonary valve function. Third, the preoperative and postoperative evaluations of pulmonary valve functions were performed using only echocardiography. The exact evaluation of pulmonary valve function is sometimes difficult and may depend on the skill of the echocardiographer. However, the echocardiographers (independent cardiac pediatrician) exchanged the patients' echocardiographic information with each other. They took special care to obtain consistent findings of echocardiography. In addition, all of the deteriorations of the pulmonary valve functions were observed during the first echocardiographic examination after the operation. In most of the cases, an echocardiographer checked the preoperative and early postoperative echocardiographic examinations. Therefore, there was little possibility of an incorrect evaluation of the pulmonary valve function. Finally, the deteriorations of the pulmonary valve functions in this study were considered to be minimal. Therefore, whether these deteriorated pulmonary valve functions might actually affect the long-term outcomes should be verified by further investigations. However, the fact that only a minimal deterioration of the pulmonary valve function was observed is important because it indicates the efficacy of the protocol for preserving the aortic and pulmonary sinuses. PR after a DKS operation should not become a problem even after long-term follow-up if the pulmonary valve is normal before the DKS operation.

CONCLUSIONS

The mid- to long-term clinical results of the DKS operation were excellent with a high rate of Fontan completion and low rate of postoperative deterioration of the pulmonary valve insufficiency. In addition, the double-barrel DKS is considered to be superior to the end-to-side DKS to preserve the postoperative pulmonary valve function when the DKS anastomosis is created without patch material. On the other hand, the double-barrel DKS may cause a deterioration of AR. Both cases of deteriorated semilunar valve regurgitations were thought to be due to the deformity of the pulmonary or aortic sinus caused by the DKS operation. Therefore, special care should be paid to prevent these deformities. The results of this study indicate that the pulmonary valve will be durable against the systemic circulation even in the long-term follow-up if the aortopulmonary anastomosis is appropriately created.

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Growth of the lateral tunnel in patients who underwent a total cavopulmonary connection at less than 5 years of age☆

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Abstract

Objective: A lateral tunnel-total cavopulmonary connection (LT-TCPC) using a right atrial (RA) free wall is the first choice of treatment for patients with a small body weight in this institute. Whether the growth of the LT is appropriate or not according to the growth of the body remains controversial. In addition, the optimal initial diameter of an LT is unknown. The purpose of this study was to verify the growth of the LT. **Methods:** Ninety-one patients of a total of 267 TCPC cases underwent an LT-TCPC at less than 5 years of age in this institute between March 1991 and June 2008. The data on 47 of the 91 patients, which were available to investigate the LT growth, were retrospectively reviewed. The mean age at LT-TCPC was 37 ± 11 months (16–57 months). The mean body weight at TCPC was 12.4 ± 2.4 kg (7.6–20.0 kg). The initial LT diameter was determined with Hegar's sizer of the estimated half-pulmonary arterial (PA) diameter, which is a diameter that results in half of the dimension of the normal pulmonary valve. The measured maximum LT diameter (mm) divided by the estimated half-PA diameter (mm) was considered as the LT index. The size of the LT was evaluated using either echocardiography or angiography. **Results:** The mean follow-up period was 7.4 ± 3.5 years (1.6–13.5 years). The LT index was initially 2.0 ± 0.7 (1.3–4.5), 2.0 ± 0.4 (1.3–3.2) at 1 year after operation, 2.1 ± 0.5 (1.5–3.2) at 5 years after operation, 1.9 ± 0.4 (1.5–2.8) at 10 years after operation and 2.1 ± 0.5 (1.6–2.5) at 13 years after operation, respectively. **Conclusions:** LT growth suitable for the body growth can be expected. Although there was some variation in the initial LT diameter, the LT index tended to converge at 2.0 with growth.

Keywords: Fontan procedure; Organ size; Child; Supraventricular tachycardia; Congenital heart defect

1. Introduction

Since Fontan and Baudet first described their procedure for the correction of tricuspid atresia in 1971, the principles of the Fontan procedure have been applied to all forms of functional univentricular heart defects [1]. After several modifications of this operation, the total cavopulmonary connection (TCPC), which was first reported by de Leval et al. [2], has become the standard method for the Fontan procedure because it provides better venous haemodynamics [3] and is less arrhythmogenic [4] than the other Fontan modifications. In the original TCPC method, a lateral tunnel (LT) was created using a halved intra-atrial polytetrafluoroethylene (PTFE) graft; however, some modifications have been implemented in this institute. Initially, an LT is created only using an autologous atrial wall as previously reported [5]. Second, a standardised method for determining the initial size of an LT is used to prevent postoperative abnormal dilatation of the LT, which will cause an intratunnel thrombus and will become arrhythmogenic. The autologous intra-atrial tunnel has a potential for growth, which is a very important feature, especially in patients with low body weight; this is because an extracardiac conduit TCPC (EC-TCPC) is not often suitable in such patients due to the limitation of the available extracardiac graft size. However, no evidence is available to determine the appropriate growth of an LT created with an autologous atrial wall that is obtained in the midterm to long-term follow-up. The purpose of this study was to describe the actual growth of the LT created with an autologous atrial wall. This study was conducted in patients less than 5 years of age because the Fontan procedure is usually completed when a patient is less than 5 years of age and also because the growth of the LT is especially important in this patient population.

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2. Materials and methods

2.1. Patients

The medical and surgical records of patients with congenital heart disease who underwent TCPC in Okayama University Hospital between March 1991 and June 2008 were retrospectively reviewed. A total of 267 patients underwent the Fontan procedure in this study period, and a lateral tunnel TCPC (LT-TCPC) was used in 117 of the 267 patients. Ninety-one of the 117 patients were less than 5 years of age. The data of the LT growth in midterm and long-term period were available from 47 of the 91 patients, and these data were evaluated.

2.2. Surgical procedures

The LT-TCPC was performed using a conventional continuous-flow cardiopulmonary bypass and mild-to-moderate hypothermia. An LT was created with an autologous atrial wall using polypropylene running sutures. First, a longitudinal atriotomy was made, which was similar to the Senning procedure (Fig. 1(a)). This incision was carefully separated from the sulcus terminalis, and then the lateral flap of the anterior atrial wall was sutured down onto the atrial septum posterior to the atrial septal defect using Hegar's dilator as a guide (Fig. 1(b)). The LT diameter was determined using Hegar's dilator of the estimated half-pulmonary arterial diameter, which is a diameter that results in half of the dimension of the normal pulmonary valve [6]. The terminal crest was carefully separated from the suture line. The orifice of the coronary sinus was placed in the atrial side of the heart. A small PTFE patch with a fenestration of 2.7–4.0-mm diameter was placed in the LT if a fenestration was required (Fig. 1(c)). After creating the LT, the atrium was closed by suturing the medial flap of the anterior atrial wall and anterior portion of the LT (Fig. 1(d)).

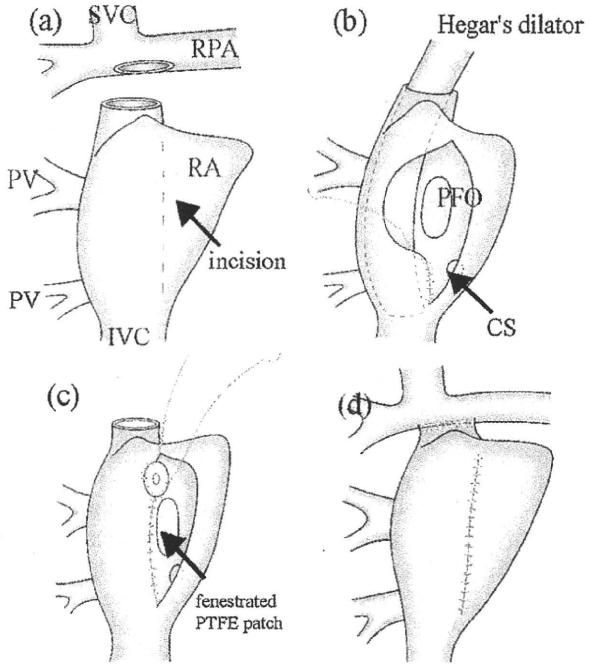

Fig. 1. Creation of the lateral tunnel. (a) A longitudinal atriotomy which was carefully separated from the sulcus terminalis was made. (b) The lateral flap of the anterior atrial wall was sutured to the posterior to the atrial septum using Hegar's dilator for guidance. The terminal crest was carefully separated from the suture line. The orifice of the coronary sinus was placed in the atrial side of the heart. (c) If a fenestration was required, a small PTFE patch with a fenestration of 2.7–4.0 mm diameter was placed in the LT. (d) After creating the LT, the atrium was closed by suturing the medial flap of the anterior atrial wall and anterior portion of the lateral tunnel. CS, coronary sinus; IVC, inferior vena cava; PFO, patent foramen ovale; PTFE, polytetrafluoroethylene; PVO, pulmonary vein; RA, right atrium; RPA, right pulmonary artery; SVC, superior vena cava.

2.3. Data collection and measurements

This study was approved by the Institutional Research Ethics Board at the Okayama University Hospital, and patient consent was waived. The data collected from the medical record review included patient demographics, cardiac diagnosis, clinical condition, surgical data and postoperative and follow-up clinical status, and contained catheter and echocardiographic data. A value, which was calculated from a measured maximum LT diameter (mm) divided by the estimated half-pulmonary arterial diameter (mm), was considered to be the LT index. The size of the LT was evaluated with echocardiography or angiography; then, the maximum value of the LT diameter was used for the evaluation. Continuous data were expressed with these mean values and the standard deviations or these median values and the range as appropriate.

3. Results

3.1. Patient characteristics

In all, there were 26 females and 21 males. The chief diagnoses of these patients were hypoplastic left heart syndrome in 11 patients, tricuspid atresia in nine patients, single left ventricle except for tricuspid atresia in six patients, mitral atresia in three patients, single right ventricle except for mitral atresia in four patients, Ebstein's anomaly in two patients and others in 12 patients. One patient demonstrated an asplenia. The mean age of these patients was 37 ± 11 months (range, 16–57 months). The mean body weight was 12.4 ± 2.4 kg (range, 7.6–20.0 kg). A preoperative catheter examination was performed in all of these patients and revealed the mean SaO_2 to be $82 \pm 6\%$ (range, 66–97%), while the average mean pulmonary arterial pressure was 11.2 ± 2.9 mmHg (range, 5.0–18.0 mmHg); the median pulmonary arterial index (Nakata index) was 248 (140–550), the mean pulmonary arterial resistance was 1.74 ± 0.58 Wood unit m^2 (range, 0.63–3.08 Wood unit m^2) and the mean systemic ventricular ejection fraction was $64 \pm 11\%$ (range, 41–86%). The mean estimated half-pulmonary arterial diameter at the operation was 8.5 ± 1.0 mm (range, 6.0–11.0 mm). There was no preoperative atrial tachyarrhythmia in these patients. The median cardiopulmonary bypass time was 105 min (range, 53–223 min), and the median aortic cross-clamp time was

64 min (range, 15–142 min). A fenestration was created in 11 patients.

3.2. Postoperative outcomes

All patients survived the operation. The median follow-up time was 7.4 years (range, 1.6–13.5 years). There was one late death due to sepsis of unknown cause. No patient experienced EC-TCPC conversion. Early atrial tachyarrhythmia occurred in three patients (6.9%), and it resolved during the hospital stay in two of these three patients. Late atrial tachyarrhythmia was observed in three patients (6.9%). One of these three patients had asplenia. One patient with asplenia (2.3%) underwent pacemaker implantation due to sick sinus syndrome. Three patients (6.9%) experienced protein-losing enteropathy, and one patient (2.3%) experienced plastic bronchitis. Four patients (9.3%) experienced surgical re-intervention in the late postoperative period: thrombectomy in the LT and a plasty of the left pulmonary artery in one patient, plasties of the ascending aorta and the left pulmonary artery in one patient, a fenestration and a plasty of the left pulmonary artery in one patient and a fenestration in one patient. A postoperative catheter examination was performed in 33 patients, which revealed that the mean pulmonary arterial pressure was 10.0 ± 2.2 mmHg (range, 5.0–17.0 mmHg), the end-diastolic systemic ventricular pressure was 5.3 ± 2.4 mmHg (range, 1–11 mmHg) and the ejection fraction of the systemic ventricle was 67 ± 9% (range, 44–85%). Eighteen of these 33 patients demonstrated a slight degree of turbulence of the venous flow in the LT, which always occurred on the most inferior side of the LT. However, 31 of the 33 patients had no pressure gradient between the inferior vena cava and the pulmonary artery. The remaining two patients demonstrated a slight pressure gradient of less than 2 mmHg between the inferior vena cava and the pulmonary artery. One patient also had a thrombus in the LT.

3.3. Growth of the LT

Fig. 2 shows the growth of the patients' body weight and changes in the LT index. The LT tunnel diameter was measured in 30 patients immediately after the operation, in 33 at 1 year after the operation, in 26 at 3 years after the operation, in 23 at 5 years after the operation, in 11 at 7 years after the operation, in 12 at 10 years after the operation and in three at 13 years after the operation. The patients' body weight was initially 12.4 ± 2.4 kg (range, 7.6–20.0 kg), 14.5 ± 2.5 kg (range, 9.9–18.5 kg) at 1 year after operation, 17.5 ± 3.0 kg (range, 11.6–23.0 kg) at 3 years after operation, 22.8 ± 7.2 kg (range, 13.8–50.0 kg) at 5 years after operation, 26.0 ± 6.7 kg (range, 15.6–37.6 kg) at 7 years after operation, 35.7 ± 13.8 kg (range, 24.0–68.0 kg) at 10 years after operation and 47.0 ± 7.6 kg (range, 39.0–54.0 kg) at 13 years after operation, respectively. The LT index was initially 2.0 ± 0.7 (range, 1.3–4.5), 2.0 ± 0.4 (range, 1.3–3.2) at 1 year after operation, 2.0 ± 0.5 (range, 1.2–3.4) at 3 years after operation, 2.1 ± 0.5 (range, 1.5–3.2) at 5 years after operation, 1.8 ± 0.4 (range, 1.4–3.1) at 7 years after operation, 1.9 ± 0.4 (range, 1.5–2.8) at 10 years after operation and 2.1 ± 0.5 (range, 1.6–2.5) at 13 years after operation, respectively. The actual LT diameter was initially 17.0 ± 4.5 mm (range, 10.0–30.0 mm), 18.0 ± 3.8 mm (range, 11.5–27.1 mm) at 1 year after operation, 19.9 ± 5.0 mm (range, 12.6–32.0 mm) at 3 years after operation, 22.8 ± 5.7 mm (range, 13.9–36.5 mm) at 5 years after operation, 21.5 ± 2.9 mm (range, 18.7–29.4 mm) at 7 years after operation, 24.5 ± 5.6 mm (range, 17.7–36.0 mm) at 10 years after operation and 29.8 ± 6.3 mm (range, 23.0–35.4) at 13 years after operation, respectively. In addition, the actual changes of the LT index in each patient are shown in Fig. 3. There was an obvious tendency for the LT index to converge to around 2.0. The initial LT index was more than 3.0 in three patients; however, these LT indexes tended to decrease. Therefore, no abnormal dilation was observed even in these three patients. On the other hand, no restriction of the LT was observed even in patients with a relatively small initial LT index.

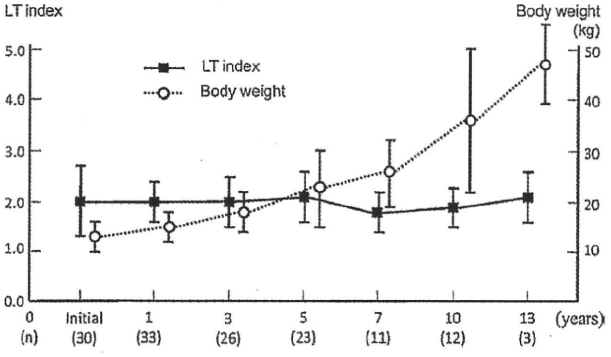

Fig. 2. Relationship between the growth of the lateral tunnel and the growth of the patient's body weight. The LT index was quite constant throughout the follow-up period despite of the body growth.

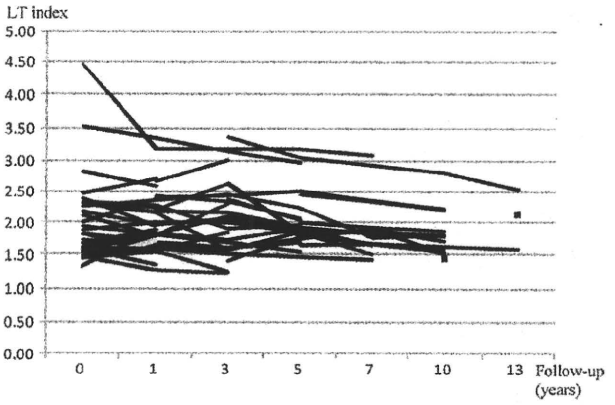

Fig. 3. Actual changes of the lateral tunnel index in each patient. A larger LT index tended to become smaller and a smaller LT index was apt to become a little bit larger or stay unchanged.

4. Discussion

The method applied for establishing an LT is different from the original method described by de Level et al. at some points. First, they used a large interior PTFE patch to create an LT; however, in the current series, the LT was created only

with the autologous atrial wall as reported previously [5]. A very small fenestrated PTFE patch is applied if a fenestration was required (Fig. 1(c)). Second, a Hegar's dilator of the normal estimated half-pulmonary arterial size is used as a guide to create an LT. There has been no standardised method for creating an LT so far. Therefore, it has depended on the surgeon's experience and judgement. The current method allows even an inexperienced surgeon to create an LT with relatively constant diameter and with smooth streamline. Although 18 of the 33 patients, who underwent postoperative catheter examinations, demonstrated a slight degree of turbulence of the venous blood stream, which always occurred on the most inferior site of the LT probably because of the size discrepancy between the inferior vena cava and the LT, no pressure gradient was observed in 31 of the 33 patients and no tendency of expansion of the LT was found in any of the 33 patients.

This is the first study, which reported the actual postoperative midterm to long-term growth of LT, which is created with the autologous atrial wall. Interestingly, the average of the LT index did not change throughout the follow-up period. In fact, there are some variations in the initial LT index. The LT indices ranged from 1.3 to 4.5 immediately after the operation. However, a larger LT index tended to become smaller and a smaller LT index was apt to become a little bit larger or stay unchanged. As a result, the LT index showed an obvious tendency to converge to around 2.0. The appropriate growth of the LT can be expected in the midterm to long-term follow-up if the patient maintains a good Fontan circulation. An extracardiac LT with pedicled pericardium may become an alternative procedure of LT-TCPC. Some authors have reported that an LT created with pedicled pericardium can grow while also preserving the tubular morphology of the LT and maintaining good haemodynamics [7,8]. However, there has so far been no report regarding the long-term outcome of LT created with a pedicled pericardium and which describes its growth in detail.

The incidences of the early and late atrial tachyarrhythmias in this study were both 6.9% with mean follow-up period of 7.3 years. The incidence of early and late tachyarrhythmia was 9.9% and 8.8%, respectively, among all of the 91 patients who underwent LT-TCPC before 5 years of age at this institute (unpublished data). The incidence of tachyarrhythmias may be slightly underestimated because neither a Holter electrocardiogram (ECG) nor an exercise ECG is conducted as a routine follow-up of arrhythmia in this institute. However, these incidences of atrial tachyarrhythmias seem to be lower than those of other reports [9–12]. The relatively restricted initial LT diameter in this study may contribute to the low incidence of the postoperative atrial tachyarrhythmia. In addition, extreme care is applied with regard to the suture line while creating an LT. First, the use of sutures carefully avoided the terminal crest because anchoring the LT to the terminal crest promotes the development of atrial flutter [13]. Second, there were few suture lines near or around the sinus node. After a right atriotomy, the lateral edge of the anterior atrial flap was sutured onto the atrial septum to create an LT. The upper limit of the suture line was relatively far from the sinus node, which also may contribute to prevent postoperative atrial tachyarrhythmias [14,15]. Third, the median longitudinal atriotomy, such as the Senning procedure, was performed and was kept far away from the sulcus terminalis. These methods prevented injuries to the longitudinal atrial conduction [13,16]. These modifications may have contributed to the low incidence of the atrial tachyarrhythmias.

Only one patient had an early thrombo-embolic event and no late thrombo-embolic event was observed in this study. One patient experienced a right atrial thrombus 2 weeks after the LT-TCPC and underwent a right atrial thrombectomy. The incidence of thrombo-embolic event was 2.2%, among all 91 patients who underwent LT-TCPC before 5 years of age at this institute (unpublished data). Although the use of anticoagulation for patients who undergo a TCPC has been controversial, warfarin has been routinely administered for all of the patients who underwent a TCPC. However, if a patient has proven to maintain an excellent Fontan circulation based on a postoperative catheter examination, which is usually performed 1 year after operation, warfarin can be converted to aspirin or ceased if required.

There was a concern that an EC-TCPC may be thrombogenic because of the use of artificial graft in the venous circulation; however, no study has found that an EC-TCPC was more thrombophilic than an LT-TCPC in midterm to long-term follow-ups. The risk of thrombo-embolism is more closely related to the suboptimal haemodynamics or an underlying coagulopathy than the type of Fontan procedure itself [17,18]. In addition, Lardo et al. revealed that an EC-TCPC had superior venous haemodynamics in comparison to an LT-TCPC [19]. Therefore, although an LT-TCPC had been the first choice in this institute, an EC-TCPC is the first-line strategy at present. However, there are still some advantages in the use of an LT-TCPC. First, the TCPC can be completed even in the patients with small body size. If the patients have atrioventricular valve regurgitation, newly developing arteriopulmonary collateral arteries or pulmonary arteriovenous shunt, then the TCPC should be completed when the children are as young as possible to prevent deterioration of these conditions. A PTFE graft with a diameter of at least 16 mm was used for the EC-TCPC. In addition, the body sizes of the patient's parents should also be carefully considered when selecting the graft size because a 16- to 18-mm PTFE graft may be too small if the patient's body size becomes bigger than an average Japanese person in the future. In addition, there is some risk of pulmonary venous obstruction when an EC-TCPC is performed for a small child. Second, an LT-TCPC will be stronger against infection than an EC-TCPC. Patients with a past history of mediastinitis or other risk factors for infection may thus be good candidates for an LT-TCPC.

An important limitation of this study is that this study was based on retrospective non-randomised research. Therefore, the data collection of the LT growth was not integrated and the collected data had many deficits. However, as shown in Fig. 3, there was an obvious tendency to growth of the LT and the methods used for constructing the LT were quite consistent during the study period. Therefore, the results of this study and subsequent conclusions, which were obtained, are thought to be reliable.

In conclusion, an LT growth suitable for the body growth can be expected. Although there were some variations in the initial LT diameter, the LT index tended to converge at around 2.0 with growth.

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Appendix A. Conference discussion

Dr V. Tsang *(London, UK)*: I've got one question about methodology. You use a lateral tunnel index calculated from a maximum measurement of lateral tunnel diameter divided by the estimated half PA diameter, and this would be repeated several time points afterwards for follow-up.

I'm not a mathematician, but it seems to me you make two major assumptions here. You used normal estimated PA diameter in your formula, and you also expected normal PA growth after Fontan completion. As we know, this may not be necessarily the case. Can you comment on the validity of your formula?

Dr Fujii: Theoretically, if a patient has pulmonary branches with normal half-pulmonary arterial diameter, the pulmonary arteries must be capable of enough cardiac output. So we think the use of the normal half-pulmonary arterial diameter is very reasonable because patient can be all right without trouble.

Dr Tsang: I have a surgical question. The longitudinal right atriotomy was similar to the Senning procedure. The lateral aspect of your atrial wall was sutured down onto the atrial septum posterior to the ASD using a Hegar.

In the case of one-stage TCPC, there was a lot of atrial tissue for the tunnel. In the case of staged TCPC, there might not be a lot of atrial tissue for your right atrial lateral tunnel, especially in the case of staged Norwood with complete atrial septectomy.

Can you tell us how your technique evolved to compensate the possible lack of atrial tissue for your right atrial lateral tunnel?

Dr Fujii: If we have some kind of difficulties for creating the lateral tunnel, we use the extracardiac TCPC.

Dr Tsang: Another surgical question. Your right atrial lateral tunnel got an awful lot of right atrial tissue exposed to high systemic venous pressure. Does that explain the high incidence of early and late arrhythmia in this group of patients?

Dr Fujii: If the patient has a high pulmonary arterial pressure, we think the extracardiac TCPC is better because, for maintaining the good lateral tunnel shape for long-term period, we need a good pulmonary condition and good ventricular function. If not so, the patient sometimes suffers from dilation of the lateral tunnel.

Dr Tsang: One final and quite simple question. In the current era, what is your first-line strategy in a small child who needs a completion of TCPC?

Dr Fujii: If the patient's body weight is 10 kg or more, generally, extracardiac TCPC is our first-line. However, recently the number of patients who need early Fontan completion has been increasing. Patient with hypoplastic left heart syndrome, atrioventricular valve regurgitation moderate or more, pulmonary arteriovenous fistula, or significant collateral right-to-left shunt, should undergo early Fontan completion before the condition deteriorates. We usually use lateral tunnel in patients less than 2 years of age.

But I said before, good pulmonary and cardiac condition is necessary.

Dr Sano: I'm going to add to the answers to your question

Number one is that we adopted the normal PA size from Kirklin's formula. According to Kirklin's formula, we estimate normal lateral tunnel size is half PA size. There are two major pathways to RA, SVC and IVC, so we think a half PA size may be enough to drain IVC blood.

Second, most of the lateral tunnel was used when we did not adopt the two-stage Fontan, so that the right atrium was quite good sized, and the free wall of the right atrium was quite good quality. If the free wall of the right atrium is small and quality is no good, we use extracardiac TCPC.

Third, most of the arrhythmias occurred in the patient with heterotaxy syndrome. Previously, we tried to do lateral tunnel in almost all patients. In these patients, some have developed arrhythmias, so we changed our policy since then. But other than heterotaxy patients, no arrhythmias occurred.

Dr C. Pizarro *(Wilmington, Delaware)*: I don't know if I missed this, but did you ever consider to include in your measurements the cross-section of the inferior vena cava orifice and then compare that to the opening where you created the upper anastomosis of the lateral tunnel to the central pulmonary arteries? In essence, to provide an unobstructed pathway, the tunnel needs to accommodate the IVC flow. This might be a more reliable way to establish if the dimension of the conduit is appropriate.

Dr Sano: I tried to change this one just one time, but it was not accepted. As you can tell, our true estimation is the area, not the size. So that the area size is much more important than just only the size from the front or lateral view.

Dr Fujii: Actually, if you can see the lateral tunnel diameter with echocardiography, it's almost round. So I think the same tendency must be observed if you evaluate this area of lateral tunnel.