

**Guidelines for the General Principles of Postoperative Care:
The Neonatal and Pediatric Cardiac Surgery Patient
What the Pediatric Critical Care Nurse Needs to Know**

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Introduction of the Problem:

Improved outcomes following pediatric cardiac surgery can be attributed to a variety of factors. Included in these are fetal diagnosis, preoperative management decreasing end organ dysfunction prior to intervention, improved intraoperative techniques including cardiopulmonary bypass and anesthesia, and postoperative management to decrease morbidity and mortality. Critical care nursing is key in the management of these patients to achieve optimal outcomes. Ongoing assessment and early intervention prevents complications in this patient population.

This guideline presents the key aspects of postoperative care including low cardiac output syndrome; fluid and nutritional management; access and infection risks; respiratory, neurologic, and hematologic care and management of pain and sedation.

Critical Thinking Points:

- Frequent and comprehensive nursing assessment of hemodynamic and physical status are critical components of patient care
- Provision of timely, appropriate interventions prevents complications.
- Critical thinking skills drive the nursing management essential to optimal patient outcomes.

Low Cardiac Output Syndrome (LCOS)

- **Definition**
 - Transient decrease in cardiac output (CO) secondary to myocardial dysfunction (Wessel, 2001)
 - Increased risk for children and infants following cardiac surgery
 - Surgery requiring cardiopulmonary bypass (CPB) places patient at higher risk (Wessel, 2001)
 - Inadequate oxygen delivery secondary to decreased cardiac output & increased metabolic oxygen demand
 - Adverse outcomes including end organ damage
 - Adequate oxygen delivery is vital to maintain normal functioning of the body's cells, tissues, and organs

- Without oxygen, cells generate ATP through the less effective pathway of anaerobic metabolism, creating lactic acid as a byproduct
 - Oxygen delivery (DO_2) is dependent on the arterial blood oxygen content and cardiac output (CO): $DO_2 = [(PaO_2 \times 0.0031) + (\text{hemoglobin} \times 1.34 \times \% \text{saturation})] \times \text{Cardiac Output}^2$
 - Cardiac Output (CO) reaches its nadir 6-12 hours following separation from CPB (Wernovsky, 1995)
 - Low CO states translate to impaired oxygen delivery states
 - Decreases the body's ability to transport oxygenated blood to the tissues (Wessel, 2001)
- **Critical Thinking Points**
 - **Cardiac Output (CO) = Stroke Volume x Heart Rate (See Table 1)**
 - Stroke Volume = amount of blood ejected from the LV in one contraction and is dependent on preload, afterload and contractility
 - Preload
 - Amount of myofibril stretch prior to each contraction
 - The volume that distends the ventricle in during diastole.
 - Infants and children following cardiac surgery often have less compliant ventricles so optimal preload is easily exceeded.
 - Afterload “the sum of all forces opposing ventricular emptying” (Masse, 2005, p.376)
 - The force the ventricle must pump against to eject blood.
 - In a structurally normal heart, the afterload of the right ventricle is the pulmonary vascular resistance and the afterload of the left ventricle is the systemic vascular resistance.
 - The ventricles are essentially two pumps in series, the afterload of one ventricle affects the preload of the other.
 - The blood ejected from the right ventricle fills the left ventricle, so right ventricular stroke volume equals left ventricular preload.
 - Increases in afterload create increases in ventricular workload and may limit CO.
 - Contractility
 - Intrinsic force generated by the cardiac muscle through sarcomere shortening, independent of preload and afterload (Masse, 2005; Klugman, 2011)
 - Describes the strength of cardiac muscle contraction

- Dependent on the degree of binding between the contractile proteins, actin and myosin (Mohrman, 1997)
 - Heart rate and rhythm determine cardiac output
 - Rhythm disturbance decreases cardiac output by decreasing amount blood delivered
 - Bradycardia decreases amount blood ejected per minute decreasing oxygen delivery
 - Tachycardia compromises ventricular filling and CO and decreases coronary artery filling time compromising myocardial oxygen delivery
- **Assessment and Diagnosis**
 - Direct measurement of CO is often not available to clinicians
 - Use markers that are more readily available such as BNP, troponins
 - Physical examination (most important)
 - Skin temperature
 - Color
 - Pulse quality
 - Capillary refill time
 - A summary of assessment findings commonly documented when CO is diminished in children is provided below: (see table 1)
 - Urine output
 - 1-2 mL/kg/hr of urine output (Infants)
 - 0.5 mL/kg/hr.¹ (Older children & Adults)
 - Decreases in CO decrease renal blood flow and glomerular filtration
 - Vital signs
 - Blood pressure (less reliable indicators of CO and oxygen delivery).
 - Dependent on systemic vascular resistance
 - Tends to move in the opposite direction of CO secondary to sympathetic activation (Hoffman, 2005)
 - Heart rate
 - Elevations may indicate decreased CO
 - Other factors include pain, agitation, temperature
 - Pulse oximetry
 - Lactate
 - Lactic acidosis
 - Marker of end-organ perfusion
 - Near-Infrared Spectroscopy
 - Marker of perfusion
 - Somatic and cerebral

- SVO2
 - Normal value 72-75%
 - In single ventricle physiology no more than 30 points below arterial saturation
 - Both rising lactate and decreased SVO2 are early signs of low CO and can occur before changes in vital signs
- Base deficit
- End Organ Function

Table 1

Low Cardiac Output Assessment Findings
<ul style="list-style-type: none"> • Urine output <1mL/kg/hr • Extremities cool, pale, and/or mottled • Capillary refill time >4 seconds • Decreased pulse amplitude • Tachycardia • Altered level of consciousness and/or irritability • Decreased blood pressure (late sign)

- **Treatment**
 - Improve Cardiac Output (CO) (See Table 2)
 - The adequacy of CO is dependent on heart rate, preload, afterload, and contractility.
 - Heart rate
 - Children are highly dependent on their heart rate to maintain adequate perfusion
 - Underdeveloped myocardium lacks the ability to increase contractility
 - Low heart rates may be inadequate to maintain CO
 - Tachycardia should be avoided in the post-operative cardiac patient as decreases diastolic filling time while increasing oxygen demand.³
 - Provide temperature control
 - Maintain normothermia to mild hypothermia
 - Minimize myocardial oxygen consumption
 - AV synchrony may assist in augmenting CO
 - May require AAI or DDD pacing to control heart rate or rhythm
 - May require antiarrhythmic medications or cardioversion to support NSR and CO
 - Stroke Volume

- If CO is decreased secondary to inadequate preload volume resuscitation is indicated (Wessel, 2001)
- Guide fluid resuscitation with careful monitoring of central venous pressure, intracardiac pressures and atrial pressures
- Provide calcium replacement when using large amounts blood products for volume resuscitation
 - Without replacement, may result in development of secondary coagulopathy
- Use blood warmer/rapid transfuser if rapidly replacing blood loss
- Provide close monitoring of left or right atrial filling pressures while infusing volume
- Afterload
 - Elevated pulmonary vascular resistance may limit left ventricular preload by limiting right ventricular output due to the ventricular septum bowing into the left ventricle which decreases left ventricular filling.
 - Derangements in both pulmonary and systemic vascular resistance may increase afterload and decrease CO (Wessel, 2001)
 - Consider afterload reduction if SVR is elevated (Masse, 2005)
 - Anesthesia and sedation as indicated for pain and anxiety to reduce afterload
- Contractility
 - Electrolyte management/replacement as indicated
 - Potassium
 - Calcium
 - Magnesium
 - Inotropic support
 - Epinephrine
 - Dopamine
 - Phenylephrine
 - Vasopressin
 - Dobutamine
 - Milrinone
- **Associated Complication**
 - Cardiac Arrest
 - Utilize PALS algorithm
 - E-CPR if indicated (See ECMO guidelines for more information)
 - End organ complications
 - Acute renal failure which may require dialysis/CRRT
 - Hypoxic-ischemic brain injury

- Stroke
- Coagulopathy
- Bowel ischemia/NEC
- Hepatic dysfunction
- **Special Considerations**
 - Positive pressure ventilation for LV afterload reduction, decrease of preload
 - Echocardiogram
 - Assess for residual lesions
 - Assess Function
 - Assess RV pressure
 - Support Right Ventricle function
 - Inhaled Nitric Oxide
 - Vasodilators
 - Negative pressure ventilation
 - Mechanical circulatory support and/or transplant

Table 2

<h2>Optimizing Oxygen Delivery</h2>	
<p style="text-align: center;">Optimize Cardiac Output</p> <ul style="list-style-type: none"> • <u>Ensure Adequate Preload</u> <ul style="list-style-type: none"> • Consider volume repletion • Closely monitor central venous pressure or right atrial pressure • <u>Enhance Cardiac Contractility</u> <ul style="list-style-type: none"> • Monitor electrolytes closely, replete as needed • Consider inotropic support • <u>Consider afterload reduction</u> • <u>Avoid tachycardia and bradycardia</u> 	<p style="text-align: center;">Optimize Arterial Blood Oxygenation</p> <ul style="list-style-type: none"> • Monitor bleeding closely • Consider packed red blood cell transfusion • Administer oxygen as appropriate • Assure adequate respiratory support

Fluids and Nutrition (See Nutrition Guidelines for more specific/problem management)

- **Introduction and definition**
 - Optimal nutrition delivery decreases mortality and morbidity

- Congenital heart patients at risk for poor growth and failure to thrive.
- **Critical Thinking Points**
 - Early feeding postoperatively reduces gut translocation of bacterial and risk of multisystem organ failure and decreases the need for total parental nutrition
 - Feedings should be held in patients with severe preoperative acidosis and those with poor postoperative hemodynamics
 - Development of hyperglycemia due to pre and intra operative steroids and stress
- **Assessment and Diagnosis**
 - Blood tests: serum albumin, total protein, pre-albumin
 - Growth curve appropriate for age, sex, diagnosis
 - Head circumference, height and weight
 - Serum glucose
- **Treatment**
 - Enteral Nutrition: Early institution of enteral feeds associated with lower infection rates and shorter hospital stays
 - Optimal:
 - Post extubation
 - Stable airway
 - Resolution of bleeding
 - Hemodynamic stability
 - If remains intubated, consider tropic enteral feedings via feeding tube on post- operative day 1
 - Extubation in OR: feeding when awake
 - Calculation of calories for growth
 - May require up to 140-150cal/kg/day
 - Evaluate for tolerance of volume and density
 - Use high density caloric formula
 - Parental Nutrition
 - Use when gut absorption capacity or motility is severely disturbed
 - Hemodynamic instability on high dose vasoactive medications with impaired bowel perfusion
 - Need close monitoring of electrolytes, liver function
 - Lipids – need to monitor triglycerides weekly to biweekly
- **Associated Complications**
 - Refeeding Hypophosphatemia: Phosphorus below 1mg/dL can cause encephalopathy, diaphragmatic failure, dysrhythmia, acute renal failure with hepatocellular injury and increased risk for bone fractures.
 - Gradual refeeding and supplementation of phosphorus are indicated
 - Hyperglycemia: tight control postoperatively decreases infection, especially in the adult patient
 - Dysphagia
 - Those with heart disease and genetic syndromes (CHARGE, VATER, 22q11.2 deletion and Trisomy 21) are strongly associated with impaired swallowing

- Arch abnormalities may require feeding and swallowing assessment.
 - Video fluoroscopic swallow study (VFSS):
 - Defines anatomy and physiology of the swallowing mechanism during deglutition
 - Defines reason for dysphagia
 - Identifies bolus and positioning variables
 - Identifies feeding strategies or maneuvers that enhance the safety of swallowing
 - GERD clinical manifestations include vomiting, poor weight gain, dysphagia, abdominal or substernal pain, esophagitis, feeding intolerance, wheezing, recurrent stridor, chronic cough, recurrent pneumonia or aspiration
- **Special considerations**
 - Transpyloric feeding for mechanically ventilated patients or patients on CPAP or high flow, reduces incidence of aspiration
 - Mesenteric arteritis following repair of coarctation of the aorta
 - Neonate
 - Risk NEC
 - Caloric and volume restriction
 - May require pre and postoperative increased protein and nutrition
 - Occupational and physical therapy consults

Neurologic

- **Introduction and definition**
 - Risks of preoperative insult, anesthesia, cardiopulmonary bypass +/- circulatory arrest, hypoxemia, acidosis, LCOS, right to left shunt may predispose neurologic injury postoperatively
 - Risks of anticoagulation postoperatively for mechanical valves, stents, shunts and low cardiac output
 - Insult may be subtle or severe consisting of seizures, stroke with hemiplegia, IVH and resultant increased mortality and morbidity
- **Critical thinking points**
 - Cardiopulmonary bypass (CPB): microembolic events can contribute to end organ injury.
 - Deep Hypothermic Circulatory Arrest (DHCA)
 - Infants have increased risk of seizures for DHCA >40 minutes.
 - Profound hypothermia may improve cerebral protection during periods of DHCA.
 - Lower limit of hypothermia which causes end organ damage is unknown
 - Cerebral perfusion pressure (CPP) compromised with high filling pressures
- **Assessment and diagnosis**
 - Neurologic exam indicated early postoperatively
 - GCS in older patient.

- Unequal strength or movement of extremity
 - Inability to console
 - Disconjugate eye movement
 - Twitching or jerking movements not related to stimuli
 - EEG or long term EEG monitoring with video recording for suspected seizure activity
 - Patient paralyzed
 - Presence of subclinical seizures
 - MRI
 - CT
 - Cranial ultrasound
 - Electrolyte panels
- **Treatment**
 - Neurological consult
 - Anti-seizure medications: phenobarbital, keppra, fosephenytoin, lorazepam.
 - Infusion Ativan, versed or pentobarbital as indicated for status epilepticus
 - Replacement of appropriate electrolytes
 - Therapeutic hypothermia with slow rewarming per institutional protocol as indicated for brain protection in LCOS or s/p arrest
 - Maintenance of CPP especially in presence of hypoxemia and LOCS
 - Use of permissive hypertension as indicated
 - PT/OT consults
- **Associated complications**
 - Seizures
 - Embolic stroke
 - Intracranial cerebral hemorrhage
 - Choreoathetosis
 - Long term cognitive delay.
- **Special considerations**
 - Neonates
 - Increased risk
 - Less than 34 weeks gestation
 - Require CPB.
 - At risk for hypoglycemia
 - Low calcium stores
 - Immature kidney function and electrolyte regulation
 - Immature brain more prone to IVH with acidosis and LCOS
 - Airway protection
 - Dysphagia and swallowing evaluation

Pain and Sedation (See Guidelines on Developmental Care for assessment tools and interventions)

- **Introduction and definition**
 - Goals of analgesia and sedation
 - Comfort and safety

- Decrease release of stress hormones and cardiac stress
 - Appropriate level of sedation and pain management
 - Decrease metabolic demand and oxygen consumption
 - Assist with imprinting for future intervention/pain procedures
- **Critical thinking points**
 - Presumed clinical course of the patient will determine whether a short or long acting preparation is used and how it is administered.
 - Postoperative factors to consider:
 - Need for mechanical ventilation
 - Need for vasoactive support
 - Presence of other complications
 - Past history of pain and sedation medication exposure
 - Length of intended use
- **Assessment and diagnosis**
 - Developmentally appropriate pain scales: PIPP, FLACC, Wong-Baker FACES, NRS, individualized NRS
 - Sedation score
 - Delirium score
- **Treatment**
 - Combination of narcotic opioid and anxiolytic, titrated to affect may be used
 - Nonsteroidal medications IV or PO as indicated
 - Use PPI prophylaxis when on scheduled nonsteroidals
 - IV Tylenol as indicated
 - Methods of delivery
 - Regional (epidural or intrathecal)
 - Intermittent or continuous infusions of analgesics and sedative medications
 - Patient controlled analgesia
 - Oral medications
 - Start as soon as possible
 - May give certain medications even if patient NPO
- **Associated complications**
 - Withdrawal
 - Signs and symptoms: jitteriness, insomnia, seizures, diarrhea, diaphoresis, agitation, nausea, vomiting, tachycardia, and hypertension
 - Withdrawal Assessment Tool (WAT) scores
 - Methadone, benzodiazepines or other agents to prevent symptoms and decrease cardiovascular stress as indicated with careful weaning schedule
 - Adjunctive agents (clonidine) as indicated
 - Nausea
 - Antiemetic medications
 - Ondansetron
 - Granisetron (Kytril)

- Metoclopramide
 - Alternate opioid or narcotic administration
 - Conversion to oral medication
- **Special considerations**
 - High dose narcotics and benzodiazepines can depress the release of intrinsic catecholamines resulting in decreased systemic vascular resistance and afterload
 - Adjunctive medications
 - Ketamine
 - Chloral hydrate
 - Constipation
 - Use bowel regimen
 - Over sedation
 - Reversal agents
 - Procedural sedation
 - Neonates
 - Tootsweet/sucrose PO
 - Nonmedical comfort techniques
 - Early feeding
 - Fetal exposure

Renal

- **Introduction and definition**
 - Duration of CPB is a risk factor for injury to the kidneys
 - As cardiac output decreases, reflex sympathetic activation results in redistribution of blood flow away from the kidneys and within the kidney
- **Critical thinking points**
 - Patients with diastolic dysfunction may have problems mobilizing; results in elevation in blood urea nitrogen (BUN) but not creatinine
 - Oliguria may occur with low cardiac output from poor systolic function
 - Risk for abdominal compartment syndrome
 - Congenital malformations may predispose patients to altered renal function
- **Assessment and diagnosis**
 - Blood test
 - Renal ultrasound
 - Urinalysis, culture and electrolytes
- **Treatment**
 - Diuretics
 - Loop diuretics
 - Thiazide
 - Spironolactone
 - Peritoneal dialysis
 - Indications for peritoneal dialysis
 - Hypervolemia
 - Metabolic Acidosis

- Azotemia
 - Neurologic complications
 - Calcium/Phosphorus imbalances
 - Generally well tolerated
 - Does not require large intravascular catheters or anticoagulation
 - Less control over fluid balance as continuous hemodialysis
- Hemodialysis
 - Diffusion and ultrafiltration
 - Cardiovascular burden do to large solute and solvent shifts; rapid blood flow rates, and significant extracorporeal blood volume predispose patient to hemodynamic instability
 - Patients should be greater than 7kg
 - Vascular catheters of 4Fr or greater indicated
- CRRT
 - Gentle form of hemofiltration
 - Does not adversely affect CO or pulmonary function
 - Vascular catheters of 4Fr acceptable
 - Electrolyte monitoring required
- **Complications**
 - Acute Renal Failure
 - Oliguria and Anuria
 - Bicarbonate wasting
 - Electrolyte imbalances
 - Nutritional incompetency and nausea from elevated BUN
 - Renal formula
 - Volume overload
 - Fluid restriction
 - Anemia and bone marrow suppression
 - Iron supplementation
 - Epoetin (Epogen)
- **Special considerations**
 - Neonates
 - Not uncommon for temporary oliguric renal dysfunction to occur after neonatal heart surgery
 - Generally improves in 24-48 hours
 - Long term dialysis
 - Renal transplant

Infection (See Guidelines on Infection Prevention for more detailed management)

- **Introduction and definition**
 - Fever associated with metabolic response to trauma and inflammation, systemic response to cardiopulmonary bypass, duration of surgery
 - Increased infection risk with hypothermia (bypass and treatment modality), presence of drainage tubes and central access
- **Critical thinking points**

- Pre-operative prevention
 - Preoperative baths or showers with chlorhexidine
 - Routine use of steroids
 - MRSA and VRE screening cultures
- Intra-operative measures
 - Skin antiseptic
 - Timing and use of prophylactic antibiotic (prior to skin incision)
- Postoperative fever
 - Fevers that develop within 48hrs after surgery are most likely benign and self-limiting; fevers that develop after the first 48hrs are more likely to have an infectious cause
 - Preexisting infections may present with early postoperative fever, previous infection and long preoperative stay are associated with postoperative infection.
 - Systemic inflammatory response, duration of CPB, hypothermia, and “surgical trauma” may present with fever of non-infectious origin
 - “Post-pump perfusion syndrome” characterized by increased capillary permeability, peripheral vasoconstriction, fever, myocardial edema, diffuse cerebral edema and a diffuse bleeding diathesis
- Nosocomial Infections
 - Blood stream infections (BSI)
 - Central line associated infections-lab confirmed BSI not secondary to another infection in patients with a central venous line (CVL) at the time or within 48hrs of onset of fever.
 - Lower Respiratory tract infection/VAP
 - Surgical Site infections
 - Superficial
 - Deep
 - Organ/space
- Urinary tract infection (UTI)
- Vigilant skin care and maintaining skin integrity to prevent infection
- **Diagnostic evaluation**
 - Physical examination
 - Temperature
 - Fever >38C rectal
 - Hypothermia <37C rectal
 - Vital Signs: tachycardia, tachypnea
 - Infants: bradycardia or apnea
 - Hemodynamic instability
 - Surgical site evaluation
 - Assess central and peripheral access sites
 - Thrombophlebitis or cellulitis
 - Drainage
 - Respiratory secretions and suctioning requirements

- Labs
 - CBC with differential and platelets
 - Surgery is associated with an elevated leukocyte count for the first 3 days
 - In sepsis the leukocyte count may be elevated or depressed for age or there may be >10% immature neutrophils
 - Thrombocytopenia and decreased platelet function associated with gram negative or fungal sepsis may occur after CPB
 - CRP/ESR
 - Procalcitonin
 - Hyper/hypoglycemia
 - ABG/VBG
 - Metabolic acidosis
 - Elevated lactate
 - Widening AV O₂ difference
 - Blood culture-peripheral and central
 - ETT gram stain and culture
 - Pleural fluid (BAL)
 - Sternal wound culture
 - UA/Culture
 - Pyuria, leucocyte esterase or nitrite
- Radiological
 - CXR
 - Abdominal X-ray- to evaluate for pneumatosis
 - Ultrasound and/or CT to r/o abscesses
- Echocardiogram– consider TEE
 - Repaired or palliation of cyanotic congenital heart disease prone to vegetation
 - Evaluation of artificial valve, conduit, stent, patch material
- **Treatment**
 - Antibiotics for staph coverage with closed chest
 - Open chest/re-exploration
 - Consider gram positive coverage (Vancomycin)
 - Follow trough levels
 - Empiric broad spectrum antibiotics after sending cultures
 - 2nd generation cephalosporin and aminoglycoside
 - Antibiotic coverage based on sensitivities for positive culture
 - Gram negative coverage for bowel event
 - ECMO
 - Gram positive coverage
- **Associated complications**
 - Mediastinitis
 - Deep tissue infection in mediastinal space
 - Usually involves sternum with disruption of sternal stability
 - Infectious endocarditis

- Risk increases with time after surgery
- High risk in immediate post-op period in patients with prosthetic valves or conduits
- Prophylaxis
 - All dental procedures that involve treatment of gingival tissue or periapical region of the teeth or oral mucosa perforation
 - Tonsillectomy and adenoidectomy
 - Tattoo or piercing
 - Medications: amoxicillin, clindamycin for PCN allergies
- **Special considerations**
 - Immunocompromised patients
 - DiGeorge syndrome with T cell dysfunction
 - Transplanted patients
 - Asplenia prophylaxis with Amoxicillin
 - Induced hypothermia
 - Postoperative patient
 - Poor nutritional status
 - Prolonged fever greater than 7 days
 - Frequent hospitalization or long term hospitalization
 - Comorbidities
 - Tracheostomy/ventilator dependence
 - Neonates
 - Synagis prophylaxis
 - Maternal GBS status
 - Maternal serologies
 - TORCH
 - Immunizations on schedule when possible

Respiratory (See Guidelines on Ventilation for further management)

- **Introduction and definition**
 - Cardiopulmonary interactions in the postoperative setting have significant impact on heart and lung function
 - Association between the heart and lungs, due to their intra thoracic proximity and functional properties, plays an important role in influencing the hemodynamic effects of respiratory support
 - Respiratory management focuses on optimizing oxygen delivery, minimizing work of breathing to decrease oxygen demand and optimize CO₂ elimination while minimizing the negative effects on hemodynamics
 - Goal is to ventilate at functional residual capacity
- **Critical thinking points**
 - Early extubation is ideal
 - Minimizes need for post-operative sedation
 - Decreases potential for infection
 - Decreases ICU length of stay
 - Positive airway pressure will increase mean intra thoracic pressure

- If high enough, will decrease systemic venous return, thereby decreasing RV output.
 - This may be corrected with volume administration.
 - Cardiorespiratory interactions are most sensitive in lesions with passive pulmonary blood flow
 - Bidirectional Glenn anastomosis or Fontan completion
 - Low PA pressure is required to maintain a pressure gradient between the systemic and pulmonary venous systems
 - High mean airway pressure and/or atelectasis will alter the flow gradient
 - Can adversely affect venous return and cardiac output
 - Optimal lung volumes (approximating functional residual capacity) augments PVR and RV afterload. Hyperinflation causes alveolar overdistension, leading to compression of perialveolar capillaries, increasing PVR. Hypoinflation can lead to atelectasis and subsequent hypoxia induced pulmonary vasoconstriction, elevating PVR. In the setting of RV dysfunction in the postoperative patient, ventilation without over or under-inflation is crucial to decreasing RV stress.
 - LV preload is dictated by mechanical ventilation effects on the RV →ventricular interdependence. Intrathoracic pressure decreases the LV transmural pressure, thereby decreasing LV afterload.
 - In conditions where ventricular dysfunction or failure exist, mechanical ventilation may be employed to decrease respiratory metabolic demands (work of breathing)
 - Consider initiating respiratory support:
 - Arterial hypoxemia despite supplemental O₂
 - Alveolar hypoventilation with hypercapnia (PaCO₂>60 in neonates or >55 in children)
 - When oxygen delivery is inadequate to meet tissue/organ oxygen demand
- **Diagnostic evaluation**
 - ABG/VBG
 - Radiographs
 - End Tidal CO₂ monitoring
 - SpO₂
 - NIRS monitoring
 - Ultrasound
 - Bronchoscopy/laryngoscopy
 - BAL
 - CT scan
 - Flow loops and use bronchodilators for diagnostic study
 - Best PEEP study
- **Treatment**
 - Noninvasive ventilation
 - High flow NC
 - CPAP +/- IMV

- BiPAP
 - SiPAP
 - Noninvasive negative pressure ventilation (Biphasic Cuirass ventilation)
- Conventional positive pressure mechanical ventilation
 - FiO₂: Avoid hypoxemia with goal SaO₂ as dictated by cardiac physiology. Goal to wean to nontoxic levels (FiO₂ <0.50)
 - Tidal volume: Obtain adequate chest rise and air entry.
 - Rate: determined by age and ability to remove CO₂
 - iTime: may be adjusted to improve oxygenation, should not deviate from normal physiologic breathing patterns
 - PEEP: recruits lung volume and prevents atelectasis improving oxygenation.
 - Mode: SIMV with pressure support or volume control
- High frequency ventilation
 - High frequency oscillatory ventilation: consider as elevated CMV settings are required to maintain adequate ventilation and oxygenation. Monitor hemodynamic effects closely. Be prepared for volume administration during initiation and increase to settings.
 - High frequency jet ventilation- consider in those with RV dysfunction or patients with passive pulmonary blood flow. May have a decreased MAP, improved CO₂ removal, increasing RV preload, decreasing PVR and improving RV cardiac output.
- ECMO (See Guideline on ECMO for more specific care)
 - VA vs VV cannulation
 - Lung conditioning
 - Rest settings
- Extubation readiness
 - Oxygenation: If hypoxic while weaning support, may represent intrapulmonary shunt with increased atelectasis due to decreasing lung volumes
 - Oxygen delivery
 - CO₂ elimination
 - Work of breathing
 - PSV: spontaneous breathing trials with small amounts of pressure support to overcome resistance of ETT.
- Medical management
 - NMT's or MDI's
 - Steroid burst and rapid wean, periextubation
 - Surfactant
 - Diuretics
 - Lung recruitment
- Surgical management
 - Insertion chest tube for effusion drainage
 - Pleurocentesis
 - Thoracic duct ligation

- Pleurodesis
- **Associated Complications**
 - Postoperative complications
 - Phrenic nerve injury: Consider when there is unequal chest wall excursion, persistently elevated diaphragm on X-ray
 - Recurrent laryngeal nerve injury/vocal cord paresis: should be considered with significant aortic arch manipulation, PDA ligation, persistent hoarseness. High risk for aspiration with PO feeds
 - Thoracic duct injury: chylous pleural effusion. May require transition to MCT formula, prolonged NPO status with TPN administration, chest tube placement, octreotide infusion, pleurodesis or surgical thoracic duct ligation
 - Ventilator associated complications
 - Pneumonia/infection
 - Sedation requirement leading to narcotic dependence
 - Associated trachobronchomalacia
 - Trachobronchomalacia
 - Tracheostomy
 - Ventilator dependent
- **Special considerations**
 - Specialty airway gases
 - Heliox: airway obstruction
 - Inhaled nitric oxide
 - Pulmonary vasodilator
 - Reduces PVR
 - May benefit those with pulmonary hypertension
 - May also be beneficial in RV dysfunction
 - ARDS
 - Neonate
 - TTPN
 - RDS
 - Pulmonary reactivity

Invasive lines (See Guidelines on Infection Prevention for more details)

- **Introduction and definition**
 - Allows hemodynamic monitoring, blood sampling, administration of inotropes, medications, volume and blood products
 - Drainage tubes placed surgically and allow for removal of fluid or blood
 - Waveforms can assist with hemodynamic monitoring and diagnostic evaluation of physiologic derangements
- **Critical thinking points**
 - Daily review of indication, placement, functionality and risk associated with line
 - Waveform interpretation to aid in identifying physiologic state and arrhythmias

- Left atrial catheters and arterial lines should be restricted to monitoring only due to the risk of air emboli
- Peritoneal catheters can be used for drainage, pressure monitoring for compartment syndrome or peritoneal dialysis
- **Assessment and diagnosis**
 - Invasive monitoring lines
 - Arterial placement verified by ultrasound verification, waveform assessment, blood gas sampling or radiography
 - Peripheral (radial, ulnar, dorsalis pedis, posterior tibial, temporal)
 - Umbilical artery
 - Central venous catheter placement verified by ultrasound, waveform assessment, blood gas sampling and radiography
 - Percutaneous (Internal jugular {IJ} subclavian, femoral, umbilical)
 - Percutaneous intravenous central catheter (PICC)
 - Tunneled (Broviac, Hickmann, indwelling ports)
 - Transthoracic lines placement verified by ultrasound, waveform assessment, blood gas sampling, radiography and direct visualization intraoperatively
 - Right atrial
 - Pulmonary artery
 - Left atrial
 - Chest tubes placement verified radiography and by assessment of fluid or air collected in collection containers
 - Pleural
 - Mediastinal
 - Peritoneal drain
 - Percutaneous
 - Tunneled
 - ECMO cannulas
 - Dialysis catheters
 - Use of invasive lines
 - Transducer placement and zeroing
 - Phlebostatic axis
 - Assessment with patient movement
 - Air within the system
 - Document hemodynamic value, waveform, presence of blood return, assessment of site
 - Interpretation of hemodynamics
 - CVP/RA pressures
 - Elevated
 - Volume overload
 - Decreased RV function
 - Increased RV afterload
 - Tricuspid valve (TV) valve stenosis
 - TV valve insufficiency
 - Outflow obstruction (thrombus)

- Cardiac tamponade
- Arrhythmias
- Pulmonary mechanics or high ventilating pressure
- Decreased
 - Hypovolemia
 - Vasodilation
- Pulmonary artery (PA) pressures
 - Elevated
 - Obstruction
 - Pulmonary vascular hypertension
 - Airway obstruction
 - Reactive or fixed, lung/alveolar hypoplasia
 - Acidosis
 - Blood hyper viscosity
 - Large left (L) to right (R) shunt
 - Pulmonary vein obstruction
 - Decreased
 - Hypovolemia
 - Obstruction to pulmonary blood flow
 - Decreased CO
- LA pressures
 - Elevated
 - Hypervolemia
 - Increased left ventricular end diastolic pressure (LVEDP)
 - Decreased left ventricle (LV) function
 - Increased LV afterload
 - Mitral valve (MV) stenosis
 - MV insufficiency
 - MV prosthetic obstruction
 - Cardiac tamponade
 - Arrhythmias
 - Decreased
 - Hypovolemia
 - Decreased pulmonary venous (PV) return
- Infection prevention
- Assessment of continued needs
- Removal of line/tubes- risk for bleeding, need for sedation, blood removal, waveform evaluation with pull back, follow up imaging
- **Associated complications**
 - Bleeding
 - Infection
 - Thrombus
 - Arrhythmias
 - Vessel perforation
- **Special considerations**

- Umbilical catheters in neonates
 - Assess placement of arterial and venous catheters done radiographically
 - Complications: ischemia, thrombus, infection

Hematology

- **Introduction and definition**

- Surgery associated with disruption of blood flow, platelet dysfunction, inflammation and blood hypercoagulability
- CPB triggers a global inflammatory response activating coagulation system, decrease in circulating coagulation factors and antithrombin levels and drop in platelet counts
- Hypothermia associated with CPB inactivates platelets
- Neonates have an immature coagulation system that exhibits a low capacity to inhibit clot formation and high resistance anticoagulation
- Small blood volume of children compared to the priming volume of CPB causes significant hemodilution. Modified ultrafiltration is used to remove excess body water and several major inflammatory mediators and results in hemoconcentration after CPB termination; has been shown to reduce postoperative bleeding and improve hemodynamics.
- Blood circulation is dependent on shunts that are prone to thrombotic and stenotic occlusion.

- **Critical thinking points**

- Primary goal after surgery is maintain adequate tissue oxygenation by optimizing oxygen transport balance.
- Transfusion indicators include hematocrit, SvO₂, SpO₂
- Factors that promote hemorrhage include preoperative cyanosis with polycythemia, reoperations and multiples sutures lines
- Sudden mediastinal drainage cessation and clots can indicate intrathoracic hemorrhage and cardiac tamponade
- Thrombosis risk increased due to coagulation abnormalities, altered blood flow and endothelial disruption
- Intrinsic Pathway
 - Partial thromboplastin time (PTT)
 - Requires factors V, VIII, IX, X, XI, XII, fibrinogen and prothrombin
 - Prolonged with heparin administration and in DIC
- Extrinsic Pathway
 - Prothrombin time (PT)
 - Requires factors V, VII, X, fibrinogen and prothrombin
 - Prolonged in warfarin administration and Vitamin K deficiencies
- Bleeding volume
 - Volume of mediastinal drainage should decrease over the first 6hrs post-op and drainage should change from frank blood to serosanguinous and then serous after 18-24hrs post operatively
- Labs

- CBC/platelets
 - PT/INR, PTT and Fibrinogen
 - Anti Xa level
 - ACT
 - Used to assess the post bypass effects of circulating heparin.
 - Normal value 120-150 seconds
 - Protamine is reversal agent
- **Diagnostic evaluation**
 - Bleeding amount
 - Volume of mediastinal drainage should decrease over the first 6 hours post-op and nature of drainage should change from frank blood to serosanguinous and then serous after 18-24 hours post op.
 - Labs
 - CBC/platelets
 - Pt/INR, Ptt and Fibrinogen
 - Anti Xa level
 - ACT
 - Used to assess the post bypass effects of circulating heparin.
 - Normal value 12-150seconds
 - Protamine is reversal agent
- **Treatment**
 - Thrombosis prevention
 - SV-Low dose ASA
 - Prosthetic valve
 - Mechanical: Warfarin
 - Bioprosthetic ASA
 - Recombinant activated factor VII
 - Generates a large burst of thrombin formation on the surface of activated platelets necessary to support clot formation
 - Risk of thrombosis
 - Platelet transfusion
 - Thrombocytopenia <10,000 in stable patient
 - Thrombocytopenia <50,000 in active bleeding
 - FFP Transfusion
 - Contains all clotting factors except platelets.
 - Replaces anticoagulant factors, antithrombin III, protein C and protein S.
 - Used in treatment of DIC, vitamin K deficiency or TTP
 - Cryoprecipitate
 - Contains fibrinogen, factor VIII, vWF and FXIII
 - Postoperative bleeding <5ml/kg/hr
 - Volume replacement with PRBCs
 - 5-10ml/kg/hr
 - Multiple coagulation defects
 - Postoperative bleeding >10ml/kg/hr

- Can result in severe hemodynamic compromise from hypovolemia and tamponade physiology
 - Chest re-exploration should be considered
- **Associated complications**
 - Transfusion effects
 - Hypocalcemia
 - Large transfusions volumes with citrate –treated blood which chelates calcium.
 - Monitor ionized calcium and supplement with intermittent IV doses of infusion.
 - Pronounced with patients with 22q11 deletion syndrome and neonates with transient hypoparathyroidism.
 - Acute hemolytic reaction
 - Result of blood group incompatibility
 - Signs and symptoms
 - Fever
 - Chills
 - Tachycardia
 - Hypotension
 - Shock.
 - Lab findings
 - Disseminated intravascular coagulation (DIC)
 - Hemoglobinuria
 - Positive Coombs test
 - Treatment
 - Cessation of blood transfusion
 - Support measures
 - Allergic reaction
 - Febrile non-hemolytic reaction
 - Results of host antibody response to donor leukocyte antigens
 - Signs and symptoms
 - Fever
 - Chill
 - Diaphoresis
 - Lab findings
 - Anemia
 - Positive Coombs test
 - New RBC antibodies
 - Hemoglobinuria
 - Treatment
 - Stop transfusion
 - Evaluate
 - Prevention includes premedication with antipyretics, antihistamines, corticosteroids and use of leukocyte poor RBCs

- Delayed hemolytic reaction
 - Due to minor blood group antigen incompatibility
 - Occurs 3-10 days post transfusion
 - Signs and symptoms
 - Fatigue
 - Jaundice
 - Dark urine
 - Lab findings
 - Anemia
 - Positive Coombs test
 - New RBC antibodies
 - Hemoglobinuria
 - Shunt Thrombosis
 - Early post-operative
 - Signs and symptoms: acute desaturation with loss of shunt murmur
 - Localized stenosis or kink of the proximal or distal anastomotic site.
 - Hypovolemia can potentiate thrombus formation
 - Late Outpatient
 - Thrombosis
 - Pulmonary embolism
 - Strokes
 - Hemorrhage
 - Cardiac failure
 - Death
- **Special considerations**
 - Single ventricle (SV) Physiology
 - Thrombosis may occur immediately post-operatively when patients are in low output state with increased PVR due to CPB
 - Neonates
 - Low levels of antithrombin, proteins S and C, contact factors and Vitamin-K dependent factors
 - Cyanotic heart disease
 - Platelet activation period is longer
 - Polycythemia

References:

Bellelli, A. (2010). Hemoglobin and cooperativity: Experiments and theories. *Curr Protein Pept Sci*, 11(1), 2-36.
http://elinks.library.upenn.edu/sfx_local?sid=OVID:medline&id=pmid:20201805.
 Accessed 20100305.

Berry, B. E., Pinard, A. E. (2002). Assessing tissue oxygenation. *Crit Care Nurse*, 22(3), 22-30.

Bohn, D. (2011). Objective assessment of cardiac output in infants after cardiac surgery. *Seminars in Thoracic & Cardiovascular Surgery. Pediatric Cardiac Surgery Annual*, 14(1), 19-23.

Checchia, P. A., Laussen, P. C. (2011). The cardiac intensive care unit perspective on hemodynamic monitoring of oxygen transport balance. *Pediatr Crit Care Med*, 12(4 Suppl), S69-71.

Dhillon, S., Yu, X., Zhang, G., Cai, S., Li, J. (2012). The relationship between plasma concentrations of ionized calcium and magnesium with cardiac energetics and systemic oxygen transport in neonates after the Norwood procedure. *J Thorac Cardiovasc Surg*, 144(2), 474-479.

http://elinks.library.upenn.edu/sfx_local?sid=OVID:medline&id=pmid:22244502.

Accessed 20120720. doi: <http://dx.doi.org/10.1016/j.jtcvs.2011.12.023>.

Duke, T., Butt, W., South, M., Karl, T. R. (1997). Early markers of major adverse events in children after cardiac operations. *J Thorac Cardiovasc Surg*, 114(6), 1042-1052.

Gutierrez, G., Wulf-Gutierrez, M.E., Reines, H.D. (2004). Monitoring oxygen transport and tissue oxygenation. *Curr Opin Anaesthesiol*, 17(2), 107-117.

Hazinski, M. F. (1999). *Manual of pediatric critical care*. St. Louis, MO: Mosby.

Hoffman, G. M., Ghanayem, N. S., Tweddell, J. S. (2005). Noninvasive assessment of cardiac output. *Pediatr Card Surg Annu*, 8(1), 12-21.

Klugman, D., Berger, J. T. (2011). Echocardiography as a hemodynamic monitor in critically ill children. *Pediatr Crit Care Med*, 12(4 SUPPL.), S50-S54.

Li, J., Zhang, G., Holtby, H., et al. (2008). The influence of systemic hemodynamics and oxygen transport on cerebral oxygen saturation in neonates after the Norwood procedure. *J Thorac Cardiovasc Surg*, 135(1), 83-90.

http://elinks.library.upenn.edu/sfx_local?sid=OVID:medline&id=pmid:18179923.

Accessed 20080108. doi: <http://dx.doi.org/10.1016/j.jtcvs.2007.07.036>.

Masse, L., Antonacci, M. (2005). Low cardiac output syndrome: Identification and management. *Crit Care Nurs Clin North Am*, 17(4), 375-383.

Mohrman, D. E., Heller, L. J. (1997) *Cardiovascular physiology* (4th ed). New York, NY: McGraw-Hill.

Phelps, H. M., Mahle, W.T., Kim, D., et al. (2009). Postoperative cerebral oxygenation in hypoplastic left heart syndrome after the Norwood procedure. *Ann Thorac Surg*,87(5), 1490-1494.

Wernovsky, G., Wessel, D., Jonas, R. A., et al. (1995). Postoperative course and hemodynamic profile after the arterial switch operation in neonates and infants: A comparison of low-flow cardiopulmonary bypass and circulatory arrest. *Circulation*,92(8), 2226-2235.

Wessel, D. L. (2001). Managing low cardiac output syndrome after congenital heart surgery. *Crit Care Med*, 29(10 Suppl), S220-30.