

The Impact of Roller Pump vs. Centrifugal Pump on Homologous Blood Transfusion in Pediatric Cardiac Surgery

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Abstract: Centrifugal pumps are considered to be less destructive to blood elements (1) when compared to roller pumps. However, their large prime volumes render them unsuitable as arterial pumps in heart lung machine (HLM) circuitry for children. In November of 2014, the circuit at Arnold Palmer Hospital, a Biomedicus BP-50 with kinetic assist venous drainage (KAVD) and 1/4" tubing was converted to a roller pump in the arterial position with gravity drainage. Vacuum-assisted venous drainage (VAVD) was mounted on the HLM as a backup, but not used. Tubing was changed to 3/16" in the arterial line in patients <13 kg. A retrospective study with a total of 140 patients compared patients placed on cardiopulmonary bypass (CPB) with Biomedicus centrifugal pumps and KAVD (Centrifugal Group, $n = 40$) to those placed on CPB with roller pumps and gravity drainage (Roller Group, $n = 100$). Patients requiring extra-corporeal membrane oxygenation (ECMO)/cardiopulmonary support (CPS) or undergoing a hybrid procedure were excluded. Re-operation or circulatory arrest patients were not excluded. Prime volumes decreased by 57% from 456 ± 34 mL in

the Centrifugal Group to 197 ± 34 mL in the Roller Group ($p < .001$). There was a corresponding increase in hematocrit (HCT) of blood primes and also on CPB. Intraoperative homologous blood transfusions also decreased 55% from 422 mL in the Centrifugal Group to 231 mL in the Roller Group ($p < .001$). The Society of Thoracic Surgeons–European Association for Cardio-Thoracic Surgery (STAT) categorized intubation times and hospital length of stay (LOS) for all infants showed a trend toward reduction, but was not statistically significant. Overall mortality was 5% utilizing the centrifugal configuration and 0% in the roller pump cohort. We demonstrated that the transition to roller pumps in the arterial position of the HLM considerably reduced our priming volume and formed a basis for a comprehensive blood conservation program. By maintaining higher HCTs on CPB, we were able to reduce intraoperative homologous blood transfusions. **Keywords:** cardiopulmonary bypass, kinetic assist venous drainage, vacuum-assisted venous drainage, modified ultra-filtration, heart lung machine. *J Extra Corpor Technol. 2017;49:36–43*

One of the challenges facing clinical perfusionists caring for neonates and infants undergoing cardiopulmonary bypass (CPB) is to reduce priming volumes and decrease blood transfusions. The Jehovah's Witness (JW) population has increased our motivation to achieve the goal of bloodless pediatric cardiac surgery. The perfusionist has

become the protagonist for blood conservation in the adult population. This role is naturally spreading into pediatric perfusion practice. We instituted a multistep protocol to reduce blood product utilization, the foundation of which was the transition from a centrifugal to a roller arterial pump. The perfusion team at our institution made several changes (delineated on the next page) prior to transitioning to the roller pump.

Protocol Changes Prior to Roller Pump Transition (June to November 2014)

1. Prior to June 2014, platelets were added to our CPB prime. There is enough evidence to suggest that platelets in the heart lung machine (HLM) have

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decreased function (2–4). We ceased adding platelets to our blood primes.

2. The volume of blood for laboratory test sampling was reduced by using appropriate tabletop devices. We retained heparin management but reduced sampling intervals to 40 minutes (from 30 minutes) wherever appropriate. We transitioned to the Hemochron Elite Plus (International Technidyne, Nevsky, NJ) from the Hepcon Heparin Management System (HMS) plus (Medtronic, Minneapolis, MN), specifically for activated clotting time (ACT) testing. This change reduced our ACT sampling volumes from 80 (.8 mL) to 15 μ L (.15 mL).
3. We transitioned from the Capiiox CP50 blood cardioplegia device (Terumo Cardiovascular System, Ann Arbor, MI) with a prime volume of 52 mL to the Sorin CSC 14 (Sorin Group, Mirandola, Italy) with a prime volume of 31 mL. The hemoconcentrator in our modified ultrafiltration (MUF) circuit for children under 15 kg was transitioned from the Hemocor HPH 400 (Sorin Group) with a prime volume of 34 mL to the Hemocor HPH Junior (Minntech Corp, Minneapolis, MN) with a prime volume of 8 mL.
4. We took this opportunity to educate the team on the benefits and methodology of transitioning to the new perfusion technique and philosophy. All changes were done over a period of 3 months prior to modifications in the CPB circuitry. The educational process included sessions with perfusion staff, anesthesiologists, cardiac surgeons, scrub techs, and other team members.

DESCRIPTION

Subsequent to approval from the Institutional Review Board (ref number 15.025.03) at our institution, 140 patients were enrolled in this retrospective single-institution chart review. The Centrifugal Group consisted of 40 patients who underwent elective congenital cardiac surgery on CPB utilizing a centrifugal arterial pump and neonatal oxygenator. In addition, the patients in this group were placed on CPB utilizing kinetic assist venous drainage (KA VD) (5) and a raised venous reservoir.

The Roller Group consisted of 100 patients utilizing a roller arterial pump and neonatal oxygenator. The inclusion criteria (Table 1) for all patients were CPB with a neonatal oxygenator, a 1/4" venous line and a 1/4" or 3/16" arterial line. Exclusion criteria (Table 1) were placement on extracorporeal life support (ECLS) and hybrid procedures. Deep hypothermic circulatory arrest (DHCA) with antegrade cerebral perfusion was not considered an exclusion criterion. Patients' demographics are delineated in Table 1.

With appropriate monitoring in place, all patients were induced with inhaled sevoflurane, and following establishment of intravenous access, anesthesia was maintained with infusions of propofol (50–100 mcg/kg/min), dexmedetomidine (.3–1 mcg/kg/h), intermittent boluses of fentanyl (up to 20 mcg/kg), and midazolam. Tracheal intubation was achieved with rocuronium (1 mg/kg) and ventilation was adjusted to maintain end-tidal CO₂ concentrations between 35 and 40 mm Hg. Intra-arterial and central venous access were obtained in suitable radial or femoral arteries and internal jugular or femoral veins, respectively. All patients were monitored with two sites (cerebral and renal) near infrared spectroscopy (Covidien, Mansfield, MA). Those patients undergoing re-operation were given three bolus doses of epsilon aminocaproic acid 100 mg/kg at induction, commencement of CPB and on termination of CPB.

After anesthesia induction, baseline arterial blood gases (ABG) were tested with the I-stat (Abbot Laboratories, Abbot Park, IL) and activated clotting time (ACT) with the Hemochron Elite Plus.

HLM Configuration

The HLM circuit was primed initially with Plasmalyte A and heparin 1,500–2,000 IU. Plasmalyte was chased with patient blood group specific or O-positive washed red cells and 25% albumin. A mixture of 8 mL of sodium bicarbonate and 50–100 mg of calcium carbonate was added. The prime was balanced by blowing off the CO₂ produced. A prime ABG was analyzed and recorded. In addition, a heparin dose response (HDR) test was performed on the Hepcon HMS plus with an unheparinized patient sample.

Table 1. Study criteria.

Study Group	Inclusion Criteria	Exclusion Criteria	DHCA/SCP (n)
Roller (n = 100)	1. Neonatal oxygenator with integrated arterial filter 2. 1/4" venous line 3. 1/4" or 3/16" arterial line	1. ECLS 2. Hybrid procedure	7
Centrifugal (n = 40)	1. Neonatal oxygenator with integrated arterial filter 2. 1/4" venous line 3. 1/4" arterial line	1. ECLS 2. Hybrid procedure	8

SCP, selective cerebral perfusion.

Prior to initiation of CPB, a pre-CPB ABG was performed (postheparinization) and the hematocrit/hemoglobin (HCT) on this ABG was used as the baseline. Per protocol, heparin concentration on the HMS was set at 3.5 mg/kg and was followed unless the slope showed heparin resistance and a higher recommended heparin dose.

The HLM was the Sorin S5 (Livanova, Mirandola, Italy), with the exception of the arterial pump in the Centrifugal Group which was the Biomedicus BP-50 (Medtronic). The CPB set up consisted of a neonatal oxygenator with integrated arterial line filter, Terumo Baby FX (Terumo Cardiovascular) or a Maquet Quadrox Neonatal (Maquet Cardiopulmonary AG, Hirrlingen, Germany). The venous line was 1/4" in both groups. The arterial lines were 1/4" in the Centrifugal Group and either 1/4" or 3/16" in the Roller Group. All tubings were coated with Terumo X coating or Carmeda (Medtronic). The MUF circuit in the Roller Group consisted of a Sorin CSC-14 and a Hemocor HPH Junior with a 1/8th Carmeda-coated tubing. The MUF circuit in the Centrifugal Group consisted of the Capiiox CP50 and the HPH Junior or HPH 400 with Terumo X coating.

The Centrifugal Group had a raised venous reservoir. A bubble trap was used additionally (Figure 1), the Capiiox BT05, along with a quarter-inch tubing tapered down to a 1/8" tubing with one-way valves to evacuate the top of the bubble trap in case of air during KAVD. The Roller Group consisted of either a small diameter (<7 kg) or large diameter (>7 kg) mast-mounted roller pump attached to a control panel (Figure 2). A schematic of the centrifugal (Figure 3) and roller circuit (inset) illustrates the more simplistic circuitry, in addition to the reduction in circuit prime volume. A continuous auto transfusion system was set up in all Centrifugal Group cases. However, on observing the low incidence of red cell salvage (average 6 mL) in the Roller Group (Figure 4), we isolated the cell saver set up to the cardiomy reservoir with heparin drip. The heparin drip

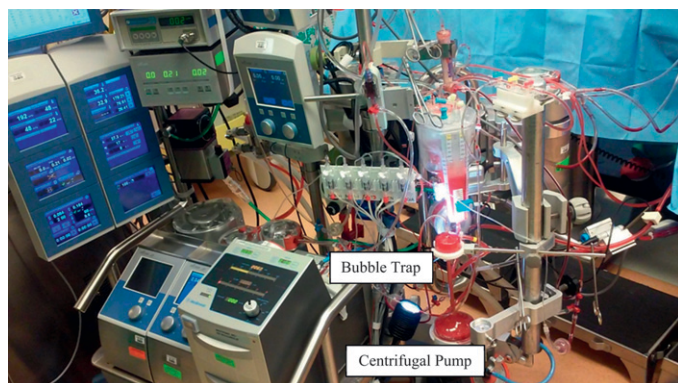


Figure 1. CPB circuitry (Centrifugal Group).

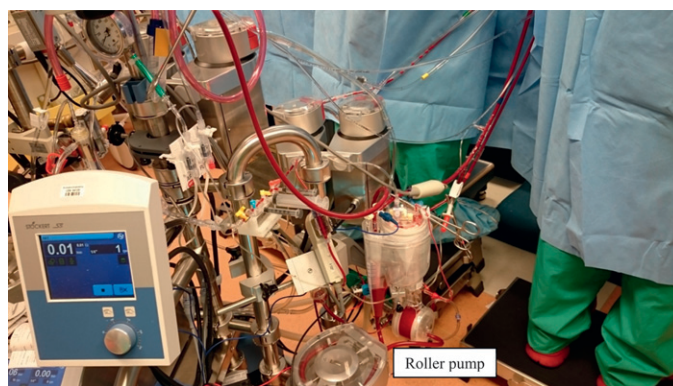


Figure 2. CPB circuitry (Roller Group).

in all cases consisted of a 1-L normal saline bag with 30,000 IU of heparin.

Cardiopulmonary Bypass

Heparin (3.5 mg/kg) was administered directly by the surgeon into the right atrium prior to cannulation. Prior to CPB, pump suckers were turned on at an ACT >300 seconds. Arterial cannulation was completed using Biomedicus 8, 10, or 12 Fr arterial cannulae (Medtronic). Venous cannulation was performed either bi-cavally or with a single right atrial cannula utilizing DLP 10–20 Fr sizes (Medtronic). A plastic tip venous cannula was preferred for the superior vena cava by our surgeons. The arterial line was tested by infusing volume and monitoring system line pressure. Once ACT reached 400 seconds, the clamp on the venous line was opened and adequate venous drainage was visually confirmed. Active KAVD with raised venous reservoir was used on all cases in the Centrifugal Group (5). Gravity drainage was used in all cases in the Roller Group. There was the ability to use vacuum-assisted venous drainage (VAVD) during all cases in the latter group but never used. A 10 Fr DLP (Medtronic) left ventricular vent was inserted through the right superior pulmonary vein and myocardial venting established. Flows in both groups were initiated according to age/weight and hemodynamic parameters and ranged from 90 to 150 mL/kg.

Depending on the congenital heart defect, the patient was then cooled to deep (22°C) or moderate (28°C–32°C) hypothermia, utilizing the 3T heater cooler system (Sorin Group). Following aortic cross clamping, blood-tinged Del Nido cardioplegia solution was delivered (Figure 5) at a 1:4 blood to crystalloid ratio (6), whenever venous reservoir volume was sufficient. Induction cardioplegia dose was 20 mL/kg with a minimum volume of 100 mL and a maximum of 500 mL. Maintenance cardioplegia doses were 10 mL/kg. Subsequent to electromechanical arrest, the cardioplegia solution was diverted back to the HLM and conventional ultrafiltration initiated by passive fill from a distal oxygenator

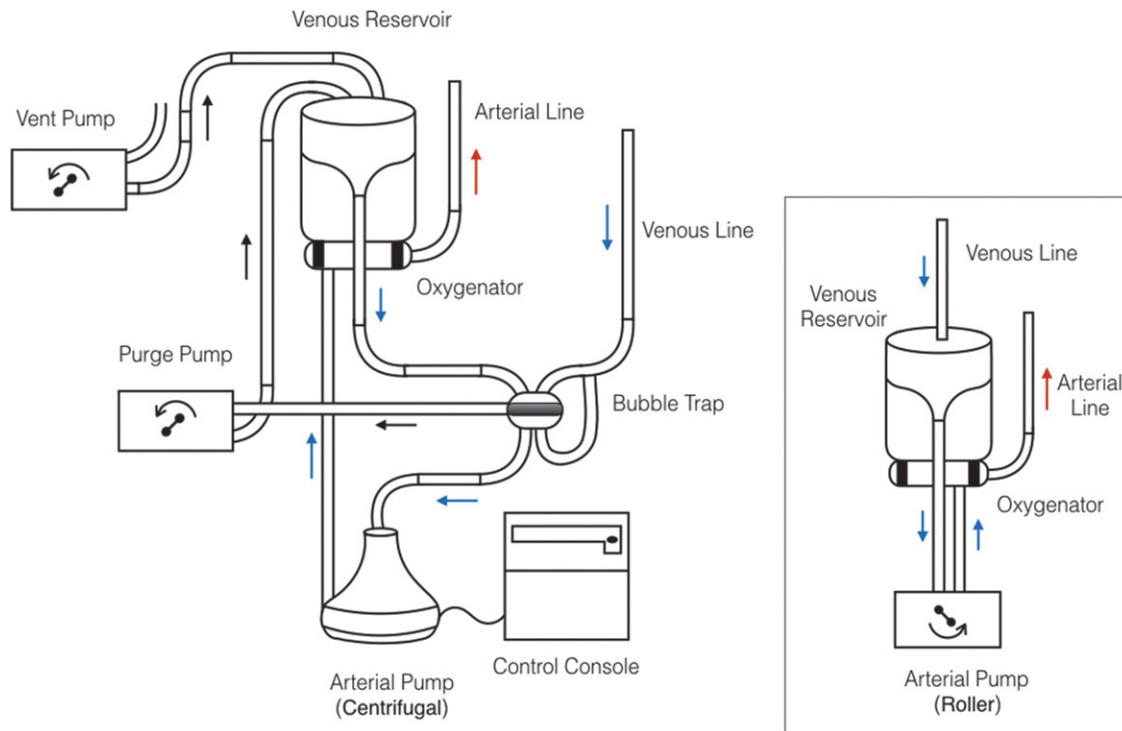


Figure 3. Schematic of CPB circuits.

outlet, through the hemoconcentrator and back to the venous reservoir. On completion of repair, the patient was rewarmed, ABG and electrolytes normalized, and Del Nido cardioplegia solution chased with warm blood through the cardioplegia/MUF circuit.

Post CPB and MUF

We used twin non-slaved pumps (Figure 5), one for cardioplegia infusion and one for MUF. On separation from CPB and evaluation of the post-operative echo, MUF was conducted for 10 minutes. In the Centrifugal Group, MUF was conducted utilizing the twin pump

intermittent method, with the roller pump (connected to the bubble trap) used as the MUF pump and the Bio-medicus pump used to reinfuse residual CPB volume in case of hypotension. The blood was not warmed and was channeled from the arterial line through the bubble trap and hemoconcentrator back into the CPB venous line.

In the Roller Group, MUF was conducted for 10 minutes utilizing the continuous dual pump method, with the MUF pump drawing arterial blood from the arterial line actively through a roller pump into the hemoconcentrator, then warmed in the cardioplegia device, and reinfused into the inferior vena cava. Simultaneously, the roller arterial pump was used to reinfuse residual CPB circuit volume while MUF was being conducted. Care was taken to sump the venous line prior to chasing residual circuit volume through circuit to maintain MUF efficacy. In both groups, MUF was carried out for 10 minutes.

After completion of MUF, protamine was administered at a 1:1.5 ratio dosage as suggested by the HMS. Post ABG and ACT samples were collected and heparin level was confirmed to be zero. In addition, a thromboelastogram was performed with a 2-channel Hemoscope Thromboelastographic analyzer (Hemonetics, Braintree, MA).

Statistical Analyses and Data Collection

All data were collected retrospectively from the perfusion electronic chart Data Management System (Sorin

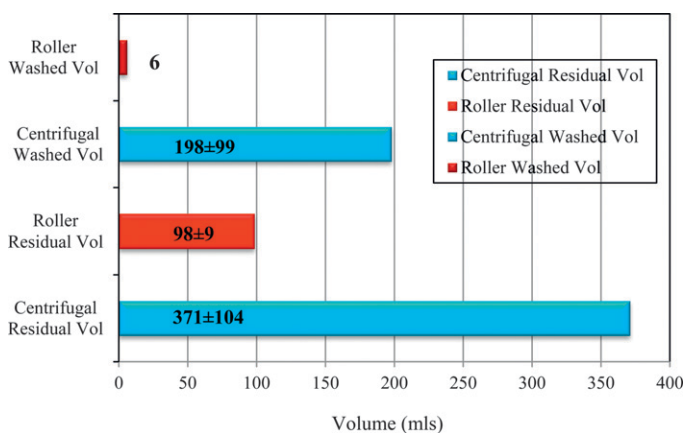


Figure 4. Residual volume in CPB circuitry and post-CPB washed blood volume.

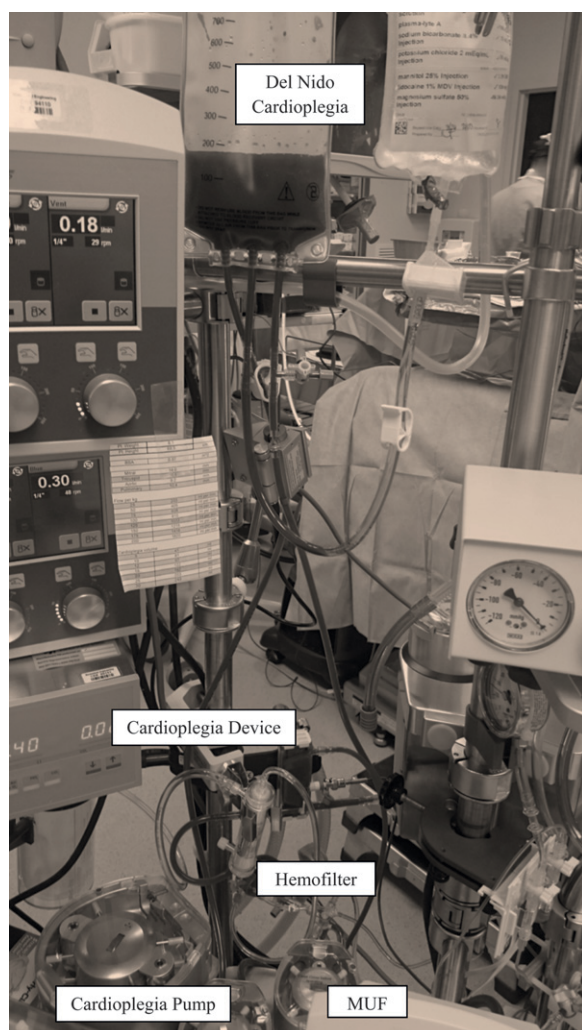


Figure 5. Cardioplegia and MUF circuitry.

Group, Munich, Germany) between January 2014 and November 2014 (Centrifugal Group) and November 2014 and January 2016 (Roller Group).

Results are expressed as means and standard deviations or median and interquartile ranges while comparing primes, homologous blood utilization, HCTs, intubation times, and hospital length of stay (LOS). All calculations stated *p* values and mean values. Comparisons were subjected to *t* test analysis.

RESULTS

A total of 140 patients were divided into two groups. A control group termed for the purposes of this study as Centrifugal Group ($n = 40$) consisting of patients placed on CPB with a centrifugal pump and KAVD. A study group termed for the purposes of this study as Roller Group ($n = 100$) consisting of patients placed on CPB

Table 2. Patient demographics (number or mean $\pm$ SD).

	Roller ($n = 100$)	Centrifugal ($n = 40$)
Weight (kg)	6.8 ± 6	5.35 ± 2
BSA	$.34 \pm .1$	$.34 \pm .2$
Age (days)	163 ± 197	99 ± 76
Sex (male/female)	66/44	31/9
CPB time (minutes)	177 ± 82	167 ± 62
Aortic clamp time (minutes)	80 ± 61	91 ± 58
Single ventricle	50	11
Bi-ventricle	50	29
Neonates/infants	26/74	14/26
Mortality (at discharge)	0 (0%)	2 (5%)

with a roller arterial pump and gravity venous drainage. The demographics (Table 2) for both groups were delineated. Although the body surface areas (BSAs) were similar, the Roller Group had a higher average age and a greater proportion of females. In addition, the CPB times were 10 minutes longer in the Roller Group, but the mean cross clamp times were 10 minutes shorter (Table 2). Fifty percent of the Roller Group had its patients as single ventricles including 10 Norwood operations. Thirty-seven percent of the Centrifugal Group had its patients as single ventricles with 4 Norwood's. Patients in both groups got a neonatal oxygenator with integrated arterial filter, a 1/4" venous line and a 3/16" or 1/4" arterial line. All patients underwent MUF post-CPB for 10 minutes.

CPB prime volume in the Roller Group was 197 ± 34 mL compared to 456 ± 54 mL in the Centrifugal Group ($p < .001$) (Figure 6). In addition, the average prime in the Roller Group in the most recent 20 cases was 153 ± 7 mL, suggesting improvement over time (Figure 6). As a consequence of reduced overall prime, prime HCT showed a jump from an average of $19\% \pm 3\%$ in the Centrifugal Group to $30\% \pm 4\%$ ($p < .0001$) in the Roller Group (Figure 7). The first HCT on CPB increased from $25\% \pm 4\%$ in the Centrifugal Group to $29\% \pm 5\%$ in the Roller Group (Figure 8).

Homologous blood utilization in the operating room (OR) for CPB dropped overall 55% (Figure 9).

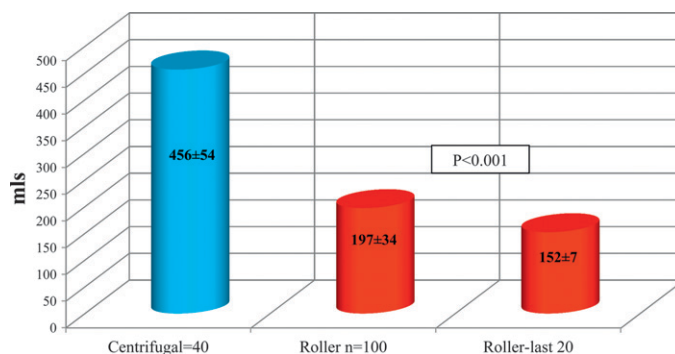


Figure 6. CPB prime volumes (mL) (mean $\pm$ SD).

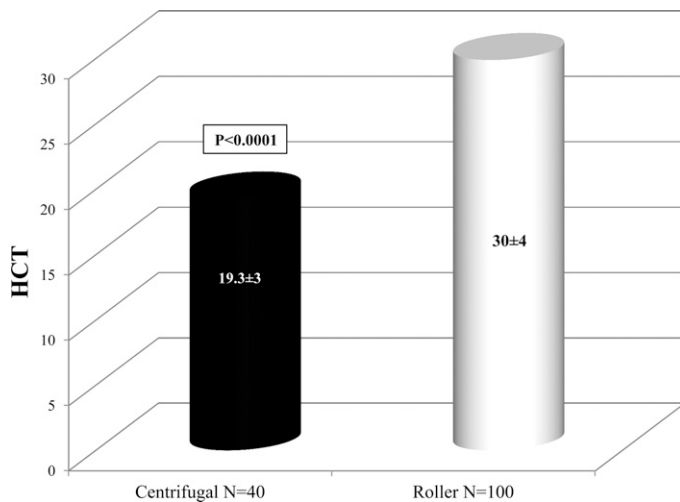


Figure 7. Pump prime HCT (% $\pm$ SD).

Homologous washed red cells used to prime the HLM with the Centrifugal Group decreased from 224 ± 50 mL to 102 ± 40 mL ($p < .001$) for the Roller Group. Additional washed red cells transfused on CPB decreased from 198 ± 129 mL in the Centrifugal Group to 129 ± 77 mL in the Roller Group ($p < .001$).

Mortality at discharge (Table 2) was 5% in the Centrifugal Group and 0% in the Roller Group. Due to the small number of patients enrolled, this difference was not considered to be statistically significant. We studied STAT-categorized intubation times and hospital LOS in all our patients. STAT category 3 was eliminated as we had only one patient in the Centrifugal Group and two in the Roller Group. All STAT categories showed a trend toward improvement in the Roller Group for intubation times (Figure 10) and hospital LOS except for STAT 5. In STAT 1 outcomes, the hospital LOS was improved (Figure 11) in the Roller Group and showed statistical significance ($p < .05$). We believe that a larger cohort would be required to confirm statistical significance.

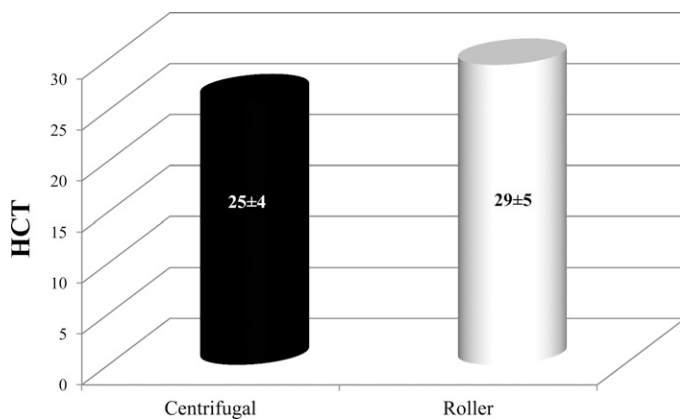


Figure 8. First HCT on CPB (% $\pm$ SD).

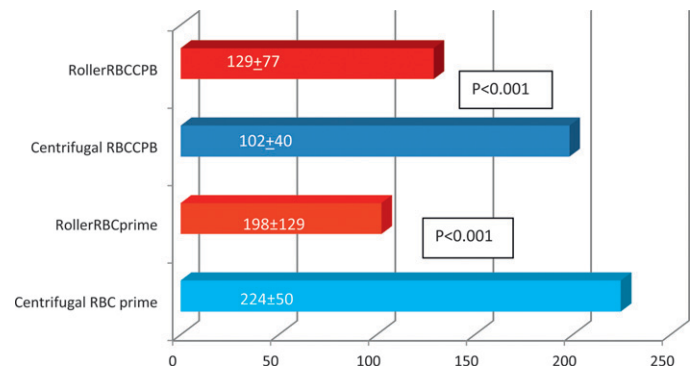


Figure 9. Homologous blood utilization (mL) (mean $\pm$ SD).

DISCUSSION

CPB in infants and neonates has always been challenging. The addition of homologous blood to the HLM had been standard practice for many years.

The advent of smaller CPB equipment/devices such as mast-mounted pumps and oxygenator with integrated arterial filters (Table 3) has reduced pediatric prime volumes. In addition, cardioplegia devices with lower prime volumes have facilitated effective MUF.

The use of mast-mounted pumps have enabled staggered pump designs, allowing arterial pumps to be closer to the oxygenator and the entire pump circuitry closer to the operative field without compromising operative field sterility. We have been able to use a small raceway arterial pump for our patients below 7 kg with the prime volume of the raceway boot approximately 10 mL. This design also allows the vent line to be closer to both the operative field and venous reservoir, thereby reducing the amount of fluid flowing in the vent circulation during CPB (Figure 2).

Our initial goal was to reduce CPB prime, hypothesizing that this would form the foundation for our goal of reducing homologous blood transfusions. We were able

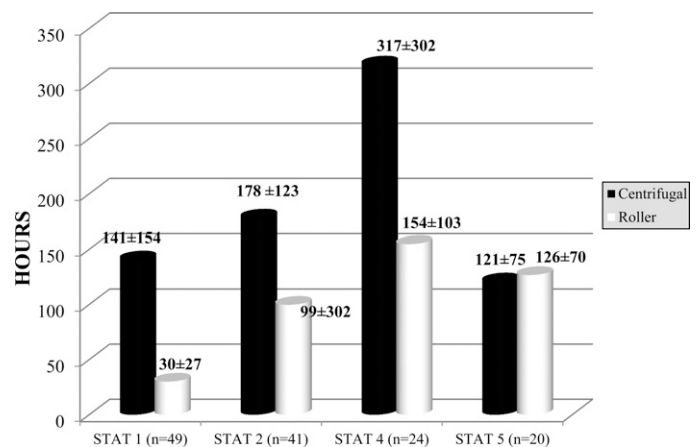


Figure 10. Intubation times (hours) (mean $\pm$ SD).

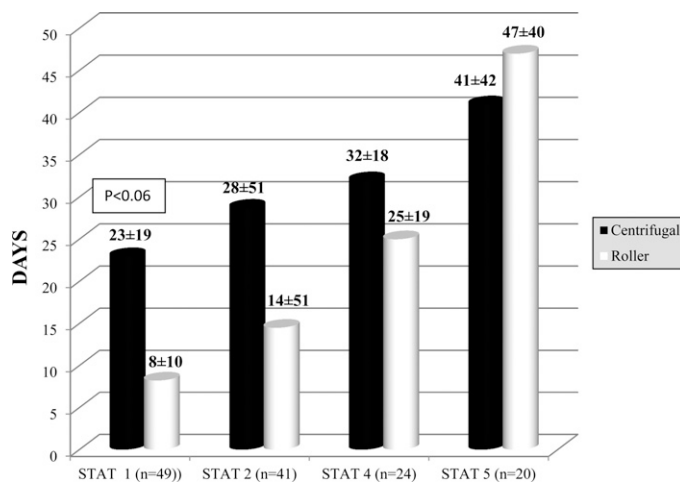


Figure 11. Hospital LOS (days) (mean ± SD).

to decrease intraoperative blood product utilization. Our next step was to make further modifications in an effort to be able to conduct bloodless pediatric cardiac surgery, as desired by many patients from the JW faith. Minimizing prime volume has led to decreased residual volume in the pump. The whole blood in the arterial line and MUF circuit are loaded into two 50-mL syringes and given to the anesthesiologist for re-transfusion. This resulted in a reduction in pump residual volume from 371 ± 104 mL in the Centrifugal Group to 98 ± 9 mL in the Roller Group (Figure 4). Reduction in residual volume led to a shift to whole blood re-transfusion as opposed to packed cells washed in the cell saver, thereby salvaging the patient's native platelets and clotting factors.

Heubler et al. have published case reports showing that it is possible to conduct bloodless CPB in patients from the JW faith (7,8). They emphasized the fact that lower HCT values for short periods of time can be tolerated, using vasopressors for blood pressure support if necessary (9). VAVD was an important part of their protocol as it allowed them to raise the venous reservoir and reduce CPB primes to fewer than 100 mL. They have conducted CPB in patients as low as 3.5 kg (9). We believe it is prudent to start with patients weighing over 10 kg (7) and to work on shortening CPB and OR times to get the best results. Huebler et al. has also reported 3-kg neonate, who underwent bloodless CPB with DHCA for hypoplastic arch reconstruction and atrial septal defect

(ASD)/ventricular septal defect (VSD) closure (10). The group at Nationwide Children's Hospital (Columbus, OH) has published a case report of bloodless pediatric cardiac surgery in a 3.5-kg JW child undergoing aortic valve repair (11). They described the use of preoperative treatment with iron and erythropoietin as well as intraoperative acute normovolemic hemodilution.

Bloodless pediatric CPB requires more than reducing HLM prime. The current accepted "norm" for safe HCT on pediatric CPB has consistently been 24% for biventricular patients and 30% for single ventricles. We generally followed this guideline. However, Ootaki et al. showed it is possible to conduct safe CPB with lower HCTs on babies (12). The decision to transfuse should always be based on physiological parameters including mean arterial pressure, regional cerebral saturations, lactate levels, and blood gases, rather than a single laboratory value.

In a 2.5-kg neonate (blood volume of approximately 200 mL) undergoing 4 hours of CPB and having 10 samples every half hour (including baseline/postprotamine), we reduced our ACT sampling volume from 8 to 1.5 mL. By reducing the number of heparin levels tested, our sampling volumes were reduced from a total of 25 mL (for the aforementioned case) to less than 10 mL.

Previous protocols used at our institution ensured enough volume was available post-CPB to treat hypotension. This has since changed with a smaller prime and efforts are underway to have a more balanced approach with vasopressors and volume. Strategic use of vasopressors to counter hypotension (when it's safe to do so) while weaning from CPB will enable the reduction of blood transfusion on CPB (13,14), most of which was transfused just prior to terminating CPB. Alternatively, a single dose of calcium chloride (20 mg/kg) can support the blood pressure on CPB termination. All these factors enable hemodynamic stability on separating from CPB and allow MUF to commence safely and efficiently.

CONCLUSION

We demonstrated that the transition to roller pumps in the arterial position of the HLM considerably reduced our priming volume and formed a basis for a comprehensive blood conservation program. By maintaining higher

Table 3. CPB disposables and prime volumes.

	Arterial Pump	Oxygenator	Cardioplegia	Hemofilter	Arterial Line (per foot)
Centrifugal	Biomedicus BP 50 = 50 mL Capiiox BT 05 = 50 mL	Terumo Baby FX = 43 mL	Capiiox CP 50 = 52 mL	HPH 400 = 34 mL	1/4" = 9.5 mL
Roller	Raceway Tubing = 10–20 mL	Terumo Baby FX = 43 mL Maquet Quadrox Neo = 40 mL	Sorin CSC 14 = 31 mL	HPH Junior = 8 mL	1/4" = 9.5 mL 3/16" = 4.5 mL

HCTs on CPB, we were able to reduce intraoperative homologous blood transfusions.

A multidisciplinary approach is essential to conducting safe changes in operative protocols and procedures. Although reducing priming volumes established a baseline for a responsible blood conservation approach, more work is required in order for us to have the ability to conduct bloodless pediatric cardiac surgery.

Although our outcomes showed a trend toward improvement in the roller group, a larger cohort of patients is needed to demonstrate whether these differences are statistically significant. Such differences have indeed been shown in other studies (15,16).

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