

Early post-operative outcomes in very young infant patients after off-pump periventricular hybrid surgery vs. on-pump traditional cardiopulmonary bypass

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ABSTRACT

Background: Traditionally ventricular septal defects (VSDs) are corrected via open-heart surgery under cardiopulmonary bypass (CPB), which involves prolonged anesthesia and increases the risk of neurological complications in very young children. In the present retrospective study, we compare early post-operative outcomes of traditional CPB versus a periventricular hybrid surgery (PHS) for VSD correction in infants aged ≤ 1 year.

Methods: The patients were divided into the PHS cohort (n=181) and the CPB cohort (n=189), treated between 2016 and 2024 at a single center.

Results: The hybrid approach significantly reduced the duration of anesthesia, mechanical ventilation, intensive care unit (ICU) stay, and in-hospital stay. The post-operative left ventricular ejection fraction (LVEF) was significantly higher while its change vs. pre-operative level was significantly lower in the PHS vs. CPB cohort. Only 21% of PHS patients required inotropic support, compared to 95.8% of CPB patients. Notably, the CPB cohort exhibited a significantly higher incidence of early post-operative transient neurological disorders vs. the PHS cohort (46.0% vs. 8.3%). We identified age as well as weight, height, and body surface area as risk factors for neurological complications in both surgical cohorts, regardless the type of a neurological complication. Additionally, we revealed lowered intraoperative arterial pressure and elevated post-operative LVEF as independent risk factors.

Conclusions: The hybrid VSD correction is a highly effective and safer alternative to traditional open-heart surgery for infants. It significantly minimizes early post-operative morbidities, reduces recovery times, and dramatically lowers the incidence of transient brain ischemia that can result in various neurological disorders.

Keywords: congenital heart defect, ventricular septal defect, infant patients, open-heart surgery, hybrid surgery, early post-operative complications, neurological disorders.

Introduction

The traditional on-pump open-heart surgery for ventricular septal defect (VSD) is the widely spread method [1,2]. However, the surgery requires cardiopulmonary

bypass (CPB) which may be risky in very young infants and is inevitably time-consuming procedure due to the use of an artificial circulatory machine. Consequently, the period of anesthesia is generally longer in the CPB setting

,compared to CPB-free methods. Moreover, the standard approach in the CPB requires operating at lowered arterial pressure. This in turn elevates risks of transient brain ischemia, occurrence of seizures, and may result in long-term neurodevelopmental impairments [3]. Also, this type of highly invasive surgery is associated to a high extent of postoperative pain and risk of post-operative wound infections [4].

The alternative to the CPB-based surgery are transcatheter closure techniques. The perventricular hybrid surgery is considered a safe alternative with much shorter duration of the procedure and much smaller surgical wound [5,6]. The success rates of this surgery are as high as 95%, with low rates of post-surgical complications [7-9]. The advantages of the hybrid surgery are especially important for very young infants due to the substantially shortened peri-operative time and therefore shortened period of anesthesia. However, little is known whether the generally shortened surgical operation may also provide better post-surgical outcomes, in particular for the incidence of neurological disorders.

The aim of our present study was to compare the pre-operative characteristics and outcomes of the cardiac surgery performed in infants aged under one year who underwent VSD correction using the traditional method (open-heart under CPB) and the hybrid surgery. We thoroughly evaluated various functional outcomes, with specific focus on neurological complications, in the infants subjected to either type of surgery. This allowed us to reveal certain risk factors affecting early post-operative safety of VSD correction in very young children.

Methods

This retrospective study included 370 infants aged ≤ 12 months at the time of surgery performed in 2016-2024 at our center. The patients were subjected to surgical VSD correction under traditional open-heart surgery (stopped heart, 189 patients, CPB cohort) or under perventricular hybrid surgery (beating heart, 181 patients, PHS cohort). In the latter cohort, no patients required conversion to the CPB surgery. All surgeries were performed by the same team of expertized pediatric cardiac surgeons who had at least 100 VSD corrections in a year.

The perventricular hybrid surgery was performed as follows: a) ministernotomy sized of 2-3 cm was performed above the xiphoid process; b) pericardium was opened over the avascular zone of the right ventricle (RV); c) RV was punctured by 7 Fr needle through which a guidewire was inserted into the VSD under transesophageal echocardiography (TEE) guidance; d) an introducer sheath was inserted through which the occluder was delivered to the defect and positioned; e) the function of aortic and tricuspid valves was assessed under continuous ECG; f) a residual shunt on the interventricular septum was evaluated and if no or minor, the occluder was opened; g) a stable position of the occluder was verified under TEE; h) in the case of proper installation of the occluder, the delivery system was disconnected from the occluder, and the wound was surgically closed. All occluders were manufactured by Lepu, China.

The traditional open-heart surgery was performed via median sternotomy with standard CPB under moderate hypothermia at 28-32°C and blood cardioplegia condition. After cardiac arrest, an 8-to-10-cm incision was made in the right atrium, and the defect was closed either with autologous pericardium patch or by polytetrafluoroethylene (PTFE, manufactured by Lepu, China) patch under visual control. The

actual choice depended on the defect size and the anatomical features of the heart.

Both cohorts received multicomponent anesthesia including analgesics (0.005% Fentanyl solution, 2 ml), muscle relaxants (Arduan and Romeran solutions), and a sedative (Diprivan solution). In addition to monitoring hemodynamic parameters and vital organ function, the infant's neurological status was assessed during all stages of treatment: during anesthesia in the operating room, in the intensive care unit (ICU), and in the hospital until the discharge.

General statistical analysis included the mean, median, standard deviation, and interquartile range which all were calculated using MS Excel. Complex statistical evaluations were performed with SPSS (version 10). To assess data normality, the Shapiro-Wilk test was applied; because the majority of samples departed from normality, non-parametric approaches were further used. Differences across cohorts were evaluated by Mann-Whitney U test. Categorical frequencies were evaluated with the Chi-square test or Fisher's exact test when analyzing 2x2 contingency tables with expected cell counts under 5. To determine how various factors influenced the occurrence of both post-operative neurological impairment, we used a Generalized Linear Model (GLZ) with a logit link function and parameter significance was measured via Type III Likelihood Ratio tests. Inverse Probability Treatment Weighting (IPTW) was applied to minimize bias of age (see Results), followed by a weighted comparison of continuous metrics between the PHS and CPB cohorts. Unless specified otherwise, continuous values are reported as median (interquartile range) through the text.

Results

All patients involved to the study were alive at the time of reporting the data. No one patient experienced rhythm disturbances or other complications before the surgery was performed. As similar, none of them had any brain or nerve problems prior to the surgery. Preoperative infections (CMV or Epstein-Barr) were found in eight and two patients in the CPB cohort and PHS cohort, respectively ($p=0.060$); these patients were treated by specific antimicrobial therapy in the preoperative period before surgery.

The cohorts were not similar in the proportion of sex: 73 males and 108 females in the PHS cohort vs. 96 males and 93 females in the CPB cohort ($p=0.043$). The PHS cohort patients were also older than those in the CPB group, with the median age of 7.4 (5.0-9.8) months vs. 5.0 (3.4-7.0) months, respectively ($p<0.001$, Figure 1A). We therefore performed age-balance adjustment by Inverse Probability Treatment Weighting, and we used age-adjusted values for all inter-cohort comparisons of continuous measurements. Despite the age-adjustment, the following median values were larger in the PHS cohort vs. CPB cohort: weight – 7.5 (6.4-8.5) vs. 5.6 (5.0-6.9) kg, height – 71 (65-74) vs. 63 (60-68) cm, body surface area (BSA) – 0.38 (0.35-0.42) vs. 0.31 (0.29-0.35) m² (all $p<0.001$, see Figure 1A). Note that we used Mosteller formula to calculate BSA from weight and height ($BSA = \text{square root of weight*height}/3600$).

The prevalence of patients with preoperative hypertension was significantly smaller in the PHS cohort vs. the CPB cohort: 18 patients or 9.9% vs. 149 patients or 78.8% ($p<0.001$). This was accompanied by significantly higher preoperative LV-to-RV gradient and LV ejection fraction (LVEF) in the PHS cohort vs. the CPB cohort: LV-to-RV gradient – 55 (48-65) vs. 28 (16-40) mmHg, LVEF – 68% (65-72) vs. 66% (64-71); $p<0.001$

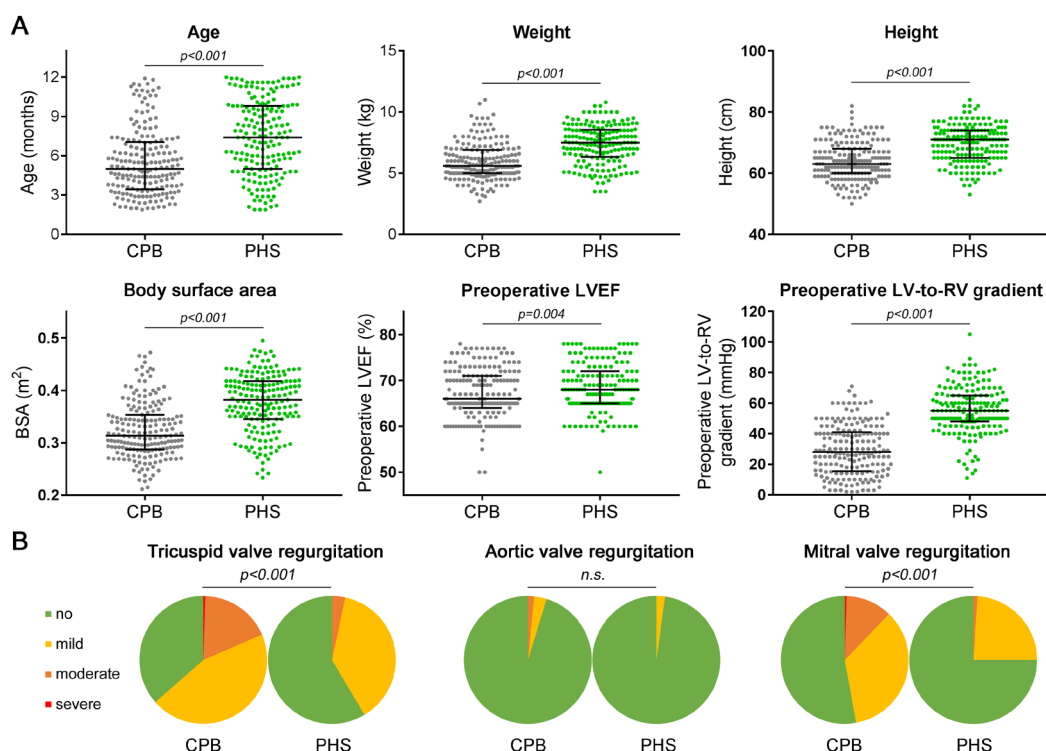


Figure 1 – Pre-operative differences in various characteristics of the patients appointed to the PHS or CPB cohorts

Panel A: raw data points for age, weight, height, body surface area (BSA), preoperative LVEF (%), and preoperative LV-to-RV gradient obtained in the patients of the PHS and CPB cohorts. Scatter plots with median and interquartile range are shown. **Panel B:** distributions for the severity of tricuspid valve, aortic valve, and mitral valve regurgitation at the time of hospital admittance. Significant difference between PHS and CPB cohorts is shown (all at the level of $p < 0.01$ except no significant difference for distribution of aortic valve regurgitation severity).

and $p = 0.004$, respectively, for these two parameters (see also Figure 1A). Despite substantially lower preoperative LVEF in the CPB cohort, the proportion of those patients who had $LVEF < 55\%$ was similar between the cohorts (0.6% and 1.1% in the PHS vs. CPB cohort, respectively, $p = 0.516$).

The prevalence of patients with more severe tricuspid regurgitation and mitral valve regurgitation was significantly higher in the CPB cohort ($p < 0.001$). Despite this significant difference, the severity grades for aortic valve regurgitation were evenly distributed between the two cohorts ($p = 0.197$),

where 97.8% and 95.2% of the patients in the PHS and CPB cohorts, respectively, had no aortic valve regurgitation. The detailed distribution of patients by the severity of valve regurgitation in the two cohorts is shown in Table 1. Note that the significantly higher proportion of patients with more severe mitral valve failure in the CPB cohort was not accompanied by significantly lower pre-operative LVEF but was strongly associated to reduced LV-to-RV gradient. According to this finding, the observed baseline LVEF in the patients with mitral regurgitation may be artificially higher not because of greater LV contractility, but due to excessive blood ejection into the left atrium. This makes difference in LVEF between PHS and CPB cohorts non-significant.

The prevalence of perimembranous type of VSD was absolute in the CPB cohort, with 98.4% cases against 1.6% of muscular type. The PHS cohort had nearly two thirds of perimembranous VSD types vs. one third of muscular type (66.3% vs. 33.7%, respectively). Accordingly, the two cohorts were significantly different in the prevalence of various VSD types ($p < 0.001$, Figure 2, left panel). Moreover, median VSD size was much smaller in the PHS cohort vs. CPB cohort: 5 (5-6) vs. 13 (11-15) mm, respectively ($p < 0.001$). More detailed view of the distribution of VSDs by their sizes is shown in Figure 2, right panel. Note that nearly half of the CPB patients had VSD side equal to or larger than 15 mm, whereas no such patients were observed in the PHS cohort. The remarkable difference is easily explained by the indication for selecting the surgical method – in case of large VSD, the patient was admitted to the CPB version of surgery. Similar to the influencing factor, the median wound size in the PHS cohort was 3 mm vs. 10 mm in the CPB cohort (Table 2). In both surgical techniques, the total blood loss during the surgery was not different between the PHS

Table 1

The distribution of severity of tricuspid, aortal, and mitral valve regurgitation in the patients of the PHS and CPB cohorts

Parameter		PHS cohort n=181	CPB cohort n=189	p-value
Tricuspid valve regurgitation, n (%)	no	106 (58.6%)	69 (36.5%)	<0.001 *
	mild	69 (38.1%)	85 (45.0%)	
	moderate	6 (3.3%)	34 (18.0%)	
	severe	0 (0%)	1 (0.5%)	
Aortic valve regurgitation, n (%)	no	177 (97.8%)	180 (95.2%)	0.197
	mild	4 (2.2%)	6 (3.2%)	
	moderate	0 (0%)	3 (1.6%)	
	severe	0 (0%)	0 (0%)	
Mitral valve regurgitation, n (%)	no	135 (75.0%)	100 (52.9%)	<0.001 *
	mild	43 (23.9%)	66 (34.9%)	
	moderate	2 (1.1%)	22 (11.6%)	
	severe	0 (0%)	1 (0.5%)	

Note: Data shown as actual number (percentage in the cohort). LV – left ventricle, LVEF – left ventricular ejection fraction, PH – pulmonary hypertension, RV – right ventricle. * indicates significant difference between PHS and CPB cohorts ($p < 0.05$).

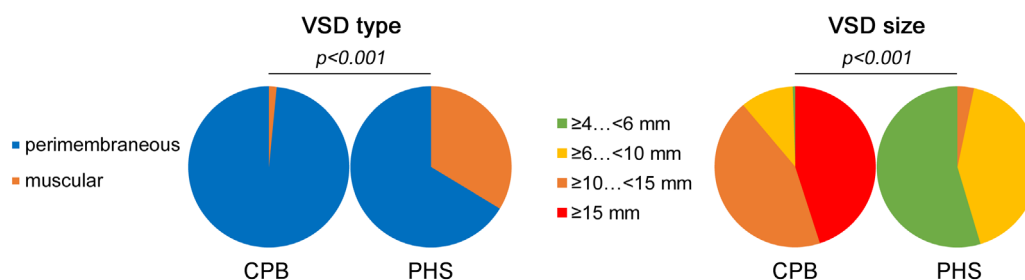


Figure 2 – The difference in VSD type (left panel) and VSD size (right panel) distributions between the CPB and PHS cohorts of patients

The difference level between the PHS and CPB cohorts is indicated.

Table 2

Peri-operative and early post-operative parameters in the patients of the PHS and CPB cohorts

Parameter	PHS cohort n = 181	CPB cohort n = 189	p-value
Wound size, cm	3 (3-3)	10 (8-10)	<0.001 *
Blood loss, mL	10 (10-15)	10 (10-20)	n.s.
Post-operative LV-to-RV gradient, mmHg	55 (48-65)	28 (16-40)	<0.001 *
Post-operative LVEF, %	60 (60-66)	55 (50-56)	<0.001 *
Post-operative change in LVEF, %	-5 (-8...0)	-15 (-20...-9)	<0.001 *
Residual RV-to-LV shunt, mm	0.2 (0.19-0.3)	0.2 (0.2-0.25)	n.s.
Duration of anesthesia, min	120 (100-140)	240 (180-240)	<0.001 *
Duration of mechanical ventilation (operating room + intensive care unit), hours	5.0 (4.0-7.0)	13.0 (9.0-26.0)	<0.001 *
Duration of stay in intensive care, days	1.0 (0.8-1.0)	2.0 (1.0-4.0)	<0.001 *
In-hospital stay, days	10 (8-15)	18 (13-28)	<0.001 *

Note: Data shown as median (interquartile range) or as actual number (percentage in the cohort). LV – left ventricle; LVEF – left ventricular ejection fraction; RV – right ventricle. * indicates significant difference between PHS and CPB cohorts ($p<0.05$).

and CPB cohorts: median values are 10 mL (10-15 mL) vs. 10 mL (10-20 mL), respectively.

The post-operative ventricular function was always better in the PHS patients vs. CPB patients. The LV-to-RV gradient was 55 (48-65) mmHg in the PHS cohort vs. 28 (16-40) mmHg in the CPB cohort ($p<0.001$, Figure 3). Similarly, the post-operative

LVEF was significantly higher in the PHS cohort compared to the CPB cohort, approximately by 5 percent units ($p<0.001$, Figure 3). Generally, the post-operative LVEF was lower compared to the pre-operative value in both cohorts; however, the absolute decrease was much higher in the CPB cohort vs. the PHS cohort: 5 percentage units against 15 percentage units, respectively ($p<0.001$, Figure 3). In other words, periventricular hybrid surgery preserved the contractility of the LV better compared to the traditional on-pump surgery. Importantly, no difference was revealed for the post-operative residual LV-to-RV shunt indicating similar technical quality of both surgical methods; it is therefore likely that the inferior functional and late post-operative outcomes (e.g. neurological disorders, see later) in the CPB surgery develop due to the overall prolonged procedure compared to the much shorter duration of the hybrid surgery.

Indeed, the duration of anesthesia, duration of mechanical ventilation (operating room + intensive care unit), duration of stay in intensive care, and overall in-hospital stay were significantly shorter in the PHS cohort vs. CPB cohort (all with $p<0.001$, see Figure 4). All the duration in the PHS cohort were approximately twice lower vs. the CPB group indicating much faster procedural duration and post-procedural recovery of the patients.

Inotropic support was needed much often in the patients of CPB cohort. We analyzed in detail whether no inotropic support, the use of a single inotropic or the combination of adrenaline, dobutamine and dopamine were needed, and how long was this inotropic support. The majority of PHS patients did not require the inotropic support at all (143 patients, 79.0%) whereas as few as just 8 patients (4.2%) in the CPB group were free from

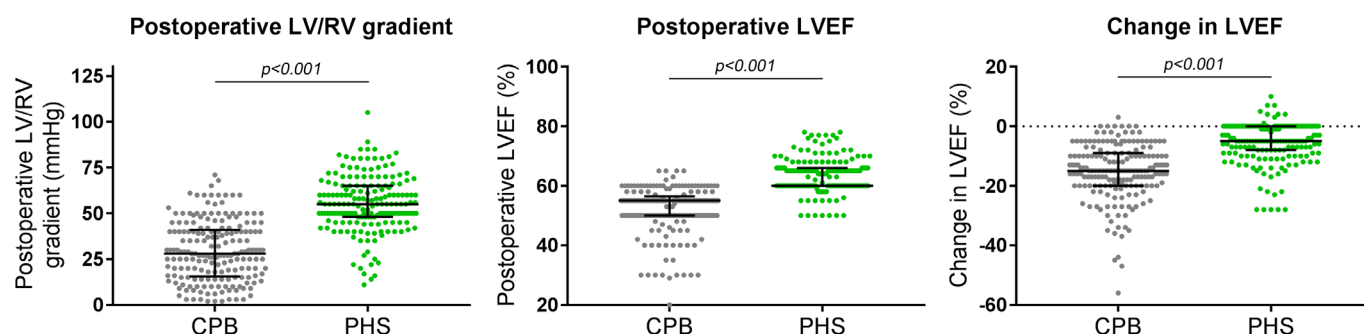


Figure 3 – The raw data plots for post-operative values of LV-to-RV gradient, LVEF, and change in LVEF compared to the pre-operative value in the CPB and PHS cohorts of patients

The difference level between the PHS and CPB cohorts is shown.

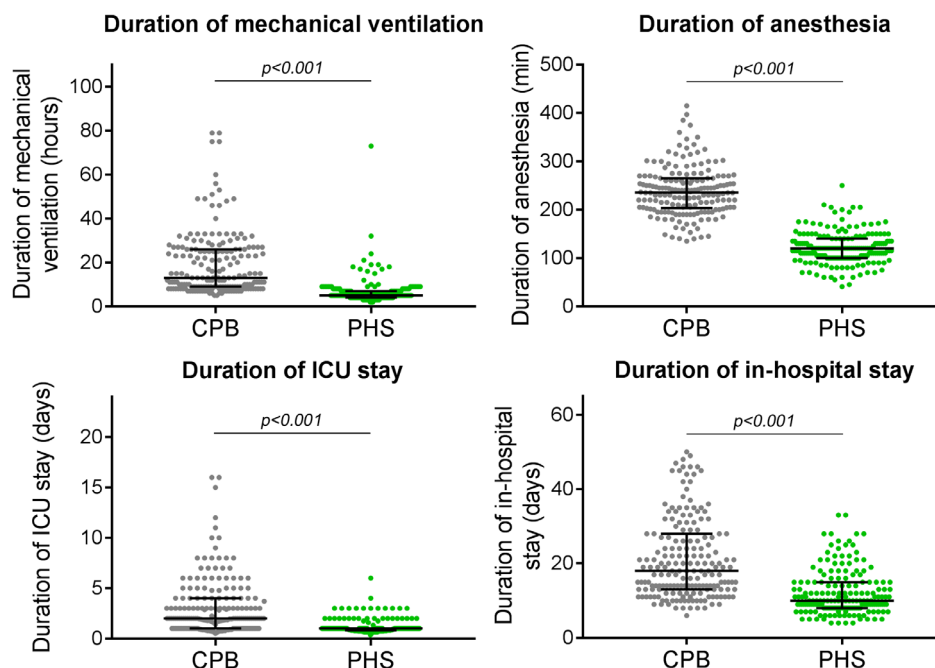


Figure 4 – The raw data values for the duration of anesthesia, mechanical ventilation, stay in the ICU, and total in-hospital stay for the patients of the CPB and PHS cohorts

The difference level between the PHS and CPB cohorts is shown.

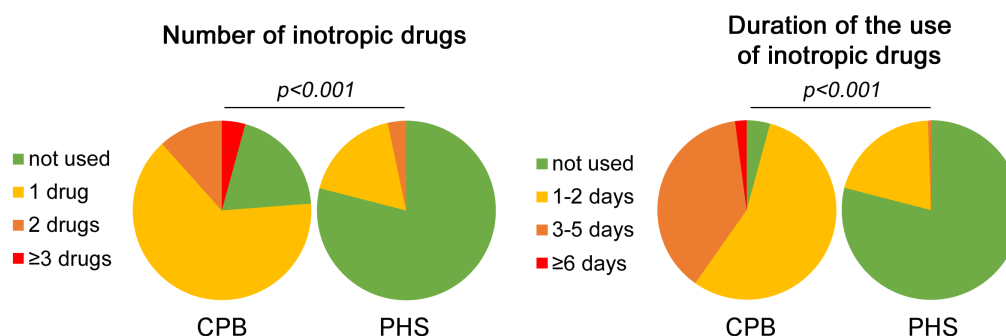


Figure 5 – The distribution diagrams for the number of different inotropic drugs (left panel) and the duration of the use of inotropic drugs (right panel) between the CPB and PHS cohorts of patients

The difference level between the PHS and CPB cohorts is indicated.

this support (Figure 5, left panel). Thirty-two patients (17.7%) in the PHS cohort required using one inotropic drug and only six patients (3.3%) required using two (and no one required more than two). In contrast, the absolute majority of the CPB patients did require inotropic support. Twenty-one (19.6%) of them required one inotropic drug. Of note, in >76% patients of this cohort it was not enough to use only one inotropic drug, so two (80 patients, 64.6%) or three inotropic drugs (16 patients, 11.6%) were needed to support adequate contractile function of the heart post-operatively. Collectively, the PHS and CPB cohort were significantly different in the number of inotropic support ($p < 0.001$). Substantially the same was found for the number of days where the inotropic support was needed (Figure 5, right panel). Only one patient in the PHS cohort required using inotropic drugs for 3-5 days but for other supported patients the duration was 1-2 days only (37 patients, 20.4%). This is much contrasting to the CPB cohort, where 105 patients (55.6%) required 1-2 days of the support, 72 patients (38.1%) – 3-5 days,

and 4 patients (2.1%) – more than 5 days. The distribution of the duration of the inotropic support was therefore significantly different between the cohorts ($p < 0.001$).

As shown in Table 3, post-operative complications were observed only in the patients of CPB cohort (11 infants, 5.8%). The complications were as follows: pleuritis (1), bleeding (1), rhythm disturbances (4), heart failure/diastolic failure (4), and neurology (1). Slightly less than a half of patients in the CPB cohort (84 patients, 44.4%) experienced post-operative pulmonary hypertension. In contrast, only 16 patients (8.8%) in the PHS cohort had this type of complication ($p < 0.001$ vs. CPB cohort). Similar to this proportion, post-operatively lowered LVEF was observed in seven patients (3.9%) of the PHS cohort vs. 91 patients (48.1%) of the CPB cohort ($p < 0.001$). Residual shunt was also much frequent in the CPB cohort vs. PHS cohort (74 infants (39.2%) against 28 infants (15.5%), respectively, $p < 0.001$). Surprisingly, the rate of RV/LV outflow tract obstruction was significantly more frequent in the PHS cohort

Table 3

The rate of post-operative complications in the patients of PHS and CPB cohort

Parameter (n of patients)	PHS cohort n = 181	CPB cohort n = 189	p-value
Post-operative complications	0 (0%)	11 (5.8%)	<0.001 *
Post-operative pulmonary hypertension	16 (8.8%)	84 (44.4%)	<0.001 *
Post-operatively low LVEF	7 (3.9%)	91 (48.1%)	<0.001 *
Residual RV-to-LV shunt	28 (15.5%)	74 (39.2%)	<0.001 *
Obstruction of RV/LV outflow tract	9 (5.0%)	1 (0.5%)	0.008 *

*Note: Data shown as actual number (percentage in the cohort). LV – Left Ventricle; LVEF – Left Ventricle Ejection Fraction; RV – Right Ventricle. * indicates significant difference between PHS and CPB cohorts (p<0.05).*

Table 4

The detailed representation of patients in the PHS and CPB cohort who had transient brain ischemia post-operatively and at the discharge

Parameter		PHS cohort	CPB cohort	p-value
All types of transient neurological disorders in early post-surgery period, n (% of all neuro-disorder cases)		15 (100%)	87 (100%)	
seizures		8 (53.3%)	22 (25.3%)	<0.001*
gaze fixation		1 (6.7%)	12 (13.8%)	
nystagmus		0 (0%)	2 (2.3%)	
hypertonicity		4 (26.7%)	25 (28.7%)	
tremor		2 (13.3%)	21 (24.1%)	
hemiparesis		0 (0%)	5 (5.7%)	0.198
Persisting neurological disorders during discharge from the hospital, n (% of patients who suffered from the neurological disorder at the ICU)	no	14 (93.3%)	69 (79.3%)	
	yes	1 (6.7%)	18 (20.7%)	

*Note: Data shown as actual number (percentage in the cohort). ICU – intensive care unit. * indicates significant difference between PHS and CPB cohorts (p<0.05).*

vs. the CPB cohort: nine patients (5.0%) vs. one patient (0.5%), respectively (p=0.008).

Finally, we compared the rate of incidence of neurological dysfunction in the patients from the PHS and CPB cohorts. We evaluated specific clinical signs of the following neurological disorders: seizures, gaze fixation, nystagmus, hypertonicity, tremor, or hemiparesis. Each finding was verified by functional ultrasound measurements of brain regions (hypoxia was confirmed by increased density of echo signal). Mini-invasive hybrid surgery resulted in a very low incidence of in-hospital neurological disorders but the opposite was for the open-heart on-pump CPB surgery (Table 4). Only 15 infants (8.3%) of the PHS cohort developed transient brain ischemia vs. as many as 87 infants (46.0%) in the CPB cohort (p<0.001). In the PHS cohort, the most common type of “at-the-ICU” disorder were seizures (8 out of 15 patients, 53.3% of all types of neurological disorders). Hypertonicity and tremor were the other two most frequent types (four patients (26.7%) and two patients (13.3%), respectively). We did not observe a single case of nystagmus or hemiparesis in the PHS cohort. The proportion of different types of neurological disorders in the CPB group was substantially dissimilar from that of the PHS cohort. Three

types – seizures, hypertonicity, and tremor – were almost equally frequent: in 22 patients (25.3%), 25 patients (28.7%), and 21 patients (24.1%), respectively. In addition, gaze fixation and hemiparesis were observed in 12 patients (13.8%) and five patients (5.7%) of the CPB group, respectively, which was much frequent compared to the PHS cohort where only one patient had gaze fixation. The distribution of the types of transient neurological disorders was therefore significantly different between the cohorts (p<0.001). However, the proportion of those infants who had persisting neurological disorders at the time of discharge was similar between the cohort: in one out of 15 in the PHS cohort and in 18 out of 87 in the CPB cohort (p=0.198).

By using a logit link model we revealed that the risk of post-operative transient neurological disorder (of any type) was higher in older patients (OR = 1.19 (1.05-1.35), p=0.004). Accordingly, weight, height, and BSA values (all inherently linked to the age) were also the variables positively affecting the risk. Moreover, the following variables were found to be independent risk factors for the incidence of neurological outcomes: lowered intraoperative arterial pressure (OR = 0.92 (0.88-0.98), p=0.003) and elevated post-operative LVEF (OR = 1.04 (1.00-1.08), p=0.030). Collectively, these findings allow stratification of patients to the groups with low and high risk of post-procedural neurological outcomes.

Discussion

Off-pump transcatheter techniques for closing VSD by a delivered occluder are considered currently as a successful alternative to the traditional on-pump open-heart surgery using CPB. The hybrid periventricular VSD closure has been introduced nearly 15 years ago [10,11]. Currently, numerous studies are available including large clinical trials that support efficacy and safety of this type of surgery, including infants with age of <1 year [2,9,12-15]. The overall duration of the procedure is almost half that of traditional open-heart surgery, and this is also associated to the shorter stay in the ICU and overall stay in the hospital [5,9,12]. The present data strongly follow these findings.

Infants, toddlers, and very young children represent a particularly at-risk patient group, especially when undergoing on-pump open-heart procedures. Open-heart surgery necessitates the use of cardiopulmonary bypass (CPB) and the stopped heart to ensure safe surgery outcome. For decades, this technique has been regarded as the gold standard and is routinely employed in hospitals across the globe, given the broad availability of skilled and experienced surgical teams [1,2,11]. Nevertheless, employing CPB in very young pediatric patients is an intricate procedure that impacts numerous physiological systems and may result in cardiac arrhythmia, systemic inflammatory response, encephalopathy, and systemic thrombosis [16]. In addition, postoperative pain resulting from full sternotomy, along with the scarring that follows, remains a significant issue – particularly when contrasted with the hybrid approach, in which the much smaller wound size makes this a comparatively minor concern. Extracorporeal circulation is also associated to diminished cerebral oxygen delivery, which is the main driver of transient cerebral hypoxia/ischemia and the neurological post-surgical complications like impaired motor function and transient hemiparesis [17-21]. Various studies consistently indicate that around 2-5% of patients undergoing open-heart surgery experience early-onset neurological complications [22-25].

Among the different forms of transient neurological disturbance, seizures emerge as the most frequently observed complication [23-25]. According to some studies, this condition can account for more than half of all reported cases [22,23]. Additional complications include stroke and delirium, which tend to appear early on, as well as cognitive impairments that emerge as longer-term or delayed effects. The reported incidence rates for these sorts of complications widely range anywhere from a small fraction of cases up to approximately 50% [21,26,27].

Our findings point to a relatively elevated incidence of various transient neurological disorders within the CPB cohort, reaching 46%. This marked difference from previously published figures may be attributable to the fact that our study focused specifically on infant patients, whereas other studies encompassed patients ranging up to 18 years of age. Additionally, we documented all transient neurological complications, including gaze fixation and nystagmus, which contributed to a higher overall incidence within the CPB cohort. By contrast, the minimally invasive hybrid technique was associated with a substantially lower incidence of early postoperative in-hospital neurological complications, affecting fewer than 10% of patients overall. Following targeted therapy, the incidence of cerebrovascular events declined in both cohorts by the time of hospital discharge, with the PHS cohort maintaining a rate several times lower than that of the CPB cohort.

Mortality among patients who develop a neurological disorder shortly after open-heart surgery poses a substantial challenge. Some reports indicate that mortality in this population can reach as high as 20% [22], with other studies citing rates approaching one-third [23]. Notably, younger age correlates with a higher incidence of neurological disorders, and this incidence rises further still among those under one year of age [24]. It appears that, linked to this younger age, lower body weight has also been identified as a contributing risk factor for neurological complications [24]. However, in our study we found that the older age plays as an additional risk factor for neurological disorders in both the open-heart and hybrid surgery groups. However, compared to other studies where the patients were aged much widely, in our study we focused only on those aged ≤ 12 months. Therefore, our finding about the age as a risk factor should be interpreted solely for this very narrow age range rather than for all ages.

In addition to the age, other factors have been reported to influence the risk of neurological disorder incidence among pediatric patients undergoing cardiac surgery for congenital heart defects. A prolonged duration of extracorporeal circulation during CPB is recognized as a risk factor for major complications [28], including neurological disorders and cognitive impairment [19]. Among infants undergoing cardiac surgery with CPB at under 3 months of age, the rate of new postoperative brain injury exceeded 50% [29] – exactly the same was found in our present study. Notably, intraoperative oxygen saturation measured following tracheal intubation was linked to poorer outcomes, whereas intraoperative cerebral oxygen saturation levels showed no such association [30]. This finding stands in contrast to other studies, which identified reduced cerebral microvascular oxygenation (as measured by near-infrared spectroscopy) as a significant predictor of major adverse events, including neurological complications [28,31,32]. Since cerebral oxygen levels were not monitored as part of our routine surgical procedures, we are unable to determine whether intraoperative changes in this parameter might predict the severity of neurological outcomes.

There is a very important aspect of our study that must be noted. Neurological outcomes following heart surgery are strongly dependent on the preoperative condition of brain tissue, largely shaped by metabolic status and oxygen availability. Congenital heart defects fall into two broad categories – commonly termed blue (cyanotic) and pale (acyanotic) defects – with the former being closely linked to diminished cerebral oxygen supply and consequently persistent cerebral hypoxia [33,34]. Notably, our dataset consisted exclusively of acyanotic patients presenting with a single muscular or perimembranous VSD, meaning their preoperative cerebral oxygen saturation would be only marginally below normal levels. This allows us to anticipate a fairly minimal contribution of preoperative status to postoperative neurological outcomes, making it reasonable to attribute our observed incidence of neurological disorders primarily to the surgical approach used (i.e., hybrid vs. open-heart). Available evidence suggests that preexisting brain injury in CHD patients – driven mainly by chronic hypoxia – accounts for the majority of neurodevelopmental outcomes seen in patients who have undergone cardiac surgery [35]. Nonetheless, any transient brain ischemia occurring in CPB-treated patients could compound preexisting brain injury, making it a critical determinant of postoperative neurological outcomes. Since this factor is inherently absent in patients treated with the off-pump hybrid technique, it may help explain the markedly higher incidence of various neurological disorders observed among patients who underwent CPB surgery.

Taken together, the use of hybrid surgery performed on a beating heart did not lead to major complications in very young infants, nor were any neurological deficits observed during mid-term or long-term follow-up [1,10,11,36,37]. Our earlier studies had not specifically examined neurological complications in relation to either CPB duration or anesthesia duration (which serves as a proxy for total surgical time in our records). In the current study, we carried out this analysis and determined that the hybrid method offers considerably greater safety with respect to neurological complication risk. Broader adoption of off-pump hybrid VSD correction is likely to reduce the frequency of central nervous system dysfunction, which affects a substantial proportion of patients undergoing traditional on-pump surgery.

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