REVIEW ARTICLE

Perioperative Care after Surgical Correction of Congenital Heart Defects in Premature Infants

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Abstract

The outcomes of premature infants with congenital heart defects following surgical correction can be improved with carefully planned and evidence-based management during the postoperative period. Many pathophysiological changes related to surgery-related tissue disruption and cardiopulmonary bypass include sodium (Na)/water overload, systemic inflammatory response syndrome (SIRS), and ischemia/reperfusion in the heart and other major organs are seen during this period. Focused intensive care is needed with close monitoring of cardiac function, tissue oxygenation, hemostasis, pain control, and sedation. There are also some center-specific needs; all care-providers need to reach a consensus on evidence-based protocols for initiation, maintenance, and weaning from assisted ventilation, which can facilitate earlier extubation and prevent ventilation-related complications. Close monitoring of the cardiac rhythm/function and the hemodynamic status can reduce critical organ dysfunction and SIRS. Measurement of specified laboratory parameters, and imaging such as chest radiography, echocardiography, and structural/functional assessment of other critical organs can help in monitoring these patients for signs of recovery. Monitoring of the sleep–wakefulness cycle, ambient noise and light control, glycemic control, monitoring of electrolytes and other metabolic parameters, feedings, nutrition, and mobilization can promote the quality of recovery. Individualized antibiotic prophylaxis may be needed based on specific defects, type of surgery, severity of illness, prior data, bacterial flora in the center, and assessments by other specialists. Finally, a checklist with clearlydefined management steps for possible needs prior to and after discharge can promote patient safety.

Keywords: Cardiac output, Cardiopulmonary bypass, Colloid, Crystalloid, Multiorgan dysfunction, Neonate, Newborn, Preload, Systemic inflammatory response syndrome, Third space.

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Key Points

- In most centers, infants born with severe congenital heart defects are evaluated for surgical management once they reach 2 kg in weight. Many of these infants are born premature/small-for-date and take some time to reach a weight/size threshold when they can sustain a major surgical procedure.
- The intra- and postoperative periods of these infants are complicated due to substantial tissue disruption due to surgical manipulation, sodium/water overload, the ensuing systemic inflammatory response syndrome (SIRS), and the suboptimal postoperative healing in various developing organs.
- The targets of pre-, intra-, and postoperative care after cardiac surgery include maintenance of cardiac function, tissue oxygenation, hemostasis, pain control, and sedation. Measurement of laboratory parameters and imaging can help in monitoring these patients for signs of recovery.
- The discharge planning should focus on normalization of sleep–wake cycle, nutrition, neurodevelopmental care, family support, communication with the primary healthcare providers, and clear plans for follow-up. Individualized antibiotic prophylaxis may be needed.
- Finally, a checklist of various needs prior to discharge and during follow-up can promote patient safety.

Introduction

In most neonatal intensive care units (NICUs), premature infants born with severe congenital heart defects (CHDs) are now evaluated for surgical management once they reach 2 kg in weight.[1]

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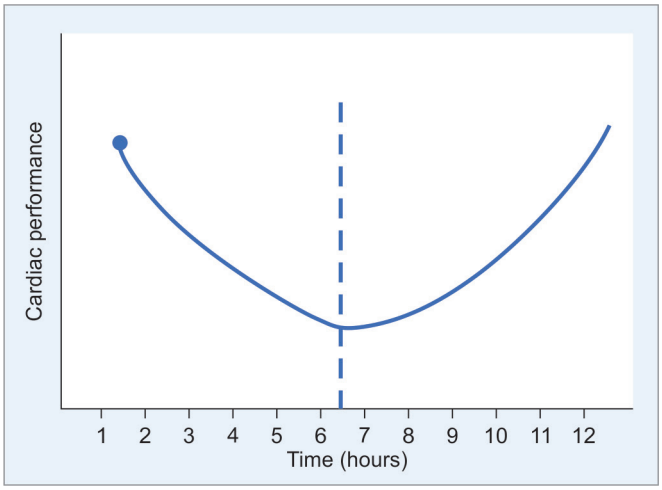

Fig. 1: Immediate postoperative period of hemodynamic instability that typically lasts 6–12 hours, but may extend up to 24 hours

Many of these infants are born very premature or are small-for-gestation and need to grow until they are more likely to sustain the surgical procedure.[2] Not surprisingly, the intra- and postoperative periods are complicated due to myocardial injury sustained during surgery, the ensuing SIRS, and the halting postoperative healing in various developing organs.[3,4] The sequelae of the intraoperative complications following cardiopulmonary bypass (CPB) and the surgical procedures can be transient or last for longer periods.[5] Understanding the pathophysiological changes during this period can facilitate prevention/timely identification and management of various systemic problems and complications.[3]

The pre-, intra-, and postoperative care of these infants is focused on (i) optimizing patient safety; (ii) timely detection and avoidance of multiorgan dysfunction; (iii) in some patients, maintenance of spontaneous breathing; (iv) supporting adequate cardiac output (CO) and end-organ O_2 delivery; (v) balancing intravascular and total body fluid volumes; (vi) ensuring pain control and patient comfort; (vii) minimize physical handling of the infant; and (viii) early initiation of enteral feeding and family-centered care.[3]

In the immediate postoperative period, the SIRS related to the CPB may lead to hemodynamic instability.[5] This period typically lasts 6–12 hours, but may extend up to 24 hours (a thematic depiction in Fig. 1).

In most patients, several factors influence the curve shown in Figure 1:[6–8]

- Severity of the underlying cardiac condition that may lead to biventricular dysfunction with multiorgan under-perfusion and SIRS;
- Intraoperative changes, including the degree of hemodilution, need for blood products, duration of aortic cross-clamping, and consequently, that of CPB, and the quality of myocardial protection;
- The results of surgical repair. Suboptimal repair and/or palliation may influence perioperative events.

The pathophysiological changes after cardiac surgery with CPB include:[9]

- *Sodium (Na)/water overload*: Fluids used for priming of the CPB circuit machine and the perioperatively administered crystalloids/colloids may change the Na/water balance.[10] Most of these fluids extravasate into the "third space" and the total intravascular volume might be relatively low.[11] Consequently, the infant may need continuous preload support to optimize the CO.[12] This increased total body fluid volume may need to be countered with generous use of diuretics, if not hemodialysis, during the recovery period in the first 24 hours after surgery.[9]
- *SIRS*: Surgical trauma and direct contact of blood-borne leukocytes to the external surfaces of the CPB circuit leads to leukocyte activation; this manifests with a SIRS with vasoplegia, coagulopathy, and multiorgan dysfunction.[13] Widespread activation of thrombin, complement, cytokines, neutrophils, mast cells, and other inflammatory mediators is typically seen in the first 12–24 hours; the SIRS might be prolonged depending on the duration of CPB. The CPB duration is a predictor of increased morbidity.[6–8]
- *Myocardial injury* may be related to the specific cardiac defect but can also be accentuated by perioperative factors such as (a) trauma caused by cardiotomy and mediastinal manipulation; and (b) ischemia and reperfusion during CPB and subsequent release of the aortic cross-clamp.[14,15] Protective countermeasures such as hypothermia and intermittent coronary perfusion with cardioplegic solutions can help to some extent.[16] The ischemia–reperfusion injury can aggravate any preexisting myocardial dysfunction during the first 12–24 hours after surgery. Based on data from adult patients, we are beginning to monitor high-sensitivity troponin levels to quantify these injuries.[17] We still need more information.[15,18,19]

Targets Of Pre-, Intra- And Postoperative Cardiac Operative Care

Adequate Oxygen (O_2) Delivery

We aim to optimize O_2 delivery (DO_2), which can be estimated as DO_2 (mL/kg/min) = CO (L/kg/min) × arterial O_2 content (CaO_2; mL O_2/dL).[20] The CO is the product of the heart rate (HR) × stroke volume (SV), whereas CaO_2 is governed by the hemoglobin (Hb) level and the arterial oxy-Hb saturation (SaO_2) and arterial O_2 tension (PaO_2) as of the following formula: $CaO_2 = (1.34 \times Hb \times SaO_2) + (0.0031 \times PaO_2)$.[21] The dissolved O_2 ($0.003 \times PaO_2$) is generally ignored, as this contributes little to the O_2 content and delivery (typically <0.3 mL/dL).[22] Clinically, the CaO_2 is estimated using the most recent Hb level and the average SpO_2 monitored continuously using a pulse oximeter. However, during surgery, when CPB is initiated, the pulse oximetry is no longer useful, as the CPB uses a continuous blood delivery instead of a pulsatile blood delivery. We usually substitute it with online continuous S_aO_2 and S_vO_2 monitoring.[21] Therapeutic targets to maintain adequate DO_2 include:

- *Hb concentrations:* The aim to keep a Hb level >12 gm/dL in first month for ventilated and >10 gm/dL for nonventilated infants

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after routine cardiac surgery with CPB. After the first month, the targets are >10 gm/dL and >8 gm/dL in ventilated and nonventilated infants, respectively.[23]

- *Hb saturations:* The accepted target of continuously monitored peripheral oxygen saturation (SpO_2) is >91% in premature and >94% for term infants in the immediate postoperative period.[24] These targets are particularly valid for those with a noncyanotic CHD. However, if the patient has had an intracardiac shunt, a Blalock–Taussig shunt, or a Glenn procedure, these values might be as low as 75–85%.[25] In cases with a single ventricle physiology, these values could be even lower. These values can be accepted if the pulmonary-systemic flow (Qp/Qs) ratio is adequate. Generally, hyper- and hypoxia should be avoided, and oxygenation limits should be individualized.

Cardiac Output

Pulmonary artery catheterization (PAC) is not possible for routine cardiac surgical assessment in most small infants. If it can be performed, intermittent or continuous assessment of CO can be obtained using PAC to stabilize the cardiac index (CI; = CO/body surface area) at ≥2 L/min/m^2.[26] Intravenous (IV) fluid therapy with or without inotropes and vasopressors can help achieve these hemodynamic targets.[22]

If PAC is not available, the CO may be estimated using surrogates of adequate O_2 delivery: (i) extremity perfusion; (ii) acid–base status; (iii) central venous oxygenation (S_cVO_2); (iv) urine output; (v) hemodynamic parameters; (vi) targeted neonatal echocardiography; (vii) point-of-care ultrasound (POCUS); (viii) near-infrared spectroscopy (NIRS); and (ix) pulse variability index.[27] When the signs of inadequate O_2 delivery are unresponsive to the standard resuscitative interventions (volume expansion and/or administration of low-dose inotropic support), POCUS, and transesophageal/transthoracic echocardiography can provide an accurate assessment of cardiac function.[28]

Hemostasis

One of the essential goals in postcardiac surgery care is ensuring balanced hemostasis. Blood loss from the chest tube output should reach <5–6 mL/kg/hour in the first postoperative hour and drop to <3–5 mL/kg/hour during the next hour.[22] High chest tube outputs may need corrections of any coagulopathy while maintaining a sufficient Hb level. If these goals are not achieved, surgical revisions might be needed. A high degree of vigilance is also needed for blood loss at other sites, such as the airways or hematuria.

In general, intensive care unit (ICU) transfers should be performed cautiously in a quiet and warm environment with care to prevent undue pain, hypothermia, and hospital-acquired infections. A judicious sedation of midazolam (0.01 mg/kg) can help. In some centers, dexmedetomidine has been found more useful as it does not suppress respiratory efforts.[27,29] The pain relief from caudal analgesia can work for about 12 hours. In our NICU, we use normo-flow nasal cannulas with flow rates of 2 L/min unless higher F_iO_2/flow rates are needed to maintain P_aO_2 >91% in premature and > 94% in term infants. Sometimes escalate the support if the F_iO_2 requirement is >40% for >30 min. Early detection of low CO is obtained by close monitoring of (i) rectal/peripheral temperature gradients (rectal probes are tolerated well); (ii) low urine output; (iii) age-appropriate mean arterial pressure; and (iv) tachycardia.[30]

Sedation

Our patients are usually sedated on arrival at the ICU. We usually plan to extubate most of these infants within 6 hours following cardiac surgery. Short-acting IV sedatives, such as dexmedetomidine, are usually used to facilitate early extubation. Intravenous sedation and analgesics with appropriate dosing for managing pain, agitation, and delirium is vital.[31]

Dexmedetomidine

It is an alpha-2 adrenergic agonist with sedative, analgesic, anxiolytic, and sympatholytic characteristics and is usually used to sedate patients after cardiac surgery.[32–34] In our hands, weaning from invasive mechanical ventilation has been possible while on sedation with small doses of dexmedetomidine infusion at about 0.2–0.4 μg/kg/hour. It causes less respiratory depression than other sedative or hypnotic agents.[35–41] However, the experience has not been the same at all ICUs.[42–45] It can cause hypotension and bradycardia at high doses, but these adverse effects are manageable.

Propofol

It is a potent IV anesthetic agent with a very short half-life and is useful when used in continuous infusions.[46] In neonates, propofol has been avoided because of the risk of severe hypotension. In more mature infants, an IV loading dose of 0.5–1 mg/kg followed with a 1–4 mg/kg/hour continuous IV infusion can be useful; the patient should be closely monitored for signs of the propofol-related infusion syndrome, which manifests with metabolic acidosis, arrhythmias, acute renal failure, rhabdomyolysis, hyperkalemia, and cardiovascular collapse.[47] Propofol has been used in children after cardiac surgery if they need longer invasive mechanical ventilation or for patients who have severe hemodynamic instability and require deeper levels of sedation. The hemodynamic side effects are minimized by using lower doses.[48,49]

Medications to Avoid

Benzodiazepines should be avoided in the postoperative care of routine cardiac surgery because of the risk of altered sensorium. This risk is higher with continuous infusions. These agents may also increase the duration of mechanical ventilation and the length of hospital stay.[50]

Analgesia

General Considerations

Multimodal pain management is a critical part of early postoperative management for cardiac surgical patients.[51–58] Both the Enhanced Recovery After Cardiac Surgery Society and the Society of Cardiovascular Anesthesiologists recommend multimodal strategies that specifically spare opioid usage. However, age-adjusted pain management plans can facilitate recovery.[51,59] In neonates, nonpharmacological measures, such as nonnutritive sucking, swaddling, or facilitated tucking, massage, and others, can be considered as a part of multimodal pain management.[58,60] Systemic nonopioid analgesics with regional and local anesthetic methods, and careful opioid use can also be helpful.[51–53,59,61–63] Multimodal pain management plans prior to, during, and after cardiac surgery may decrease the perioperative opioid needs up to 30%.[32,64,65]

Importance of Adequate Analgesia

Pain-scoring tools are used at specific periods for both ventilated and nonventilated patients to allow early identification and treatment of acute pain after cardiac surgery.[66] Failure to attain proper analgesia level may lead to some complications after cardiac surgery that include:

- *Pulmonary complications*: Respiratory splinting to protect from pain after median sternotomy or thoracotomy may cause pulmonary insufficiency and also curtail pulmonary protection mechanisms, such as mucus flow, which may predispose to pneumonia and possible reintubation.
- *Cardiovascular complications*: Pain is associated with a high sympathetic output through increased levels of circulating catecholamines. This state of high sympathetic output may lead to serious effects by increasing myocardial O_2 demand and increase the incidence of arrhythmias, such as atrial fibrillation.[64] It may also lead to hypoxemic crisis in patients with obstruction to pulmonary flow and/or pulmonary hypertension.
- *Altered sensorium*: Although giving analgesics and sedatives can lead to delirium, acute uncontrolled pain may also be an associated factor, especially in sick or frail patients.[67]
- The development of constant *postoperative pain* on the third postoperative day may increase the risk of developing persistent pain syndromes.[60,64,68]

Specific Agents and Techniques

In our ICU, we have tried to limit the use of opioids and use acetaminophen whenever possible.

Opioids

For patients with pain, an IV opioid may be needed. Fentanyl is a judicious selection as a bolus, scheduled administration, or continuous infusion.[69] It can be used in intermittent IV doses for both preterm and term neonates. The initial dose is 1–3 μg/kg/dose pushed over at least 5 minutes to avoid adverse effects such as chest rigidity. The dose may be repeated every 2–4 hours, as needed. It can also be used as a continuous IV infusion. In some infants who show signs of pain, a loading dose of 1–2 μg/kg can be given once over 5–30 minutes followed by a continuous IV infusion of 0.5–1 μg/kg/hour. This infusion range of 1–3 μg/kg/hour is then titrated to achieve the desired effect. The typical maximum dose is 50 μg/dose; however, a higher maximum dose of 100 μg/dose can sometimes be used in critically ill patients in the PICU/NICU.[3]

After extubation, oral opioids like morphine may also be useful. Judicious opioid use can help minimize or avoid prolonged intubation due to excessive sedation and respiratory depression.[54,70,71] Altered gut motility is less frequent in young infants, but ileus can still be seen when high doses are used for prolonged periods, but this is not seen very often in infants.[52,56,71–76]

Nonopioid Systemic Analgesics

These agents may be considered during and after cardiac surgery; they include dexmedetomidine, acetaminophen, ketamine, and others.[32,51–53,62,63,77]

Dexmedetomidine

See above.

Acetaminophen

It is used in preterm infants of 28–32 weeks' gestation.[78] The usual oral dose is 10–15 mg/kg/dose every 6–12 hours as needed for a maximum daily dose of 40 mg/kg/day. For those with gestational age of 33–36 weeks or term newborn babies <10 days of age, 10–15 mg/kg/dose can be given orally every 6–8 hours with a maximum daily dose of 60 mg/kg/day. In term newborns older than 9 days of postnatal age, an oral dose of 10–15 mg/kg/dose can be given every 4–6 hours. A maximum of 5 doses in 24 hours or 75 mg/kg/day should not be exceeded.[79]

The use of opioids, expressed as morphine equivalents, in the first 24 hours after surgery is typically lower in those receiving acetaminophen. The IV is administered at 7.5–15 mg/kg/dose every 6 hours with a maximum daily dose of 60 mg/kg/day. For rectal use, a loading dose of 40 mg/kg for one dose is administered after surgery. A maintenance dose of 20–25 mg/kg/dose every 6 hours, as needed, for 2–3 days has been suggested if further pain control is required postoperatively. A maximum daily dose of 100 mg/kg/day should not exceed 4,000 mg/day; durations of longer than 5 days have not been evaluated.[80–83]

Other Agents

Nonsteroidal anti-inflammatory drugs (NSAIDs) are usually avoided because of cardiovascular and renal adverse effects.[63,84,85] However, this effect is rarely clinically relevant in those with normal postsurgical renal function.[75,86–88] If a patient has a persistent pain refractory to opioids and acetaminophen, the NSAIDs can be added, for their cyclooxygenase (COX)-1 and COX-2 effects, to limit the duration of pain in some patients with acceptable renal function and without a substantial risk of bleeding or acute kidney injury.[84,89–93]

Clinical Management

Imaging Considerations

A chest X-ray is requested shortly after arrival to the ICU to ascertain the correct position of the endotracheal tube and of the vascular line tip; in addition, the images can help check for lung pathology like pulmonary edema, atelectasis, or pneumothorax. Bedside POCUS lung can be used to assess the possibilities of pneumothorax, atelectasis, pneumonia, pulmonary embolism, diaphragmatic excursion abnormalities, pulmonary effusion, hemothorax, and other postsurgical problems.[94]

Implementing Mechanical Ventilation

Setting a target fraction of inspired oxygen concentration (FiO_2) is based on saturation targets in the operating room, during transport, and on arrival to the ICU, and is then adjusted as necessary to aim for desired tidal volumes and $PaCO_2$ levels. Continuously monitoring transcutaneous or end-tidal carbon dioxide ($EtCO_2$) can be helpful per the preference/experience of the staff. Intermittent arterial blood gases to assess arterial oxygen tension (PaO_2), arterial carbon dioxide tension ($PaCO_2$), and acid–base status can help evaluate the ventilatory status of the patients. Implementing lung-protective ventilation strategy in continuation with the intraoperative management may reduce the incidence of postsurgical pulmonary complications:[95,96] (i) low tidal volume (V_T) of 3.5–6 mL/kg working body weight; (ii) respiratory rate (RR) 20–60/minute then adjusted depending on $EtCO_2$ monitoring and $PaCO_2$ in blood gas; (iii) positive end-expiratory pressure (PEEP) of 5–8 cm H_2O; (iv) implementation of higher PEEP levels may help improve oxygenation in some patients with pulmonary edema or altered lung mechanics, but we need to be cautious to not compromise the right ventricle preload; (v) plateau pressure (PP) maintained at <20 cm H_2O with adjustments of V_T, (vi) controlling flow, pressure, and volume graphics; (vii) watching important loop dynamics; (viii) use of noninvasive blood gas monitoring might be useful; and (ix) low driving pressure or delta wave (PP-PEEP) at <15 cm H_2O.

Weaning from Mechanical Ventilation

After a cardiac surgical procedure, based on the experience in the ICU, the infant should be carefully evaluated/monitored for

extubation and conversion to nasal intermittent positive-pressure ventilation.[51,65,97–99] Prolonged ventilation is associated with increased morbidity, mortality, and cost.[95,99] To facilitate early extubation, appropriate pre- and intraoperative management strategies are continued in the postoperative period, which may include (i) multimodal opioid-sparing pain management; (ii) limited use of benzodiazepines; (iii) reversal of neuromuscular blocking agents at the end of the procedure; (iv) use of lung-protective ventilation; (v) temperature control; (vi) ensuring hemostasis; (vii) careful fluid management; (viii) use of corticosteroids; and (ix) observation for signs of abstinence syndrome when high opioid doses were used.

Reversal of Residual Neuromuscular Blockade

It is advisable to avoid rapid reversal of residual neuromuscular blockade before the patient has been rewarmed to more than 36°C as this might lead to increased O_2 consumption.

Neostigmine: It is used to reverse the nondepolarizing neuromuscular blockade in postsurgical periods.[100] Once rewarming is complete, the neuromuscular blockade can be reversed in a combination with glycopyrrolate or sugammadex.[100,101] In the neonatal period, a dose of 0.03–0.07 mg/kg can be useful. The maximum cumulative dose of neostigmine is 0.07 mg/kg. Furthermore, a 0.03 mg/kg dose can typically reverse the shorter half-life neuromuscular blocking agents (NMBAs) such as rocuronium. However, a 0.07 mg/kg dose is advisable for longer half-life NMBAs such as vecuronium and pancuronium.[102]

Glycopyrrolate: In newborn infants, a single IV dose of 4–10 μg/kg is acceptable, but it is not the preferred vagolytic. An IV dose of 0.2 mg for each 1 mg of neostigmine or 5 mg of pyridostigmine is advisable.[103]

Sugammadex: Dosing is based on body weight to reverse rocuronium- or vecuronium-induced blockade. For a moderate degree of neuromuscular block, a single IV bolus of 2 mg/kg over 10 seconds can help achieve reversal.

Once the patient is active, weaning from invasive mechanical ventilation is initiated. Rewarming and early extubation strategies are associated with better outcomes.[27] Patients with preoperative hypoxemia or severe chronic obstructive lung disease problems may need a high-flow nasal cannula or noninvasive ventilation after extubation for a certain period of time.[103,104]

Hemodynamic Management

Circulatory Support

Inotropic support and vasoactive therapy, including inotropes, vasopressors, and vasodilators are frequently used during postcardiac surgical care to support left ventricular (LV) and/or right ventricular (RV) function, especially in the initial 6–12 hours postbypass period. These medications are then weaned if the hemodynamic parameters are maintained. The selection of inotropic and vasoactive medications and their doses can be changed as indicated. Once the pathophysiological changes related to CPB and due to low CO are resolved, these agents can be weaned off.[105,106]

Mechanical Circulatory Support

Postcardiotomy cardiogenic shock occurs in 0.2–6% patients after open-heart surgery.[107,108] Temporary mechanical circulatory support, such as with an intra-aortic balloon pump counter-pulsation, percutaneous or implantable ventricular assist devices, or extracorporeal membrane oxygenation (ECMO), can be used for support if there is refractory ventricular dysfunction with persistently low CO.[102] These devices are typically inserted in the intraoperative postbypass period. The selection of a circulatory-assist device depends on the hemodynamic factors of the patient, surgical preferences, and institutional resources. Some patients may need ECMO.

Management of Arrhythmias

Normal sinus rhythm is needed to maintain optimal CO. This rhythm ensures sufficient blood filling by providing an atrial contribution to a synchronized ventricular contraction. The management of postoperative arrhythmias begins with assessment and correction of reversible causes, such as hyperthermia, electrolyte imbalance, inadequate doses or type of inotropes, and hypovolemia. Early use of a beta-blocker might be a strategic intervention. Metoprolol is administered with an immediate IV dose of 0.1–0.2 mg/kg with a maximum dose of 10 mg/dose. The long-term treatment is usually provided with an enteral dose of immediate-release (metoprolol tartrate) at 0.5–1 mg/kg/dose twice daily with a maximum daily dose of 6 mg/kg/day on postoperative day 1 or as soon as the hemodynamics are normalized. Subsequent doses are titrated upward to achieve a heart rate between 70 and 90 beats per minute while maintaining adequate CO and blood pressure (BP).

Management of Cardiac Arrest

Cardiac arrest may occur at any time after cardiac surgery, although most occurrences are seen in the first 5 postoperative hours.[109,110] The incidence was 0.7% in the first 24 hours after surgery in one series of nearly 4,000 patients.[109] Causes include myocardial ischemia, significant bleeding, cardiac dysfunction such as with cardiac tamponade or tension pneumothorax, and arrhythmias such as ventricular fibrillation, pulseless ventricular tachycardia, or loss of temporary pacemaker capture in a pacer-dependent patient.[109,111,112] In the first few hours after CPB, most of these causes are reversible. There are critical differences in the management of cardiac arrest in the intraoperative or ICU setting after open cardiac surgical procedures compared with standard pediatric advanced cardiac life support (PACLS) management protocols: (i) external cardiac compressions are not initiated immediately due to concern for the disruption of the surgical repair. However, this depends on the institutional practice and the seriousness of the situation; (ii) administration of a full standard PACLS dose of epinephrine is avoided, since this may lead to extremely high BPs that could disrupt arterial suture lines. Instead, only half of the usual doses of epinephrine may be administered with continuous reassessment; (iii) administration of atropine for asystole or severe bradycardia is avoided. Instead, pacing is initiated. All patients returning to the ICU after cardiac surgery should have pacemaker cables for rapid initiation of pacing if needed.

The following specific management strategies are employed; these have been adapted from adult postcardiac care.[113] If VF or pulseless VT is identified, three successive defibrillation shocks should be administered. Defibrillation has a success rate of 78% after the first shock compared with 35% and 14% after the second and third shocks, respectively.[111] Amiodarone (5 mg/kg) has been used with a rapid bolus followed by two repeated doses to a maximum total dose of 15 mg/kg during acute treatment.

If asystole or severe bradycardia is identified, pacing is initiated. The pacemaker is set for dual chamber pacing (DDD mode at 80–120 bpm at a max output voltage of 20 milliamps atrial and 25 milliamps ventricle.[113] If a pulseless electrical activity (PEA) is noted, the pacing is interrupted to ensure the underlying rhythm is not VF. If PEA is confirmed, proceed with external cardiac compressions while opening the chest as described below. If VF, VT, asystole, severe bradycardia, or PEA is present and unresponsive to initial defibrillation or pacing after 1 minute, the management must escalate as follows: (i) initiate external cardiac compressions while the chest is opened through the existing fresh sternotomy as expeditiously as possible (within 5 minutes); (ii) during manual cardiac massage, mechanical ventilation and sedation medications are discontinued, and manual bag ventilation is employed, using a fraction of inspired oxygen (FiO_2) set at 1.0 and a rate of two breaths for every 30 compressions; (iii) administer epinephrine boluses at half doses rather than standard PALS doses, which may lead to extremely high BP that could disrupt arterial suture lines after restoration of spontaneous circulation.[111]

If the chest needs to be re-opened for any reason, we (a) initiate two-handed internal cardiac massage at the rate of 100–120 bpm. The two-handed internal cardiac massage technique involves pressing the heart like a pancake with two flattened hands and straightened fingers to avoid pushing a thumb into an atrial chamber.[113] In patients with an intra-atrial BP (IABP) monitoring device in place, the triggering mode may be switched during cardiac massage from the use of the electrocardiogram to the arterial pressure tracing; (b) use internal defibrillation at 2 J/kg in the first attempt, then at 4 J/kg in the second attempt, then at 4 J/kg or higher in the subsequent attempts until a max dose 10 J/kg, or adult maximum (200 J, biphasic; 360 J monophasic); and (c) continue resuscitation with internal cardiac massage, epinephrine, internal defibrillation, and/or pacing as indicated until the heart restarts contracting or until resuscitation efforts are terminated due to futility.

Detection and Management of Altered Sensorium or Stroke

Altered Sensorium

Screening for postoperative altered sensorium should be part of standard postoperative orders after neonatal and pediatric cardiac surgery.[49,50] Increased risk of delirium occurs in patients with risk factors such as frailty or obstructive sleep apnea.[110,114,115] Both pharmacological and nonpharmacological analgesia is used as the first-line treatment for both prevention and treatment of delirium.[56] These include: (i) standardized sensory inputs with hearing aids, glasses, music, and others; (ii) cognitive stimulation; (iii) encouraging sleep–wakefulness cycles; (iv) adequate hydration and nutrition; (vi) investigating known treatable causes of altered sensorium such as pain or medications, medication withdrawal, and some superimposed medical conditions.

Pharmacologic interventions, such as with dexmedetomidine, quetiapine, olanzapine, and haloperidol, may be used in some centers for selected patients.[52,114]

Stroke

Asymptomatic stroke is more common in adults than infants after cardiac surgery.[116] The management of acute ischemic stroke occurring in the postoperative period after cardiac surgery is not very different between adult and pediatric patients. The management may include endovascular thrombectomy and/or intra-arterial thrombolysis.[117]

Glycemic Control

We maintain blood sugar (BS) level in the range of 4–8 mmol/L (74–144 mg/dL) using a continuous IV insulin and/or dextrose infusion with nomogram(s) based on frequent (hourly) BS assessment. There is no difference in glycemic control between the postbypass period during cardiac surgery and other critical care periods.[118] Poor glycemic control around the surgery can lead to increased morbidity and mortality.[119,120]

Hyperglycemia is frequently seen during and after CPB. Many infants develop stress-induced hyperglycemia and may need insulin therapy.[121] A dose of 0.1–0.2 units/kg is given and then titrated to maintain plasma glucose levels. There should be clear hyperglycemia and hypoglycemia protocols for newborns and infants.

Others

These patients have a high severity of illness and need close monitoring for specific organ failure such as kidney and liver. Some infants need mineralocorticoids to support BP and Na/potassium balance. In our experience, the overall fluid/electrolyte needs have to be individualized. Monitoring central and peripheral body temperatures is also a key component of intensive care. In addition to continuous observation by neonatologists, pediatric intensive care specialists, cardiologists, cardiac surgeons, and anesthesiologists, we include many other services, such as pulmonologists, nephrologists, hematologists, pain control, respiratory services, occupational and physical therapists, and social work. Some families have also requested for religious support.

Diet and Feeding

There are unit-based protocols for starting enteral diets in clinically stable patients prior to or after extubation. In newborns, minimal enteral feeding could possibly help in preventing fasting gastropathy. Although hemodynamic instability, with or without the need for significant vasopressor support, has been regarded as a contraindication to enteral feeding, newer protocols are more permissive and encourage feedings in euvolemic patients with good tissue perfusion.[122] If a patient cannot tolerate enteral feedings, oral immune therapy can be started at 0.2 mL every 2–4 hours of expressed mother's own or donor breast milk at both angles of the mouth. If human milk is not available, a term (20 kCal) formula can be used. We have also used a semi-elemental formula in selected patients. Feeding protocols have helped. If the decision or the conditions might affect enteral feedings for ≥3 days, then it is preferred that the total parenteral nutrition be initiated.

In our own NICU, we have been relatively conservative in starting enteral nutrition; most patients are still started within 24–36 hours on partial or total parenteral nutrition to prevent a catabolic state.[121] We have been reluctant in feeding infants with instability of vital signs, those who are being treated with narcotics or inotropes, or have abdominal distension, vomiting, or prefeeding residuals ≥25%. An indirect assessment of bowel perfusion can also help in these decisions; we avoid feeding infants with hypotension, tachycardia, urine output <1 mL/kg/hour, delayed capillary refill time, or sluggish/negative bowel sounds. Serum lactate levels should be closely monitored before starting oral feeding. Bowel

ultrasound examination and ancillary diagnostic detectors of bowel perfusion such as NIRS of the mesenteric area and Doppler of the splanchnic and mesentery artery can help.[80,81,83]

Mobilization

Many ICUs initiate movements along an active range of motion with help from physiotherapy services. This is an extension of the perceived benefits in critically ill older patients; further studies are needed for infants.[123] After prolonged sedation, young infants may begin to show adverse effects such as decreased circulating blood volume, loss of muscle mass, insulin resistance, and altered sleep patterns.[39] Repositioning infants every 4–6 hours after the surgical procedure may help.

Neurophysiological Developmental Care

In older patients, sleep regulation is believed to improve recovery, decrease pain, and reduce admission time. Studies are needed in infants. Sound control down to <70–90 decibels are advisable. Use of ear plugs or adapting soft music or recorded maternal heartbeats are used in some centers. Similarly, control of ambient light to mimic the diurnal cycle can promote physiological sleep patterns. Covering of the incubator or using dark eye googles are additional measures used in some units. Clustering of monitoring/care interventions to minimize handling of these infants to four to six times per day is advisable. Using a nest bed, safe coverings, and swaddling may increase contented relaxed sleep. Use of pain scoring scales and increasing pleasant stimuli, such as the presence of parents, sucrose suck, use of pacifiers, and use of safety space around the bed, can need for analgesics/sedation, improve sleep patterns, weight gain, and neurophysiological development.[124]

Venous Thromboembolism Prophylaxis

Children and adolescent patients who have undergone cardiac surgery show a moderate risk of venous thromboembolism due to the duration of intra-/postoperative immobility.[122] The risk is lower in infants, but we still need careful studies to detect cerebral and pulmonary thromboembolism that might not be clinically obvious. In young infants with CHDs who have received high-risk central venous lines; undergone procedures for diversion of systemic blood flow to the pulmonary artery such as a Sano shunt, Blalock–Taussig shunt, central shunts; or those who have a known hypercoagulable state or a history of previous thrombosis, thromboprophylaxis is achieved in the neonatal period by a continuous IV heparin infusion at 10–15 units/kg/hour, and this low dose is advisable in infants too. There is some variation in existing guidelines and institutional protocols for pharmacologic prophylaxis after cardiac surgery.[39,125]

Criteria for Discharge from ICUs [NICU/Pediatric ICU (PICU)]

In the postoperative period, we focus on early extubation after a few hours, prevention and treatment of nausea and vomiting, pain control, maintenance of sleep–wake cycle, delirium screening, early initiation of movements, and prompt and adequate provision of nutrition. Invasive monitors and urinary catheters are removed as soon as possible, even on the first postoperative day. Although institutional practices vary, pleural and mediastinal drains are typically removed if output is <100 mL in an 8-hour shift for two shifts. If the criteria are met, most patients who have undergone cardiac surgery can be transferred to a lower level of monitored care. Risk factors for re-admission to the ICU include low LV ejection fraction, renal failure, surgical re-exploration for bleeding, and need for controlled ventilation, and a catabolic state.[31,126]

Antibiotics Prophylaxis

Antibiotic selection should be based on the type of cardiac procedure and the phase of care. Antibiotic dosing should follow guidelines based on age and phase of care in addition to the result of cultures and the consultation with pediatric ID. For surgical procedures performed in the ICU, antibiotic prophylaxis should be selected based on the pre-/intraoperative recommendations.[126–128] Even if the patient is already receiving antimicrobials for postoperative prophylaxis from another procedure, appropriate antibiotic prophylaxis should be re-dosed before a new procedure. For instance, if a patient undergoes chest closure in the unit, cefazolin should be given within 60 minutes prior to the procedure unless the previous dose was given within the intraoperative re-dosing interval (4 hours). The duration of prophylaxis should be limited, generally to 48 to 72 hours regardless of the presence of line or drains. However, gestational age and postnatal age should be considered while making the decision. Antibiotic allergies are fortunately uncommon in infants. If needed, the team should refer to the inpatient beta-lactam allergy guidelines. Many patients with beta-lactam allergy can tolerate cefazolin, which provides more effective surgical-site infection prophylaxis than vancomycin. For those with a history of colonization/infection with methicillin-resistant *Staphylococcus aureus*, vancomycin should be added to the prophylaxis regimen.[126–128]

Long-term Monitoring of Growth and Development

Neonate and infants who undergo cardiac surgery for CHD may have several long-term neurodevelopmental consequences.[127] These may include:

- Many children with complex CHD experience neuro-developmental and psychosocial impairments that impact their quality of life. This can include cognitive, motor, and language delays.
- Brain insults are common, particularly in the frontal and temporoparietal white matter regions in newborns and infants during and after cardiac surgery.
- Children who have undergone cardiac surgery may have lower cognitive and motor functions, in addition to potential language and learning problems.
- During adolescence, many of these children require educational and psychosocial services to support their development.
- These neurodevelopmental impairments can persist into adulthood, which may affect educational achievements, employment, and the overall quality of life.

Early detection and intervention are vital for improving outcomes. Multidisciplinary follow-up plans, including regular neuromotor and psychological evaluations, can help address these issues.[127]

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