The Effect of Volume Loading on Systemic Oxygenation After Bidirectional Superior Cavopulmonary Anastomosis

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Background. **The unique series arrangement of the cerebral and pulmonary circulation in bidirectional superior cavopulmonary anastomosis (BCPA) makes the pulmonary blood flow dependent upon the cerebral blood flow. Until now, several investigators have tried to correct post-BCPA hypoxemia with various methods such as induced hyperventilation, the addition of carbon dioxide, and inhaled nitric oxide with variable success rates.**

Methods. **We prospectively studied 25 children with univentricular physiology undergoing BCPA surgery at 5 different time points in the preoperative (1 time point) and postoperative period (4 time points, each separated by at least 3 mm Hg changes in the superior vena cava [SVC] pressure). Intravenous fluids were administered in the postoperative period to raise the SVC pressure.**

Results. **The systemic arterial oxygen saturation (Sa_{O_2}) increased significantly ($p = 0.000$) from a preoperative value of 80% ± 7% to 86% ± 7%, 91% ± 3% and 95% ± 4% at SVC pressures of 9 ± 1.6 mm Hg, 13 ± 1.3 mm Hg, and 16 ± 1.4 mm Hg, respectively, and then decreased to 94% ± 4% at SVC pressure of 20 ± 1.7 mm Hg. Systolic and diastolic blood pressure increased significantly and simultaneously with SVC pressure from 71 ± 8 mm Hg and 42 ± 6 mm Hg to 89 ± 11 mm Hg and 52 ± 7 mm Hg, respectively ($p = 0.000$).**

Conclusions. **Administration of intravenous fluids improves the SVC pressure, possibly due to an increase in the cerebral blood flow and the SVC flow, and thus raises the arterial oxygen tension (Pa_{O_2}) and Sa_{O_2}. Each patient has a unique SVC pressure where the Sa_{O_2} and the Pa_{O_2} are maximum; beyond that limit, the Sa_{O_2} does not improve.**

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Bidirectional superior cavopulmonary anastomosis (BCPA) provides pulmonary blood flow by connecting the superior vena cava (SVC) to the undivided pulmonary arteries and is performed as stage 1 or stage 2 palliation before the definitive Fontan completion. After completion of the BCPA, blood from the SVC is directly diverted to the pulmonary circulation and hence relieves the single ventricle from volume overload [1]. Systemic arterial oxygen saturation (Sa_{O_2}) improves after the BCPA due to an increase in the effective pulmonary blood flow and is affected by several factors such a SVC to inferior vena cava (IVC) flow ratio, SVC pressure, pulmonary vascular resistance, and sources of additional pulmonary blood flow [2–5]. However, the optimum postoperative SVC pressure consistent with maximum Sa_{O_2} has not been established. Several investigators have tried to correct post-BCPA hypoxemia by various methods such as induced hyperventilation, addition of carbon dioxide (CO_2) and inhaled nitric oxide with variable success rates. However, these methods appear to be quite impractical and cannot be applied in awake and spontaneously breathing patients. Intravenous fluid administration is a physiologic means to achieve an improvement in the SVC flow and pressure. In this prospective study the authors hypothesized that the increase in the SVC pressure after intravenous fluid administration would raise the partial arterial oxygen tension (Pa_{O_2}) and Sa_{O_2}. Furthermore, the end tidal CO_2 ($ETCO_2$) monitoring is essential for the assessment of efficacy of ventilation in the operating room and it depends upon the pulmonary blood flow, metabolism, ventilation, and ventilation-perfusion match [6]. In a normal unobstructed series, circulation change in $ETCO_2$ parallel changes in partial arterial carbon dioxide tension (Pa_{CO_2}) [7]. However, in the cyanotic heart diseases, right to left shunting of blood and diminished pulmonary blood flow, leads to an increase in ΔPa_{CO_2} - P_{ETCO_2} (difference between arterial CO_2 tension and $ETCO_2$ tension) [8, 9]. The next aim of this study was to establish the utility of $ETCO_2$ and ΔPa_{CO_2}-P_{ETCO_2} as a noninvasive surrogate indicator of the pulmonary blood flow after the BCPA.

Material and Methods

After institutional ethics board approval, cyanotic children with univentricular physiology and reduced pulmonary blood flow were enrolled into the study.

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Informed and written consent was obtained from the parents of all children. Children with a previous aortopulmonary shunt (Blalock-Taussig shunt, central shunt), cardiac failure, lung disease, or on mechanical ventilatory support were excluded from the study. All children underwent the same anesthetic management by a single anesthesia team. Anesthesia induction was achieved by preoxygenation, sevoflurane, intravenous ketamine, fentanyl, and rocuronium. After tracheal intubation, general anesthesia was maintained with sevoflurane, fentanyl, midazolam, and vecuronium. The 7900 SmartVent ventilator (GE Medical Ohmeda Avance Carestation; GE Healthcare, Port Washington, NY) and Servo - i ventilator (Maquet, Rastatt, Germany) were used in the operating room and the intensive care unit, respectively. Ventilator settings were kept same before and after the completion of the BCPA with a tidal volume of 10 mL/kg, an inspired oxygen fraction (Fio_2) of 1.0, an inspiratory to expiratory phase ratio of 1:2, and a respiratory rate of 15 to 30 breaths/minute. The intravascular monitoring catheters were placed after the induction of anesthesia (SVC, IVC, or femoral veins and femoral artery). The SVC pressure was measured through a single lumen internal jugular catheter while IVC pressure was measured through a triple lumen catheter (7 to 20 cm) inserted through the femoral vein. The $ETCO_2$ was measured from gas sampled from the Y-piece of the ventilator tubing using a side-stream capnometer calibrated according to the manufacturer's instructions (Intellivue G5M1019A; Philips Healthcare, Andover, MA). Preoperative hemodynamic parameters and arterial blood gas data (Cobas b 221 system; Roche, Basel, Switzerland) were recorded when the patients achieved stable hemodynamics for at least 5 minutes. The BCPA was performed using cardiopulmonary bypass (CPB) without cardioplegic arrest and aortic cross-clamp. The lung was manually expanded at the completion of the CPB. Intermittent boluses of the intravenous fluids (crystalloids, colloids and blood products) were administered in the post-BCPA period to achieve four different levels of SVC pressure and each level of SVC pressure was 3 mm Hg higher than the previous one. Each child was studied at 5 consecutive times (T) points. (1) After the placement of intravascular catheter and before skin incision T 0, and (2) After completion of BCPA at different SVC pressures T 1 (10 minutes after the end of CPB), T 2 ($\geq$3 mm Hg increase in the SVC pressure from T 1), T 3 ($\geq$3 mm Hg increase in the SVC pressure from T 2), T 4 ($\geq$3 mm Hg increase in the SVC pressure from T3). After 10 minutes of stability at each level of SVC pressure, we recorded the hemodynamic and blood gas parameters. The postoperative measurements were obtained after the sternal closure in the operating room and further in the cardiac intensive care unit. The upper body arteriovenous oxygen saturation gradient (a-v o_2 saturation) was calculated by subtracting the SVC saturation from the Sao_2. Regional (frontal) cerebral oxygenation (rSo_2) was measured by near infrared spectroscopy (equinox 7600; Nonin Medical, Plymouth, MN). The study was performed while patients were sedated, paralyzed, and mechanically ventilated, and the study was completed within 2 hours after the termination of the CPB. Throughout the study, the nasopharyngeal temperature was maintained between 35.5 and 36.5°C. All children received intravenous sodium nitroprusside (0.5 μgm/kg/minute) and dobutamine (5 μgm/kg/minute) during rewarming and after weaning from CPB.

Statistical Analysis

The statistical package SPSS for Windows version (SPSS Corporation, Chicago, IL) was used for all statistical calculations. Data are shown as mean ± SD. Comparison of the multiple time points in the study was by means of repeated-measures analysis of variance. Multiple comparison testing was done with a Bonferroni correction. The Pearson correlation coefficient was used to establish the relationship between Sao_2 and $\Delta Paco_2$-$Petco_2$, SVC pressure, and Sao_2. Statistical significance was considered at a p value less than 0.05.

Results

Twenty-five children undergoing BCPA were prospectively studied. Seventeen were male and 8 were female. Diagnoses were the following: tricuspid atresia (10 patients); double outlet right ventricle (8 patients); transposition of great arteries (5 patients); and atrioventricular septal defects (2 patients). All the patients had pulmonary stenosis. Presurgical coiling of aortopulmonary collaterals were required in only 6 patients to obliterate the source of additional pulmonary blood flow. A left-sided superior vena cava was present in 7 patients and bilateral BCPA was performed for them. Demographic data and results of the study are summarized in Tables 1 and 2 and Figures 1 and 2. The median CPB time was 48 minutes. The mean tidal volume, mean peak airway pressure, and mean airway pressure were 130 ± 65 mL, 15 ± 3 mm Hg, and 7 ± 1 mm Hg, respectively, in the pre-CPB period; they were 127 ± 67 mL, 16 ± 2 mm Hg, and 8 ± 1 mm Hg, respectively, in the post-CPB period. Crystalloids (normal saline and ringer lactate), colloids (albumin and starch), and blood products (packed red blood cells and fresh frozen plasma) were administered in equal proportion (1:1:1). The median (range) of the total intravenous volume administered during the study period was 100 mL (54 to 330). We observed a significant increase in SVC pressure from 9 ± 1.6 mm Hg to 20 ± 1.7 mm Hg (p = 0.000). The maximum value of Sao_2 (95% ± 4%) was observed at T3. The increase in Sao_2 from T 1 to T 2 (p = 0.001) and from T 2 to T 3 (p = 0.000) was significant.

Table 1. Demographic Data

Variable	Value
Age (months)	24 (8–120)
Gender (male/female)	17/8
Weight (kg)	10 (8–30)
Height (cm)	88 (61–140)

Values are given as median (range).