Cardiopulmonary Bypass

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Background

The first heart lung machine (HLM) was used by Gibbon 1953 for an atrial septal defect closure. HLM was developed as an alternative to cross circulation. The disc oxygenator was one of the first generation oxygenators and increase the time cardiac surgery could be performed safely. The initial HLM were bulky requiring up to 7 L for priming. Hypothermia was used topically and the heart was allowed to fibrillate for extended periods of time.

Pre Bypass Stage

Perfusion Equipment

Heart lung machines components include one arterial head, three sucker pumps, and one cardioplegia pump for a total of five. Mandatory alarms contain: level alarm, bubble sensor alarm, arterial and cardioplegia pressure line alarm. Battery back up system is also necessary in case of emergency (Fig. 1).

There are two main types of arterial pump heads which are centrifugal and roller head. Centrifugal pumps contain a cone that uses centrifugal force to propel blood forward. It is pre load and after load dependent that delivers a characteristic laminar

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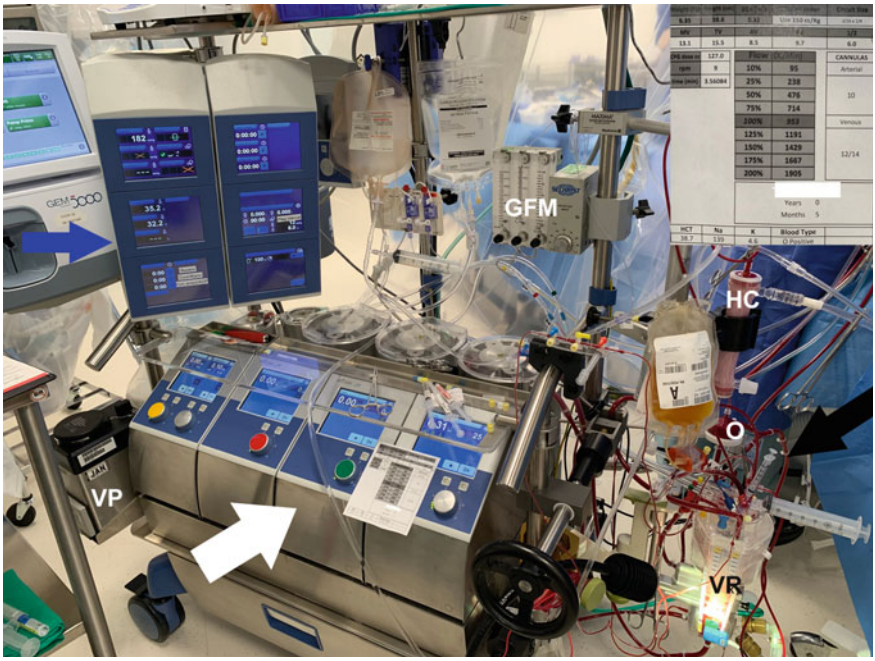

Fig. 1 Picture of a heart and lung machine. The black arrow shows the venous reservoir (VR), the oxygenator (O), and the hemoconcentrator (HC). The white arrow shows the roller head arterial pump (right grey knob), three sucker pumps (green, red, and yellow), and one cardioplegia pump (left grey knob). The blue arrow shows the alarm panel with pressure, volume, and temperature alarms. In addition, the gas flow meter (GFM) and the vaporizer (VP) can be seen. Finally in the right upper corner customized patient information with cannulas used and target cardiopulmonary bypass flows is visualized

flow. The pro for this pump is safety. A cardiopulmonary bypass (CPB) circuit with a centrifugal pump may be clamped anywhere and the pump will not explode. The con is that the pumps run at very high speeds creating heat which can lead to hemolysis and platelet dysfunction. The characteristic non pulsatile delivered by centrifugal pumps is not the preferred flow for end organ preservation. Centrifugal pumps are almost exclusively used in adults. Roller head pumps are positive displacing occlusive pumps that deliver a pulsatile flow. The amount of pulsatility is small usually only approximately 4 mmHg. However any amount of pulsatility is viewed as beneficial and more physiologic. The other advantage of roller head pump are not load dependent and are very accurate. The set flow by the perfusionist is what is delivered not being affected by downstream resistance or any other factors. Its accuracy makes it the most popular system among pediatric centers in which precise flows is a mandatory requirement.

The selection of the CPB circuit is based on patient size and the amount of flow needed. The circuit selection is detailed in Table 1. Patients who are greater than 75 kg have a 1/2 inch pump head boot to decrease the RPM's of the arterial head

Table 1 CPB circuit selection by patient size

Patient size (kg)	Arterial cannula size (Fr)	Arterial line (inches)	Venous line (inches)	Single RA cannula (Fr)	Bicaval cannulae (Fr)	Flow (mL/min)
0–7	6	3/16	1/4	16	8/10	0–350
	8			18	10/12	350–650
7–25	10	1/4	3/8	20	12/14	650–1000
	12			24	12/16	1000–1250
					14/16	1250–1800
25–45	14	3/8	3/8	28	14/18	1800–2000
					16/18	2000–2400
	16			32	18/20	2400–3000
					20/24	3000–4000
>45–75	18	3/8	1/2	36	24/24	4000–4500
					24/28	4500–5000
	20				28/28	5000–6500
>75	22	3/8	1/2	36	28/28	6500

Abbreviations: kg, kilograms; Fr, French; mL, milliliters; min, minutes

when using a roller pump. All the tubing packs include three 1/4 inch suction lines that are color coded for ease of differentiation at the surgical table as well as in the selected pump heads on the pump. A variety of connectors are included in the tubing packs as to accommodate different cannulation possibilities.

Several cannulation techniques are used based on the type of procedure being performed. Cannula size is determined by the amount flow need for each patient. The general guideline for cannula size and selection is detailed in Table 1. Typically bicaval cannulation is used on any procedure that requires intracardiac repair. For example atrial septal defect repair, ventricular septal repair and/or auriculoventricular valve repair or replacement. A single atrial venous cannula is used predominately on "closed procedures" where the heart does not have to be opened. (e.g. coronary artery bypass graft (CABG) and pulmonary valve repairs or replacement). Innominate and subclavian arterial graft cannulation is employed when antegrade cerebral perfusion (ACP) is going to be used in lieu of deep hypothermic circulatory arrest (DHCA). This technique is used to establish and maintain flow to the brain while the rest of the arch vessels are snared so an aortic arch reconstruction may be preformed.

The venous reservoirs and oxygenators are sold by many manufactures and most CPB oxygenators are microporous hollow fiber. When selecting a product careful consideration must be paid to the volume of the reservoir to insure it will accommodate the volume of a given size patient. The oxygenator size must also be considered since they have limited ability to oxygenate and flow. One must again insure that the oxygenator selected will be able to meet the needs of the patients given size (see Table 1).

A variety of filters are used during CPB to avoid emboli. Pre-bypass 5 microns filter is used in the bypass circuit to dispose the circuit of any particulate from the manufacturing process. Once the circuit is crystalloid primed and circulated this filter is removed before any blood is added. Pall filters (40 micron) are used for the addition of blood products. The venous reservoir has an internal "sock" filter (47 microns) is used to ensure any clot or bone chips sucked through the pump suckers is not reintroduced to the patient. The arterial line filter is primarily used as a last line of defense to catch any air that may have passed though the oxygenator. It is usually placed at the highest point in the circuit.

The cooler heater is used to cool and warm the patient and the cardioplegia circuit. Water lines from the cooler heater are connected to both the oxygenator and cardioplegia circuits. Water is pumped through both units at a high rate of speed to raise and low the temperature as so desired by the team.

Continuous ultrafiltration also known as Zero Balance Ultrafiltration (ZBUF) is the practice of adding a set amount of volume into the circuit and removing the same amount of volume via the hemoconcentrator during the bypass run. This practice has proven to remove inflammatory mediators such as inteleukins 6 and 8 and decrease the inflammatory response. ZBUF has been linked to shortened ventilator, ICU and hospital length of stay. Continuous ultrafiltration is also utilized to manipulate electrolytes as well as lowering the lactate. Modified ultra filtration (MUF) is a technique used after bypass completion to hemoconcentrate. Blood is pulled off the arterial limb of the circuit and pumped through the hemoconcentrator and returned to the patient via the venous line.

A pre-bypass checklist is an essential tool to insure the safety of the patient. Similar to a pre-flight safety checklist used in the aviation industry. It should go over all the major systems and components of the CPB system. Careful inspection of all system components, settings, connections and alarms must be checked and assured they are correct before bypass may being. The check list we use at Texas Children's Hospital is presented in Table 2.

Bypass Prime

While most institutions we employ a strategy of a crystalloid priming with 5000 units of heparin in the adult population. The type of prime depends on the size of the patient, underlying cardiac lesion (e.g. cyanotic vs non cyanotic) and type of bypass circuit. Institutionally we try and maintain a haematocrit > 25% in acyanotic patients and > 30% in cyanotic patients and/or comorbitidities. Research has shown that hematocrits under 24% during hypothermic cardiopulmonary bypass in infant heart surgery are associated with lower psychomotor development index scores and increased lactate levels. In our practice will tolerate lower hematrocirts in selected situations (e.g. to avoid blood transfusion) as long as it is clinically acceptable guided by cerebral oxymetry at or above baseline values and no increase in the arterial lactate. Hemodilution calculation is preformed in all the patients and if the

Table 2 Texas children's hospital perfusion checklist

I. Equipment inspection	II. Assembly of perfusion circuit per TCH protocol
A. Pump 1. Visual inspection of electrical plugs and components 2. Roller assembly and modes checked 3. Hand cranks functional	1. Gas flow initiated if indicated 2. CO_2 flush if indicated 3. Sterile connection of circuit components 4. Fluid paths are correct with the lines loaded in the pump housing correctly 5. Cardiotomy reservoir is vented 6. Oxygenator and heat exchanger integrity 7. Proper pharmacological agents added to the prime (double check with anesthesiologist) 8. Prime is heparinized 9. Circuit is debubbled 10. Check for leaks in the circuit 11. Final occlusions are properly set
B. Safety devices 1. Air bubble detector operating correctly 2. Level sensor operating correctly 3. Check blender alarms	
C. Heater–cooler 1. Operational modes operating correctly 2. Visual inspection of electrical plug and components 3. Proper connections are made	
D. Gas inspection 1. Flow meters operating correctly 2. Tubing and connections checked for leaks/obstruction 3. Blender is operational	
E. Brackets 1. Oxygenator 2. Cardiotomy reservoir 3. Arterial filter	
F. Disposables 1. Package integrity (each item) 2. Observe for manufacturer defects (each item) 3. Sterilization is current (each item) 4. Spare disposables are available	
G. Accessories 1. Tubing clamps, scissors/sterile blade and tape are available 2. Heparin available (check expiration date) 3. Coagulation monitoring equipment available and operational 4. Arterial blood gas machine available and operational	

predicted hematocrit value is borderline a collegial conversation between the surgeon, anesthesiologist and the perfusionist will take place about the decision to use blood or not in the prime. The use of plama however is not a clearly defined. Plasma may be used in the prime in selected situations such as cyanotic patients with a high

hematocrit (> 45%), multiple redo chest, and/or suspected ATIII deficiency. The neonate or infant circuit is primed with 0.45% NaCl (350 mL) before blood products are added. In the toddler or pediatric the circuits is primed with 0.45% NaCl (500 mL) and Plasmalyte-A (150 mL) before blood products are added. Older patients the prime consist of plasmalyte A, 0.45% NaCl, 25% Albumin and 5% Dextrose. Detailed examples of cardiopulmonary bypass primes are presented in Table 3.

Pharmacology of Bypass

CPB involves extreme changes in physiologic conditions incluing hypothermia, hemodilution, lung isolation, non pulsatile blood flow, low flow and even situation with no flow (deep hypothermic circulatory arrest – DHCA). CPB provides non-pulsatile blood flow which reduces hepatic blood flow by 20–50% depending on the concurrent presence of hypothermia and/or low CPB flow and tiggers the inflammatory cascade. Inflammation results from hemolysis, ischemia, reperfusion, and exposure to foreign CPB surface material. All these factors of affects drug pharmacokinetis and pharmacodynamics. Hydorfilic drugs suffer dilution on initation of CPB decreasing plasma levels. The amount of dilution in direct relationship between the patient blood volume and the prime volume. The hemodilution effect is more pronounced in neonates and infants in which there is an 100% dilution. It can be calculated using this formula:

$$\Delta C_{D''} = C_{D'} x \left(V_{prime} / V_1 + V_{prime} \right)$$

where:

$\Delta C_{D''}$ Drug change in concetration
V_{prime} prime volume
$C_{D'}$ drug concentration before hemodilution
V_1 central compartment volumen of distribution.

To compensate the hemodilution effect hydrophilic drugs (e.g. non depolarizing muscle relaxants or antibiotics) need to be redosed on initiation of CPB. In addition the CPB circuit is not inert and adsorption of drugs by CPB circuit materials occurs. Lipophilic drugs have a higher volume of distribution and trend to accumulate in the tissues while on CPB. The isolated lung works as a drug reservoir for basic drugs (i.e. fentanyl, propofol or lidocaine) and plasma levels of these type of drugs may increase after weaning of CPB. Hypothermia decreases the activity of microsomal hepatic metabolism system. Furthermore, hypothermia preferentially shifts blood flow to the coronary and cerebral circulation decreasing blood flow to the liver and kidney favouring drug accumulation. In addition hypothermia affects the affinity of opiod agonist with its receptors and decreases MAC requirements.

Table 3 Examples of CPB primes varying with age

	Priming volume (mL)	Arterial line (inches)	Venous line (inches)	PRBC (mL)	FFP or 25% Albumin (mL)	0.45% NaCl	Plasmalyte A (mL)	Heparin (U)	$NaHCO_3$ (mEq)	$CaCl_2$ (mg)	5% Dextrose (mL)
Neonate/ infant	350	3/16	1/4	175	125[a]	50		1500	8	350	
Toddler/ pediatric Blood prime	650	1/4	3/8	300	100[b]	150	100	3000	15	400	
Toddler/ pediatric clear prime	650	1/4	3/8		100[b]	150	400	3000	20	200	15
Adolescent	1000	3/8	3/8		150	250	600	4000	30	300	25
Adult	1250	3/8	1/2		200	300	700	5000	40	450	50

[a]Infant prime always uses FFP

[b]FFP used in place of albumin when clinically indicated (e.g. cyanotic heart disease)

Abbreviations: PRBC, packed red blood cells; FFP, fresh frozen plasma

During rewarming the opposite process occurs making the patient prone to light anesthesia and recall unless provisions are taken.

Anticoagulation is mandatory before the initation of CPB to avoid bypass circuit clotting. Unfractioned intravenous heparin is used to accomplish anticoagulation at a dose of 300 U/kg. Achieving adecute anticoagulation is confirmed with an activate clotting time (ACT) > 480 seconds. Neonates and infants due to a large volume of distribution secondary to increase water content require higher doses of heparin (400 U/kg). Heparin resistance is seen in patient with low levels of antithrombin III (AT III) (heparin cofactor) such as patients previously exposed to heparin. These may require recombinant AT III administration (50 U/kg) to achieve the desire level of anticoagulation. Fresh frozen plasma has low levels of AT III (1 U/mL) so its administration to correct AT III is not recommended in neonate and infants to avoid fluid overload. Reversal of anticoagulation is achieved with protamine in a relationship of 1.2 mg per 100 units of heparin.

Heparin induced thrombocytopenia (HIT) is dangerous complication to heparin administration which makes CPB management very challenging. The clinical presentation is characterized by rapid decline of platelet count (>50%) but manifest with arterial and/or venous thrombosis. Patient with confirmed diagnosis of HIT that need to undergo cardiac surgery on CPB require a careful pharmacologic management with direct thrombin inhibitors (i.e. argatroban or bivalirudin).

Antifibrinolytic drugs are effective in reducing bleeding and transfusion associated with cardiac surgery involving CPB in adults and children. The lysine analogs ε-aminocaproic acid (EACA) and tranexamic acid (TXA) competitively inhibit the binding of plasminogen to fibrin. The EACA concentration of required to inhibit fibrinolysis varies with age. In neonates the concentration of EACA needed is (50 mg/l) due to the immaturity of the fibrinolytic system at birth. In adults and children the recommended concentration of EACA is 130 mg/l. EACA is mostly cleared by renal filtration. Due to the decrease glomerual filtration rate in the neonatal period ($\sim$30% of the adults) the recommended dose is about half those required in adult and children see Table 4. TXA is likewise mostly excreted by the kidney and dose adjustments are needed in renal impairment. Both antifibrynolitcs carry the risk of increase thromobisis so its administration (bolus and infusion) should be delayed until CPB has been initiated in patients with shunt dependent pulmonary circulation. In addition TXA use has been associated with four fold increase incidence of postoperative seizure. Its use should be avoided in patiens with seizure disorders. Comparative studies between EACA and TXA have heart surgery, there was no statistically significant difference according to postoperative blood loss.

Antibiotics are used in all cardiac surgery cases to decrease the incidence of surgical site infections (SSI). The majority of SSI are caused by staphylococcus aureus and coagulase-negative staphylococci, including staphylococcus epidermidis. Cephalosporins are the first line prophylactic antibiotic used in cardiac surgery. The antibiotic plasma concentration should be therapeutic all through out the procedure to be effective and is continued for 48 hours. CPB affects the antibiotic level due to several pharmacokinetic changes mentioned above.

Table 4 EACA dose and age

	Bolus (mg/kg)	Infusion (mg/kg)	Prime dose (μg/ml of prime volume)
Neonate	30	40	100
Children	75	75	250
Adult	50	50	250

Abbreviations: EACA, ε-aminocaproic acid

In addition CPB compromises humoral defenses, reduces phagocytosis and affects the activations of white blood cells imparing natural defense against infections. Hypothermia and coagulopathy also increase the risk for SSI. The first dose of antibiotics should be administered 30 minutes or less before skin incision and every two half-lives of the antibiotic while the chest is open. An additional dose is given to the bypass prime to elude the effect of hemodilution.

The pharmacokinetics of intravenous anesthetics is also affected by CPB initiation, cooling and rewarming. Changes are detailed in Table 5. Inhalatory anesthetics (IA) solubility changes with the start of CPB. Decrease temperature increases IA solubility where as hemodilution decreases IA solubilty. There is also potential sequestration of IA by the oxygenator. It is important to monitor the IA concentration beyond the oygenator to confirm and adequate delivery of IA. Deep of anesthesia by spectral analysis should be monitored too. Finally non depolarizing muscle relaxant (NDMR) agents due to its hydrophilic nature and intravascular distribution are affected initially by hemodilution requiring a dose on the CPB prime. During cooling requirements for NDMR decrease so interval dosing should be prolonged. Neuromuscular monitoring is important to avoid under and/or over dosing. Currently with the availability of sugamedex overdosing has become less of a problem since complete neuromuscular blockage can be achieved at any level of neuromuscular relaxation.

Table 5 CPB pharmacokinetics of anesthetic agents

	CPB initiation (Dilution)	Hypothermia (↓ metabolism)	Rewarming (↑ metabolism)
Propofol	↓	↑	↑[a]
Benzodiazepine	↓	↑	↓
Dexmedetomidine	↓	↑	↓
Etomidate	↓	↑	↓
Ketamine	↓	↑	↓
Narcotics	↓	↑	↑[a]

Abbreviation: CPB, cardiopulmonary bypass; Drug plasma concentration↓ decrease; ↑ increase; ↔ unaffected

[a]Plasma concentration might increase due to release from lung reservoir upon restarting lung ventilation

Conduct of Bypass

The initiation of CPB begins by opening the venous line to drain and then starting the arterial head. As venous drainage increases, the arterial flow increases until full flow is reached (100% flow). The ideal flows are calculated by body surface area (BSA) and are age specific (See Table 6). This commencement should be done in a manner and rate that maintains a reasonable perfusion pressure. If initiation is done too slowly the patient blood volume will be drained and not enough forward flow will be present to maintain blood pressure. If done too fast the patient would not be fully drained and the cannulas would overflow the patient. If the appropriately sized positioned cannulas and optimal drainage is still not achieved vacuum assisted venous drainage (VAVD) can be implemented. The negative pressure on the vacuum must never exceed negative 60 mmHg to avoid hemolysis and/or air emboli. VAVD must be discontinued before the termination of bypass air as may draw across the membrane.

At the beginning of bypass the temperature set on the cooler/heater should be the same of the patient nasal temperature. Often times especially on redo operations the patients temperature may drift down a few degrees. If the patient naturally drifted to 34 °C and CPB is initiate bypass at 37 °C the patient will be warmed, worsening the hypotension caused by the clear prime. The temperature gradient between the cooler/heater and the nasal temperature should be maintained at 8 °C or less on both cooling and warming phases. Every 7 °C of cooling the oxygen demand of the decreses by 50%. The degree of hypothermia required varies with the complexity and duration of the procedure (see Table 7). Any procedure that requires antero-grade cerebral perfusion or DHCA, a target nasal temperature of 18 °C should be achieved.

The blood gas management on bypass at Texas Children's e employs the strategy of permissive hypercapnia with target a CO_2 of 48–55 to improve cerebral perfusion. This is the PH stat technique where all blood gas values are temperature corrected. Other institutions employ alpha stat where all values are calculated at 37 °C. The mixed venous saturation is used as a determination of optimal perfusion

Table 6 Recommended CBP flow by weight and BSA

Patients weighing < **10 kg**	Flow = Wt (kg) × 150 ml/min
Patients weighing > **10 kg**	Flow = BSA × Cardiac Index (Age Specific)

$BSA = \sqrt{\frac{Ht(cm) \times Wt(kg)}{3600}}$

0–2 yr 3.0–3.2 × BSA
2–4 yr 2.8 × BSA
4–6 yr 2.6 × BSA
6–10 yr 2.5 × BSA
>10yr 2.4 × BSA
Abbreviations: BSA, body surface area

Table 7 Classification of degree of cooling

	Temperature °C	Type of procedure
Mild	37–32	Closed procedures i.e. CABG, BDG, or Fontan
Moderate	31–28	Open procedures i.e. VSDs, MVR, TOF, etc
Deep	28–18	Complex open procedures i.e. TOF with extensive PA reconstruction
Profound	18–0	Aortic reconstruction procedures
		(i.e. Norwood, arch advancement, etc.)
		TAPVR

Abbreviations: CABG, coronary artery bypass graft; BDG, bidirectional Glenn shunt; VSD, ventricular septal defect; MVR, mitral valve repair or replacement; TOF, tetralogy of Fallot and TAPVR, total anomalous pulmonary vein return

and a value 75% is sought. Blood gas should be monitored at least every 15–20 min.

After CPB cooling is underway, preparation for cross clamp (XC) and cardioplejia (CPG) administration follows. Once the surgeon is ready to apply the XC the CPB flow is decreased ($\sim$20% of full flow values) and then XC is applied. Once the XC is on CPG administration begins. Anti-grade flow rates 250 mL/min and a pressure target of at least the patient's baseline diastolic blood pressure or slightly higher (5–10 mmHg) is administered. Severe aortic insufficiency is particularly challenging situation because CPG preferentially flows into the left ventricle (LV) and not into the coronaries. This causes LV distension and fails to arrest the heart in timely maner. In these situation aortotomy is needed with direct ostial CPG injection. Anti-grade administrations is preferable to retrograde as it protects the right side of the heart. Adults with coronary artery disease will require retrograde however and usually given at 150 ml/min near baseline diastolic pressures. There are many types of CPG solutions that are given at different time intervals and temperatures. The dosing interval is also determined by the type of solution used. At Texas Children's Hospital we use the Del Nido CPG which after the initial arresting dose of 20 mL/kg (maximum dose of 1000 mL for patients > 50 kg) is delivered the subsequent maintenance doses are given every 60 min. If the XC time is expected to be < 30 min, a half dose can be used (e.g. ASD closure). Another alternative is to use the Buckburg dextrose based solution which is administered as an induction arresting dose, maintenance doses (every 15–20 min) and reperfusion normothermic dose ("hot shot") just before aortic unclamping (Table 8).

The target mean arterial pressure (MAP) is discussed between during surgical time out before the procedure begins. Careful and frequent monitoring of all predetermined physiologic parameters should be performed constantly throughout the bypass run. The cerebral oxymetry is monitored and kept at baseline levels (e.g. patient awake ventilating in room air). A step wise approach to cerebral desaturation on bypass is used, similar to the one proposed by Denault et al. Unilateral desaturations are usually related to cannula malposition and position needs to be

Table 8 Comparison between the modified buckberg CPS and del Nido CPS*

	Modified Buckberg CPS		del Nido CPS
Base solution	Induction	D5 1/4 NS 392 mL	Plasma-Lyte A 1000 mL
	Maintenance	D5 1/4 NS 798 mL	
	Reperfusion	Sterile water 235 mL	
Total volume (approximate)	Induction	500 mL	1100 mL
	Maintenance	1000 mL	
	Reperfusion	500 mL	
KCL	Induction	36 mEq/500 mL	26 mEq
	Maintenance	36 mEq/L	
	Reperfusion	15 mEq/500 mL	
Tromethamine 0.3 M	Induction	60 mL/500 mL	None
	Maintenance	123 mL/L	
	Reperfusion	56 mL/500 mL	
C-P-2-D	Induction	30 mL/500	None
	Maintenance	61 mL/L	
	Reperfusion	113 mL/L	
$NaHCO_3$	None		13 mEq
Mannitol 20%	None		16 mL

Abbreviation: CPS, cardioplegia

Adapted with authorization from Kim K, Ball C, Grady P, Mick S. Use of del Nido Cardioplegia for Adult Cardiac Surgery at the Cleveland Clinic: Perfusion Implications. J Extra Corpor Technol. 2014;46(4):317–323

verified by the surgeon. Bilateral desaturations which are the majority are treated initially by increasing CPB flow to increase MAP. In addition the FiO_2, hematocrit and/or CO_2 may need to be optimized too. Monitoring of the lactate level is done with every arterial blood gas during the bypass run (every 15 min).

Upon the conclusion of the surgical procedure after rewarming has been completed weaning from CPB will ensue. All electrolytes should be corrected and a predetermined target hematocrit achieved. To wean off CPB all shunts should be closed and vacuum assisted drainage terminated if in use. Ventilation should be resumed fully and that the depth of anesthesia should be adequate. In close communication with the surgical and anesthesia teams weaning begins by partially occluding the venous line transferring volume from the reservoir to the patient. The patient will begin to show ejection in the arterial tracing and the central venous pressure (CVP) should be closely monitored to avoid over distension of the heart. Once ejection has commenced weaning of the pump flow should begin while maintaining ejection and a targeted CVP. Reduce the flow to 75%, then 50, then 25 and finally turning the pump off and fully clamping the venous line.

Deep hypothermic circulatory arrest (DHCA) is a technique that is employed to achieve a completely bloodless field (e.g. TAPVR repair). Basically is achieved by cooling the patient to 18 °C and shutting the pump off. Cooling to 18 °C must take

at least 20 min to ensure even and effective cooling. Once instructed to shut the pump off the arterial line must be clamped and the venous line should be clamped either at the field or at the perfusion end. Selective anti-grade cerebral perfusion (ACP) is a technique that is usually employed when aortic arch work must be done. Performed at 18 °C by cannulating the innominate or subclavian artery (directly or with a graft) and snaring the other head vessels so the flow is directed anti-grade only to the head. A flow rate of approximately 30% is used at this time with careful monitoring of cerebral oximetry to ensure the circle of Willis is intact. The TCH ACP protocol is detailed in Table 9.

Table 9 Texas children's hospital infant antegrade cerebral perfusion technique

1. Heparinization	• 100 units/kg heparin
2. Graft placement	• PTFE graft to right innominate artery[a]
3. Aortic cannulation	• 10 Fr standard aortic cannula to distal end of graft
4. Venous cannulation	• Single atrial or bicaval cannulation
5. Neuromonitoring	• Bilateral cerebral oximetry and TCD through anterior fontanelle for cerebral physiological monitoring • Establish baseline mean cerebral blood flow velocity using TCD, and rSO2 (18–22° C at full flow CPB: 150 ml/kg/min)
6. Conduct of CPB	• Goal MAP 30–35 mm Hg (α-receptor blockade if necessary) • rSO2 90–95% bilaterally—mean CBFV normally 18–25 cm/sec • Target hematocrit 30–35% • Use pH stat management during all phases of CPB
7. Conduct of ACP	• ACP initiated after brief DHCA for atrial septectomy for Norwood • All brachiocephalic vessels and descending thoracic aorta snared • Temperature at 18° C • Begin at 37.5 ml/kg/min • Adjust ACP flow using TCD to achieve CBFV within ± 10% of baseline at full CPB flow • rSO2 should be within ± 10% of baseline, or 90–95% bilaterally • If left rSO2 falls to more than 10% below right, increase ACP flow
8. Rewarming	• Once repair completed full flow CPB is resumed and ACP stopped • Rewarming has to be cautious to avoid cerebral hyperthermia

Abbreviations: PTFE, polytetrafluroethylene; NIRS, near-infrared spectroscopy; TCD, transcranial Doppler; rSO2, regional brain oxygen saturation; CPB; cardiopulmonary bypass; MAP, mean arterial pressure; CBFV; cerebral blood flow velocity; ACP, antegrade cerebral perfusion; DHCA, deep hypothermic circulatory arrest

[a]3.0 to 4.0 mm shunt depending on patient size with 8–0 prolene sutures

Complications

There are several potential complications during a CPB run. Some are related to equipment failure, cannulation difficulties, transfusion and/or medication related. A "run away" pump is the situation in which the arterial pump head rapidly accelerates spontaneously. This can result in draining the venous reservoir and introducing air into the circuit. With a roller head pump the corrective action is to power down the individual pump head and hand crank until a replacement pump head can be implemented. With a centrifugal pump the outflow needs to be clamped, the cone removed and hand crank until a replacement pump is available. In the event of a line disconnection in either the arterial or venous lines the first action step must be to isolate and protect the patient by clamping that side of the line. Then re-priming and reconnecting the line or lines and reestablish CPB flow. Presently with increased popularity of vacuum assisted venous drainage, negative pressure air emboli are more common than in the past. Thankfully with today's microporous hollow fiber membrane oxygenators and venous purge lines (most micro) gross air can be eliminated by the reservoir antifoam sock. Careful attention must be placed on not allowing the negative venous pressure to exceed −60 mmHg. In the event of a power outage most hospitals have generators that will back up critical areas. The majority of current HLM are equipped with battery backups as well. However in the scenario of total lack of power the only option is to hand crank until power is resorted.

Surgical cannulation problems include aortic dissection, preferential blood flow and superior and/or inferior vena cava obstruction. Transesophageal echocardiography and pressure differente between the extremities can aid in the diagnosis of aortic dissection. Preferential blood flow and superior vena cava obstruction can be detected by asymmetric cerebral oxymetry readings. During cannulation there is also potential for massive blood loss in case of tearing a mayor vessel so the anesthesiologis and perfusionist should be ready to massively transfuse and cell save. Atrial arrhythmias can develop during heart manipulation. Usually this arrhytimias are self limited but measures need to be taken to be able to internally cardiovert if poorly tolerated hemodynamically. Finally clerical mistakes during drug and blood product administration should be avoided by double checking by two providers.

Finally the systemic inflammatory reaction syndrome (SIRS) inflammatory response to CPB is a fairly common (incidence of $\sim 30\%$) and feared complications of a bypass run. SIRS increases morbiborbidity and mortality after cardiac surgery. In adults the SIRS is inversely related with age and extracardiac arteriopathy, and directly related with preoperative white blood cell count. In infants SIRS is associated with the CPB duration and the use of fresh frozen plasma on the prime. Neonates seem to be less prone to develop SIRS.

Recommended Reading

1. Kunst G, Milojevic M, Boer C, et al. EACTS/EACTA/EBCP guidelines on cardiopulmonary bypass in adult cardiac surgery. Br J Anaesth. 2019; 123 (6):713e757.
2. Wypij D, Jonas RA, Bellinger DC et al. The effect of hematocrit during hypothermic cardiopulmonary bypass in infant heart surgery. Results from the combined Boston hematocrit trials. J Thorac Cardiovasc Surg 2008; 135:355–60.
3. Denault A, Deschamps A, Murkin JM. A proposed algorithm for the intraoperative use of cerebral near-infrared spectroscopy. Seminars in Cardiothoracic and Vascular Anesthesia 2007; 11:274–281.
4. Martin K, Breuer T, Gertler R et al Tranexamic acid versus e-aminocaproic acid: efficacy and safety in paediatric cardiac surgery. Eur J Cardio-Thorac Surg 2011; 39:892–897.
5. Paruk F, Sime FB, Lipman J et al Dosing antibiotic prophylaxis during cardiopulmonary bypass—a higher level of complexity? A structured review. Int J Antimicrob Agents 2017; 49:395–402.
6. Kim K, Ball C, Grady P et al Use of del Nido Cardioplegia for adult cardiac surgery at the Cleveland clinic: perfusion implications. JECT. 2014; 46:317–323.