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Comparative outcomes of cardioplegic arrest versus beating heart in pediatric undergoing extracardiac total cavopulmonary connection

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Abstract

Background Total cavopulmonary connection (TCPC) is a definitive palliative procedure for functionally univentricular congenital heart disease. The study aims to compare the impact of on-pump cardioplegic arrest and on-pump beating heart cardiopulmonary bypass (CPB) on the prognosis of pediatric patients undergoing extracardiac TCPC.

Methods The medical data of patients (< 18 years) who underwent extracardiac TCPC with CPB between January 2008 and December 2020 in the cardiac surgery center were retrospectively analyzed. Depending on CPB strategies, the patients were assigned to the beating-heart (BH) and cardioplegic arrest (CA) groups. Data including baseline characteristics, intra/postoperative variables, and clinical outcomes were collected for analysis with 1:1 propensity score matching and multivariable stepwise logistic regressions.

Results Fifty-seven matched patient pairs were obtained. No significant difference existed between the two groups in the in-hospital mortality (3.5% vs. 1.8%, $P=1$) and one-year survival rate (100% vs. 96.4%, $P=0.484$). The BH group had significantly less intraoperative platelet transfusion (10 mL vs. 150 mL, $P=0.019$) and blood loss (100 mL vs. 150 mL, $P=0.033$) than the CA group. The CA group had significantly higher vasoactive-inotropic scores ($P<0.05$) and longer postoperative ICU stays (2.0 d vs. 3.7 d, $P=0.017$). No significant difference existed between the two groups in the incidence of postoperative adverse events.

Conclusion Although both CPB strategies are safe and feasible for extracardiac TCPC, the BH technique would cause less intraoperative platelet transfusion and blood loss, and achieve faster early-term postoperative recovery.

Keywords Cardiopulmonary bypass, Beating heart, Cardioplegic arrest, Extracardiac total cavopulmonary connection, Outcomes

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Introduction

Functionally univentricular heart belongs to complex forms of congenital heart disease (CHD) that afflict approximately 0.08‰ to 0.4‰ of live births worldwide [1]. Total cavopulmonary connection (TCPC) provides the optimal palliative treatment for children born with functionally univentricular CHD [2]. This operation allows systemic venous blood to enter the pulmonary circulation through an artificial catheter to correct hypoxia caused by its mixing with oxygenated arterial blood, thereby establishing almost normal arterial oxygenation in the body [3].

In our center, we usually perform TCPC procedures with CPB and systematic anticoagulation and adopt on-pump beating heart (BH) or on-pump cardioplegic arrest (CA) strategies for CPB. According to previous literature [4, 5], CA strategy is applied for CPB in patients who need to receive an intracardiac or extracardiac TCPC surgery accompanied by intracardiac malformation correction; BH or CA strategy is used for CPB in other extracardiac TCPC surgeries. The choice of BH or CA for TCPC surgeries mainly depends on the surgeon's autonomous choice based on their professional experience.

Various complications after TCPC would make the care of patients challenging and are closely related to poor prognosis and decreased quality of life. To date, the impact of CA versus BH on the early-term prognosis in children undergoing extracardiac TCPC remains unclear. Therefore, we aimed to investigate their possible impact on outcomes in such pediatric patients and make corresponding comparisons between the two CPB techniques.

Methods

Study subjects

This single-center, retrospective study included pediatric patients who underwent extracardiac TCPC with CPB at Fuwai Hospital of the Chinese Academy of Medical Sciences (Beijing) from January 2008 to December 2020. The pediatric patients undergoing extracardiac TCPC surgery with no need for simultaneous correction of intracardiac abnormalities were assigned to the BH group or CA group depending on the CPB strategies applied by the surgeon according to their experience. The same anesthesia/CPB/ICU team performed perioperative management of all patients according to our center's clinical practice protocol. The exclusion criteria were: (i) off-pump; (ii) incomplete CPB data; (iii) intracardiac TCPC; (iv) TCPC surgery accompanied by correction of intracardiac abnormalities. This work was approved by the Ethical Committee of Fuwai Hospital, Beijing, China (No. 2014−600). Written informed consent was waived because of the retrospective nature of the study.

Clinical practice

All patients were subjected to general anesthesia, standard hemodynamic and temperature monitoring, CPB circuit and prime strategy. After a standard median sternotomy and adequate systemic heparinization, the pulmonary trunk, the right and left pulmonary arteries, and the inferior and superior venae cavae were isolated and fully exposed, and cardiac catheterization was performed through ascending aorta and superior and inferior venae cavae respectively for establishing CPB. When various conditions permit, an extracardiac conduit was used to achieve direct attachment of the distal superior vena cava to the pulmonary trunk. Fenestration (4 to 5 mm) was performed between the right atrial free wall and the conduit in some patients according to the surgeon's consideration.

In the BH group, the superior and inferior venae cavae were cross-clamped without aortic cross-clamping and perfusion of any cardioplegic solution to allow adequate blood flow in the left heart and maintain a rhythmic empty beating state of the heart.

In the CA group, after systemic cooling of core body temperature, the ascending aorta was cross-clamped and then the heart was arrested with the antegrade perfusion of a cardioplegic solution via the aortic root and by the cooling of ice chips applied into the pericardial cavity.

For both groups, CPB/extracorporeal circulation was started when an activated clotting time reached more than 480 s. An activated clotting time of >480 s was maintained during CPB, and electrolytes, blood gas, and hematocrit were adjusted based on laboratory results. It was necessary to prepare sufficient fluid and gradually replenish the body's capacity to achieve satisfactory arterial and central venous pressure and stable circulation before weaning from CPB. Heparin was reversed with protamine after bleeding control in the surgical field. If necessary, blood products and anticoagulant drugs were used. Afterward, the thorax was closed in layers with appropriate closed thoracic drainage. All patients were transferred to the ICU after extracardiac TCPC.

Data collection and endpoints

Clinical information including demographics, preoperative laboratory tests, clinical characteristics, intraoperative CPB recordings, and other intraoperative and postoperative data was obtained from the medical records of included patients. Baseline characteristics, intraoperative variables, perioperative blood transfusions, and clinical outcomes were compared between the two groups. Cyanosis was defined as the presence of a bluish discoloration of the lips and nail beds. The Nakata index was the sum of the cross-sectional areas of the left and right pulmonary arteries divided by the patient's body surface area. Chylothorax was diagnosed when persistent pleural effusion drainage was 5 mL/kg/d or above, drainage fluid was positive for chylomicrons, or lymphocytes accounted for more than 80% of drainage fluid on postoperative day 5. Postoperative acute kidney injury (AKI) was diagnosed or classified according to the KDIGO (Kidney Disease: Improving Global Outcomes) guidelines [6]. Vasoactive-inotropic score (VIS) was the sum of dopamine dose (μg/kg/min), dobutamine dose (μg/kg/min), milrinone dose × 10 (μg/kg/min), epinephrine dose × 100 (μg/kg/min), norepinephrine dose × 100 (μg/kg/min), and vasopressin × 10,000 (U/kg/min) [7]. Cooling time was defined as the sum of the time from initiation of active cooling to target temperature and the duration of low-temperature maintenance before rewarming. Postoperative central venous pressure (CVP) was measured in the ICU on the day after surgery. Intraoperative platelet transfusion was administrated to secondary cardiac surgery patients or patients with uncontrollable oozing blood during surgery or confirmed low platelet function.

The primary endpoints were the in-hospital mortality and one-year survival rate. The secondary endpoints were CPB-related variables, blood components transfused in the perioperative period, intraoperative blood loss, postoperative recovery measures, and early adverse events. Postoperative recovery measures included postoperative VIS, mechanical ventilation (MV) time, length of postoperative ICU stay, postoperative CVP, postoperative fenestration, and postoperative chest drainage volume. Adverse events included postoperative AKI, infections, chylothorax, pleural effusion, ascites, arrhythmia, delayed sternal closure, re-admission to ICU, and ECMO (extracorporeal membrane oxygenation) use.

Statistical analysis

A 1:1 propensity-score matching (PSM) was applied to balance the between-group baseline characteristics; 0.1 of the pooled standard deviation of the logit of propensity score was used as the caliper width. The PSM model included demographics, preoperative laboratory tests, and clinical characteristics to adjust for confounding factors. Two-tailed *P* values less than 0.05 represented the statistical significance. The Kaplan-Meier curves were used to visually estimate the time-related survival probabilities and compared with log-rank tests. The variables with *P* values less than 0.2 in a univariable logistic regression analysis were exported into a multivariable stepwise logistic regression model. The distribution of continuous variables was assessed visually using quantile-quantile plots and histograms. Continuous variables were displayed as mean ± standard deviation (SD) or median (interquartile range/IQR) and were subjected to the Mann-Whitney U test or student *t*-test for skew or normal data, respectively. Categorical variables were expressed as number (percentage) and subjected to the Fisher exact test or Chi-square test. All statistical analyses were conducted using R (version 4.1.2; R Core Team, Vienna, Austria) and MedCalc (version 20.1) statistical software. The significance level was set at $P < 0.05$.

Results

Baseline characteristics

In this cohort, 341 eligible patients (213 males and 128 females) who underwent extracardiac TCPC were included in this study. The median age at TCPC surgery was 4.9 years. 58 patients were assigned to the CA group, and 283 patients were assigned to the BH group. Compared with the CA group, the BH group had more patients with tricuspid atresia or mesocardia but fewer patients with levocardia. After PSM, 57 patient pairs were matched between the two groups, and no significant difference in baseline characteristics existed between the two groups ($P > 0.05$) (Table 1). SMD are shown in Supplementary Table S1. Concomitant surgical procedures with TCPC of BH and CA patients after PSM are shown in Table 2.

Primary outcome

There was no significant difference in the in-hospital mortality between the BH group and the CA group. Kaplan-Meier analysis showed that there was no significant difference in the one-year survival rate between the two groups (Table 3; Fig. 1).

Secondary outcome

Intraoperative CPB data

CPB time, cross-clamping time, cooling time, and rewarming time in the BH group were significantly shorter than those in the CA group. The minimum rectal temperature and the minimum nasopharyngeal temperature during CPB among BH patients were significantly higher than those among CA patients. No significant difference in intraoperative mean arterial pressure and intraoperative fenestration existed between the two groups. In the CA group, 36.8% of the patients used histidine-tryptophan-ketoglutarate solution and 59.6% used St. Thomas solution for myocardial preservation after cardioplegic arrest. Detailed CPB data during TCPC after PSM is listed in Table 4.

Perioperative use of blood components

BH patients had significantly less intraoperative platelet transfusion and blood loss than CA patients. No statistical difference in platelet transfusion rate existed between the two groups. No significant difference existed in intraoperative plasma/red blood cell transfusion and postoperative platelet/plasma/red blood cell/albumin transfusion between the two groups (Table 3).

Table 1 Baseline characteristics of included patients

Characteristics		Before PSM			After PSM		
		BH (*n* = 283)	CA (*n* = 58)	*P*	BH (*n* = 57)	CA (*n* = 57)	*P*
Age at surgery (years)		4.7 (3.8, 6.2)	5.2 (4.1, 6.6)	0.175	5.0 (4.0, 6.4)	5.2 (4.1, 6.6)	0.419
Male, *n* (%)		178 (62.9)	35 (60.3)	0.828	31 (54.4)	35 (61.4)	0.569
Body weight (kg)		16.7 (14.5, 19.7)	17.5 (15.6, 20.2)	0.152	16.3 (14.8, 19.5)	17.5 (15.5, 20.2)	0.175
Body surface area (m^2)		0.7 (0.6, 0.8)	0.8 (0.7, 0.8)	0.116	0.7 (0.6, 0.8)	0.8 (0.7, 0.8)	0.274
Nakata index (mm^2/m^2)		316.7 (257.2, 316.7)	316.7 (262.9, 316.7)	0.451	316.7 (272.5, 316.7)	316.7 (275.1, 316.7)	0.840
Cyanosis, *n* (%)		78 (28.9)	17 (31.5)	0.827	13 (23.2)	17 (32.1)	0.412
Preoperative laboratory measurements							
	Hemoglobin (g/L)	174.0 (158.5, 190.5)	175.0 (163.3, 196.0)	0.319	174.0 (158.0, 186.0)	175.0 (163.0, 196.0)	0.316
	Hematocrit (l/L)	0.5 (0.5, 0.6)	0.5 (0.5, 0.6)	0.261	0.5 (0.5, 0.5)	0.5 (0.5, 0.6)	0.202
	Platelets ($\times 10^9$/L)	256.0 (204.0, 299.0)	262.0 (198.0, 311.0)	0.409	248.0 (211.0, 297.0)	260.9 (198.0, 305.0)	0.692
	Creatinine (mg/dL)	4.4 (3.8, 4.8)	4.5 (3.8, 5.1)	0.354	4.4 (3.9, 5.1)	4.5 (3.8, 5.0)	0.598
	Blood urea nitrogen (mmol/L)	4.4 (3.7, 5.1)	4.5 (3.9, 5.1)	0.641	4.7 (4.0, 5.3)	4.5 (3.9, 5.1)	0.292
[a]**Cardiac diagnosis**, ***n*(%)**							
	Single ventricle	110 (38.9)	18 (31.0)	0.33	21 (36.8)	18 (31.6)	0.693
	Double outlet right ventricle	73 (25.8)	22 (37.9)	0.086	19 (33.3)	22 (38.6)	0.696
	Tricuspid atresia	64 (22.6)	4 (6.9)	0.011	5 (8.8)	4 (7.0)	1
	Pulmonary atresia	41 (14.5)	10 (17.2)	0.739	12 (21.1)	9 (15.8)	0.629
	Complete transposition of great arteries	32 (11.3)	4 (6.9)	0.446	0 (0.0)	4 (7.0)	0.127
	Congenitally corrected transposition of great arteries	34 (12.0)	8 (13.8)	0.876	8 (14.0)	8 (14.0)	1
Ventricle position, ***n*(%)**							
	Mesocardia	195 (68.9)	30 (51.7)	0.018	30 (52.6)	30 (52.6)	1
	Levocardia	39 (13.8)	15 (25.9)	0.036	13 (22.8)	15 (26.3)	0.828
	Dextrocardia	50 (17.7)	13 (22.4)	0.508	14 (24.6)	12 (21.1)	0.823
Atrioventricular valve regurgitation, ***n*(%)**							
	Mild	39 (13.8)	12 (20.7)	0.253	14 (24.6)	11 (19.3)	0.651
	Moderate	6 (2.1)	2 (3.4)	0.894	2 (3.5)	2 (3.5)	1
	Severe	1 (0.4)	0 (0.0)	1	0 (0)	0 (0)	1
Left ventricular ejection fraction (%)		62.0 (60.0, 65.0)	62.8 (60.0, 65.0)	0.435	63.0 (60.0, 66.0)	62.8 (60.0, 65.0)	0.549
[b]**Palliative operations before TCPC**, ***n*(%)**							
	Bidirectional Glenn	182 (64.3)	39 (67.2)	0.783	37 (64.9)	38 (66.7)	1
	Pulmonary artery banding	6 (2.1)	1 (1.7)	1	0 (0.0)	1 (1.8)	1
	Systemic pulmonary artery shunt	9 (3.2)	0 (0.0)	0.354	0 (0.0)	0 (0.0)	1
Cardiac catheterization before TCPC							
	Mean pulmonary pressure (mmHg)	12.7 (11.0, 13.0)	12.7 (11.0, 14.0)	0.815	12.7 (12.0, 13.0)	12.7 (11.0, 14.0)	0.699
	Aortic systolic pressure (mmHg)	98.0 (91.0, 105.0)	99.1 (95.0, 105.0)	0.279	99.0 (95.0, 104.0)	99.3 (95.0, 105.0)	0.761
	Aortic diastolic pressure (mmHg)	60.0 (54.5, 65.0)	60.5 (54.5, 66.5)	0.736	60.0 (55.0, 64.0)	61.0 (56.0, 67.0)	0.228
The interval between Bidirectional Glenn to TCPC (years)		3.1 (2.7, 3.1)	3.1 (3.0, 3.8)	0.083	3.1 (2.4, 3.1)	3.1 (3.0, 3.8)	0.101
Cardiothoracic surgery history, ***n*(%)**							

Table 1 (continued)

Characteristics	Before PSM			After PSM		
	BH (*n* = 283)	CA (*n* = 58)	*P*	BH (*n* = 57)	CA (*n* = 57)	*P*
Yes	189 (66.8)	39 (67.2)	1	37 (64.9)	38 (66.7)	1
No	94 (33.2)	19 (32.8)		20 (35.1)	19 (33.3)	

Values are expressed as mean ± SD, median (IQR), or *n* (%). [a]Each patient has one or more cardiac diagnoses. [b]The patient may undergo one or more palliative surgeries before TCPC surgery

TCPC total cavopulmonary connection; *BH* on-pump normothermic beating heart TCPC; *CA* on-pump hypothermic cardioplegic arrest TCPC; *PSM* propensity-score matching

Table 2 Concomitant surgical procedures with TCPC of BH and CA patients after PSM

Variables	BH (*n* = 57)	CA (*n* = 57)
Arterial catheter ligation, *n*	1	3
Arterial catheter cutting and suturing surgery, *n*	1	1
Pulmonary arterioplasty, *n*	6	5
Body lung collateral angiography, *n*	1	1
Occlusion of systemic pulmonary collateral arteries, *n*	1	1
External channel atrial fenestration, *n*	1	1
Removal of pulmonary artery constriction, *n*	0	1
Reconstruction of the central branch of the proximal pulmonary artery in the hilar region, *n*	0	1
Ligation of the left hepatic vein, *n*	1	0
Ligation of azygos vein, *n*	1	0
Correction of complete anomalous pulmonary venous drainage, *n*	0	1

The patient may have one or more concomitant surgical procedures with TCPC

TCPC total cavopulmonary connection; *BH* on-pump normothermic beating heart TCPC; *CA* on-pump hypothermic cardioplegic arrest TCPC; *PSM* propensity-score matching

Risk factors related to perioperative platelet transfusion

The results of univariable and stepwise multivariable regression analyses of perioperative platelet transfusion are shown in Table 5. After stepwise multi-factor adjustment, the independent risk factors of perioperative platelet transfusion included bidirectional Glenn operation history, cardiothoracic surgery history, and cross-clamping time.

Postoperative recovery indexes

BH patients had significantly lower VIS and shorter postoperative stays in the ICU than CA patients (Table 3). No significant difference existed in MV time, postoperative fenestration, postoperative CVP, and chest drainage volume between the two groups.

Postoperative adverse events

No significant difference existed in stage 1 AKI, stage 2 AKI, stage 3 AKI, ECMO support, infection, chylothorax, pleural effusion, ascites, arrhythmia, delayed sternal closure, re-admission to ICU between BH patients and CA patients (Table 3).

Discussion

In this study, after PSM and data analysis, we found that CA and BH were equally safe, but BH patients had significantly less intraoperative platelet transfusion and blood loss and shorter postoperative ICU stays than CA patients. Overall, we provide evidence that BH is more beneficial in patients who underwent extracardiac TCPC, providing a foothold for improving the prognosis of this patient population.

Although TCPC surgery is widely accepted for the treatment of functionally univentriculare CHD, there is still significant controversy over the optimal surgical strategy. Hypothermia has a protective effect in cardiac surgery, but it can also bring some harm. Previous studies have shown that in some pediatric cardiac surgeries, hypothermic CPB does not bring more short-term or long-term benefits than normothermic CPB [8, 9]. At the same time, adult data studies have shown that on-pump beating heart is superior to on-pump cardiac arrest during surgery [10]. In the present study, BH patients were administered with significantly less intraoperative platelet transfusion and blood loss than CA patients. We infer that the between-group difference in intraoperative platelet transfusion is mainly due to the different temperature management during CPB between the two strategies. CA is usually performed under mild hypothermia, and the resulting longer CPB time and cooling and rewarming times would increase surgery-associated complications, particularly bleeding and coagulation disorders. Rotational thromboelastometry showed that thrombus formation time and clotting time significantly increased as temperature decreased between 25 °C and 37 °C [11]. Mild hypothermia tends to attenuate oxygen consumption, slow down blood cells' metabolic rate, and improve cellular tolerance to cumulative metabolites [12]. Deeper hypothermia may cause prolonged prothrombin time, increased blood concentration, leukopenia, and fibrinolytic disorders [13]. A lower core temperature would cause a more pronounced impairment of the function of vascular endothelium and platelets and thrombin activity [14]. The median of the minimum rectal temperature during CA in this study was 31.1 °C. Typically, temperatures under 33 °C could bring about changes in coagulation cascades leading to decreased thrombin activity and platelet function [15].

Table 3 Early-term outcomes after TCPC of BH and CA patients after PSM

Variables	BH (*n* = 57)	CA (*n* = 57)	*P*
Primary endpoints, *n*(%)			
In-hospital mortality	2 (3.5)	1 (1.8)	1
Death within one year after TCPC	0 (0.0)	2 (3.6)	0.484
Second endpoints			
Intraoperative blood component transfusion			
Platelets (mL)	10.0 (0.0, 300.0)	150.0 (0.0, 300.0)	0.019
Platelet transfusion rate, *n* (%)	27 (50.9)	34 (68.0)	0.119
Plasma (mL)	100.0 (0.0, 200.0)	100.0 (0.0, 200.0)	0.610
Red blood cells (mL)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.457
Intraoperative blood loss (mL)	100.0 (80.0, 150.0)	150.0 (80.0, 200.0)	0.033
Postoperative blood component transfusion			
Platelets (mL)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.329
Plasma (mL)	300.0 (200.0, 400.0)	400.0 (200.0, 400.0)	0.392
Red blood cells (mL)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.461
Albumin (g)	5.0 (0.0, 10.0)	5.0 (0.0, 10.0)	0.159
Recovery indexes			
POD0 VIS	13.0 (10.0, 17.2)	16.0 (13.0, 20.7)	0.011
POD1 VIS	10.0 (8.0, 16.7)	14.0 (12.0, 20.0)	0.014
POD2 VIS	9.0 (0.0, 14.0)	11.0 (9.0, 18.0)	0.023
POD3 VIS	0.0 (0.0, 10.0)	9.0 (0.0, 14.0)	0.020
POD4 VIS	0.0 (0.0, 6.0)	0.0 (0.0, 13.0)	0.016
Mechanical ventilation time (h)	22.0 (17.1, 31.0)	22.9 (18.5, 32.2)	0.241
Length of ICU stay (d)	2.0 (1.0, 4.0)	3.7 (1.9, 6.8)	0.017
Postoperative central venous pressure (mmHg)	10.0 (9.0, 12.0)	11.0 (10.0, 13.0)	0.166
Postoperative fenestration, *n* (%)	1 (1.8)	0 (0.0)	1
Chest drainage volume (mL/d)	229.5 (119.8, 423.0)	231.0 (136.0, 301.0)	0.620
Postoperative adverse events, *n*(%)			
AKI 1 stage	26 (47.3)	23 (41.8)	0.701
AKI 2 stage	0 (0.0)	1 (1.8)	1
AKI 3 stage	4 (7.3)	3 (5.5)	1
ECMO use	2 (3.5)	1 (1.8)	1
Infection	7 (12.3)	15 (26.3)	0.097
Chylothorax	8 (14.3)	11 (20.4)	0.554
Pleural effusion	13 (22.8)	15 (26.3)	0.828
Ascites	3 (5.3)	10 (17.5)	0.077
Arrhythmia	4 (7.0)	4 (7.0)	1
Delayed sternal closure	2 (3.5)	0 (0.0)	0.476
Re-admission to ICU	3 (5.3)	5 (8.8)	0.714

Values are expressed as M±SD, median (IQR), or *n* (%). *ICU* intensive care unit; *POD* postoperative day; *AKI* acute kidney injury; *TCPC* total cavopulmonary connection; *BH* on-pump normothermic beating heart TCPC; *CA* on-pump hypothermic cardioplegic arrest TCPC; *PSM* propensity-score matching; *VIS* vasoactive-inotropic score; *ECMO* extracorporeal membrane oxygenation

In this cohort, there was no significant difference in the perioperative consumption of fresh frozen plasma, red blood cells, and albumin between the two CPB groups, but the patients in the CA group were transfused with more platelets during TCPC. Andreasen et al. found a total reversal of the coagulopathy after pediatric cardiac surgery with the ex-vivo addition of pooled platelets [16]. In their further investigation, hypothermia during CPB impaired platelet function instead of its count, and the duration of CPB is associated with a decrease in platelet count and a reduction in platelet function [17]. As Frelinger et al. explained, hypothermia inhibits platelet aggregation, promotes the formation of adenosine diphosphate-induced leukocyte-platelet aggregates, attenuates the decrease in leukocyte-platelet aggregates induced by glycoprotein IIIa/IIb inhibitors, and reduces platelet factors' activity [18]. Accordingly, we speculated that platelets may be the most vulnerable to hypothermia than other blood components. However, this study found no significant difference in the intraoperative platelet transfusion rate between the two groups. This is related to the balance of patients undergoing secondary surgery between the two groups. Compared with CA, BH is usually carried out under normothermic conditions and the median of the minimum rectal temperature during BH in this study was 34.8 °C, which requires less CPB time and cooling and rewarming times. Therefore, BH may theoretically be superior to the CA.

Ran et al. reported a significant decrease in protein C and a decline in antithrombin III and protein S levels after bidirectional Glenn surgery [19], which may be attributed to the increased intraoperative platelet transfusion in the patients. Consistently, this study showed that bidirectional Glenn surgery history was an independent risk factor for intraoperative platelet transfusion. In terms of myocardial protection, hypothermic cardioplegic arrest contributes to increased intracellular calcium and energy expenditure, increased left ventricular pressure, and increased coronary vascular resistance [20], while prolonged ischemia due to cardioplegic arrest may increase the production of anaerobic metabolites including reactive oxygen species and lactate and raise the risk of bleeding [21]. This study showed that cross-clamping time was an independent risk factor for intraoperative platelet transfusion.

According to our experience, fenestration is often performed in patients who develop low cardiac output syndrome after surgery, have significantly higher CVP, or are still unable to maintain achieved favorable hemodynamics after the use of inotropes, pulmonary vasodilators, or diuretics. No significant difference was seen in intraoperative and postoperative fenestration between the two groups in this cohort. While no significant difference in postoperative CVP was found, postoperative VIS

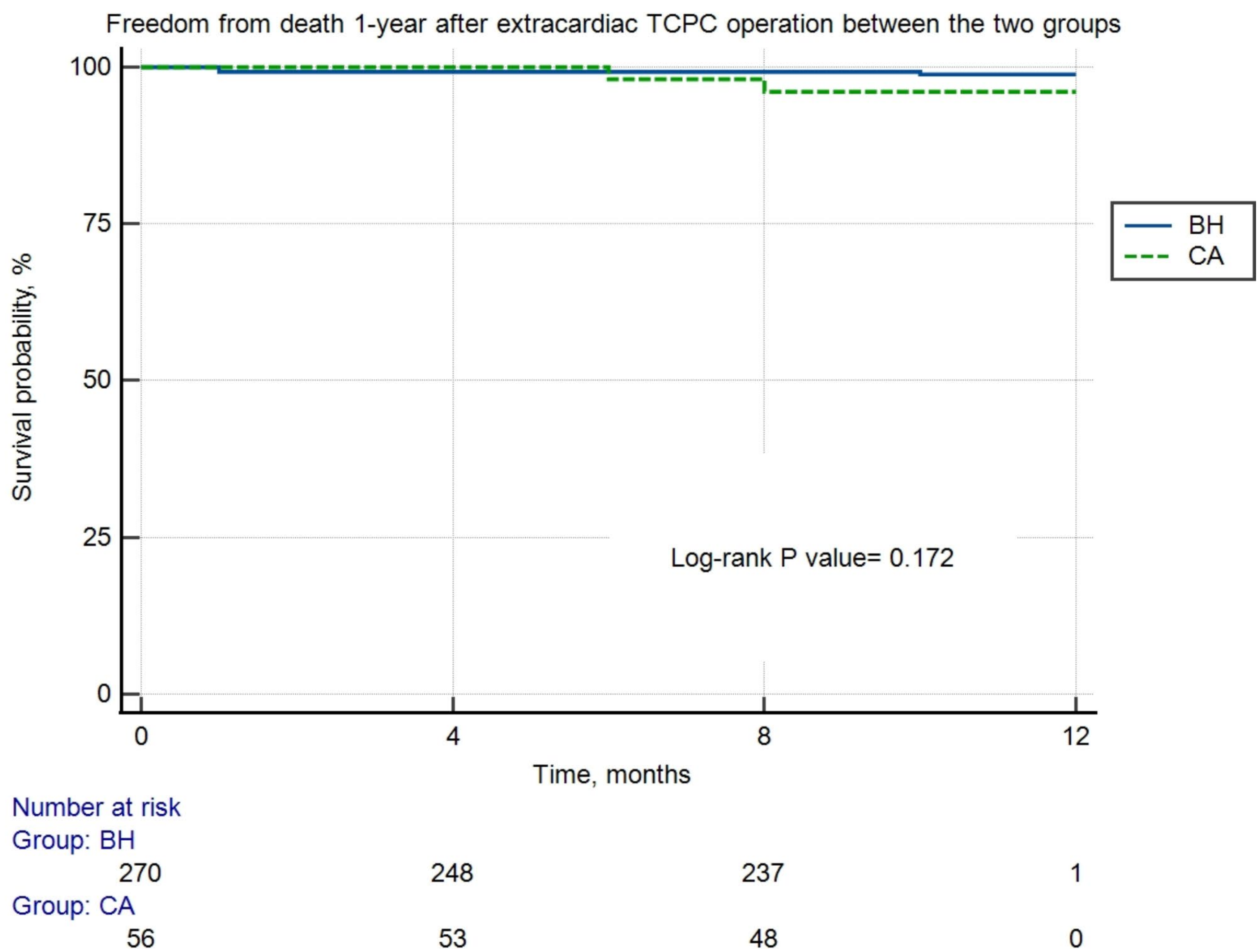

Fig. 1 Freedom from death within one year after TCPC between the BH (on-pump beating heart TCPC) and CA (on-pump cardioplegic arrest TCPC) groups before PSM

was significantly higher in the CA group than in the BH group, indicating that patients in the former group had greater postoperative hemodynamic fluctuations which could be corrected by inotropic drugs. In this study, the patients in the BH group had better recovery from the surgery than the patients in the CA group. Prolonged postoperative ICU stays in CA patients may be due to increased platelet transfusion under intraoperative hypothermic conditions, significantly prolonged myocardial ischemia time, and increased postoperative VIS [22].

Common complications after TCPC are massive pleural effusion, chylothorax, arrhythmia, AKI, infections, serious conditions for which ECMO is used, and death [23, 24], which pose great challenges to the prognosis and management of patients. In this study, no significant difference in the incidence of postoperative adverse events was found between the two CPB groups, which verified the feasibility and rationality of both CPB techniques. Both techniques have their advantages. Non-beating (arrested) hearts provide surgeons with satisfactory cardiac exposure to correct defects and benefit vascular anastomosis, and an arrested heart can be easily moved in a quiet state. In the future, a large, multicenter, randomized, prospective study is warranted to compare these two CPB strategies from various aspects and to find their optimal populations of extracardiac TCPC.

This study has many strengths. We adjusted for many confounding factors and PSM was conducted to minimize confounding bias. To our knowledge, this study is a relatively large sample of pediatric patients who underwent extracardiac TCPC. This study has an important clinical guideline for the selection of surgical methods in clinical practice and will help to improve the postoperative outcomes in this population.

However, this present study has several limitations. First, this study is a single-center retrospective study, and despite the inclusion of a lot of variables to control the potential confounders, selection bias and unknown heterogeneity are present. This may limit the introduction of our findings to clinical use in all health-providing centers.

Table 4 Intraoperative data after PSM

Variables	BH ($n=57$)	CA ($n=57$)	*P*
CPB time (min)	91.0 (76.0, 118.0)	139.0 (110.0, 169.0)	< 0.001
Cross-clamping time (min)	0.0 (0.0, 0.0)	60.0 (51.0, 81.0)	< 0.001
The minimum rectal temperature during CPB (℃)	34.7 (34.2, 35.2)	31.1 (29.0, 32.2)	< 0.001
The minimum nasopharyngeal temperature during CPB (℃)	33.8 (33.1, 34.7)	28.7 (27.2, 30.0)	< 0.001
Cooling time (min)	0.0 (0.0, 46.0)	74.0 (43.0, 103.0)	< 0.001
Rewarming time (min)	0.0 (0.0, 16.0)	38.0 (28.0, 45.0)	< 0.001
Mean arterial pressure (mmHg)	50.0 (44.0, 60.0)	51.0 (42.8, 61.3)	0.901
Fenestration, *n* (%)	16 (28.1)	24 (42.1)	0.170
Cardioplegia, *n* (%)			< 0.001
Histidine-tryptophan-ketoglutarate solution	0 (0.0)	21 (36.8)	
St. Thomas solution	0 (0.0)	34 (59.6)	

Values are expressed as mean ± SD, median (IQR), or *n* (%). *CPB* cardiopulmonary bypass; *PSM* propensity-score matching; *BH* on-pump normothermic beating heart TCPC (total cavopulmonary connection); *CA* on-pump hypothermic cardioplegic arrest TCPC

Second, the limited sample size and data may not allow reporting of other potential risks. Besides, only short-term results were reported and further long-term follow-up data and analyses are of significance. Third, even though the sample size of this study is currently relatively large under this topic, we still cannot avoid type 1 and type 2 errors due to our limited sample size. Fourth, We have recorded whether there is a cardiothoracic surgery history. However, we did not record the number of cardiothoracic surgeries before TCPC surgery in the data.

In conclusion, both CPB techniques are safe and feasible in extracardiac TCPC, but CA would increase intraoperative platelet transfusion and blood loss, increase postoperative VIS, and prolong postoperative ICU stay. BH may be superior to CA due to less blood component consumption and faster early-term postoperative recovery.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12872-024-04210-5.

Supplementary Material 1

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Author contributions

Author contributions: Jinping Liu: Conceptualization, Methodology, Software. Wenting Wang: Data curation, Wring-Original draft preparation. Peiyao Zhang: Software, Validation. Yu Jin: Wring-Reviewing and Editing. Jia Liu: Visualization. He Wang: Data curation. All authors reviewed this manuscript.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval and consent to participate

This work was approved by the ethical committee of Fuwai Hospital of the Chinese Academy of Medical Sciences (Beijing, China) (NO.2014–600). Written informed consent was waived due to the retrospective nature of the study and approved by the Ethic Committee of Fuwai Hospital.

Consent for publication

Not applicable.

Clinical trial number

Not applicable.

Competing interests

The authors declare no competing interests.

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Table 5 Univariable and stepwise multivariable logistic analyses of risk factors of perioperative platelet transfusion before PSM

Variables	Univariable analysis			Multivariable analysis		
	OR	95% CI	*P*	OR	95% CI	*P*
CPB time (min)	1.003	0.999, 1.008	0.132			
Cross-clamping time (min)	1.012	1.001, 1.022	0.027	1.019	1.005,1.034	0.009
Cooling time (min)	1.011	1.005, 1.017	0.001			
Rewarming time (min)	1.019	1.005, 1.034	0.008			
The minimum rectal temperature during CPB (℃)	0.843	0.740, 0.961	0.010			
Bidirectional Glenn before TCPC, *n* (%)	25.312	13.595, 47.129	< 0.001	5.929	1.454, 24.177	0.013
Cardiothoracic surgery history, *n* (%)	25.358	13.463,47.764	< 0.001	5.436	1.277,23.136	0.022

PSM propensity-score matching; *OR* odds ratio; *CI* confidence interval; *CPB* cardiopulmonary bypass; *TCPC* total cavopulmonary connection

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