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Respiratory Care for Neonates With Congenital Heart Disease

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Respiratory disease often complicates the course of neonates with congenital heart disease (CHD). It is imperative to understand the pathophysiology and treatment of these respiratory diseases, as well as their impact on cardiovascular function. In this review, we discuss: relevant cardiopulmonary interactions that may impact the care of neonates with CHD; the pathophysiology of and strategies to minimize development of ventilator induced lung injury (VILI); invasive and noninvasive respiratory support modalities, including strategies for managing mechanical ventilation in patients receiving extracorporeal membrane oxygenation (ECMO); disorders of the lung parenchyma, including the respiratory distress syndrome (RDS), bronchopulmonary dysplasia (BPD), and the acute respiratory distress syndrome (ARDS); and lung malformations, airway disorders, and pulmonary hypertension.

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HEART-LUNG INTERACTIONS

Heart lung interactions may play a significant role in the pathophysiology and treatment of critically ill patients. This review will focus on the impact of respiration on biventricular loading conditions and output and the impact of respiratory muscles energetics on the distribution of a limited cardiac output (CO).[1]

Increased intrathoracic pressure induced by positive pressure ventilation (PPV) tends to decrease systemic venous return. As intrathoracic pressure rises, the right atrial (RA) transmural pressure (P_{tm}) decreases (P_{tm} = RA pressure – surrounding [intraplueral or intrathoracic] pressure). As a result, RA volume decreases, causing the pressure within to rise, decreasing the pressure gradient for systemic venous return (mean systemic pressure [P_{ms}] – RA pressure). The extent to which increases in intrathoracic pressure decrease systemic venous return depends on 3 important factors. The first is the position of the right ventricle (RV) on its pressure stroke volume curve. A ventricle that is congested can tolerate a decrease in venous return without compromising stroke volume; however, if the ventricle resides on the ascending portion of the curve, a decrease in venous return will cause stroke volume to decrease. The second is the adequacy of systemic circulatory reflexes to maintain the upstream pressure (P_{ms}) that drives systemic venous return to the RA.[2] Acutely, this occurs with

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venoconstriction, which decreases the capacitance of systemic venous reservoirs, increasing the P_{ms}. Activation of neurohormonal systems increases intravascular volume, contributing to an increase in the P_{ms}. The third factor is the extent to which airway pressure is transmitted to and sensed by the RA, which is affected by lung and chest wall compliance.[3] For a given airway pressure, as lung compliance decreases, airway pressure transmission decreases, and for a given airway pressure and lung compliance, as chest wall compliance decreases, pleural and therefore RA pressures increase.[3]

Just as intrathoracic pressure affects the return of systemic venous blood to the RA, it also affects the egress of the blood from the thoracic to extrathoracic arterial system.[4] As intrathoracic pressure increases, the P_{tm} (and thus wall stress) for the thoracic arterial vessels decreases, decreasing their volume and causing the pressure within to rise relative to the extrathoracic arterial vessels, creating a waterfall-like affect. This decrease in systemic ventricular afterload causes stroke volume and CO to increase. The opposite occurs during spontaneous respiration, particularly in the setting of parenchymal lung disease, where exaggerated negative intrathoracic pressure is generated.

Under normal conditions, respiratory muscle oxygen consumption (VO_2) is a small fraction of total body VO_2 and thus receives a small percentage of CO. However, as the respiratory load increases, so too does VO_2 and perfusion to the respiratory pump. Under normal conditions, the respiratory muscle arterial venous oxygen content difference is large, necessitating an increase in perfusion to compensate for an increase in VO_2.[5,6] When CO is limited, blood flow is distributed away from other organs to maintain adequate oxygen delivery (DO_2) to the respiratory pump. If the metabolic demands are not met, ventilatory capacity will wane. In any case, the redistribution of the limited CO may come at the expense of other vital organs. In animal models of shock (cardiogenic, septic), those receiving mechanical ventilation experienced a significant decrease in perfusion of respiratory muscles, whereas blood flow to other vital organs was significantly greater, including the brain, compared with the spontaneously breathing animals.[7,8]

In addition to affecting RV preload (systemic venous return), PPV also impacts RV afterload as a result of changes in mixed venous and alveolar oxygen tension (PO_2), pH, and lung volume. This may have a profound impact on stroke volume and CO, as the RV is much more sensitive to increases in afterload than the left ventricle (LV). It is particularly important to consider these relationships in patients with underlying RV and/or pulmonary vascular disease.

At low lung volumes, alveolar hypoxia induces vasoconstriction of extra-alveolar vessels, increasing pulmonary vascular resistance (PVR). As lung volume rises above functional residual capacity (FRC), alveolar PO_2 increases, alleviating hypoxic pulmonary vasoconstriction. However, with excessive lung volumes, PVR increases as overdistended alveoli compress interalveolar vessels. Importantly, pulmonary vascular pressure effects the extent to which overdistended alveoli compress interalveolar vessels. Pulmonary venous hypertension increases the P_{tm} of the alveolar vessels, minimizing, if not eliminating, the adverse effect of alveolar distension on PVR.

The impact of significant positive airway pressure on RV afterload has been gleaned from studies of adults and children with acute respiratory distress syndrome (ARDS).[9–13] ARDS manifests with fluid leakage into alveoli, inflammation, and alveolar cell injury, leading to surfactant degradation and hypoxemia. ARDS is characterized by a diffuse increase in extravascular lung, with the effects of gravity causing atelectasis and pulmonary shunt in the dependent portion of the lung. Meanwhile, the nondependent portion of the lung has fairly normal mechanical characteristics and thus receives a disproportionate amount of the airway pressure, causing alveolar overdistension.[14] Studies of adults and children with ARDS have found an incidence of cor pulmonale to be approximately 30%, and its presence is associated with an increase in mortality.[9,10] Based on the aforementioned, PPV may cause RV output to fall because of a decrease in systemic venous return and or increase in RV afterload.[11] Echocardiography is necessary to determine the mechanisms responsible for impaired RV output and therefore to tailor therapies accordingly, optimizing oxygenation, CO, and systemic DO_2.[11–13]

VENTILATOR-INDUCED LUNG INJURY

The objectives of mechanical ventilation in neonates with CHD include optimizing gas exchange, reducing the work of breathing and VO_2, and maintaining patient comfort, while minimizing VILI. Mechanisms of VILI may be divided into effects of high F_IO_2 and effects of mechanical forces of PPV.[15] Judicious oxygen administration requires use of the lowest F_IO_2 compatible with oxygenation goals, but it is not clear what those objectives should be. Studies comparing lower versus higher arterial oxygen saturations (S_pO_2) targets suggest higher mortality with lower oxygen saturation target ranges and increased BPD and retinopathy of prematurity with higher target ranges, leading to a recommended target range of S_pO_2 between 90% to 95% for preterm infants born before 37 completed weeks of pregnancy.[16]

Mechanical lung injury from ventilation is often attributed to barotrauma (injury from applied pressures), but it is clear that it is volume (volutrauma), not pressure, that correlates with induction of cytokine release, inflammation, and disordered lung structure. Avoidance of excessive lung inflation, from the initial stabilization at birth onwards, is therefore paramount. High frequency ventilation (HFV), by generating very small tidal volumes, may reduce cyclical volutrauma. With either approach, use of positive end expiratory pressure (PEEP) with conventional ventilation or mean airway pressure with HFV sufficient to maintain an open lung and avoid expiratory atelectasis (atelectrauma) is imperative, as cyclic recruitment and decruitment contributes to VILI.

Recommendations:

1. In preterm infants, to minimize the competing risks of mortality and retinopathy of prematurity, target S_pO_2 between 90% to 95% for preterm infants when considered appropriate based on their cardiac lesion (Class I, LOE A)
2. Provide adequate PEEP (at least 5 cm H_2O) to prevent atelectrauma while maintaining physiologic tidal volume of 4 to 6 mL/kg to avoid volutrauma (Class I, LOE C-LD)

NONINVASIVE RESPIRATORY SUPPORT

Noninvasive respiratory support may consist of nasal intermittent positive pressure ventilation (NIPPV), nasal continuous positive airway pressure (NCPAP), or high flow nasal cannula (HFNC). NIPPV can effectively assist ventilation, but assisted tidal volumes are typically small unless breaths can be synchronized with the infant's spontaneous breaths.[17–19] Both NIPPV and NCPAP[20,21] are effective methods for maintaining FRC by increasing distending airway pressure. HFNC therapy produces modest and inconsistent[22,23] increases in hypopharyngeal pressure and thus may not provide adequate transpulmonary pressure in patients with reduced lung and or chest wall compliance.[24,25] Physiologic effects of HFNC therapy appear to be mediated by washout of the nasopharyngeal dead space, reducing rebreathing and contributing to CO_2 clearance in patients with impaired ventilatory capacity.[23,26] There are few studies of use of these modes of support in neonates with congenital heart disease.

INVASIVE RESPIRATORY SUPPORT

Modern neonatal ventilators offer several modes for support and/or control of ventilation. The nomenclature for various ventilation modes is not well standardized, but common modes include synchronized intermittent mandatory ventilation, pressure support ventilation, and assist and control (AC). These modes differ with respect to which components of inspiratory timing are determined by the operator and which by patient behaviors. The authors are unaware of any data supporting superiority of 1 mode of ventilation over another in neonates with or without CHD. The mode employed should be based on institutional preferences and clinician experience and tailored to the cardiopulmonary pathophysiology of each patient. All conventional infant ventilators are fundamentally flow-generated, time-cycled, pressure-limited devices, but software allows dynamic adjustment of peak inspiratory pressure (PIP) to produce predetermined expired tidal volumes (volume-targeted ventilation).[27]

There are limited studies of high frequency oscillatory ventilation (HFOV) or high frequency jet ventilation (HFJV) in newborn infants with CHD. These ventilation modes may have particular utility in management of neonates with RDS or postoperative ARDS.[28] Because their use entails application of sustained high airway pressure, careful attention to the impact of PPV on RV loading conditions is indicated.

Use of Neurally Adjusted Ventilatory Assist (NAVA) has not been widely studied in neonates with CHD. Retrospective studies have found NAVA to be safe and well tolerated,[118] with some potential beneficial effect on postoperative duration of mechanical ventilation and reintubation in young infants after cardiac surgery, requiring cardiopulmonary bypass.[119] Noninvasive NAVA after extubation has not shown to be specifically helpful.[120]

Invasive support requires placement of an endotracheal tube. Because their patients often require invasive support for extended periods, neonatologists prefer uncuffed tubes,[29] tolerating and compensating for leaks around the tube in the interest of minimizing pressure injury to the tracheal mucosa and risk for subsequent subglottic or tracheal stenosis. Anesthesiologists and cardiac intensivists often prefer cuffed tubes (even in neonates),[30] to better control the airway and optimize consistent ventilation in the intraoperative and immediate postoperative periods. A recent multicenter study found that the use of uncuffed endotracheal tubes was an independent risk factor for reintubation following neonatal cardiac surgery.[31] When cuffed endotracheal tubes are used, cuff pressure should be checked regularly, and the cuff should be deflated when clinical improvement permits.[32]

Recommendations:

1. The use of cuffed endotracheal tube may be considered to reduce

reintubation risk following cardiac surgery (Class I, LOE B-NR)
2. Cuff pressure of endotracheal tubes should be checked regularly, and the cuff should be deflated when appropriate (Class I, LOE C-EO)

MECHANICAL VENTILATION AND ECMO

Sustaining life with ECMO allows more judicious use of mechanical ventilation to minimize accrual of additional lung injury and permit lung recovery. The optimal ventilation strategy during ECMO support remains unknown. Strategies based on permissive atelectasis to minimize VILI[33–36] or on the use of generous PEEP to prevent atelectasis[37] have both been advocated for adults with ARDS; implications for management of infants during ECMO are uncertain. Retrospective analysis of experience in adults[38] and a randomized trial in neonates with respiratory failure[39] suggest that higher PEEP (12–14 cm H_2O) to maintain lung aeration during ECMO may reduce mortality[37] and hasten lung recovery.[40]

Adaptation of these generic recommendations to individual diagnoses or to promote lung recovery in preparation for transition to conventional support may be necessary. In particular, for neonates with primary cardiac failure who have an anticipated short duration of ECMO support, it is prudent to keep the lungs open and provide some supplemental oxygen with the intent of oxygenating blood returning from the lungs, which may be injected into the coronary circulation, and to avoid atelectasis to facilitate early decannulation.

Recommendations:

1. Although an optimal ventilation strategy during ECMO support is unclear, maintaining adequate lung volume and avoiding atelectasis by utilizing PEEP (eg, 5–10 cm H_2O) and providing supplemental oxygen (eg, ~0.3 FiO2) via the ventilator may improve myocardial oxygen delivery and facilitate early decannulation (Class IIb, LOE C-EO)

NEONATAL RESPIRATORY DISTRESS SYNDROME

When CHD is complicated by preterm birth, and occasionally after term pregnancies complicated by diabetes mellitus or in the setting of elective cesarean delivery without labor,[41] management of RDS may complicate treatment of CHD. Affected neonates are best managed proactively, with initiation of NCPAP immediately after birth.[42] If that is not sufficient, as indicated by an F_IO_2 requirement > 0.50 to maintain S_pO_2 > 88%, hypercarbia, hemodynamic instability, or persistent apnea, intubation and surfactant administration may be indicated.[43,44] If PPV is required, short inspiratory times (0.3–0.35 seconds), rates of 30 to 60 breaths per minute, physiologic tidal volumes (4–6 mL/kg), and PEEP sufficient to maintain FRC are recommended.[45] Choice among synchronized intermittent mandatory ventilation, pressure support, or assist and control modes is determined by local preferences and is not evidence-based. In premature neonates, compared with pressure-limited ventilation at a fixed PIP, volume-targeted ventilation is associated with shorter duration of ventilation and lower rates of the combined outcome of death or BPD, BPD, pneumothorax, hypocarbia, and periventricular leukomalacia or severe intraventricular hemorrhage.[46,47]

Recommendations:

1. To minimize VILI in premature neonates with RDS, initiate NCPAP soon after birth (Class I, LOE B-R)
2. In preterm neonates, volume-targeted ventilation may improve respiratory and neurologic outcome (Class I, LOE A)

BRONCHOPULMONARY DYSPLASIA

The diagnosis of BPD is typically based upon continued requirement for supplemental oxygen at 36 weeks postmenstrual age in a preterm infant who has received assisted ventilation. Clinically similar lung disease may develop even in term infants who require prolonged exposure to high oxygen concentrations and PPV. In both instances, the best management is preventive and appears to consist of early adoption of noninvasive respiratory support, use of low tidal volume-targeted ventilation, short inspiratory times, and optimal PEEP to maintain FRC.[15,48] These strategies are also likely to reduce the risk of chronic lung disease in infants with CHD who require ventilation for conditions other than RDS. Development of BPD in an infant with CHD may substantially complicate management, prolong postoperative ventilation, delay hospital discharge, and is associated with high mortality rates.[49]

Concurrent BPD may influence the timing and selection of interventions for CHD and vice versa. Potential benefits of earlier surgery, such as removal of left-to-right shunts or improved systemic oxygenation, must be balanced against risks of operating on small preterm infants with lung disease, particularly if CPB is required.[50,51] Palliative operations, such as pulmonary artery banding, stenting of the ductus arteriosus, or stenting of the RV outflow tract, avoid exposure to deleterious effects of CPB and may be considered for select patients.[52–54] Pulmonary vascular disease occurs in 16% to 25% of infants with BPD[55,56] and can be compounded by

increased pulmonary blood flow and pressure in the setting of CHD.

Ventilator management of infants with established BPD must specifically address their disordered lung mechanics. In infants with "old" BPD, the pattern characteristic of larger preterm infants managed in the early years of infant ventilation, lung mechanics are dominated by heterogenous increased airways resistances, resulting in diversity of time constants among lung units. "New" BPD, typical of extremely preterm infants in the current era, is characterized by arrested alveolar and pulmonary capillary development.[57,58] In these infants, lung mechanics are dominated by noncompliance of the inflated lung and large alveolar dead space (reflected in an elevated arterial to end tidal PCO_2 gradient or alveolar dead space fraction). Many infants with BPD have features of both patterns.[59] If ventilator support is required, experts recommend use of long inspiratory and expiratory times to improve gas distribution within the lungs and allow completion of expiratory flow, respectively.[48] This mandates low respiratory rates (often <20 breaths per minute), so larger targeted tidal volumes (8–12 mL/kg) are often needed. Achievement of these tidal volumes may require inspiratory pressures > 25 cm H_2O. Relatively high PEEP (5–8 cm H_2O) is needed to optimize gas exchange, maintain FRC, prevent focal atelectasis, and minimize air trapping caused by expiratory flow limitation. Infants with tracheomalacia or bronchomalacia require significantly higher PEEP to prevent expiratory airway closure. Flow waveforms and flow-volume loops are useful guides to adjustment of these parameters. Pressure support or assistand control ventilation modes, resulting in high respiratory rates and short inspiratory times, are inconsistent with these goals and are not recommended. Similarly, HFV is likely to increase V/Q mismatch, despite its potential utility for prevention of BPD in infants with acute RDS and ability to acutely lower P_aCO_2.

Recommendations:

1. In preterm infants with lung disease, early palliative cardiac operations may help avoid risk of early repair on CPB (Class IIb, LOE C-LD)
2. Prevention of BPD: early adoption of noninvasive respiratory support, use of low tidal volume-targeted ventilation, short inspiratory times, and optimal PEEP to maintain FRC (Class I, LOE B-NR)
3. Established BPD: use of long inspiratory and expiratory time, low respiratory rates (less than 20 breaths per minute), and larger targeted tidal volume (8–12 mL/kg) may help optimize lung mechanics and facilitate gas exchange BPD (Class IIa, LOE C-EO)

ACUTE RESPIRATORY DISTRESS SYNDROME

ARDS can complicate the course of neonates and infants with CHD, particularly following cardiopulmonary bypass (CPB). CPB induces a systemic inflammatory response, which leads to alterations in lung structure and function that are similar to those found in ARDS.[60,61] Diagnostic criteria for ARDS are complicated in children (and particularly for neonates with CHD), and include acute hypoxemic respiratory failure not fully accounted for by the cardiac anomaly, congestive failure, or another perinatal pulmonary disorder.[62] The authors are not aware >of any evidence to support recommendation of any specific ventilator mode. Consensus guidelines for ventilatory support in children with ARDS have been reviewed in the VILI section of this manuscript. HFOV may be considered if high distending pressures are required with conventional ventilation,[63] but studies in children and adults have not shown improved outcomes with the use of HFOV.[64–67]

Other therapies to consider include inhaled nitric oxide (iNO) and prone positioning. Prone positioning has consistently been shown to significantly improve oxygenation in pediatric and adult ARDS.[68–71] Although initial studies failed to demonstrate a favorable impact on outcomes in children and adults,[69,70] a relatively recent study demonstrated a significant increase in ventilator free days and a decrease in mortality at day 28 and 90 in adults with ARDS,[68] and expert opinion recommends prone positioning.[71] iNO significantly improves oxygenation in ARDS. iNO has not been shown to improve outcomes in adults with ARDS, whereas studies in children have found mixed results.[72,73] It is important to note that neonates with complex CHD were systematically excluded from the aforementioned ARDS studies.

Recommendations:

1. HFOV may be considered if high distending pressures are required to ventilate ARDS patients, although its impact on outcomes is unclear (Class III No Benefit, LOE B-R)
2. Prone positioning and iNO may improve ventilation-perfusion matching in infants with ARDS (Class IIa, LOE C-EO)

AIRWAY DISORDERS

CHD may be associated with congenital or acquired airway anomalies. Management depends upon by the predominant pathophysiology: airway leak or airway obstruction.

Airway Leak

The approach to ventilator support is similar for infants with congenital or acquired airway leaks (eg, tracheoesophageal or bronchopleural fistulas) and consists of strategies to minimize gas flow through a low-resistance fistula tract into a high-compliance structure, such as the stomach or pleural space. When PPV is necessary, low PEEP and PIP, short inspiratory time, and low tidal volume ventilation are recommended to minimize ongoing air leak.[74] HFV using a low lung volume strategy may provide effective gas exchange while reducing air leak.[75–78]

Special considerations apply with esophageal atresia (EA) and tracheoesophageal fistula (TEF), a not uncommon comorbidity in CHD patients. EA and TEF patients are often premature (29% to 38%) and require preoperative respiratory support.[79–81] When PPV is necessary, intubation rather than noninvasive ventilation is recommended.[82] Before TEF repair, gastric distention should be minimized, as it can compromise ventilation by elevation of the diaphragm and increase the risk of aspiration.[83] Decompressing gastrostomy, placed to water seal to reduce the pressure gradient between the ventilator and the gastrointestinal tract, may be necessary.[84] If these measures are insufficient, fistula occlusion using a balloon catheter[85] or surgical ligation may be useful.

After surgical repair of the EA and TEF, the anastomotic suture line along the esophagus should be protected to prevent leakage. Transesophageal echocardiogram is typically avoided early after esophageal atresia repair. Delayed extubation of patients with preoperative respiratory failure or an anastomosis under tension may help avoid emergent reintubation.[83] Postoperative use of noninvasive ventilation is controversial; CPAP appears to be safe, whereas nasal intermittent PPV or HFNC are associated with increased risk of anastomotic leak.[86,87] Many patients with EA or TEF (16% to 33%) develop tracheomalacia requiring a prolonged period of positive airway pressure.[88–92] Infants with EA or TEF often have abundant, tenacious airway secretions, and impaired mucociliary clearance.[93] Frequent airway suctioning and/or mucolytic therapy may be beneficial.

Recommendations:

1. For airway leak:
   a. Low PEEP and PIP, short inspiratory time, and low tidal volume ventilation strategy may be beneficial to minimize ongoing air leak (Class I, LOE C-EO)
   b. HFV using low lung volume may help provide effective gas exchange (Class IIa, LOE C-EO)
2. For patients with EA or TEF who require ventilatory support before TEF repair:
   a. Intubation rather than noninvasive ventilation may be preferred (Class I, LOE C-EO)
   b. Consider decompressing gastrostomy tube to minimize gastric distension (Class IIa, LOE C-EO)
3. For EA and TEF population who require noninvasive ventilatory support after EA repair, CPAP is preferred over nasal intermittent PPV or HFNC in preventing anastomostic leak (Class IIb, LOE C-LD)

AIRWAY OBSTRUCTION

Airway stenosis or extrinsic compression (eg, by vascular rings, ectatic pulmonary arteries, or large left atrium) may accompany CHD. Airway obstruction prolongs time constants, leading to inadequate lung emptying during expiration, resulting in hyperinflated lungs, inefficient ventilation, V/Q mismatch, and hypoxemia.[94] Long inspiratory times, allowing delivery of air beyond the obstruction, and prolonged expiratory times, essential for adequate expiration, mandate low respiratory rates. PEEP should be adjusted based on the flow-volume loop to maintain airway patency while avoiding air trapping. Dynamic airway obstruction, such as seen with tracheomalacia or absent pulmonary valve syndrome, may require high PEEP (>10 cm H_2O).[95] HFV (HFJV or HFOV) is associated with increased air entrapment[96] and may be ineffective; rare successful case reports are limited to brief intraoperative HFJV.[97,98] In severe cases of airway obstruction, ECMO may be used. Definitive management consists of surgical repair of the airway and/or the associated vascular structures.

In absent pulmonary valve syndrome, the main and branch pulmonary arteries dilate and compress the distal trachea and bronchi.[99] By allowing gravity to pull the dilated pulmonary arteries away from the tracheobronchial tree, prone positioning can alleviate airway compression.[100] Patients requiring preoperative ventilation often have both large and small airway compression.[95] Surgical decompression may improve airflow within the large airways, but distal small airways often remain collapsible, and tracheobronchomalacia may persist for weeks to months.[99] These patients may require prolonged ventilatory support (as described above) and vigorous airway clearance. Tracheostomy may be necessary.

Recommendations:

1. For airway obstruction, to facilitate gas exchange, using prolonged inspiratory (longer than 0.7 seconds) and expiratory times may

improve efficiency of gas exchange (Class I, LOE C-EO)
2. In infants with airway obstruction, HFV may be ineffective and potentially worsen air entrapment (Class III: Harm, LOE C-LD)
3. In infants with absent pulmonary valve syndrome and impaired gas exchange, prone positioning may allow gravity to pull the dilated pulmonary arteries off the tracheobronchial tree and thus alleviate airway compression (Class IIa, LOE C-LD)

PRIMARY PULMONARY MALFORMATIONS

Parenchymal lung disease may exacerbate challenges posed by neonatal CHD. Approaches to ventilator management of infants whose CHD is complicated by significant lung disease must be individualized to address both conditions.

Congenital Diaphragmatic Hernia

Significant CHD is found in 10% to 18% of infants with congenital diaphragmatic hernia (CDH).[101–103] Although atrial and ventricular septal defects predominate, left heart obstructive lesions, such as coarctation of the aorta and hypoplastic left heart syndrome, are the most common defects warranting concomitant neonatal cardiac surgery.[101–103] Hospital survival of CDH can now be expected in over two-thirds of infants, but survival of CDH with major CHD remains low (30% to 40%).[101,103] For CDH infants, gentle ventilation with tolerance of permissive hypercapnia and relatively lower postductal oxygen saturation is preferred.[104] Although pulmonary hypertension from underdevelopment of the pulmonary vascular bed, with consequent right-to-left interatrial and/or ductal shunting, is typical, iNO is not beneficial.[104] Guidelines for optimal management for CDH with major CHD are lacking, however. Support with ECMO may increase short term survival to discharge of infants with CDH and CHD (47% of cases in the Extracorporeal Life Support Organization Registry).[105]

Recommendations:

1. Tolerance of permissive hypercapnia and relatively lower postductal oxygen saturation may help minimize VILI in patients with CDH (Class IIa, LOE B-NR)
2. iNO may not be beneficial in treating pulmonary hypertension in CDH (Class III, No Benefit/ LOE B-R)

EBSTEIN'S ANOMALY

Prenatal development of severe cardiomegaly in babies with Ebstein's anomaly may compress the lungs,[106–108] compromising postnatal ventilation. In most instances, this appears to result in lung compression rather than lung hypoplasia.[108] If assisted ventilation is required, adequate FRC should be established using PEEP with conventional ventilation or mean airway pressure with HFV. Surgical decompression of the lungs by right atrial reduction has been proposed.[108] Use of supplemental oxygen and iNO to decrease PVR, without maintenance of ductal patency by prostglandin E1 infusion, may promote antegrade pulmonary blood flow and help distinguish functional from structural pulmonary valve atresia.[109]

Recommendations:

1. Maintaining adequate lung volume, decreasing PVR, and not maintaining ductal patency should be considered in neonates with severe Ebstein's anomaly to avoid the need for neonatal cardiac surgical intervention (Class IIb, LOE C-LD)

Lymphangiectasia and CHD

Congenital pulmonary lymphangiectasia is associated with impaired gas exchange, chylous pleural effusions, and often obligates mechanical ventilation.[110] This condition may be represent a primary lymphatic malformation, as seen in Noonan and related syndromes,[111] or be a consequence of obstruction to pulmonary venous return, as with total anomalous pulmonary venous connection[112] or hypoplastic left heart syndrome with a restrictive atrial septal defect.[113,114] Respiratory failure may be severe. No strategies for assisted ventilation specific for this condition have been identified.

PULMONARY HYPERTENSION

Elevated pulmonary arterial pressures may result from cardiac and noncardiac causes or both. Large, nonrestrictive communications at the ventricular level or at the level of the great vessels, exposes the pulmonary circulation to systemic arterial pressures; large left-to-right shunts increase pulmonary blood flow and contribute to pulmonary vascular disease. Elevated pulmonary venous pressure may be caused by left sided heart disease or pulmonary venous obstruction. Noncardiac causes of pulmonary hypertension (PH) include mechanical compression because of overdistended alveoli and a marked increase in blood viscosity. Increased PVR may be because of pulmonary parenchymal disease (RDS, pneumonia), precocious development, and dysregulation of pulmonary arterial muscularis (persistent pulmonary hypertension of the newborn), pruning of pulmonary arterial arborization as seen with lung hypoplasia, and maldevelopment of the pulmonary capillary bed (alveolar capillary dysplasia, BPD). Any of these conditions may complicate the course of CHD.

Management of PH must be guided by the underlying cause. Severe polycythemia (hematocrit > 65%) can be corrected by partial exchange transfusion. Reduction of obligatory pulmonary overperfusion may require identification and correction of the causal anatomic abnormality. For PH associated with airspace disease, optimizing lung function is imperative.[115] Inadequate or excessive lung inflation both increase PVR, so judicious use of distending airway pressure is essential. Neonates with pulmonary vascular reactivity may benefit from correction of acidosis, hypoxemia, and hypothermia; conversely, they may not tolerate permissive hypoxemia and or hypercapnia and acidemia. However, hyperventilation to induce alkalosis may cause lung injury.[116] PPV induced alterations in RV loading conditions may not be tolerated, as discussed above. In this case, intrathoracic pressure (and its impact on systemic venous return) and lung volume (and its impact on RV afterload), must be considered and mechanical ventilation adjusted accordingly to optimize not only gas exchange but DO_2 as well.

There are fewer options for management of PH associated with capillary or venous obstruction. Alveolar capillary dysplasia is often transiently responsive but has a poor prognosis. Time, good nutrition, and growth may ameliorate capillary bed underdevelopment in BPD.

In cases with refractory PH (intolerable hypoxemia or cardiac dysfunction), iNO may be useful.[115,117]

Because of the risk of pulmonary vascular injury because of excessive pulmonary blood flow in infants with CHD, special care must be taken to avoid overtreatment once the acute hypoxemia and circulatory derangements associated with PH have resolved. Historically, in infants with large mixing cardiac lesions or single ventricle physiology, promoting pulmonary perfusion is usually contraindicated, since increasing pulmonary blood flow may come at the expense of systemic perfusion. If such lesions are complicated by PH, however, affected infants can become dangerously hypoxemic and improving pulmonary perfusion may be indicated.

Recommendations:

1. Excessive or inadequate lung inflation can increase pulmonary vascular resistance and pulmonary artery pressure – lung inflation should be optimized in infants with heart disease and PH undergoing mechanical ventilation (Class I, LOE B)
2. Hypoxemia, acidosis, and agitation should be avoided to prevent severe PH in infants undergoing mechanical ventilation (Class I, LOE B)
3. Use of iNO may be considered in infants with cardiac disease and acute PH (Class IIa, LOE B)

CONCLUSIONS

Ventilator support for infants with congenital heart disease must be selected carefully and thoughtfully adjusted to take both lung mechanics and cardiorespiratory interactions into account.

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