



Comparison of Parameters for Detection of Splanchnic Hypoxia in Children Undergoing Cardiopulmonary Bypass With Pulsatile Versus Nonpulsatile Normothermia or Hypothermia During Congenital Heart Surgeries

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Abstract: The aim of this study is to evaluate gastric mucosal oxygenation together with whole-body oxygen changes in infants undergoing congenital heart surgery with cardiopulmonary bypass (CPB) procedure and the use of either pulsatile or nonpulsatile mode of perfusion with normothermia and pulsatile or nonpulsatile moderate hypothermia. Sixty infants undergoing congenital cardiac surgery were randomized into four groups as: nonpulsatile normothermia CPB (NNCPB, $n = 15$), pulsatile normothermia CPB (PNCPB, $n = 15$), nonpulsatile moderate hypothermia CPB (NHCPB, $n = 15$), and pulsatile moderate hypothermia CPB (PHCPB, $n = 15$) groups. In NNCPB and PNCPB groups, mild hypothermia was used (35°C), whereas in NHCPB and PHCPB groups, moderate hypothermia (28°C) was used. Gastric intramucosal pH (pHi), whole-body oxygen delivery (DO_2) and consumption (VO_2), and whole-body oxygen extraction fraction were measured at sequential time points intraoperatively and up to 2 h postoperatively. The measurement

of continuous tonometry data was collected at desired intervals. The values of DO_2 , VO_2 , and whole-body oxygen extraction fraction were not different between groups before CPB and during CPB, whereas the PNCPB group showed higher values of DO_2 , VO_2 , and whole-body oxygen extraction fraction compared to the other groups at the measurement levels of 20 and 60 min after aortic cross clamp, end of CPB, and 2 h after CPB ($P < 0.0001$). Between groups, no difference was observed for pHi, lactate, and cardiac index values ($P > 0.05$). This study shows that the use of normothermic pulsatile perfusion (35°C) provides better gastric mucosal oxygenation as compared to other perfusion strategies in neonates and infants undergoing congenital heart surgery with CPB procedures. **Key Words:** Splanchnic hypoxia—Perfusion modes—Cardiopulmonary bypass—Hypothermic cardiopulmonary bypass—Normothermic cardiopulmonary bypass—Pediatric.

The ideal temperature for congenital cardiac surgery is a challenging point and is changing according to the surgical procedures. Until a decade ago, nearly in all congenital cardiac operations, hypothermia was used during cardiopulmonary bypass (CPB)

to permit perfusion at lower flows and hematocrits. It has been documented that hypothermia interferes with enzyme and organ function, aggravates bleeding, increases systemic vascular resistance, and delays cardiac recovery (1,2).

Although normothermic CPB has gained popularity in congenital heart surgery to conquer adverse effects of hypothermia (3) (4), there is no consensus on the use of perfusion modes (pulsatile vs. nonpulsatile flow) during CPB. There are no reports on the effects of pulsatile or nonpulsatile CPB on splanchnic perfusion in infants, whereas the use of

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normothermia or hypothermia during pulsatile or nonpulsatile CPB has not been compared in a prospective randomized study.

The goal of this study is to evaluate splanchnic hypoxia by evaluation of gastric mucosal oxygenation with measurement of changes at different time points of whole-body oxygen changes (gastric intramucosal pH [pHi], whole-body oxygen delivery [DO₂] and consumption [VO₂], and whole-body oxygen extraction fraction) in infants undergoing congenital heart surgery with CPB and the use of either pulsatile or nonpulsatile normothermia and pulsatile or nonpulsatile moderate hypothermia.

PATIENTS AND METHODS

In a prospective study, 60 patients with congenital heart disease from January 19 to March 27, 2011 were randomized into four groups as:

- 1 Nonpulsatile normothermia CPB (NNCPB, *n* = 15);
- 2 Pulsatile normothermia CPB (PNCBP, *n* = 15);
- 3 Nonpulsatile moderate hypothermia CPB (NHCPB, *n* = 15); and
- 4 Pulsatile moderate hypothermia CPB (PHCPB, *n* = 15) groups.

Normothermia was maintained at 35°C, whereas moderate hypothermia was established at 28°C during CPB. Patients undergoing biventricular repair with the use of CPB were included in the study. The exclusion criteria included: patients with clinical conditions that were associated with decreased cardiac output (CO) state, congestive heart failure, and surgical interventions with univentricular repairs and shunts. The study was approved by the Institutional Ethics Committee, and written informed consent was obtained from the patients' parents.

Anesthesia protocol

All patients were premedicated with intramuscular ketamine 5 mg/kg, midazolam 0.1 mg/kg, and atropine 0.02 mg/kg. Induction of anesthesia was performed with midazolam 0.1–0.2 mg/kg, fentanyl 8–10 µg/kg, and ropivacaine 0.6 mg/kg, and after the tracheal intubation, the maintenance of anesthesia was done with midazolam 0.04 mg/kg/h, fentanyl 5–8 µg/kg/h, and ropivacaine 0.2 mg/kg every 30 min. Additional volatile anesthetic use (sevoflurane % 1–2) was provided during the surgical procedure.

Right and left atrial catheters and a pulmonary arterial catheter (Baxter Edwards, 3.5 Fr thermodilution catheter, Irvine, CA, USA) were inserted after anesthetic induction. Blood samples are simulta-

neously drawn from the systemic and pulmonary arterial lines as well as from a line introduced in the venous cannulae (mixed venous blood) during extracorporeal circulation (ECC) to determine total-body DO₂, consumption, and extraction before, during, and after ECC. CO and index were measured at the end of CPB and 2 h after. Measurement of CO was determined as follows: 1 mL of normal saline solution was cooled to 4° and injected rapidly into the right atrial cannula during the end-expiratory phase of respiration. For each variable, the average of three separate readings taken with 1-min intervals was taken into consideration for an accurate CO measurement.

CPB protocol

A standardized CPB protocol was used for both groups. CPB was established using bicaval cannulation and an arterial cannula (Medtronic DLP; DLP Pediatric One Piece Arterial Cannulae 8–10 Fr Medtronic Ltd, Watford, UK) placed in the ascending aorta. In both groups, Capiiox Baby RX hollow-fiber membrane oxygenator (Capiiox, Baby RX, Tokyo, Japan) was used. The circuit was primed with red blood cells, mannitol (0.2 g/kg), and sodium bicarbonate (25 mEq). The left ventricle was vented through the interatrial septum during aortic cross-clamping. CPB was performed at a flow rate around 2.4 L min⁻¹ m⁻² in the normothermia group and 1.8 L min⁻¹ m⁻² in the hypothermia group, respectively. ECC was carried out under moderate hypothermia (28°C) or normothermia (35°C). In accordance to the CPB protocol, we tried to keep hemoglobin (Hb) levels at around the 9–9.5 mg/dL in the hypothermic groups and 10–10.5 mg/dL in normothermic groups. Pulsatile flow was maintained only during the aortic cross-clamping (X-clamping). The Stöckert pump with or without pulsatile module (S5, Sorin Group GmbH, Munich, Germany) with the pulsatile setting at 70% and the base flow at 30% was used to maintain pulsatile flow during X-clamping. The same heart-lung machine was used for nonpulsatile cases as well.

In the period of CBP, mean arterial blood pressure was kept between 50 and 60 mm Hg. Alpha-stat management of acid-base status was used. Ultrafiltration (Dideco D570 conventional ultrafiltration kit, Mirandela, Italy) was used in all patients in this study with a target hematocrit value of 35%.

NNCBP–PNCBP groups

Temperature was sustained at around 35°C. Cardioplegia was administered by infusion of warm

hyperkalemic blood every 10 min. Pulsatile flow was done after cross-clamping the aorta in the PNCPB group and nonpulsatile flow was done in the NNCBP group. Ultrafiltration was initiated closer to the end of the CBP.

NHCPB–PHCPB groups

Body core temperature was lowered to 28°C. After cross-clamping of the aorta, an initial dose of warm cardioplegia was followed by intermittent infusion of cold blood (at 8°C) cardioplegia every 20 min. Pulsatile flow was achieved after cross-clamping the aorta in the PHCPB group, whereas in the NHCPB group, nonpulsatile flow was maintained throughout the aortic cross-clamping. Ultrafiltration of blood was initiated during the rewarming phase and was terminated at the end of CPB.

Assessment of gastric mucosal oxygenation

Gastric mucosal oxygenation and pHi can be measured by tonometry catheter (5). An automated air tonometry technique was used to measure the partial pressure of carbon dioxide in the gastric lumen (PgCO₂), using an 8 Fr nasogastric catheter connected to a Tonocap monitor (TRIP, Tonometry Catheter 8 Fr; Tonometrics, Helsinki, Finland). The catheter was inserted during anesthetic induction, and the correct placement was confirmed by auscultating the epigastrium, while 2 mL of air was insufflated through the nasogastric tube. pHi and DCO₂ determined as follows; 2.5 mL saline solution was infused into the catheter opening port to fill the tonometer balloon. A time period of 30 min was left to allow CO₂ in the stomach lumen to diffuse through the silicone balloon into the saline solution. One milliliter of saline solution was aspirated and discarded, then the remaining saline solution was used for analysis of partial pressure of CO₂ (PiCO₂).

The following formula was used for gastric pH (pHi) calculation:

$$\text{pH}_i = 6.1 + \log(\text{arterial bicarbonate concentration} \times 0.03^{-1} \times \text{PiCO}_2^{-1} \times \text{k}^{-1})$$

Assessment of whole body oxygen utilization

Whole-body oxygen utilization was measured at the same time points as gastric mucosal oxygenation. Blood was simultaneously drawn from the arterial line and the pulmonary artery catheter or during ECC from a line introduced to venous cannulae (mixed venous blood). The following formulae were used:

$$\begin{aligned} \text{Blood oxygen content (mL/dL)} \\ = (\text{Hb [g/dL]} \times \text{blood \% oxygen saturation} \\ \times 1.39) + (\text{oxygen partial pressure [mm Hg]} \times 0.03) \end{aligned}$$

$$\begin{aligned} \text{Whole-body oxygen delivery DO}_2 \text{ (mL/min per m}^2\text{)} \\ = \text{arterial blood oxygen content} \times \text{cardiac index} \\ (\text{CI}) \text{ CI (mL/min per m}^2\text{)} \times 0.1 \end{aligned}$$

$$\begin{aligned} \text{Whole-body oxygen consumption (VO}_2\text{)} \\ \text{(mL/min per m}^2\text{)} = (\text{arterial blood oxygen} \\ \text{content} - \text{mixed blood oxygen content}) \\ \times \text{CI (mL/min per m}^2\text{)} \times 0.1 \end{aligned}$$

$$\begin{aligned} \text{Whole-body oxygen consumption extraction} \\ \text{fraction (\%)} = \text{VO}_2 / \text{DO}_2 \times 100 \end{aligned}$$

Measurements were obtained at the following intervals for pHi, gastric-arterial carbon dioxide partial pressure difference (CO₂ gap), whole-body DO₂ and VO₂, and whole-body oxygen extraction fraction. Mean values of the three readings were considered for each interval value.

- 1 Before CPB (Baseline before midline incision);
- 2 During CPB (2–5 min);
- 3 20 min after X-clamp;
- 4 60 min during X-clamp;
- 5 End of CPB and ultrafiltration; and
- 6 2 h after CPB

Statistical analysis

The SPSS statistical program for Windows, version 15 (SPSS, Inc., Chicago, IL, USA) was used to perform data analysis. The Shapiro–Wilk test was used for the analysis of compliance with the normal distribution. Normally distributed continuous data are presented as mean ± standard deviation and nominal variables as counts and/or percentages. Non-normal distributed continuous data are presented as median (interquartile range). In statistical comparison of groups, the analysis of variance (ANOVA) test was used for continuous variables, when normally distributed. While analyzing results of the ANOVA test, Levene's test was applied for evaluation of variance homogeneity. Bonferroni statistical test was used to evaluate the statistically different groups in the ANOVA test. In the comparison of groups where abnormal distribution was observed, the Kruskal–Wallis test was used for comparison of groups, and if a statistically significant difference was found, then comparison of groups was confirmed by the Mann–Whitney *U*-test. Spearman's correlation tests were used. All statistical tests were two-sided. A *P* value <0.05 was considered statistically significant except in comparison with the Mann–Whitney *U*-test. In this

TABLE 1. Demographic values of the groups and consequent surgical procedures

	Group NNCPB	Group NPCPB	Group HNCPB	Group HPCPB	P
Age (mo.)	3.8 ± 2.5 (0.2–9.2)	3.2 ± 2.6 (0.3–9.2)	4.4 ± 2.4 (0.2–8.3)	4.2 ± 2.7 (0.2–8.3)	0.55*
Weight (kg)	4.9 (2.1)	3.9 (2.5)	5 (3.1)	5 (2)	0.72†
BSA (m ²)	0.24 (0.04)	0.23 (0.05)	0.25 (0.08)	0.25 (0.03)	0.57†
CBP time (min)	79 (39)	68 (33)	81 (46)	77 (28)	0.99†
AXC time (min)	61 (34)	59 (29)	62 (45)	55 (22)	0.99†
Associated cardiac anomaly and performed corrective surgeries					
Fallot tetralogy, total repair	3	5	3	4	
Ventricular septal defect, defect closure	8	7	5	8	
Double outlet right ventricle, total repair	1	—	1	—	
Atrioventricular canal defect, total repair	1	2	1	1	
Transposition of great arteries, arterial switch	1	1	2	1	
Transposition of great arteries, arterial switch (Senning procedure)	1	—	1	—	
Total anomalous pulmonary venous return, repair	—	—	1	1	
Truncus arteriosus, repair	—	—	1	—	

Non-normal distributed continuous data are presented as median (interquartile range).

Values are expressed as mean ± standard deviations (ranges) for normal distributed continuous data and numbers (percentages) for dichotomous variables.

* ANOVA test was used.

† Kruskal–Wallis test was used.

AXC, aortic cross-clamp; BSA, body surface area; CBP, cardiopulmonary bypass; CPB, cardiopulmonary bypass; HNCPB, nonpulsatile moderate hypothermic CPB group; NNCPB, nonpulsatile normothermic CPB group; PHCPB, pulsatile moderate hypothermic CPB group; PNCPB, pulsatile normothermic CPB group.

test, as there are four different groups, $P < 0.01$ is considered as statistically significant. Comparisons of the subgroups were done as follows: P_1 , group 1 versus group 2; P_2 , group 1 versus group 3; P_3 , group 1 versus group 4; P_4 , group 2 versus group 3; P_5 , group 2 versus group 4; P_6 , group 3 versus group 4.

RESULTS

The median age was 3.94 months (range; 0.2–9.2 months). The median weight and basal surface area (BSA) values were 4.96 kg (range 2.7–9.7 kg) and 0.25 m² (range 0.2–0.49 m²), respectively. The median duration of CPB was 85 min (range 50–171 min), and the median aortic cross-clamp (X-clamp) time was 67 min (range 37–143 min). The parameters including age, weight, BSA, CBP time, and X-clamp times were compared, and no differences were found (Table 1) ($P < 0.05$). Baseline features, cardiac anomaly, and consecutive corrective surgeries summarized for patients are presented in Table 1.

During CPB, CI index was maintained at a flow rate around 2.4 L/min/m² in the NNCPB and PNCPB normothermia groups, while 1.8 L/min/m² was used in the HNCPB and PNHCP hypothermia groups. CI was measured and no differences were found between the groups at the end of CPB and 2 h after CPB (Table 2).

At the 20th minute of X-clamp, in comparison of the pH_i measurements, there was a significant differ-

ence among the four subgroups ($P = 0.002$; Table 2). In the evaluation of subgroups, the difference was only significant between group NNCPB and PNCPB ($P_1 < 0.0001$); however, there were no significant differences in comparison with other subgroups. At the 60th minute of X-clamp, at the end of the CPB and 2 h after surgery, in comparison with the pH_i measurements, there were no significant differences found among the four subgroups ($P = 0.94$, 0.96, and 0.99, respectively; Table 2).

At each time point of four different measurements, the values of total body DO₂ were significantly different among the four subgroups for each time point ($P < 0.0001$, < 0.0001 , < 0.0001 , and 0.009, respectively; Table 2). This difference is mainly observed at the time points: 20th minute of X-clamp, 60th minute of X-clamp, and at the end of CPB between groups NNCPB and PNCPB, between groups HNCPB and PHCPB, and also between groups PNCPB and PHCPB (for the three different time points, $P_1 < 0.0001$, $P_4 < 0.0001$, and $P_5 < 0.0001$, respectively). For the time point where measurement was collected 2 h after CPB, the statistical difference was significant between NNCPB and PNCPB and also between groups NNCPB and PHCPB ($P_1 < 0.007$ and $P_3 = 0.006$, respectively; Fig. 1).

The patients who underwent congenital heart surgery with normothermic pulsatile CPB demonstrated better VO₂ as compared with other groups. The measurements of total body oxygen consumption revealed that at each of the four different time

TABLE 2. Operative and postoperative gastric mucosal oxygenation results

	NNCPB	PNCPB	NHCPB	PHCPB	P
Before CPB (baseline)					
pHi [‡]	7.38 (0.03)	7.38 (0.01)	7.38 (0.01)	7.38 (0.03)	0.28
DO ₂ [‡]	350 (50)	350 (20)	340 (40)	340 (40)	0.18
VO ₂ [‡]	92 (8)	91 (10)	90 (10)	88 (10)	0.098
O ₂ EXT [‡]	36 (7)	34 (6)	34 (6)	33 (6)	0.083
Lactate [†]	4.1 ± 0.7 (3.1–5.6)	4.2 ± 0.7 (3.1–5.5)	4 ± 0.5 (3.1–5.5)	4.2 ± 0.7 (3.1–5.5)	0.88
Hb [‡]	12.3 (0.7)	12.7 (0.8)	12.4 (0.7)	12.3 (0.7)	0.42
During CPB (2–5 min)					
pHi [‡]	7.38 (0.02)	7.38 (0.02)	7.38 (0.01)	7.38 (0.03)	0.28
DO ₂ [‡]	350 (60)	350 (20)	350 (50)	340 (50)	0.24
VO ₂ [‡]	92 (2)	93 (20)	90 (10)	89 (10)	0.075
O ₂ EXT [‡]	39 (13)	36 (3)	36 (5)	33 (12)	0.3
Lactate [‡]	3.3 (1.5)	3.1 (1.2)	3.3 (1.2)	3.3 (0.7)	0.94
Hb [‡]	11.1 (0.8)	11.3 (0.7)	11.4 (0.8)	11.2 (0.8)	0.68
20 min. X-clamp					
pHi [‡]	7.36 (0.02)	7.35 (0.01)	7.36 (0.02)	7.36 (0.03)	0.24
DO ₂ [†]	386 ± 18 (350–420)	456 ± 22 (420–490)	397 ± 28 (330–440)	399 ± 10 (380–420)	0.002*
VO ₂ [‡]	92 (10)	115 (10)	90 (20)	88 (20)	<0.0001*
O ₂ EXT [‡]	44 (10)	50 (2)	40 (0.00)	40 (4)	<0.0001*
Lactate [‡]	3.4 (2)	3.1 (1.5)	4.4 (2)	3.1 (2)	0.57
Hb [‡]	10.3 (0.7)	10.6 (0.8)	9.7 (0.7)	9.9 (0.8)	0.55
60 min. X-clamp					
pHi [‡]	7.34 (0.02)	7.34 (0.02)	7.34 (0.01)	7.34 (0.03)	0.94
DO ₂ [‡]	390 (30)	450 (20)	420 (20)	390 (10)	<0.0001*
VO ₂ [‡]	92 (10)	120 (10)	90 (10)	88 (10)	<0.0001*
O ₂ EXT [‡]	45 (10)	49 (6)	40 (0)	40 (8)	<0.0001*
Lactate [‡]	4.1 (2)	3.1 (1.5)	3.1 (2)	4.1 (2)	0.93
Hb [‡]	9.7 (0.5)	9.8 (0.6)	9.2 (0.6)	9.1 (0.1)	<0.0001*
End of CPB and ultrafiltration					
pHi [‡]	7.34 (0.02)	7.34 (0.02)	7.34 (0.01)	7.34 (0.03)	0.96
DO ₂ [‡]	390 (30)	450 (20)	420 (20)	390 (10)	<0.0001*
VO ₂ [‡]	92 (10)	120 (10)	90 (10)	88 (10)	<0.0001*
O ₂ EXT [‡]	45 (10)	49 (6)	40 (0.00)	40 (8)	<0.0001*
Lactate [‡]	4.1 (2)	3.1 (1.5)	3.1 (2)	4.1 (2)	0.93
Hb [‡]	12.3 (0.7)	12.7 (0.8)	12.5 (0.8)	12.4 (0.7)	0.56
CI [†]	4.3 ± 0.2 (4–4.7)	4.3 ± 0.2 (4–4.7)	4.2 ± 0.1 (4–4.5)	4.2 ± 0.1 (4.1–4.6)	0.6
2 h after CPB					
pHi [†]	7.30 ± 0.02 (7.27–7.35)	7.30 ± 0.02 (7.25–7.34)	7.30 ± 0.04 (7.27–7.34)	7.30 ± 0.02 (7.27–7.35)	0.99
DO ₂ [‡]	410 (40)	450 (20)	440 (40)	460 (30)	0.009*
VO ₂ [‡]	92 (10)	120 (10)	90 (10)	87 (10)	<0.0001*
O ₂ EXT [‡]	50 (10)	54 (5)	45 (5)	45 (5)	<0.0001*
Lactate [‡]	3.1 (1.5)	4 (2)	4.6 (0.9)	4.4 (1.3)	0.05
Hb [‡]	12.1 (0.8)	12.0 (0.8)	11.9 (0.7)	12.3 (0.9)	0.88
CI [†]	3.8 ± 0.1 (3.5–4.1)	3.8 (0.1)	3.8 ± 0.1 (3.6–4.1)	3.8 ± 0.1 (3.6–4.1)	0.94

Other abbreviations are the same as in Table 1.

* Statistically significant.

† ANOVA test was used.

‡ Kruskal–Wallis test was used.

CPB, cardiopulmonary bypass; DCO₂, CO₂ delivery; DO₂, O₂ delivery; EXT, O₂ extraction fraction; Hb, hemoglobin level; pHi, intramucosal pH; VO₂, O₂ consumption.

points, a statistically significant difference was observed at: 20 min X-clamp; 60 min X-clamp, end of CPB, and ultrafiltration; 2 h after CPB ($P < 0.0001$, <0.0001 , <0.0001 , and <0.0001 , respectively; Table 2). At each of the four different time points, there were statistically significant differences between groups NNCPB and PNCPB, between groups NNCPB and HNCPB, and between groups PNCPB and PHCPB.

Total-body oxygen extraction was sustained superiorly in normothermic pulsatile CPB. The measure-

ments of total body oxygen extraction revealed that at each of the four different time points, statistically significant differences were observed among the four subgroups ($P < 0.0001$, <0.0001 , <0.0001 , and <0.0001 , respectively; Table 2). The subgroups were compared with different time intervals in Fig. 2.

At each of the three different time points, Hb values were statistically insignificant. The only statistical difference was found in the 60 min X-clamp time

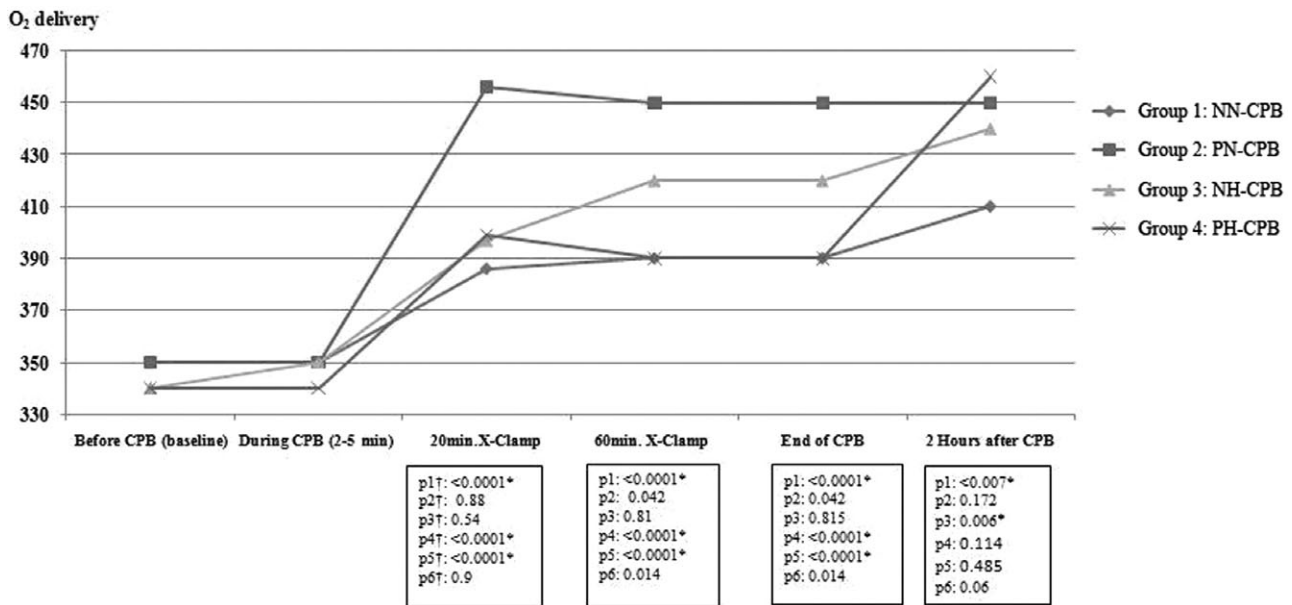


FIG. 1. Results of total body oxygen delivery. *Statistically significant ($P < 0.05$ for multiple comparisons and $P < 0.0125$ for Mann-Whitney U -test. †Multiple comparisons were used. p1, group 1 versus group 2; p2, group 1 versus group 3; p3, group 1 versus group 4; p4, group 2 versus group 3; p5, group 2 versus group 4; p6, group 3 versus group 4.

period ($P < 0.0001$; Table 2). At that time period also, a positive correlation was found between Hb value and DO_2 levels in the PNCPB group ($P = 0.04$ and $r = 0.53$).

DISCUSSION

To the best of our knowledge, this was the first study for splanchnic perfusion comparing the pulsatile versus nonpulsatile flow, and at the same time correlating perfusion with normothermia and hypothermia. Numerous previous studies evaluated gastrointestinal tonometry as an early predictor for postoperative complications in the adult and pediatric population (6,7). However, to our knowledge, no study was performed before to compare the effects of hypothermic and normothermic CPB using gastric tonometry for the pediatric and neonatal patients with complex cardiac malformations. In this study, we have demonstrated that pulsatile flow and normothermia had a better effect on gastric mucosal perfusion in neonates and infants. According to our results, the pulsatile and normothermic group had superior values of gastric DO_2 , VO_2 , and oxygen extraction fraction (Fig. 2).

Hypothermia is one of the causes of reduced mesenteric perfusion. Splanchnic ischemia is a result of the imbalance between splanchnic oxygen supply and demand (8,9). The level of tissue oxygenation can be calculated indirectly by CO , DO_2 , and the lactate

level (5,8,10). According to our results, lactate levels were not changed depending on the perfusion protocols, but DO_2 , VO_2 , and oxygen extraction fraction changed.

The ideal temperature during congenital heart surgery is an important factor (11). The current trend in CPB protocols in adult cardiac surgery is to perform CPB at normothermia (12). In contrast, congenital cardiac surgery using CPB is still performed at low temperatures in many centers (13). In favor of normothermic CPB in neonates and infants, other centers showed their superior results previously (14). Hypothermia and tissue acidosis cause oxyhemoglobin dissociation curve shifts to the left making it more difficult for oxygen to be unloaded to the tissues. Furthermore, during the rewarming phase of hypothermia, a considerable increase in plasma adrenaline and noradrenaline initiates splanchnic vasoconstriction (15). Gut tissue is also one of the most susceptible organs in the body to hemodynamic stress during and after surgical procedures. Hypothermic bypass affects the cardiac, cerebral, respiratory, and endocrine systems. Hypothermia has adverse effects including impaired hemostasis, microcirculatory dysfunction, capillary leakage and deteriorations in parenchymal DO_2 , endotoxin release, glucose metabolism, and myocardial contractility (16,17).

Instead of hypothermia, normothermic CPB is associated with a lower safety margin for organ preservation during CPB. In such circumstances

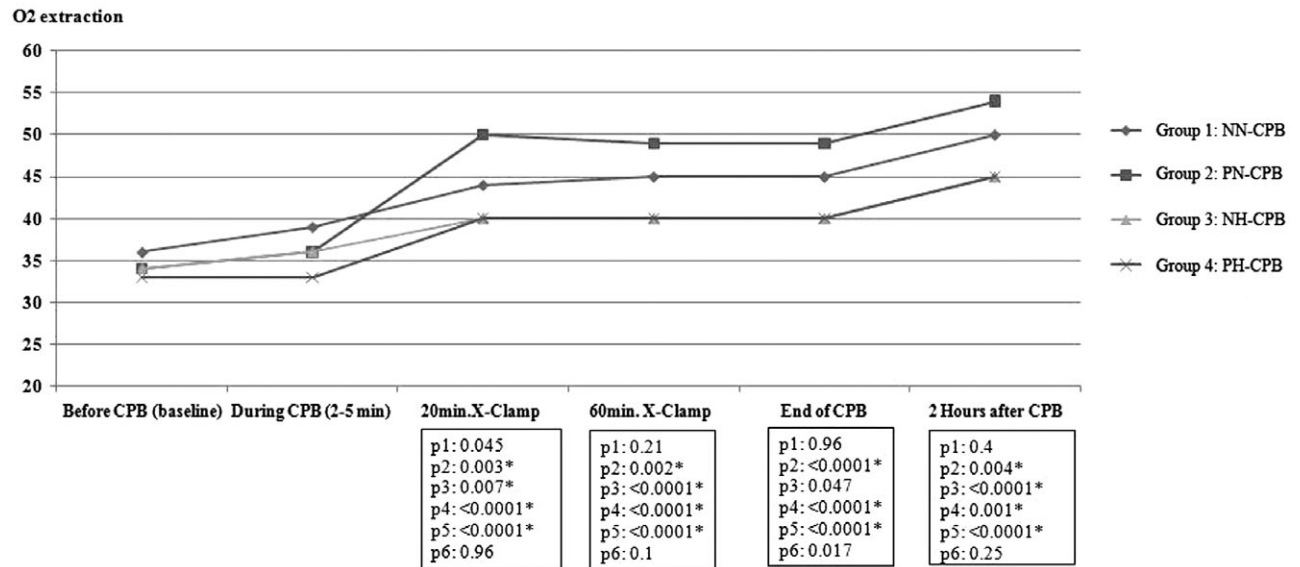


FIG. 2. Results of total body oxygen extraction. *Statistically significant. p1, group 1 versus group 2; p2, group 1 versus group 3; p3, group 1 versus group 4; p4, group 2 versus group 3; p5, group 2 versus group 4; p6, group 3 versus group 4.

of hypoperfusion under normothermia, important organs like the brain and the kidneys will be at severe risk of cellular damage due to high cellular metabolism rate. Furthermore, normothermic CPB in the infantile period needs to be supported by repeated use of intermittent warm blood cardioplegia (every 10 min for 1 min) (17). According to our experience during surgery, normothermic CPB is associated with more frequent cardioplegia causing increased duration of aortic cross-clamping.

Based on our results, we can state that maintenance of DO_2 occurred at higher levels in the normothermic groups at the period of 60 min X-clamping because of an increased oxygen-carrying capacity of the blood in that time period: the Hb value was statistically significant in the normothermic groups, inconsistent with hypothermic groups, despite the fact that no insignificance was found between perfusion modes ($P < 0.0001$). Also, we can state that the superior DO_2 , VO_2 , and O_2 extraction was maintained in the pulsatile normothermic group in that time period ($P < 0.0001$; Table 2).

Ündar demonstrated that pulsatile flow maintains capillary patency by supplying more energy into the vascular system (18). In another study, Ündar revealed that surplus hemodynamic energy (19) sustains more microcirculation perfusion at physiological levels, decreases inflammatory response, and improves vital organ recovery, leading to better

clinical outcomes (20). Also, he proved in neonatal piglets that pulsatile perfusion maintains higher cerebral DO_2 and lower cerebral vascular resistance and causes improved cerebral metabolic rate (21). Alkan et al. (22) revealed that the use of pulsatile flow resulted in improved patient outcomes in terms of preserving better cardiac, renal, and pulmonary functions in the early postoperative period. The same group also concluded that pulsatile perfusion maintains better thyroid hormone hemostasis at the early stages of CPB (23). The quality of pulsatility is extremely important to show differences between the groups. We have already shown that with identical heart-lung machine, oxygenator, and arterial cannulae used in this study (24), the quality of pulsatility was adequate to make a difference in patients' outcomes.

Furthermore, Orime et al. (25) demonstrated lower endothelin-1 and interleukin-8 levels in pulsatile perfusion, suggestive of decreased endothelial damage.

According to our results, the benefit of pulsatility was found only for normothermic CPB in infants and was lost for the hypothermic protocol. This is a similar finding to a canine model of CPB investigating the influence of pulsatility and temperature on liver blood flow (26). In that study also, the benefits of pulsatility were evident at normothermia but were lost using hypothermic CPB.

CONCLUSIONS

In this study we demonstrated that the use of gastric tonometry for detection of splanchnic hypoxia can be helpful by determining whole-body oxygen consumption values in children undergoing congenital heart surgery with CPB. As a result of the comparison of gastric tonometry values in four groups, normothermic pulsatile CPB is better in terms of DO_2 , VO_2 , and O_2 extraction.

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