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Surgical outcomes of reoperation after Fontan completion

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Key question

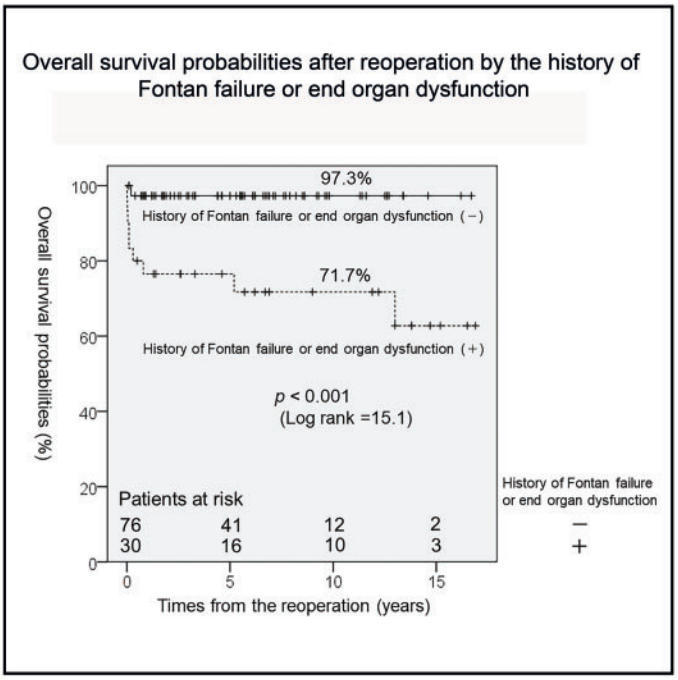
What are the surgical outcomes of reoperation after Fontan completion and what are the risk factors for poor outcomes?

Key finding(s)

A history of failed Fontan circulation and the requirement for deep hypothermic circulatory arrest negatively affected survival outcomes.

Take-home message

If a patient is in Fontan failure or has protein-losing enteropathy, it is too late to reoperate for any haemodynamic adversity.



Abstract

OBJECTIVES: Patients who have achieved Fontan circulation may require reoperation. We reviewed the outcomes of reoperation after Fontan completion and assessed the risk factors for poor outcomes.

METHODS: This was a retrospective study of 106 patients undergoing open-heart reoperations after Fontan completion in 2003 at a single institution.

RESULTS: The mean age at reoperation was 24.6 ± 8.3 years. A history of Fontan failure or end-organ dysfunction was noted in 30 patients. The reoperations included 73 total cavopulmonary connection conversions, 29 atrioventricular or semilunar valve operations (17 with total cavopulmonary connection conversions) and 4 other operations. Eight early deaths occurred. During a median follow-up of 5.5 (0.01–16.2) years, there were 3 late deaths and 9 second cardiac operations. The 10-year survival rate after reoperation was 89.8%, and the 5-year second cardiac operation-free survival was 84.3%. The 10-year survival rates were significantly lower in patients who underwent surgery before 2011 (75.8% vs 100%), had a history of Fontan failure or end-organ dysfunction (71.7% vs 97.3%), had preoperative central venous pressure >15 mmHg (64.9% vs 96.5%) and were operated on with deep hypothermic circulatory arrest (DHCA) (60.0% vs 91.3%). A

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history of Fontan failure or end-organ dysfunction, preoperative central venous pressure >15 mmHg and requirement of DHCA were identified as risk factors for mortality.

CONCLUSIONS: Reoperation after Fontan completion resulted in excellent mid-term outcomes. A history of failed Fontan circulation and the requirement of DHCA negatively affected survival outcomes.

Keywords: Reoperation • Fontan failure • Single ventricle • Conversion • Valve operation

ABBREVIATIONS

AV	Atrioventricular
CVP	Central venous pressure
DHCA	Deep hypothermic circulatory arrest
PLE	Protein-losing enteropathy
TCPC	Total cavopulmonary connection

INTRODUCTION

As the surgical outcome of the Fontan procedure for patients with a functional single ventricle has improved, more patients with Fontan completion reach adulthood [1] and require long-term reoperations. One previous study showed that 21% of adolescents and adults required surgical reintervention [2], and another study found that 11% and 5% of Fontan survivors required total cavopulmonary connection (TCPC) conversion and atrioventricular (AV) valve operation in the long-term, respectively [3]. Conversely, reoperation after Fontan completion has been recognized as a high-risk procedure due to multiple previous surgical histories, single ventricle physiology itself and other possible end-organ dysfunction. In fact, the TCPC conversion was reported to have the highest risk of mortality among adult congenital heart operations [4], and the AV valve operation after Fontan completion was reported to be associated with substantial late mortality and morbidity [5].

In our institution, the number of reoperations after Fontan completion has increased recently, and dedicated efforts to improve surgical outcomes have been made. Therefore, we reviewed the outcomes of reoperation after Fontan completion and assessed the risk factors for poor outcomes at our institution.

PATIENTS AND METHODS

Ethical statement

This study was approved and monitored by the Tokyo Women's Medical University's research ethics committee. The institutional review board approval number was 5455, and the need for patient consent was waived due to the retrospective nature of the study.

Data availability statement

The data are not available due to ethical restrictions, because there is their containing information that could compromise the patient's privacy and no agreement for their data to be shared publicly.

Study design

This was a retrospective study of patients undergoing open-heart reoperation after Fontan completion at the Tokyo Women's Medical University Hospital from 2003 to 2020. Recipients of pacemaker-related procedures were excluded from the study. Medical records were reviewed, and the following data were retrieved and analysed: basic demographic data, anatomical information, surgical history, preoperative date, intraoperative data and postoperative outcomes.

Statistical analysis

Statistical analysis was performed using SPSS software (version 18.0; SPSS, Inc., Chicago, IL, USA). Normally distributed continuous variables were expressed as median and range or mean and standard deviation. Fontan failure was defined as protein-losing enteropathy (PLE) or symptomatic heart failure. End-organ dysfunction was defined as cerebral apoplexy, pulmonary embolism or haemorrhage, kidney dysfunction, or liver cirrhosis diagnosed by specialists. Overall survival was defined as the time from the reoperation date to the date of death. The patient was censored at the last contact. Early death and late death were defined as death before and after hospital discharge, respectively. Kaplan–Meier estimates were computed for survival probabilities after reoperation. A log-rank test was performed to evaluate the survival difference across the different strata. The differences in the operative outcomes and era effect between the groups were assessed using the *t*-test, chi-square test or Fisher's exact test. Multiple comparisons were not adjusted. All *P*-values were two-sided, and *P*-values of <0.05 were considered statistically significant. The Cox proportional hazard model was used to determine the risk factors for mortality after Fontan completion. Each variable found to be significantly associated by univariate analysis ($P < 0.05$) was entered into the multivariate analysis.

Primary surgical strategy for Fontan completion

Until approximately the year 2000, the majority of Fontan operations were atriopulmonary connections or Bjork operations performed at the surgeon's discretion. This was changed to TCPC after 2003, and now our standard for Fontan completion is staged extracardiac conduit TCPC.

Indication of the reoperation after Fontan completion

TCPC conversion was indicated for patients with an enlarged right atrium volume of >80 ml/m^2, intra-atrial thrombus, history of pulmonary embolism, recurrent supraventricular tachycardia

or cyanosis due to baffle leak [6]. In patients with PLE, TCPC conversion was indicated in the early series. Valve operation was indicated for patients with systemic ventricular enlargement caused by more than moderate semilunar or AV valve regurgitation. The aortic annulus enlargement procedure was also indicated for aortic or neoaortic regurgitation with a small annulus, as well as root replacement for an aortic root aneurysm with a diameter of >55 mm or rapid progression. Concomitant intraoperative ablation was indicated in patients with recurrent supraventricular tachycardia.

Preoperative imaging and evaluation

Cardiac catheterization was performed to evaluate haemodynamic status, except for patients with intra-atrial thrombosis or unstable haemodynamic status. Electrophysiological studies have been aggressively performed recently. As regular evaluation for resternotomy, the existence of the space between the sternum and the heart or vessels, major collateral vessels and diameter or patency of femoral and neck vessels were evaluated by contrast computed tomography.

Surgical techniques of the reoperation after Fontan completion

All reoperations were performed via redo median sternotomy and cardiopulmonary bypass. In case of injury to the heart, great vessels, or implanted graft, an emergent cardiopulmonary bypass was established through a separate groin incision. Deep hypothermic circulatory arrest (DHCA) or retrograde cerebral perfusion was used in cases of difficulty of antegrade cerebral perfusion or massive air embolism.

TCPC conversion was performed mainly using an expanded polytetrafluoroethylene graft with a previously reported technique [7]. The atrial wall that recognized the low-voltage area by the electrophysiological study was resected. The bi-atrial Maze procedure was concomitantly performed initially as intraoperative ablation with pacemaker generator implantation. However, preoperative percutaneous catheter ablation with or without intraoperative right atrial Maze procedure was more favourable than the bi-atrial Maze procedure. The fenestration might be concomitantly performed at the TCPC conversion in case of anticipated Fontan failure. The atrial and ventricular pacemaker leads were placed concomitantly, and the pacemaker generator was implanted only when necessary.

AV valve repair can be considered for addressing AV valve disease. Recently, valve replacement has been favoured, especially for patients with dysplastic AV valve or prior AV valve repair. In cases where there were 2 adequately sized AV valves or semilunar valves and sufficiently large ventricular communication, the regurgitant valve closure was selected.

RESULTS

Patient's profile

One hundred and six patients were included in the study. Previous Fontan operations included atriopulmonary connection in 79 (75%) patients, Bjork operation in 9 (8%) patients and TCPC in 18 (12 lateral tunnel and 6 extracardiac conduit; 17%) patients. The mean age at the time of reoperation was 24.6 ± 8.3 years, including 26 patients aged >30 years (25%). A history of Fontan failure or end-organ dysfunction was noted in 30 patients (28%), including 4 patients with PLE and 2 patients with shock vital caused by pulmonary embolism or ventricular fibrillation. The preoperative New York Heart Association functional class was I in 12 patients (11%), II in 66 (62%), III in 18 (17%) and IV in 10 (10%). Preoperative arrhythmia was found in 68 patients (64%), and preoperative percutaneous catheter ablation was performed in 36 patients (34%). Patient profiles are summarized in Table 1.

Preoperative haemodynamics

One hundred patients (94%) underwent preoperative cardiac catheterization. Preoperative haemodynamic evaluations showed 21 patients (20%) with central venous pressure (CVP) >15 mmHg, 22 patients (21%) with a cardiac index of <1.8 l/min/m^2, 6 patients (6%) with pulmonary vascular resistance >4 unit·m^2 and 6 patients (6%) with systemic ventricle ejection fraction <40% (Table 3). For the patients indicated for the TCPC conversion, the right atrial volume was 95.6 ± 43.2 ml/m^2.

Reoperations after the Fontan completion

The reoperations included 73 TCPC conversions, 29 AV or semilunar valve operations (17 with TCPC conversions) and 4 other operations. The 29 valve operations consisted of 13 AV valve repairs, 7 AV valve replacements, 2 semilunar valve replacements, 3 aortic root replacements (1 with aortic annulus enlargement) and 4 valve closures (4 AV valve closures combined with 1 semilunar valve closure). Among the 24 patients who underwent AV valve operations, 9 (38%) had undergone AV valve repair prior to or with the Fontan procedure. Concomitant intraoperative ablation was performed in 37 patients (35%), including 12 bi-atrial Maze procedures. Planned pacemaker implantation was performed in 42 patients (40%). For 18 patients undergoing the previous TCPC, the reoperations included 12 AV or semilunar valve operations (2 with TCPC conversions from lateral tunnel type TCPC), 4 TCPC conversions and 2 other operations. Peripheral cannulation was required in 38 patients (36%). Eleven patients (10%) had injury to the heart, vessels or implanted graft during the resternotomy, and 5 patients (5%) required DHCA. The cardiopulmonary bypass time was 201 ± 112 min, with 13 patients (12%) over 300 min. The details of the reoperation are summarized in Table 2.

Outcome for the reoperation

There were 8 early deaths, with 3 caused by low cardiac output syndromes, 2 sepsis, 1 pulmonary venous obstruction, 1 multiple organ dysfunction and 1 cerebral infarction. Among them, 6 patients (75%) had a history of Fontan failure or end-organ dysfunction. Among the hospital survivors, there were 24 unplanned reoperations (12 postoperative haemorrhages requiring reoperation), 7 cases of arrhythmia necessitating unplanned permanent pacemaker implantation, 7 cases of renal failure requiring dialysis, 2 cases of paralyzed diaphragms and 1 case of neurological deficit persisting upon discharge. The median length of intensive care unit stay and hospital stay was 6 (2–73) and 32 (11–154) days, respectively.

Table 1: Patient characteristics at the time of reoperation

Variables	All patients (n = 106)
Age upon reoperation after Fontan completion (years), mean ± SD	24.6 ± 8.3
>30 years old, *n* (%)	26 (25)
Heterotaxy syndrome, *n* (%)	21 (20)
Asplenia	11 (10)
Fundamental diagnosis, *n* (%)	
Functional single left ventricle	57 (54)
Functional single right ventricle	33 (31)
Unbalanced atrioventricular septal defect	9 (8)
Hypoplastic left heart syndrome	2 (2)
Indistinguishable	5 (5)
Previous Fontan procedure, *n* (%)	
Atrio-pulmonary connection	79 (75)
Bjork operation	9 (8)
Total cavopulmonary connection	18 (17)
Lateral tunnel	12 (11)
Extra-cardiac type	6 (6)
Previous fenestrated Fontan procedure	6 (6)
Age upon previous Fontan completion (years), median (Range)	5.0 (1.6–25.5)
Duration from Fontan completion to reoperation (years), median (Range)	18.1 (0.2–36.6)
Duration from onset of symptoms to reoperation for symptomatic patients (years), median (Range)	2.1 (0.02–16.7)
Previously aortic reconstruction, *n* (%)	10 (9)
Damus-Kaye-Stansel procedure	7 (7)
Norwood procedure	2 (2)
Extended aortic arch anastomosis	1 (1)
History of Fontan failure or end-organ dysfunction, patient's number, *n* (%)	30 (28)
Heart failure	13 (12)
Cerebral apoplexy	7 (7)
Pulmonary embolism	5 (5)
Pulmonary Haemorrhage	4 (4)
Protein-losing enteropathy	4 (4)
Kidney dysfunction	2 (2)
Liver cirrhosis	1 (1)
Other findings, *n* (%)	
Thrombus within the giant right atrium	13 (12)
Arrhythmia, patient's number, *n* (%)	68 (64)
Supraventricular tachycardia	60 (57)
Ventricular tachycardia or fibrillation	6 (6)
Sinus node dysfunction	1 (1)
Complete atrioventricular block	1 (1)

SD: standard deviation.

Table 2: Reoperations after Fontan completion

Variables	All patients (n = 106)
Number of previous sternotomies, *n* (%)	
1	77 (73)
>2	29 (27)
Detail of reoperation, *n* (%)	
Total cavopulmonary connection conversion	73 (69)
Atrioventricular or semilunar valve operation	29 (27)
(With total cavopulmonary connection conversion)	(17) (16)
Atrioventricular valve repair	13 (12)
Atrioventricular valve replacement	7 (7)
Aortic root procedure including aortic annulus enlargement	3 (3)
Semilunar valve replacement	2 (2)
(With ascending aortic grafting)	(1) (1)
Atrioventricular valve closure	3 (3)
Atrioventricular valve and semilunar valve closure	1 (1)
Other operations	4 (4)
Planned pacemaker implantation	42 (40)
Detail of total cavopulmonary connection conversion	
Conduit material, *n* (%)	
Expanded polytetrafluoroethylene graft	89 (99)
Tissue engineering graft	1 (1)
Conduit size (mm), median (Range)	22 (16-24)
Concomitant fenestration, *n* (%)	4 (5)
Requirement of the peripheral cannulations, *n* (%)	38 (36)
Injury to the organ or implanted graft, *n* (%)	11 (10)
Requirement of deep hypothermic circulatory arrest, *n* (%)	5 (5)
Cardiopulmonary bypass time (min), mean ± SD	201 ± 112
>300 min, *n* (%)	13 (12)
Aortic cross-clamp time (min), mean ± SD	91 ± 50
Mechanical ventilation length (days), median (Range)	2 (1-43)
Length of intensive care unit stay (days), median (Range)	6 (2-73)
Length of hospital stay (days), median (Range)	32 (11-154)

SD: standard deviation.

Follow-up was completed for all but 5 patients (95%). During the median follow-up of 5.5 (0.01–16.9) years, 3 late deaths occurred. Two patients undergoing TCPC conversion, AV valve repair and bi-atrial Maze procedure died due to low cardiac output syndrome at 0.3 and 5.2 years after the operation. The remaining patient with preoperative PLE underwent TCPC conversion and died due to hepatocellular carcinoma 13.0 years after the operation. The overall survival probabilities at 5 and 10 years after reoperation were 91.4% and 89.8%, respectively (Fig. 1a). The survival probabilities at 10 years after the reoperation were not significantly different between the patients with only TCPC conversions and those with valve operations with/without TCPC conversions (94.5% vs 80.5%; $P = 0.153$) (Fig. 1b). There were 9 second cardiac operations during the follow-up, including 2 pulmonary thrombectomies or vegetectomies; 1 thrombectomy within the conduit, re-aortic valve replacement for paravalvular leakage, TCPC conversion after valve operation, release for subaortic stenosis and cardiac resynchronization therapy implantation; and 1 each of fenestrated creation and repair for superior vena cava stenosis. The second cardiac operation-free survival probabilities at 1, 5 and 10 years after reoperation were 88.5%, 84.3% and 80.2%, respectively (Fig. 2).

Postoperative clinical status and haemodynamics

The postoperative oxygen saturation and brain natriuretic peptide levels significantly improved to 93.9 ± 2.9% and 56.6 ± 53.6 pg/dl, respectively. Among the 4 patients with preoperative PLE, 3 had suffered from the disease, even after performing the TCPC conversion, and 1 patient died due to hepatocellular carcinoma. Among the 90 current survivors, the latest New York Heart Association functional class was I in 45 patients (50%), II in 38 (42%) and III in 7 (8%), and the proportion of patients in the New York Heart Association functional class III or IV was significantly decreased postoperatively ($P < 0.01$).

Postoperative cardiac catheterization was performed in 71 patients at 1.5 (0.1–15.6) years after reoperation. The cardiac index was significantly improved from 2.3 ± 0.7 to 2.7 ± 0.6 l/min/m^2 ($P < 0.01$). The pulmonary vascular resistance was significantly reduced from 2.0 ± 1.2 to 1.3 ± 0.6 unit m^2 ($P < 0.01$). The CVP and

Table 3: Preoperative and postoperative clinical and haemodynamic status

	Preoperative	Postoperative	*P*-value
Oxygen saturation (%), mean ± SD	90.9 ± 0.7	93.9 ± 2.9	<0.01
Oxygen saturation below 85%, *n* (%)	15 (14)	3 (3)	<0.01
Brain natriuretic peptide (pg/dl), mean ± SD	186 ± 175	57 ± 54	<0.01
Protein-losing enteropathy	4	3	0.32
New York Heart Association functional class III or IV, *n* (%)	28 (26)	7 (8)	<0.01
CVP (mmHg), mean ± SD	12.7 ± 3.2	12.5 ± 3.3	0.85
Patients with preoperative CVP >15 mmHg	17.4 ± 3.0	14.4 ± 3.7	0.02
Patients with preoperative CVP <15 mmHg	11.5 ± 2.0	12.0 ± 3.1	0.35
Cardiac index (l/min/m^2), mean ± SD	2.3 ± 0.7	2.7 ± 0.6	<0.01
Systemic ventricle, mean ± SD			
Endo-diastolic volume (% of normal size)	86.9 ± 33.1	87.2 ± 27.8	0.91
Ejection fraction (%)	52.0 ± 8.6	51.6 ± 9.2	0.57
Pulmonary vascular resistance (unit m^2), mean ± SD	2.0 ± 1.2	1.3 ± 0.6	<0.01

CVP: central venous pressure; SD: standard deviation.

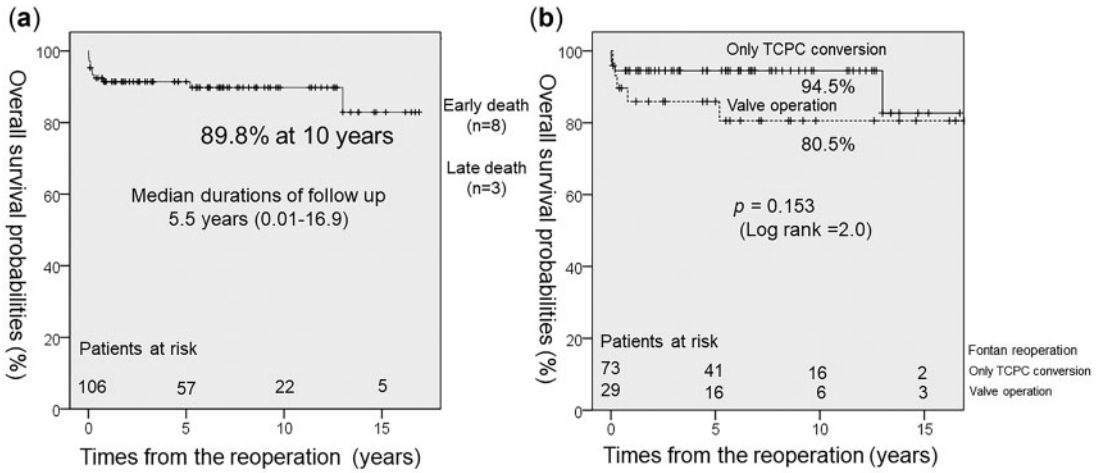

Figure 1: Kaplan–Meier curve of the overall survival probabilities after reoperation: (**a**) overall and (**b**) dividing with only the total cavopulmonary connection conversion and the valve operation.

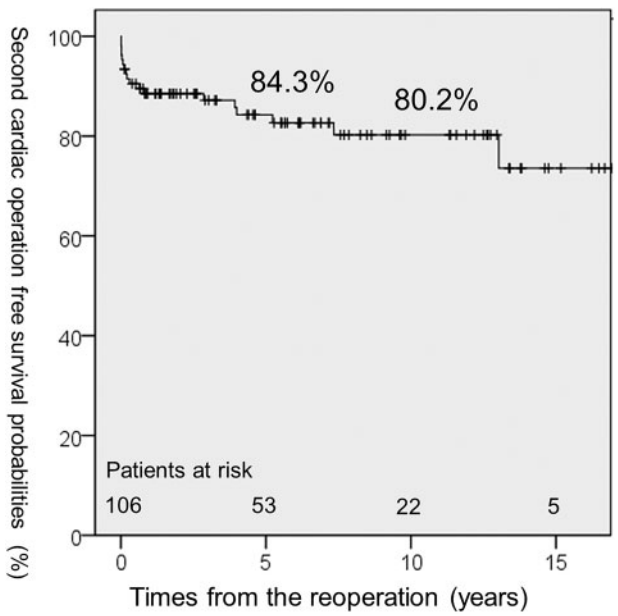

Figure 2: Kaplan–Meier curve of the second cardiac operation-free survival probabilities.

ejection fraction of the systemic ventricle were not significantly changed at 12.5 ± 3.3 mmHg and 51.6 ± 9.2%, respectively. However, among 21 patients with preoperative CVP >15 mmHg, the CVP was improved from 17.4 ± 3.0 to 14.5 ± 3.7 mmHg ($P = 0.02$). Preoperative and postoperative data are summarized in Table 3.

Transition of surgical era

As the surgical experience of reoperation after Fontan completion accumulated, our practice had been shifted to perform reoperations earlier before the patients had Fontan failure or end-organ dysfunction and to perform preoperative percutaneous catheter ablation. Furthermore, Fontan completion tended to be performed at a younger age. As a result, when the patients were divided into 2 groups by era (2003–2011: 42 reoperations vs 2012–2020: 64 reoperations), there were significant differences in the age at Fontan completion (9.6 [2.0–25.5] vs 3.6 [1.6–15.7] years; $P < 0.01$), rates of history of Fontan failure or end-organ dysfunction (48% vs 16%; $P < 0.01$), rates of preoperative catheter ablation (19% vs 45%; $P = 0.01$), rates of intraoperative ablation (57% vs 20%; $P < 0.01$), early mortality (19% vs 0%; $P < 0.01$) and overall survival probabilities at 5 years (78.5% vs 100%, log

Table 4: Transition of the era

Variables	All patients ($n = 106$)	Surgical era		P-value
		2003–2011 ($n = 42$)	2012–2020 ($n = 64$)	
Age upon Fontan completion (years), median (Range)	5.0 (1.6–25.5)	9.6 (2.0–25.5)	3.6 (1.6–15.7)	<0.01
History of Fontan failure or end-organ dysfunction, *n* (%)	30 (28)	20 (48)	10 (16)	<0.01
Preoperative percutaneous catheter ablation, *n* (%)	37 (35)	8 (19)	29 (45)	<0.01
Intraoperative ablation, *n* (%)	37 (35)	24 (57)	13 (20)	<0.01
Bi-atrial Maze procedure	12 (32)	12 (29)	0	<0.01
Right atrial Maze procedure	25 (68)	12 (29)	13 (20)	0.36
Early death, *n* (%)	8 (8)	8 (19)	0	<0.01
Follow-up period (years), median (Range)	5.5 (0.01–16.9)	11.4 (0.01–16.9)	4.5 (0.1–9.2)	<0.01
Late death, *n* (%)	3 (3)	3 (8)	0	0.16
Second cardiac operation, *n* (%)	9 (8)	2 (5)	7 (11)	0.31

rank = 15.2, $P < 0.01$). The transition of the surgical era is summarized in Table 4.

Patients with preoperative catheter ablation

Intraoperative ablation was not necessary in 21 of the 37 patients who underwent preoperative catheter ablation. Patients without concomitant intraoperative ablation had significantly shorter aortic cross-clamp time (67 ± 32 vs.112 ± 30 min, $P < 0.01$) than patients with concomitant intraoperative ablation.

Intraoperative ablation and postoperative catheter ablation

Intraoperative ablation included 12 bi-atrial Maze procedures and 25 right atrial Maze procedures. Intraoperative ablation was used more frequently in patients with only TCPC conversion than in those who underwent valve operation (32/73 [43.8%] vs 5/29 [17.2%], $P = 0.01$). In these patients, postoperative catheter ablation was not necessary. However, mortality in the patients who underwent the bi-atrial Maze procedure tended to be higher than in patients who underwent the right atrial Maze procedure (33% vs 4%, $P = 0.07$). Among the remaining 63 survivors without intraoperative ablation, 5 (8%) required postoperative catheter ablation. Among 34 hospital survivors undergoing intraoperative ablation, 5 required postoperative pacemaker implantation for sick sinus syndrome, although no patient had postoperative AV block.

Atrioventricular valve operation

Among 13 patients undergoing AV valve repair, there were 1 early death caused by pulmonary venous obstruction and 2 late deaths caused by low cardiac output syndrome. Moreover, 3 of 10 late survivors after AV valve repair experienced recurrence of moderate AV valve regurgitation. Conversely, all of 7 patients with the AV valve replacement and 4 patients with the AV valve closure survived at the median follow-up of 4.9 (0.4–15.7) years. There were no anticoagulant therapy-related adverse events or a second AV valve replacement. However, 1 patient with AV valve closure had moderate AV valve regurgitation on the other unclosed AV valve. It seemed that the patients with AV valve replacement or closure had better prognosis than those with AV valve repair (100% vs 74% at 10 years, $P = 0.133$), although there was no significant difference between the groups.

Overall survival probability after the reoperation at the various variables

The overall survival probabilities were significantly lower in patients with a history of Fontan failure or end-organ dysfunction (71.7% vs 97.3% at 10 years, log rank = 15.1, $P < 0.001$), those with CVP >15 mmHg (64.9% vs 96.5% at 10 years, log rank = 18.4, $P < 0.001$) and those requiring DHCA at reoperation (60.0% vs 92.9% at 5 years, log rank = 7.2, $P = 0.007$) (Fig. 3).

Risk analysis for mortality after the reoperation

Univariate analysis for all cohorts identified the history of Fontan failure or end-organ dysfunction, preoperative CVP >15 mmHg, concomitant bi-atrial Maze procedure and requirement of DHCA as a risk factor for mortality. Multivariate analysis for all cohorts identified the history of Fontan failure or end-organ dysfunction, preoperative CVP >15 mmHg and requirement of DHCA as a risk factor for mortality (Table 5). Multivariate analysis for patients with only TCPC conversion or those with valve operation did not show significant risk factors for mortality.

DISCUSSION

As the number of reoperations after Fontan completion has increased, multiple efforts to improve surgical outcome have been made recently [8].

Regarding the timing of reoperation, previous studies reported that the earlier indication for TCPC conversion was associated with better transplantation-free survival in Australia and New Zealand [9], and older age at the time of operation, AV valve regurgitation and the presence of PLE were poor prognostic factors for TCPC conversion [10, 11]. Our study also showed that patients with a history of Fontan failure or end-organ dysfunction and a high CVP level had worse outcomes. Furthermore, among the 4 patients with preoperative PLE, 3 had persistent PLE even after TCPC conversion, suggesting that preoperative PLE may not be fully recovered by TCPC conversion. Backer and Mavroudis [8] reported that patients with PLE were not indicated for TCPC

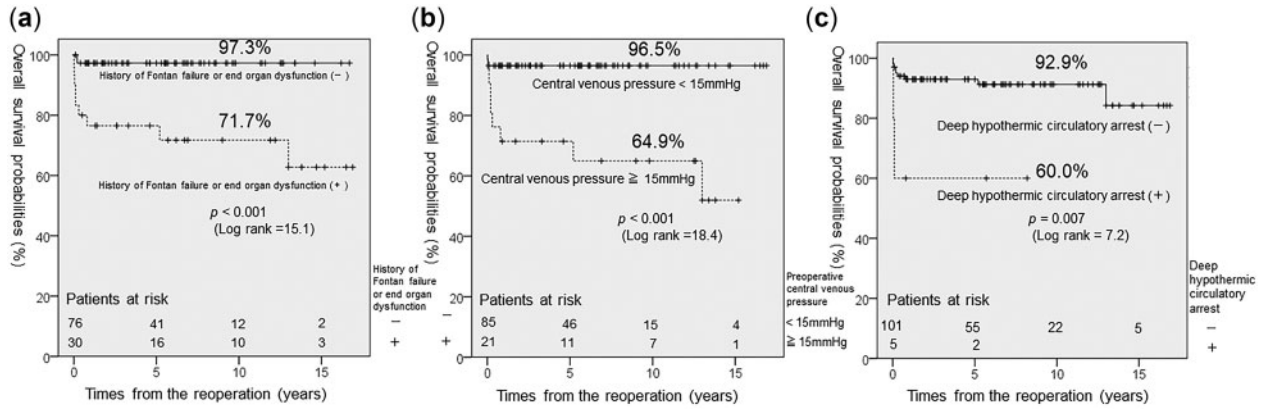

Figure 3: Kaplan–Meier curve comparison of the overall survival probabilities after reoperation: (**a**) by the history of Fontan failure or end-organ dysfunction, (**b**) by the respective degrees of central venous pressure and (**c**) by the requirement of deep hypothermic circulatory arrest.

Table 5: Risk analysis for mortality after reoperation

Predictors	Comparison	Univariate analysis		Multivariate analysis	
		P-value	Hazard ratio	*P*-value	Hazard ratio
Total cohort					
History of Fontan failure or end-organ dysfunction	Yes	<0.01	11.5 (2.5–53.7)	0.048	5.3 (1.0–27.7)
Preoperative central venous pressure >15 mmHg	Yes	<0.01	10.6 (2.8–40.2)	0.02	6.1 (1.3–27.9)
Preoperative pulmonary vascular resistance >4 unit m^2	Yes	0.12	3.4 (0.7–15.8)		
Preoperative cardiac index <1.8 l/min/m^2	Yes	0.19	2.3 (0.7–7.7)		
Valve operation	Yes	0.23	2.1 (0.6–6.8)		
Aortic root procedure including aortic annulus enlargement	Yes	0.16	4.4 (0.6–35.5)		
Concomitant bi-atrial Maze procedure	Yes	0.03	4.0 (1.1–14.0)	0.70	1.3 (0.3–5.7)
Requirement of deep hypothermic circulatory arrest	Yes	0.02	6.4 (1.3–30.1)	0.04	6.3 (1.1–36.5)
Injury for organ or implanted graft during resternotomy	Yes	0.50	1.7 (0.4–8.1)		
Only TCPC conversion patients					
History of Fontan failure or end-organ dysfunction	Yes	0.04	10.7 (1.1–99.8)	0.05	9.4 (1.0–88.9)
Preoperative central venous pressure >15 mmHg	Yes	0.06	6.0 (0.9–38.3)		
Preoperative pulmonary vascular resistance >4 unit m^2	Yes	0.69	0.04 (0.01–182085)		
Preoperative cardiac index <1.8 l/min/m^2	Yes	0.33	2.4 (0.4–14.6)		
Concomitant bi-atrial Maze procedure	Yes	0.27	3.0 (0.4–20.1)		
Requirement of deep hypothermic circulatory arrest	Yes	0.03	13.5 (1.4–131.5)	0.07	9.2 (0.9–97.8)
Injury of organ or implanted graft during resternotomy	Yes	0.15	3.9 (0.6–25.8)		
Valve operation patients with/without TCPC conversion					
History of Fontan failure or end-organ dysfunction	Yes	0.08	7.0 (0.8–63.0)		
Preoperative central venous pressure >15 mmHg	Yes	0.27	505 (0.001–0.01)		
Preoperative pulmonary vascular resistance >4 unit m^2	Yes	<0.01	15.0 (2.1-108)	0.09	7.8 (0.7–80.5)
Preoperative cardiac index <1.8 l/min/m^2	Yes	0.23	3.0 (0.5–18.1)		
Aortic root procedure including aortic annulus enlargement	Yes	0.30	3.3 (0.3–32.0)		
Atrioventricular valve repair	Yes	0.41	50.9 (0.004-634118)		
Concomitant bi-atrial Maze procedure	Yes	0.01	9.9 (1.6–60.0)	0.18	4.5 (0.5–39.8)
Concomitant with TCPC conversion	Yes	0.34	0.4 (0.1–2.5)		
Requirement of deep hypothermic circulatory arrest	Yes	0.16	4.9 (0.5–44.5)		
Injury for organ or implanted graft during resternotomy	Yes	0.66	0.04 (0.1–47068)		

TCPC: total cavopulmonary connection.

conversion. Therefore, reoperation is warranted prior to PLE occurrence. Based on our past experience, the proportion of patients with a history of Fontan failure or end-organ dysfunction has been reduced recently, and all patients who underwent reoperation after 2012 survived. This could indicate that the timing of the reoperation affected the patient's prognosis, and it may be desirable to have an earlier operation for the Fontan patient with haemodynamic issues.

Regarding intraoperative management, the rate of cardiac injury in adult congenital heart disease operations was reported to be 6% [12]. In our study, the incidence of injury to the organ or implanted graft was 10%, and patients with DHCA had significantly worse survival. However, injury to the organ or implanted graft itself was not a risk factor for mortality. This might indicate that a thorough evaluation of the cardiac injury risks and careful preoperative planning for the unexpected event helped improve surgical outcomes [13]. Moreover, the aggressive introduction of preoperative percutaneous catheter ablation was encouraged at our institution recently, because the concomitant Maze procedure with TCPC conversion was reported to be a risk factor for cardiac death or heart transplantation [14]. This helped reduce the necessity of intraoperative ablation and aortic cross-clamp

time and potentially helped improve surgical outcomes. If necessary, the right atrial Maze procedure is preferred over the bi-atrial Maze procedure to reduce surgical invasion.

Regarding the valve operation after Fontan completion, it was reported that approximately 60% of patients experienced more than moderate AV valve regurgitation, even when performing the valve operation at the time of the Fontan procedure [15], and approximately 40% of patients with AV valve repair after Fontan completion experienced valve failure at approximately 1 year after the operation [16]. Therefore, we favoured valve replacement or valve closure rather than valve repair for the following reasons: (i) 9 of 24 (38%) patients who required AV valve reoperation after Fontan completion in our cohort had prior AV valve repair; (ii) valve reoperation after Fontan completion was reported to be high-risk [5], and it could be advantageous for short-term survival to completely avoid the recurrence of regurgitation; and (iii) in Japan, many Fontan patients were already placed on coumadin after Fontan completion. Among 9 patients undergoing AV valve or semilunar valve replacement, 8 patients survived during the median follow-up of 7.1 (0.1–15.7) years. The reason for the improved survival of valve replacement after Fontan completion compared to previous reports with 45–60% late mortality was unclear [12, 17]. However, we assume that it is multifactorial, and operative timing can be the most important factor. The valve operation should be performed in a timely fashion without hesitation when indicated, and before the Fontan failure or end-organ dysfunction occurs.

Limitations

The limitations of this study were its retrospective nature and the relatively small sample size. A prospective randomized trial is required to further evaluate surgical risk factors in more detail.

CONCLUSION

Reoperation after Fontan completion had excellent mid-term outcomes. A history of failed Fontan circulation and the intraoperative requirement of DHCA negatively affected the survival outcomes of the reoperations after Fontan completion. Considering the recent improved outcome of the reoperation, the Fontan patient with haemodynamic issues may benefit more from earlier surgical consultation.

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Author contributions

Yuki Nakayama: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Supervision; Validation; Visualization; Writing—original draft; Writing—review & editing. **Takeshi Shinkawa:** Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Supervision; Validation; Visualization; Writing—review & editing. **Ryogo Hoki:** Investigation. **Hisashi Yoshida:** Data curation; Investigation. **Junko Katagiri:** Investigation. **Kei Inai:** Investigation. **Hiroshi Niinami:** Supervision.

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