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Original Article

Current challenges in cardiac intensive care: optimal strategies for mechanical ventilation and timing of extubation

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Mechanical ventilation is commonly employed in the paediatric cardiac intensive care unit. In order to utilize this therapy effectively, one must have a thorough understanding of both the principles of mechanical ventilation and the patient's underlying cardiovascular physiology. Dynamic and structural properties of the heart and lungs and their close anatomical and functional relations, play an important role in determining the haemodynamic influences of mechanical ventilation. Ventilation can profoundly alter cardiovascular function via complex and often opposing processes. These processes reflect the interaction between ventricular function, circulating blood volume, the distribution of blood-flow, autonomic tone, lung volume, and intrathoracic pressure. Additionally, advances in cardiac anaesthesia, cardiac surgery and intensive care have changed the expectations for mechanical ventilation and the timing of extubation following cardiac surgery. In this review, we discuss the principles of mechanical ventilation, the impact of respiration on cardiovascular function, the impact of heart failure on respiratory function and the role of early extubation in children with cardiac disease.

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Principles of mechanical ventilation

In patients with congenital heart disease, general reasons for requiring mechanical ventilation include:

- the treatment of respiratory failure
- the therapeutic manipulation of important cardiorespiratory interactions
- reduction of metabolic demands on the cardiovascular system
- facilitation of postoperative recovery.

In addition, the range in age of patients being treated may vary significantly, from the premature infant with tetralogy of Fallot to an adult patient with a sinus venous defect and atrial fibrillation. In spite of this complexity, the basic principles of delivering mechanical ventilation remain constant across this spectrum of patients.

Conventional mechanical ventilation

Basic principles

Mechanical ventilation can be classified on the basis of those components, which are set by the clinician,

the control parameters, and those which are measured by the ventilator, the output variables. The control parameters determine the output of the mechanical ventilator and phases of the respiratory cycle. The four basic parameters determining a mechanical breath are[1]:

- The mechanism for triggering a breath
- The pattern of inspiratory flow
- The mechanism for limiting the breath
- How the breath is terminated.

In addition, a level of positive end-expiratory pressure must be chosen in order to maintain or recruit lung volume. In the final analysis, the medical team controls all of the above parameters by selecting the type or mode of ventilation (Table 1) and the settings on the ventilator within the given mode of ventilation (Table 2).

Triggering

This may occur upon an inspiratory effort made by the patient or because an elapsed time has passed between breaths. During triggering initiated by the patient, a breath is given when either a change in ventilator circuit pressure or inspiratory flow is detected below or above a previously set threshold.[2] Although, flow-triggering is generally thought to be better than pressure-triggering, it is unclear if there are clinical benefits in terms of the work required for breathing, or synchrony between the patient and the ventilator.[3] Both forms of triggering initiated by the patient may result in auto-triggering, also called auto-cycling where the ventilator is triggered without a patient-initiated breath. Auto-triggering may be the result of cardiac oscillations, leakage in the circuit, water in the circuit tubing, or ventilator noise. It can be particularly detrimental to patients with functionally univentricular physiology who are vulnerable to pulmonary overcirculation. Enhanced patient triggering of mechanical ventilation may be seen through neural sensing of diaphragmatic activity, but the clinical benefits are unknown at this time.[4]

Pattern of inspiratory flow

Historically, there has been interest in the effects of different waveforms of inspiratory flow such as sine, square, and decelerating forms, on the exchange of gases.[5] Most of the newer ventilators used for children are restricted to decelerating inspiratory flow or constant flow, using a square waveform, and are based upon the mode of ventilation.[6] In general, peak pressures are lower and mean airway pressure is higher at the same minute volume when a decelerating flow waveform is used during pressure- or volume-limited ventilation compared with a pattern of constant flow. Lower airway pressures occur with a decelerating waveform because the rates of inspiratory flow are highest at the beginning of the respiratory cycle, when the elastance, represented by 1/compliance, is lowest. In addition, with a constant pattern of flow, pressures continue to arise in the airways until inspiration is terminated, producing higher pressures at the end of inspiration.

Cycle

The end of inspiration is most commonly determined by a time variable. For most of the ventilators, this amounts to adjusting the "inspiratory time" setting. Other determinants of the end of inspiration may be the rates of flow in the ventilator circuit, such as in the pressure support mode of ventilation. In this mode, inspiration ends once the rate of flow declines below a set threshold, usually from one-quarter to a half below the peak inspiratory rate of flow.[7]

Limit

During a mechanically delivered breath, the parameter that limits the flow of gas during the breath, as constrained by the parameter determining the inspiratory cycle, may be limited by either pressure or volume.

Positive end expiratory pressure

In general, positive end-expiratory pressure equivalent to from 3 to 5 centimetres of water is well tolerated when maintaining lung volumes in children. Inflation pressures rise above the set positive end-expiratory pressure during mechanical breaths. Higher levels may be necessary to improve the matching of ventilation and perfusion, and to recruit additional lung volume in patients with reperfusion injury, pulmonary oedema, or significant atelectasis.[8] Levels may need to be minimized in the setting of significant right ventricular dysfunction or in patients with passive flow of blood to the lungs, such as those with the Fontan circulation.

Modes of ventilation

A mode of ventilation is chosen for a particular patient with heart disease based on the cardiac physiology, the presence and extent of acute lung injury, and the current trajectory of critical illness or postoperative recovery. The different modes of ventilation delivering mechanical respiratory support depend on the flow of gas and preset parameters that initiate, limit and terminate the breaths. In some of the modes, patients may breathe spontaneously, either in between mechanical breaths, or at any time in the respiratory cycle with some of the advanced modes. Additionally, some modes have features of ventilation limited by both

Table 1. Types and modes of mechanical ventilation.

Mode of Ventilation	Definition	Variables
Controlled Mechanical Ventilation (CMV)	The ventilator provides a mechanical breath on a preset timing. Patient respiratory efforts are ignored. This mode of ventilation is generally uncomfortable for children and adults who are conscious and is usually only used in an unconscious patient. This mode of ventilation is typically NOT used in pediatrics.	
Assist Control (AC)	The ventilator provides a mechanical breath with either a preset tidal volume or peak pressure every time the patient initiates a breath. In most ventilators, a back-up minimum breath rate can be set in the event that the patient becomes apneic. This mode of ventilation is similar to SIMV but in AC every patient breath is supported. * = Assist Controlled (AC) ventilation can be used with any of the 3 modes of ventilatory control: VC, PC, or PRVC.	 *
Synchronized Intermittent Mandatory Ventilation (SIMV)	The ventilator provides a preset mechanical breath (pressure or volume limited) every specified number of seconds. Within that cycle time, the ventilator waits for the patient to initiate a breath using either a pressure or flow sensor. (Regardless of the patient's spontaneous respiratory rate, the ventilator will generate full breaths at the set rate. If the patient initiates a breath within the time of the cycle, the ventilator will support that breath.) SIMV is combined with pressure support (PS) and is frequently employed as a method of decreasing ventilatory support. Pressure support is a set amount of pressure that is provided with every breath to overcome the resistance of the endotracheal tube and circuit * = Synchronized Intermittent Mandatory Ventilation (SIMV) can be used with any of the 3 modes of ventilatory control: VC, PC, or PRVC.	 *
CPAP/Pressure Support (PS)	A continuous level of elevated pressure is provided through the ventilatory circuit to maintain adequate oxygenation and decrease the work of breathing. This mode of ventilation is used commonly in conjunction with PS, which is a set amount of pressure that is provided with every breath to overcome the resistance of the endotracheal tube and circuit. This mode is often used to assess readiness for extubation as the patient must initiate all breaths.	FiO_2 PEEP PS
High Frequency Ventilation (HFV)	A type of mechanical ventilation that employs very high respiratory rates (up to 900 breaths per minute) and very small tidal volumes. In High Frequency Oscillatory Ventilation (HFOV) the pressure oscillates around the constant distending pressure (equivalent to the PEEP). Thus, gas is pushed into the lung during inspiration, and then pulled out during expiration. HFOV generates very low tidal volumes, which are dependent on endotracheal tube size, power and hertz. This modality involves different mechanisms of gas transfer compared to normal mechanical ventilation. It is often used in patients who have hypoxia refractory to normal mechanical ventilation.	FiO_2 Hz MAP Power (Amplitude)
Volume Control (VC)	Breaths are delivered mandatorily to assure preset volumes. The flow pattern is square, which results in a higher peak pressure at any given tidal volume that varies depending on lung compliance. This mode of ventilatory control can be combined with PS to facilitate ventilator weaning. * = Volume Control (VC) can be used with either Assist Controlled (AC) ventilation or Synchronized Intermittent Mandatory Ventilation (SIMV).	FiO_2 Rate VT PEEP +/− PS
Pressure Control (PC)	Breaths are delivered mandatorily to assure preset peak inspiratory pressure. The flow pattern is decelerating. The resulting tidal volume will vary depending on airway resistance, chest wall and lung compliance. This mode of ventilatory control can be combined with PS to facilitate ventilator weaning. * = Pressure Control (VC) can be used with either Assist Controlled (AC) ventilation or Synchronized Intermittent Mandatory Ventilation (SIMV).	FiO_2 Rate PIP PEEP +/− PS
Pressure-Regulated Volume Control (PRVC)	Breaths are delivered mandatorily to assure preset volumes, with a constant inspiratory pressure continuously adapting to the patient's condition. The flow pattern is decelerating. This mode of ventilatory control combines the advantages of volume controlled and pressure controlled ventilation. * = Pressure-Regulated Volume Control (PRVC) can be used with either Assist Controlled (AC) ventilation or Synchronized Intermittent Mandatory Ventilation (SIMV).	FiO_2 Rate VT PEEP +/− PS

V_T = tidal volume; PEEP = positive end-expiratory pressure; PIP = peak inspiratory pressure; PS = pressure support; FiO_2 = fractional inspired oxygen; MAP = mean airway pressure; Hz = hertz.

Table 2. Definitions of setting used in the control of mechanical ventilation.

Variable	Definition
Inspired oxygen (FiO_2)	Percent of oxygen delivered to the patient. Changes in FiO_2 alter alveolar oxygen pressure and thus oxygenation. FiO_2 and MAP both determine oxygenation.
Frequency/rate	Number of breaths per minute. The ventilator rate affects alveolar minute ventilation, which is determined by the product of tidal volume and frequency. Changes in rate primarily influence $PaCO_2$
Tidal volume (V_T)	The volume of air inhaled and exhaled at each breath.
Positive end-expiratory pressure (PEEP)	Constant distending pressure delivered at end expiration. PEEP helps to maintain functional residual capacity to prevent atelectasis. Increases in PEEP generally improve oxygenation.
Peak inspiratory pressure (PIP)	Peak pressure at the end of inspiration. Changes in PIP can affect either PaO_2 (by altering mean airway pressure) or $PaCO_2$ (by altering tidal volume).
Inspiratory time	Time spent during the inspiratory phase of ventilation.
Hertz (Hz)	This parameter is set when high frequency oscillatory ventilation is used. It is a measure of frequency. As frequency increases, the total time for a single cycle decreases (the oscillatory curve is shortened thereby decreasing the area under the curve) and thus ventilation decreases. Patient characteristics and ventilator settings determine whether $PaCO_2$ changes may be more sensitive to amplitude or frequency (hertz) manipulation.
Mean airway pressure (MAP)	This parameter is set when high frequency oscillatory ventilation is used. Average airway pressure delivered throughout the respiratory cycle.
Power (Amplitude)	This parameter is set when high frequency oscillatory ventilation is used. Amplitude is analogous to tidal volume in conventional ventilation. Amplitude is a function of power and is subject to variability due to changes in compliance or resistance. Therefore, power requirements may vary significantly during treatment and from patient to patient. Patient characteristics and ventilator settings determine whether $PaCO_2$ changes may be more sensitive to amplitude or frequency (hertz) manipulation.

pressure and volume. These hybrid modes are used fairly commonly since control of minute ventilation is especially desirable in the patient with a congenitally malformed heart, due to the potential deleterious effects of respiratory acidosis on pulmonary vascular resistance.[9,10] Postoperative atelectasis, pulmonary oedema, and mismatch between ventilation and perfusion are also common in this population of patients and thus a guaranteed tidal volume may be advantageous for lung recruitment and changing respiratory mechanics.[8,11–13]

Over the past several years, there has been increasing recognition of the detrimental effects of excessive mechanical ventilation in the setting of acute pulmonary injury. Specifically, larger tidal volumes and higher peak airway pressures have been associated with ventilator-induced lung injury and increased local and systemic inflammation.[14,15] With acute lung injury, mechanical ventilation employing a decelerating flow waveform may be advantageous through a reduction in peak airway pressures and enhanced distribution of the flow of gas. In patients without lung injury, in contrast, the benefits of a strategy based on low tidal volumes are unknown. Randomized controlled trials in postoperative adults with cardiac disease requiring mechanical ventilation in the intensive care unit demonstrated no clinical benefit of using high as opposed to low tidal volumes.[16,17] Only minor or no differences were found in the levels of measured systemic or pulmonary inflammatory mediators.

Pressure-regulated volume control mode

Pressure-regulated volume control mode delivers pressure-limited breaths with a decelerating flow waveform while attempting to deliver the tidal volume set by the clinician, thus maintaining the desired minute ventilation during changes in respiratory system compliance. The ventilator based upon an algorithm using a series of the previous returned exhaled tidal volumes in order to meet the pre-set tidal volume adjusts the pressure-limited breaths. Pressure-regulated volume control mode is attractive to use in pediatric patients with congenital heart disease, especially in the post-operative setting where larger tidal volumes may be used and close control of minute ventilation is desired. In a study of infants recovering from congenital heart surgery, Kocis and colleagues found that pressure-regulated volume control mode results in 20% lower peak inflation pressures compared to volume control mode without affecting other important hemodynamic and respiratory variables.[18]

Synchronized intermittent mandatory ventilation pressure control or volume control mode

Synchronized intermittent mandatory ventilation implies that a pre-set number of time-cycled pressure- or volume-limited mandatory breaths are delivered synchronously with the patient's spontaneous breaths. Mandatory breaths are delivered for patients who are unable to breathe spontaneously. Pressure support is

usually provided to augment the patient's spontaneous breathing efforts in between the synchronized ventilator breaths and to facilitate weaning as the number of mandatory synchronized ventilator breaths is decreased. The level of pressure support added should generally be enough, from 5 to 10 centimetres of water, to improve the synchrony between the patient and the ventilator, and to compensate for the increase in resistive work of breathing imposed by the endotracheal tube.[19] Some clinicians may use higher levels of pressure support in the setting of a prolonged ventilator wean.

In the volume control mode, a preset tidal volume is delivered with each breath using a constant flow pattern. Volume control may be used when close control of minute ventilation is desirable, but may result in high peak inflation pressures in the setting of decreased compliance or increased resistance of the airway. In the pressure control mode, the breath is delivered using a decelerating flow pattern and is terminated when a preset peak inspiratory pressure is reached. A pressure control mode may be advantageous in patients with worsening lung compliance by lowering the risk of harmful increases in airway pressure.[20]

Continuous positive airway pressure and pressure support

With this mode of ventilation a desired end-expiratory pressure is set and pressure support is added to augment spontaneous breathing. The patient both initiates and terminates the pressure-augmented breath. The pressure-supported breath may be triggered by either flow or pressure and terminates once the rate of inspiratory flow declines below a proportion of peak inspiratory flow determined by the type of ventilator being used. Some clinicians use this mode for a brief period of time to assess readiness for extubation.[21] In patients breathing through an endotracheal tube, especially infants, since the endotracheal tubes are smaller, use of this mode for longer periods of time may pose a problem due to the increased resistive work of breathing and smaller generated tidal volumes that may promote atelectasis. In patients with a tracheostomy, nonetheless, the lower resistance imposed by a tracheostomy tube allows this mode of ventilation to be used over the longer term.

High frequency ventilation

Severe pulmonary disease is uncommonly seen post-operatively in children with congenitally malformed hearts, and most of these patients can be managed with conventional ventilation. Rarely, high frequency ventilation may be necessary in those patients with refractory acute respiratory failure. High frequency jet ventilation, and high frequency oscillatory ventilation, deliver supra-physiologic numbers of breaths at low tidal volumes, usually from 240 to 480 breaths per minute for high frequency jet ventilation as opposed to 180 to 900 breaths per minute for high frequency oscillatory ventilation. High frequency ventilation has been frequently used in neonates with respiratory distress syndrome or persistent pulmonary hypertension. Both high frequency jet ventilation and high frequency oscillatory ventilation have also been reported to be useful in children with congenitally malformed hearts when in severe respiratory failure.[22–24]

Several key features differentiate these two modes:

- inspiration and expiration is piston driven and occurs actively during high frequency oscillatory ventilation, while exhalation is passive and occurs with interruption of inspiratory flow during high frequency jet ventilation
- high frequency oscillatory ventilation requires no adaptor on the endotracheal tube or additional ventilator, while high frequency jet ventilation requires an adapter connected to the endotracheal tube and a conventional ventilator
- high frequency oscillatory ventilation uses higher mean pressures in the airways, whereas high frequency jet ventilation can be used at low mean pressures
- the tidal volumes delivered with high frequency oscillatory ventilation are slightly smaller compared to those delivered by high frequency jet ventilation.

High frequency oscillatory ventilation is best suited for patients with significant lung disease in order to limit the risk of ventilator associated pulmonary injury. While high frequency jet ventilation may be used in the previous setting as well, one potential advantage is the ability to provide exchange of gases at lower mean airway pressures. This feature may be useful in the setting of air leak syndromes, or when it is haemodynamically desirable to ventilate at low airway pressures.

Non-invasive positive pressure ventilation

The incidence of failed extubation after paediatric cardiac surgery is higher compared to the general population treated in the paediatric intensive care unit, approaching one-fifth in some groups at high risk.[25,26] These patients often have a combination of cardiovascular and respiratory failure. Residual cardiac lesions, ongoing lung disease, poor respiratory mechanics, diaphragmatic dysfunction, apnea of prematurity, airway malacia, or neuromuscular weakness all may be contributory. Such patients are particularly vulnerable to the increased metabolic

demands imposed by spontaneous breathing and cardiac output may be compromised by:

- altered respiratory mechanics
- the increase in ventricular afterload imposed by spontaneous ventilation
- hypoxia
- the effects of a metabolic and/or respiratory acidosis.

In a patient with respiratory failure in the immediate postoperative period, the trachea can be re-intubated and mechanical ventilation resumed until the identified aetiology has resolved or sufficiently improved to allow another attempt at extubation. In some circumstances, non-invasive ventilation may be used to transition selected patients from tracheal extubation to ventilation via a natural airway. Non-invasive mechanical ventilation using positive airway pressure is most frequently delivered via nasal prongs, nasal mask, or pillow, but can be delivered by a face mask in older children. Some problems with non-invasive ventilation include:

- trauma to the eyes or nose
- insufficient exchange of gases
- breakdown of skin at the pressure points induced by the mask
- gastric distention
- discomfort requiring sedation.

Nasal continuous positive airway pressure is the most widely used form of non-invasive ventilator support. Continuous positive airway pressure splints the airway throughout the respiratory cycle, increases functional residual capacity, provides effective stabilization of the chest wall, improves the mismatch between ventilation and perfusion, and thereby improves the exchange of gases.[27] The use of nasal continuous positive airway pressure has been well studied in the neonatal intensive care unit. Extensive studies, however, are lacking in the population of children with congenitally malformed hearts. Anecdotal reports describe successful prolonged treatment in patients with hypercapneic respiratory failure, and in patients with diaphragmatic dysfunction.[28,29]

Cardiopulmonary interactions

Respiration has profound effects on cardiovascular function. These effects are mediated primarily by changes in intrathoracic pressure and lung volume. Negative pressure ventilation increases venous return by altering the pressure gradient between extra- and intrathoracic veins. As intrathoracic pressure falls, there is an increase in right atrial transmural pressure, which is the intrathoracic pressure (ITP) subtracted from the pressure in the right atrium (RAP). The following mathematical formula depicts this relationship:

$$\text{Right atrial transmural pressure} = \text{Right atrial pressure} - \text{Intrathoracic pressure}$$

$$\text{Right atrial transmural pressure} = \text{RAP} - \text{ITP}$$

As a result, the right atrium distends, the pressure within it falls, and there is an increase in systemic venous return.[30] Similarly, with negative pressure ventilation, the ventricular diastolic transmural pressure increases and so too does ventricular filling.[31,32]

Positive pressure ventilation improves left ventricular ejection by altering the pressure gradient between intra- and extrathoracic arterial vessels. As intrathoracic pressure rises, the transmural pressure decreases in the intrathoracic arterial vessels. This causes the volume of these vessels to decrease, and the pressure within them increases relative to that in the extrathoracic arterial vessels, driving blood into the extrathoracic compartment.[33] Even though aortic systolic pressure increases, intrathoracic pressure rises to a greater extent and the net effect is a reduction in the calculated left ventricular systolic transmural pressure.

Respiration effects pulmonary vascular resistance by altering blood pH, alveolar tension of oxygen, and lung volumes. Respiratory alkalosis causes pulmonary vasodilatation, while acidosis causes vasoconstriction. Alveolar hypoxia constricts pulmonary arterioles, diverting the flow of blood from poorly ventilated to well ventilated alveoli. This improves the matching of ventilation to perfusion, thereby improving oxygenation. Respiration effects pulmonary vascular resistance by altering lung volumes. Pulmonary vascular resistance increases when lung volumes are less than, or greater than, functional residual capacity. As lung volume decreases below functional residual capacity, the radial traction provided by the pulmonary interstitium diminishes, decreasing the cross sectional area of the extraalveolar vessel. In addition, at low lung volumes, alveoluses collapse, hypoxic pulmonary vasoconstriction ensues, and the resistance of extraalveolar vessels increases further. As lung volumes rise above functional residual capacity, with either negative pressure ventilation or positive pressure ventilation, pulmonary vascular resistance increases. This results primarily from overdistended alveoluses compressing interalveolar vessels.

Left ventricular systolic failure

Systolic cardiac failure is characterized by small stroke volumes, and low cardiac output despite elevated ventricular volumes. The failing ventricle resides on the flat portion of its pressure-volume curve. As a result, the effects of changes in intrathoracic pressure

on left ventricular afterload predominate over the effects on venous return. So long as an adequate, albeit elevated, ventricular filling pressure is maintained, positive pressure ventilation improves ventricular emptying and cardiac output increases.[34] The same physiologic goals may be achieved using non-invasive continuous positive airway pressure. By increasing intrathoracic pressure, the administration of non-invasive continuous positive airway pressure increases stroke volume and cardiac output.[35–37] In addition to increasing cardiac output, positive pressure ventilation reduces myocardial consumption of oxygen by decreasing left ventricular end-diastolic volume and left ventricular systolic transmural pressure, two major determinants of left ventricular wall stress. Furthermore, mechanical ventilation unloads the respiratory pump, as to be discussed below, allowing for a redistribution of cardiac output from the respiratory apparatus to other vital organs, decreasing consumption of oxygen by the respiratory muscles and the myocardium. The net effect of these changes is an improvement in the balance of transport of oxygen between the respiratory muscles, the heart, and the global circulation. In other words, the relationship of delivery to consumption of oxygen improves in all major organ systems.

The beneficial effects of positive pressure ventilation on myocardial oxygen transport balance in patients with left ventricular systolic dysfunction have been demonstrated in several studies.[38–40] In one study, progressing from full ventilator support to spontaneous breathing adversely affected myocardial oxygen transport balance in just under half a small cohort of patients with acute myocardial infarction complicated by respiratory failure.[38] In these patients, increasing electrocardiographic ischaemia, and a significant rise in left ventricular filling pressure, occurred upon removal of positive pressure ventilation. Others evaluated the effects of the Mueller maneuver, which is a decrease in airway pressure against a closed glottis, in patients with left ventricular systolic dysfunction.[41] Using radionuclide ventriculography they demonstrated the development of akinesis in at least 1 region of the left ventricle in over half the patients with left ventricular dysfunction, and in none of their control subjects. In addition to ensuring adequate exchange of gases, therefore, positive pressure ventilation plays a vital role in the management of patients with low cardiac output due to left ventricular systolic failure.

Diastolic cardiac failure

Diastolic failure is characterized by small stroke volumes and low cardiac output, the result of inadequate ventricular filling. As a result, the effects of positive pressure ventilation on venous return and ventricular filling predominate over the effects on ventricular afterload. This is exemplified in the post-operative management of patients following repair of tetralogy of Fallot. Biventricular systolic function is generally normal, albeit there is invariably some degree of right ventricular diastolic disease. In approximately one-third of these patients, there is development of right ventricular diastolic failure. A highly significant increase in right ventricular output was shown when such patients were converted from positive to negative pressure ventilation.[42] This favourable response was greatest in those patients with the most severe diastolic disease. In a retrospective analysis of patients undergoing repair of tetralogy of Fallot, conversion from positive pressure ventilation to spontaneous negative pressure breathing produced significant increases in cerebral near-infrared spectroscopy saturation and arterial blood pressure, while heart rate remained unchanged.[43] The fact that cerebral blood flow increases with conversion to spontaneous negative pressure breathing suggests that cerebral blood flow, and therefore cardiac output, were limited. And, despite loading the respiratory apparatus and an obligatory increase in perfusion to the respiratory muscles, not only did cardiac output increase but more importantly so too did cerebral blood flow. Another potential mechanism for impaired cardiac output during positive pressure ventilation is an increase in right ventricular afterload. As discussed, this occurs as lung volumes rise above functional residual capacity, regardless of the means by which means ventilation occurs. In either case, the adverse effect of increases in pulmonary vascular resistance would be exaggerated in the presence of incompetency of the pulmonary valve, a finding present in many patients after repair of tetralogy of Fallot. To this point, it has been shown that the duration of pulmonary regurgitation increased during inspiration and was shortened during expiration.[44]

Functionally univentricular hearts

Preoperative neonates with the some of the classic variants of functionally univentricular hearts have atresia of an atrioventricular or arterial valve, and thus have complete intracardiac mixing of systemic and pulmonary venous returns. In this arrangement of parallel circulations, the dominant ventricle provides the entire cardiac output, and the ideal ratio of pulmonary to systemic flows of blood is approximately equal. With such a balanced circulation, provision of oxygen and nutrients to the end organs is adequate, while flow of blood to the lungs is sufficient to maintain effective exchange of gases without excessive volume overload of the dominant

ventricle. The ratio of pulmonary to systemic flows may be estimated by using the equation: saturation of oxygen in systemic arterial blood minus saturation of oxygen in systemic venous blood divided by the saturation of oxygen in pulmonary venous blood minus the saturation of oxygen in pulmonary arterial blood. Although it is generally assumed that a systemic arterial oxygen saturation of 75 to 85 percent will be indicative of a ratio of pulmonary to systemic blood flow of approximately unity, the correlation is poor without the additional knowledge provided by sampling of the mixed venous and pulmonary venous saturations of oxygen.[8]

For the minority of preoperative neonates with excessive pulmonary blood flow, controlled positive-pressure ventilation and medical gas manipulation are employed as strategies directed at increasing pulmonary vascular resistance.[45,46] Use of end-expiratory pressure that delivers lung volumes above functional residual capacity can result in elevation in pulmonary vascular resistance through compression of vasculature. As high concentrations of inspired oxygen are known to produce vasodilation of the pulmonary vascular bed, a low supplemental concentration of oxygen, at 21 to 25%, is provided.[46] The addition of inspired nitrogen to ambient air has been used to create a fractional inspired concentration of oxygen varying from 16 to 18%, which transiently increases pulmonary vascular resistance and reduces the ratio of pulmonary to systemic flows.[47] This strategy leads to obligatory pulmonary venous desaturation and thus does not reliably improve systemic oxygen delivery. Alternatively, hypercarbia either through controlled ventilation or provision of inspired carbon dioxide has been shown to reduce the ratio of pulmonary to systemic blood flow and improve systemic and cerebral oxygen delivery.[47,48] Often deep sedation with benzodiazepines or narcotics, and less often pharmacologic paralysis, are needed to prevent increases in minute ventilation in response to elevated arterial levels of carbon dioxide. Another management option is to minimize positive end expiratory pressure, and allow pulmonary volumes to fall below functional residual capacity. Extra-alveolar pulmonary vessels become tortuous, and there is alveolar collapse and hypoxic pulmonary vasoconstriction, both of which may increase pulmonary vascular resistance.[49]

Following initial surgical palliation in neonates with classic functionally univentricular hearts, resistance to flow of blood to the lungs is largely influenced by the size and length of a modified Blalock-Taussig or right ventricular to pulmonary artery[50–52] shunt or a pulmonary artery band. In contrast to the preoperative period, pulmonary vascular resistance is less of a concern. Following exposure to cardiopulmonary bypass, provision of supplemental oxygen will overcome pulmonary venous desaturation and improve systemic delivery of oxygen.[8,53] In a small subset of patients, if flow through the modified Blalock-Taussig shunt is generous or the pulmonary band is loose, overcirculation may occur. In these instances, ventilator management directed at increasing pulmonary vascular resistance, and augmenting systemic flow, as discussed above, has been employed with limited success. In the current era, improved results are achieved through manipulation of systemic vascular resistance rather than linkage of ventilator management and systemic perfusion.

Less commonly, neonates with functionally univentricular hearts who are awaiting or acutely recovering from surgical palliation have excessive cyanosis. The aetiology of cyanosis may be related to pulmonary venous desaturation, systemic venous desaturation, inadequate flow of blood to the lungs, or some combination of these features. Patients with pulmonary venous desaturation require evaluation to determine the underlying aetiology. If parenchymal lung disease is identified, increased levels of positive end expiratory pressure and supplemental oxygen may be useful. Systemic venous desaturation may result from inadequate systemic delivery of oxygen, anaemia and/or excessive metabolic demands. Inadequate flow of blood to the lungs may be present due to anatomical obstruction to pulmonary arterial flow or pulmonary venous egress, or elevated pulmonary vascular resistance. In the later instance, ventilator maneuvers to lower pulmonary vascular resistance, including the use of supplemental oxygen and inhaled nitric oxide, may be beneficial. An open lung strategy, with judicious use of positive end expiratory pressure to maintain functional residual capacity, may also lower pulmonary vascular resistance.

The bidirectional superior cavopulmonary anastomosis, as produced by the bidirectional Glenn or hemi-Fontan procedures, is commonly used as a second stage of palliation for infants with functionally univentricular hearts. Following this operation, flow of blood to the lungs occurs passively from the superior caval vein, while systemic venous return from the inferior caval vein continues to enter the common atrium, where it mixes with the pulmonary venous return. As a result, pathophysiologic disturbances that increase pulmonary vascular resistance are poorly tolerated. As discussed, lung volumes are an important determinant of pulmonary vascular resistance. Although some authors have advocated the avoidance of positive end expiratory pressure, the judicious use of positive end expiratory pressure to maintain functional residual capacity of the lungs is prudent.[54]

Occasionally, significant hypoxaemia in the absence of significant parenchymal lung disease is present following a bidirectional superior cavopulmonary anastomosis, particularly if the procedure is performed in patients who are less than 3 months of age. Efforts to hyperventilate such patients with the aim of lowering pulmonary vascular resistance will paradoxically exacerbate hypoxemia.[55] In such patients, a mild respiratory acidosis, for example, a partial pressure of carbon dioxide between 45 and 55 millimetres of mercury, achieved either with mild hypoventilation or provision of inspired carbon dioxide, leads to decreased cerebral and systemic vascular resistance. This leads to significant increases in cerebral and pulmonary blood flows, and therefore arterial oxygen saturations, and to significant increases in systemic perfusion.[56,57] In the absence of pulmonary venous desaturation, inhaled nitric oxide is generally not beneficial in patients with excessive cyanosis following a bidirectional superior cavopulmonary anastomosis.[58]

The total cavopulmonary connection, producing the Fontan circulation, is commonly used as the third and definitive surgical palliation for children with functionally univentricular hearts. Flow of blood from the inferior caval vein is rerouted directly to the pulmonary vascular bed, using either a lateral tunnel or an extra-cardiac conduit. Following construction of the Fontan circulation, there is invariably some degree of diastolic dysfunction, while systolic function generally is normal. In addition, ventricular filling is further compromised because the entire systemic venous return must now passively traverse the pulmonary circulation. As a result, failure to adequately oxygenate and ventilate patients with the Fontan circulation may precipitate an intractable cycle of high pulmonary vascular resistance, elevated central venous pressure and low cardiac output. Furthermore, in patients with Fontan physiology, the effects of changes in intrathoracic pressure on venous return and ventricular filling generally predominate over those effects on the afterload of the systemic ventricle. A marked increase in pulmonary blood flow was shown when converting patients from positive to negative pressure ventilation immediately following the Fontan procedure.[59] Additionally, progressive increases in positive end-expiratory pressure were shown to produce significant increases in pulmonary vascular resistance and decreases in cardiac index.[54] The use of an open lung strategy with low mean airway pressures, the avoidance of hypercarbia and hypoxia, and prompt drainage of pleural effusions or pneumothoraces are all of paramount importance. Once bleeding, temperature, and heart rhythm are controlled, patients recovering from the Fontan operation should be considered for early extubation, as flow of blood to the lungs is augmented by spontaneous inspiration.[60]

Effects of cardiac failure on respiratory function

Respiratory pump failure occurs when neuromuscular competency of the ventilatory pump is impaired, as for example with apneoa, and/or when the load imposed on the respiratory system is excessive, as for example, severe asthma, and/or when the balance of diaphragmatic transport of oxygen is impaired. The benefits of mechanical ventilation in supporting respiratory function in the setting of impaired neuromuscular function, or severe respiratory disease, are well documented. Mechanical ventilation also plays a vital role in the management of the low cardiac output state by improving not only respiratory muscle, but also oxygen transport balance to the myocardium and the global circulation.[61,62]

Under normal conditions, the diaphragm consumes less than 3% of global oxygen consumption and receives less than 5% of cardiac output. With an increase respiratory load, diaphragmatic consumption may increase to values over half of the total consumption of oxygen. In order to meet these increased demands, the flow of blood to the diaphragm must also increase. When the balance of transport of oxygen to the diaphragm is inadequate, either because of excessive requirements or limited delivery, respiratory pump failure ensues.[63] Using a dog model of cardiogenic shock, it was shown that the ability of the diaphragm to generate force was not much greater than that required for ordinary quiet breathing.[64] In another canine model of cardiogenic shock, in which cardiac output was decreased by 70%, respiratory muscle blood flow increased to 21% of cardiac output during spontaneous respiration.[62] The minute ventilation nearly tripled in the spontaneously breathing dogs and was elicited by acidaemia and hypoxia.[65] In the dogs receiving mechanical ventilation, respiratory muscle blood flow decreased to 3% of cardiac output and blood flow to the liver, brain and kidneys increased significantly.

The importance of maintaining the balance of transport of oxygen to the respiratory muscles has also been demonstrated in patients receiving mechanical ventilation for acute respiratory failure accompanied by underlying ventricular dysfunction. Several studies in adults have found that up to one-third of patients receiving mechanical ventilation for respiratory failure cannot be weaned from mechanical ventilation due to a worsening of left ventricular function and the balance of transport of oxygen to the respiratory muscles.[66]

These studies demonstrate not only the importance of diaphragmatic blood flow in preserving

respiratory pump function, but also the phenomenon that diaphragmatic blood flow is preserved to an equal or even greater extent than is cerebral and myocardial blood flow when cardiac output is limited. With mechanical ventilation, substantial quantities of oxygen are released for other organs, while consumption of oxygen by the respiratory muscles and the heart is decreased significantly.

Early extubation following cardiac surgery

Traditionally, children having cardiac surgery requiring cardiopulmonary bypass have remained intubated for prolonged periods postoperatively. Advances in cardiac anaesthesia, cardiac surgery and intensive care have changed the expectations for mechanical ventilation and the timing of extubation following cardiac surgery. Appropriate rapidity of weaning from mechanical ventilation, and timing of extubation following cardiac surgery, nonetheless, remains controversial. The potential advantages of early extubation include:[67–70]

- Increased venous return, ventricular filling and cardiac output in patients with diastolic heart failure
- Decreases in ventilator-associated nosocomial infections
- Decrease use of sedative medications
- Shorter stays in the intensive care unit and the hospital
- Decreased cost.

Regardless of the timing, it was shown[71] that patients with initial failed extubation in the paediatric intensive care unit require longer hospital, intensive care unit, and ventilator courses but are not at increased risk of death relative to those successfully extubated at the first attempt.

The potential for early extubation was shown in 1980.[72] Extubation immediately following the surgical procedure was accomplished in almost three-quarters of patients, with only 4% of these requiring reintubation. In a more contemporary series,[73] half the children undergoing cardiac surgery requiring cardiopulmonary bypass were extubated early, nine-tenths of these in the operating room. Patients extubated early were older, larger, and had lower scores using the system developed by the American Society of Anaesthesia than those extubated later. The youngest patient extubated early was 2 months old, and none of those extubated early required special airway support, re-intubation, or increased inotropic support after admission to the intensive care unit. The advantages of extubation in the operating room versus immediately upon arrival in the intensive care unit, however, remained unclear. The factors associated with early extubation have also been studied[74] with half of children extubated in less than 24 hours, with only 1% failed extubation. Pre-operative factors associated with successful early extubation included age greater than 6 months, absence of pulmonary hypertension, gestational age greater than 36 weeks, and absence of congestive heart failure. Interestingly, intraoperative factors such as the type of incision, complex versus simple procedures, and palliative versus complete repair were less likely to be predictive of the success of early extubation. In another series[75] of cases reviewed, almost three-fifths were aged less than 1 year of age, and one-fifth were neonates. Extubation in the operating room was achieved in one-quarter, and almost three-fifths were extubated at less than 24 hours. A retrospective study[68] demonstrated that selective extubation of patients following the Fontan procedure can be performed safely and improves postoperative haemodynamics, decreases use of hospital resources, and reduces the time required for recovery in hospital.

Summary

The use of mechanical ventilation in the cardiac intensive care unit has evolved over time. In order to maximize the opportunity for a successful outcome in the critically ill child, the practitioner must understand the foundations of mechanical ventilation and the influences of cardiopulmonary interactions, especially in those with unconventional circulations. Continued advances in cardiac anaesthesia, cardiac surgery, and intensive care have changed the expectations for mechanical ventilation and the timing of extubation following cardiac surgery.

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