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Understanding Neonatal Ventilation: Strategies for Decision Making in the NICU

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Abstract

Neonatal ventilation is an integral component of care delivered in the neonatal unit. The aim of any ventilation strategy is to support the neonate's respiratory system during compromise while limiting any long-term damage to the lungs. Understanding the principles behind neonatal ventilation is essential so that health professionals caring for sick neonates and families have the necessary knowledge to understand best practice. Given the range of existing ventilation modes and parameters available, these require explanation and clarification in the context of current evidence. Many factors can influence clinical decision making on both an individual level and within the wider perspective of neonatal care.

Providing respiratory support in the sick or preterm neonate is a significant component of the care delivered in the neonatal unit. Many of the neonates admitted to neonatal care require some degree of mechanical ventilation. A core aim of neonatal ventilation is to achieve adequate gaseous exchange without any resultant lung injury or chronic lung disease (CLD),[1] a potential and significant long-term effect of prolonged mechanical ventilation in the neonatal period. Understanding the complexities of care given to any neonate requiring mechanical ventilation is essential to deliver safe and effective care. The range of modes and parameters in ventilation practice can pose a challenge for both the novice nurse and for those more experienced who require an update of knowledge. The decision to use a specific type of strategy depends on a complex interplay of factors such as the nature and progression of the underlying condition, the state of the lungs, age, and gestation. The first aim of this article is to provide the reader with an understanding of the range of strategies used to fully support the neonate's respiratory system in the intensive care unit. Secondly, the article will outline the factors that can guide and assist decision making for learners in this area of practice. The reader is directed to many sources for further reading in this area that provide an overview of ventilation modes and strategies in neonatal practice.[1–13]

NEONATAL POSITIVE PRESSURE VENTILATION: OVERVIEW

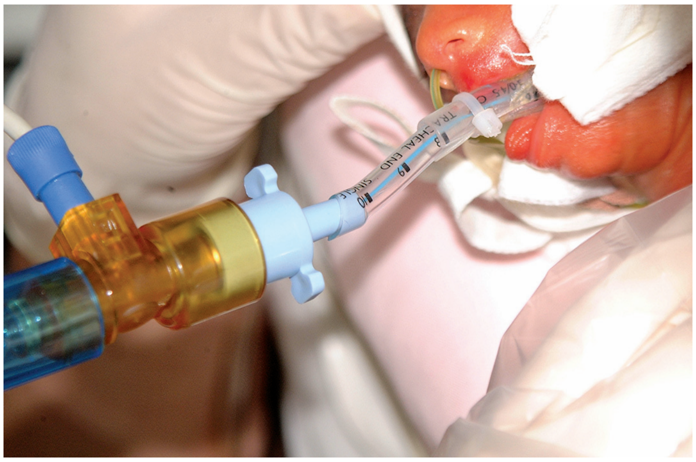
Ventilation strategies can be viewed across a continuum of dependency starting with the neonate who requires oxygen only, through to the fully ventilated neonate requiring intensive care. This article will focus on the latter area; that of positive pressure ventilation for the intensive care neonate specifically.

Positive pressure ventilation (sometimes referred to as mechanical, mandatory, or intermittent positive pressure ventilation [IPPV]) is a term that applies to the whole spectrum of ventilation modes that deliver pressure according to

Accepted for publication March 2013.

http://dx.doi.org/10.1891/0730-0832.32.4.246

FIGURE 1 ■ An intubated neonate receiving full ventilator support.



parameters set on a ventilator. It is used for full respiratory support in neonates who have undergone endotracheal intubation (Figure 1) and are unable to self-ventilate adequately and where noninvasive methods such as continuous positive airway pressure (CPAP) are not sufficient to maintain adequate respiratory function. Full ventilation includes firstly "conventional" modes that aim to mimic the normal respiratory cycle and are based on traditional pressure-limited, time-cycled ventilators.[11] More recently, "nonconventional" and newer modes of mechanical ventilation have been introduced, including pressure support, volume targeting, and high-frequency oscillation.[2] Adjunct therapies such as inhaled nitric oxide (NO) and extracorporeal membrane oxygenation (ECMO) that are used as "rescue" therapies for specific cases are beyond the scope of this article.

VENTILATOR MODES

The terminology used to identify modes of ventilation *may* differ between makes and models of different ventilators. The reader should refer to Table 1 for explanations of ventilator terminology and relevant formulas referred to throughout this article. In addition, Case Studies 1 through 3 provide examples of ventilator modes and the rationale for selecting them based on the individual pathophysiology and assessment.

Continuous Mandatory Ventilation (CMV)

This term refers to mandatory ventilation with a continuous flow of gases, where the neonate can attempt to take spontaneous breaths between ventilator breaths.[9,10,12] With CMV, the ventilator will deliver a breath regardless of the neonate's efforts, leading to the potential for asynchronous ventilation between the neonate and the ventilator. This mode is used for neonates who require maximum support in the presence of little or no spontaneous effort or where breathing should be minimal to avoid "asynchrony" between the neonate attempting to breathe and the ventilator delivering a mechanical breath.

Synchronized Intermittent Mandatory Ventilation (SIMV)

SIMV delivers a predetermined number of breaths per minute (BPM), but the breaths are triggered by detecting the neonate's spontaneous breathing efforts and synchronizing the delivery of the ventilator breaths to match the neonate's own breaths.[2–4,6,7,13] In SIMV, the neonate can take additional spontaneous breaths between the ventilator-assisted breaths. SIMV can be used to wean the ventilator support and move toward extubation by reducing the preset rate and pressure over time. If a neonate has a high respiratory rate, it is challenging for him to fit all his own breaths along with those set as backup into one minute, unless the inspiratory time (I_T) is minimal (less than 0.4 seconds; see later section). This mode is a widely used choice in neonatal practice.[5]

Patient Trigger Ventilation (PTV) or "Assist Control" (A/C)

For this mode, each time the neonate starts to breathe, this triggers the ventilator to deliver a breath or assist the neonate's breath at a set pressure and I_T. Therefore, the rate delivered and recorded is determined by the neonate. If the neonate becomes apneic and does not trigger a breath, the ventilator will deliver the set backup rate, again with the predetermined pressure and I_T. This mode can also be used to wean from ventilation support by reducing pressure only, because rate is controlled by the neonate. A meta-analysis[14] comprising 14 studies concluded that triggered ventilation leads to a shorter duration of ventilation overall as well as a reduction in air leaks compared with mandatory conventional ventilation. Another recent randomized, crossover trial of 26 stable preterm neonates with a mean gestational age of 27 weeks found that a reduced backup rate (30 BPM compared with 50 BPM) resulted in greater triggering of breaths and no discernible difference in cardiovascular stability.[15] Supporting a neonate's own respiratory efforts should therefore be encouraged by the use of triggered ventilation with an optimum backup rate while allowing him to take control of his own breathing in time.

Target Tidal Volume (TTV) or Volume Guarantee (VG)

TTV or VG can be added to either SIMV, PTV, or A/C. A desired tidal volume (V_T) is set by the operator and delivered by the ventilator using the lowest possible pressure necessary to reach the set volume. A further explanation of V_T follows later in the article and within Table 1. TTV or VG ensures that the neonate receives an optimal V_T but at minimal pressures to avoid the risk of barotrauma[8] and volutrauma to the lungs. It should be remembered that the *measured* peak inspiratory pressure (PIP) is likely to vary with each breath particularly as the lung compliance changes; in other words, how easy or not it is to expand the lung. For example, as the lung compliance worsens, the desired V_T will be more

TABLE 1 ■ Ventilation Terminology, Definitions, and Useful Formulas[49,59,60]

Parameter	Definition	Formula if Applicable and Further Information
	Parameters that influence adequate ventilation status	
Fraction of inspired oxygen (FiO_2)	How much oxygen is delivered—expressed as a fraction of 1. Can also be expressed as a percentage.	Multiply FiO_2 by 100 to calculate the percentage oxygen delivered (e.g., FiO_2 of 1 = 100% oxygen) FiO_2 of 0.3 = 30% oxygen
Mean airway pressure (MAP)	The total pressure (in cm H_2O) within the lungs throughout the respiratory cycle as determined by PIP, PEEP, I_T, and E_T. Along with FiO_2, this influences oxygenation.	$MAP = \frac{Rate \times I_T}{60} \times (PIP - PEEP) + PEEP$ Pressure is displayed graphically on the ventilator's pressure graph
Tidal volume (V_T)	The volume of gas entering the lungs in one breath; expressed in milliliters (mL)	Recommended tidal volume (V_T) = 4–6 mL/kg[19] V_T is displayed graphically on the ventilators V_T graph
Minute volume (Vmin)	The volume of gas entering the lungs in more than 1 min expressed as liters/minute; affects CO_2 elimination	$Vmin = V_T - \text{dead space} \times \text{rate}$[49]
	Ventilator parameters (conventional)	
Rate	The number of breaths delivered in a minute—as breaths per minute	Set by a dial or touch screen or set independently by adjusting I_T and E_T—see Table 3. Range delivered can be 20 up to greater than 70.
Peak inspiratory pressure (PIP)	The peak pressure reached at the end of inspiration (cm H_2O)	Aim to keep as low as possible, ideally less than 20 cm H_2O; if greater than 25–30 cm H_2O, HFOV is considered.
Positive end-expiratory pressure (PEEP)	The end pressure reached at the end of expiration (cm H_2O)	Normal range is 4–6 cm H_2O although some neonates may need up to 7–8 cm H_2O depending on the underlying pathophysiology.[50]
Inspiratory time (I_T)	The inspiratory time of one respiratory cycle expressed in seconds	This should be kept short particularly when using high rates.[44,50] Range is 0.35–0.40 s.[6]
Expiratory time (E_T)	The expiratory time of one respiratory cycle expressed in seconds	With a constant or predetermined I_T, the E_T will vary depending on the required rate (see above)
I:E ratio	The ratio of inspiration to expiration time	E_T should be longer than I_T.[50]
Flow	The flow of gas delivered, expressed as liters per minute (liters/minute). Ventilators will measure inspiratory and expiratory flow.	Flow is displayed graphically on the ventilator's flow graph.
Trigger threshold	The sensitivity of the ventilator and flow sensor to detect the neonate's breaths	In most ventilators, this is a flow trigger, i.e., the threshold of flow that needs to be registered by the ventilator to detect the neonate's spontaneous breathing.
Leak	Flow that is lost from the respiratory circuit	Measured as the difference between inspiratory and expiratory flow.
	Parameters in high-frequency oscillatory ventilation (HFOV)	
MAP	As above—controls oxygenation along with FiO_2	Set using the PEEP control on some ventilators that deliver both conventional and HFOV modes; set according to pressure requirements on conventional mode (1–2 cm higher)
Frequency	Measured in Hertz (Hz)—there are 60 oscillations in 1 Hz	Set at a range of 8–10 Hz
Amplitude	The variation round the MAP, also known as Delta P or power and affects chest "wiggle"; controls CO_2 elimination	Set according to extent of chest wiggle/bounce and blood gas analysis
	Other ventilation terms	
Oxygenation index (OI)	A calculated value to determine a neonate's oxygen demand and associated level of oxygenation; used as criteria for NO and/or extracorporeal membrane oxgenation in the very sick newborn	$OI = \frac{MAP\ (cm\ H_2O) \times FiO_2 \times 100}{PaO_2\ (mmHg)}$

TABLE 1 ■ Ventilation Terminology, Definitions, and Useful Formulas *(continued)*

Parameter	Definition	Formula if Applicable and Further Information
Functional residual capacity (FRC)	The volume of gas present in the lung alveoli at the end of passive expiration	FRC is reduced in conditions such as respiratory distress syndrome where there is poor lung compliance. A low FRC will affect optimum gaseous exchange.
Compliance	The elasticity or distensibility of the respiratory system including the lungs and chest wall	Compliance = Volume/Pressure The volume/pressure loop displayed on some ventilators represent this relationship graphically.
Resistance	The capability of the airways and endotracheal tube to oppose airflow; expressed as the change in pressure per unit change in flow	Resistance = Pressure/Flow Again, this is displayed graphically on some ventilators.
Pulmonary dynamics	The real-time graphical representations of the neonate's ventilation parameters	As stated above, graphs can be viewed within the graph section of the ventilator of pressure, V_T, flow, compliance, and resistance. These can also be termed waveforms, loops, mechanics, and/or trending displays, all of which represent the neonate's ventilation status in real-time.

Note: All measurements and graphical displays of parameters are dependent on the presence of a flow sensor. Absence of a flow sensor will mean the ventilator will still deliver breaths, but there will be no "measured" readings.

Abbreviations: I:E ratio = inspiratory to expiratory; NO = nitric oxide; PaO_2 = partial pressure of oxygen in arterial blood; s = second.

difficult to deliver at lower pressures, and so the maximum set PIP will be reached. Therefore, it is very important to set an appropriate *maximum* pressure limit should it become difficult to deliver the set V_T in deteriorating lung conditions. Conversely, as lung compliance improves, it is easier for the desired volume to be delivered at lower pressures, and therefore the measured PIP will be lower, not reaching the maximum limit. When the PIP needed to generate the desired V_T decreases, this signals improving lung conditions and readiness for weaning. The ability of VG to show changes in lung compliance is seen as one of the main benefits of this ventilation mode.[16,17] Further benefits stem from the ability to deliver a guaranteed and *consistent* V_T at the lowest pressure which potentially reduces trauma to the lungs,[18] a feature not achievable by traditional pressure-limited time-cycled ventilation.[16]

Based on a review of the literature, Brown and DiBlasi propose that the use of small V_T in the range of 4–6 mL/kg is one of the key strategies for protecting the neonatal lung during mechanical ventilation.[19] Cheema and colleagues state that 4 mL/kg should be aimed for.[20] However, a higher V_T than this may be required with conditions such as pneumonia, bronchopulmonary dysplasia (BPD), or other lung pathology that results in increased resistance to airflow and the need for a greater volume to be delivered.[21] The reader should refer to three systematic reviews in this mode of ventilation for a full summary of the research in this area and the potential benefits of VG ventilation.[22–24] A comprehensive guide is also available on the practical application of this mode.[8]

Pressure Support Ventilation (PSV)

With PSV, the neonate's breathing efforts are supported with ventilator breaths set to a predetermined pressure. Pressure support alone does not supply a backup rate; it merely assists the infant's own breath by pressurizing the breath to the set pressure support level. The flow termination sensitivity is set so that the I_T will terminate at a predetermined percentage of the peak flow. Full pressure support (PS) is a mode in its own right and may be useful for neonates who are weaning from their support, allowing them more control in line with their own breathing dynamics.[25] The main principles of PSV are summarized within the recent literature as a new and emerging mode.[3–6,10,25–28]

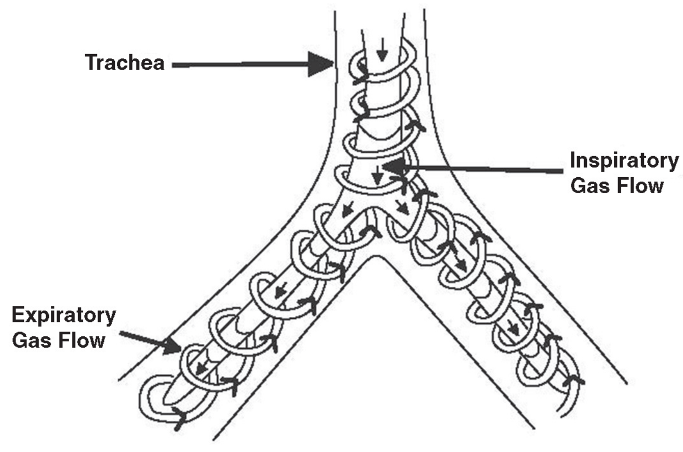
PSV can also be used in conjunction with other modes by turning this on as an additional feature.[13] For example, synchronized intermittent mandatory ventilation with pressure support (SIMV with PS) added will ensure that every spontaneous breath is supported by the ventilator at a set percentage pressure relative to peak pressure set for the mandatory breaths on SIMV.

So, whereas with PS mode alone or PTV (A/C) with PS, all breaths are supported; in SIMV with PS, the neonates' breaths only are supported. However, this imparts greater support for a neonate who perhaps will not be able to manage on SIMV alone and who requires additional support for his own breathing efforts. Adding in PSV *with* SIMV can be useful as a more gradual step down once the backup rate on SIMV starts to be reduced during weaning. Here, the neonate's own breaths continue to be supported at a certain pressure until such time that he does not require this additional PS. It should be remembered that the measured V_T will vary with each pressure-supported breath.

High-Frequency Ventilation

This is a mode of ventilation that uses breath rates or "frequencies" much greater than normal physiologic breath rates with a V_T near anatomic dead space. One example is high-frequency jet ventilation (HFJV) that introduces small pulses of gas under pressure into the airway at a very fast rate

FIGURE 2 ■ Pattern of gas flow in high-frequency jet ventilation.



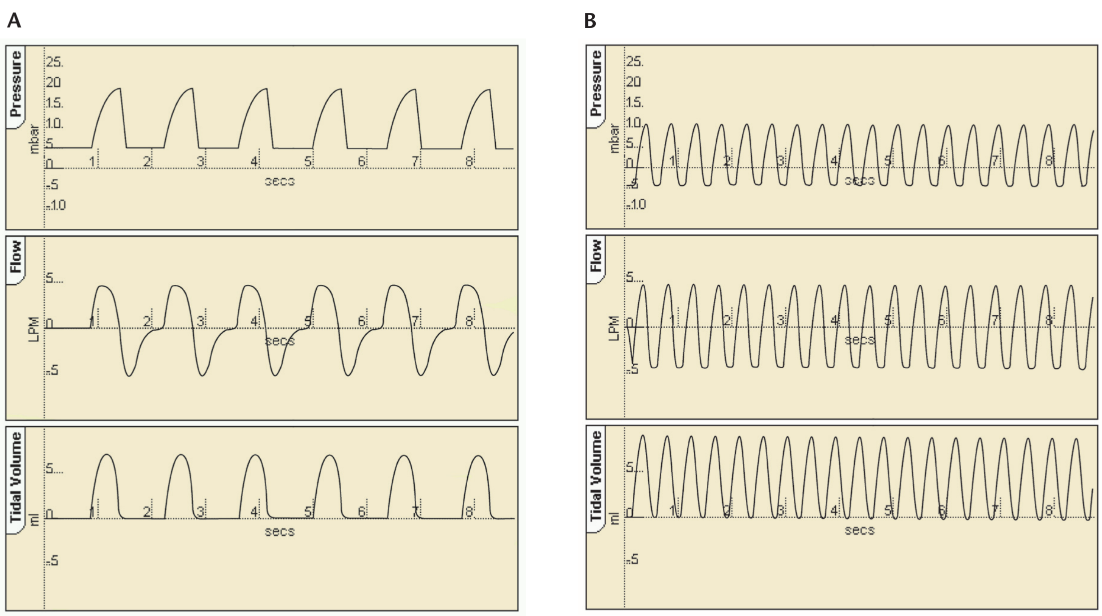
Adapted by Solon JF, from: Rausch K via Ellis R, unpublished data, Milpitas, California. Reprinted by permission.

or frequency (4–11 Hertz [Hz]; see in the following text) for a brief duration (approximately 0.02 seconds), using very small V_T of ≤1 mL/kg, thus creating lower distal airway and alveolar pressures than those produced by a mechanical ventilator. Exhalation during HFJV is passive. It was thought this may reduce the severity of lung injury associated with mechanical ventilation.[29,30] The jet actively pulses gas into the neonate's lungs which travels down the center of the tracheal tube. A CO_2 then spirals up and around that jet of gas and out of the expiratory circuit passively (Figure 2). This mode was originally used for short-term ventilation during airway surgery because of its capability to ventilate in the presence of air leaks. The short I_T and small V_T are thought to minimize flow through leaks within the lung fields,[31] for example, in a condition such as pulmonary interstitial emphysema (PIE). In addition, in meconium aspiration syndrome (MAS) where gas trapping may occur, passive exhalation of the jet helps CO_2 be removed without causing further trapping and preventing overexpansion of the lungs. Literature also indicates its use for other short-term conditions such as pulmonary hypertension of the newborn (PPHN) and during transport.[32–34] However, the practicalities of administration and the necessity for two machines have meant that other forms of high-frequency ventilation may be more suitable; hence, it is not as widely used.

More commonly used is high-frequency oscillatory ventilation (HFOV) where the pressure "oscillates" around a constant distending pressure that in effect is the same as positive end-expiratory pressure (PEEP) and equivalent to mean airway pressure (MAP).

A further explanation of MAP will follow later and is detailed in Table 1. Thus, gas is pushed into the lung during inspiration and then pulled out during expiration. HFOV generates very low V_T that is generally less than the dead space of the lung. Figure 3 (A and B) depicts the waveforms for conventional versus high-frequency ventilation; the typical pressure graph for HFOV is therefore very different from what we see in conventional modes. Oscillation causes the chest to "wiggle" or vibrate. The increasing use of HFOV in neonates has been documented.[35] In neonatal practice, this is a mode used either

FIGURE 3 ■ Waveforms for (A) conventional ventilation and (B) high-frequency oscillatory ventilation (HFOV).



From SLE. SLE5000 Neonatal Ventilator with High Frequency Oscillation, 2010. SLE Limited; Surrey UK. Reprinted with permission.

as a "rescue" therapy when conventional modes have been ineffective or, in some neonatal units, as a first-line ventilation strategy. However, like HFJV, a link between HFOV and improved outcomes has not been demonstrated.[36–38]

Proportional Assist Ventilation (PAV)

This mode gives assistance that is proportional to the neonate's effort, whereby the applied pressure increases in proportion to the V_T and flow generated by the neonate, with the frequency, timing, and rate of lung inflation being controlled by the neonate.[39,40] However, this new mode is not frequently used at present compared with other modes discussed thus far. In order for PAV to work effectively, there should be no leak, and a mature respiratory system should be in place; clearly, this is not the case in preterm neonates.[4]

Neurally Adjusted Ventilatory Assist (NAVA)

NAVA is another new mode of ventilation designed to reduce the asynchrony that can exist between the ventilator and the neonate. Gas delivery from the ventilator is triggered, controlled, and cycled by a diaphragmatic electromyelogram (EMG) signal. The ventilator is aware of the change in EMG by the insertion of a specially designed nasogastric tube (NGT) with EMG electrodes that cross the diaphragm. Several preliminary studies in neonates have demonstrated that patient–ventilator synchrony is improved with the application of NAVA,[41–43] and this may be a strategy for future work and application.

UNDERSTANDING SETTINGS IN VENTILATION

In addition to understanding what each mode is and how it works, it is important for the neonatal nurse to also understand the settings on the ventilator (see Table 1). Nurses record settings hourly on an ongoing basis, and so having the knowledge behind what they mean is paramount.

Firstly, in CMV and SIMV, the desired number of BPM is set either by a BPM dial, or, in some ventilators, the rate is set by adjusting I_T and expiratory times (E_T) separately (see in the following text).

A *backup* respiratory rate is set for some modes (e.g., PTV, A/C, and PS). As seen in Tables 1 and 2, rate along with the V_T affects "minute volume" (Vmin) and so affects CO_2 clearance. Increasing Vmin improves CO_2 elimination, and decreasing it will lower this elimination.

The I_T is usually set at no higher than 0.36–0.40 seconds in the preterm neonate particularly, recommended because of short physiologic time constants in neonates.[44] The I_T may be slightly higher than this in older neonates or when the rate used is slow, but it is usually no higher than 0.50 seconds. Increasing I_T will raise the MAP, thereby improving oxygenation, while lowering the I_T may lower partial pressure of oxygen in arterial blood (PaO_2) levels (see Table 1). Both I_T and E_T can be independently set on some ventilators to adjust and set the rate. In that case, I_T is confirmed and then E_T adjusted until the desired rate is obtained. Information on setting a rate using this method can be seen in Table 3. E_T should always be longer than I_T.

Both the PIP (at the end of inspiration) and the PEEP (at the end of expiration) are set according to the needs of the neonate and condition. These are depicted in the pressure graph in Figure 3A (top image). Increasing PIP and PEEP will raise the MAP and improve oxygenation because, as for I_T, they are integral components of the MAP formula. Conversely, reducing PIP and PEEP will lower MAP when oxygenation is adequate. Making changes to PIP and PEEP will also affect the V_T for each breath and so also influence CO_2 elimination—this will be covered again later in the article. The side effects of high or low settings for PIP and PEEP should be kept in mind while setting these parameters. A high PIP particularly above 25 cm H_2O can damage the delicate lung alveoli by barotrauma in association with shearing forces of mechanical ventilation. Raising the PIP also increases V_T, and therefore a risk of volutrauma is also present. Conversely, a PIP that is too low may not be effective in achieving adequate chest expansion, leading to hypoventilation. A high PEEP can lead to an inadequate expiratory phase with poor emptying of gas and limiting CO_2 elimination as the end pressure for each breath is not sufficient to allow CO_2 removal from the respiratory dead space. Conversely, setting the PEEP too low may lead to alveolar collapse and diminished functional residual capacity (FRC). Therefore, optimum settings should be provided with sound rationale and evaluation tailored to the individual neonate.

Oxygen is set from a dial that blends air and oxygen, keeping this to the minimum possible because of the potential damaging effects of oxygen toxicity. Flow (in liters/minute) is set in some ventilators (to 8–10 liters/minute), whereas in others this is automatically delivered without needing to be set. A flow graph is depicted in Figure 3A (middle image). In addition, the trigger threshold should be set on the *maximum* sensitivity in neonates (i.e., the minimum effort for the neonate). For neonatal flow triggering, it is ideal if a change in flow of approximately 0.2–0.4 mL/kg is recognized by the ventilator as a spontaneous effort. If it is any higher than this, the neonate's effort may not be strong enough to actually trigger the flow.

In addition, if PS is added to an existing mode, a percentage of support is set; that is, any spontaneous breaths by the neonate will be supported by flow-cycled, pressure-limited breaths to the predetermined percentage of the set PIP. Flow termination sensitivity is also set—that is, when the pressure-supported breath flow is terminated. When using TTV or VG, the desired V_T is set at approximately 4–6 mL/kg[19] or higher if the neonate's condition necessitates this, as stated earlier. Refer to Case Studies 1 and 2 to see how PSV and VG are used with other existing modes.

Alarm limits should also be set; for example, high and low pressure, V_T alarm, and high and low Vmin alarm thresholds are set. An apnea alarm is also set on some ventilators, often functional if the BPM is less than 20.

TABLE 2 ■ Changing Ventilation—A General Guide[10,12,49,50]

Manipulating oxygenation		
MAP controls oxygenation, *so oxygenation can be influenced by changing any of the variables that alter MAP (PIP, PEEP, I_T, and E_T).*		
Conventional Ventilation		
Desired Outcome	**Aim and Possible Actions**	**Evaluation**
To increase oxygenation (increase MAP)	Increase FiO_2 in increments of 5%–10% Increase MAP by increasing PIP or PEEP in increments of 1–2 cm H_2O Increase I_T but no higher than 0.4 seconds for preterm neonates Consider adding PSV, if on SIMV Consider starting HFOV if MAP and FiO_2 significantly increase	Observe oxygen requirement, pulse oximetry, or transcutaneous oxygenation and PaO_2 on blood gas analysis Look for improvements in lung compliance; e.g., chest expansion Observe pulmonary dynamics/ graphs—e.g., volume/pressure loop and pressure graph
To decrease oxygenation when condition improves and/or during weaning (decrease MAP)	Aim to get FiO_2 to an acceptable level Reduce MAP by reducing PIP or PEEP (again, in small steps of 1–2 cm H_2O at a time) I_T can also be reduced slightly, aiming for range 0.36–0.40 s for the preterm neonate Stop PSV if this has been added to another mode Change mode to a "trigger" mode that synchronizes spontaneous breaths and/or responds to a trigger threshold and neonate's own breathing.	As above
Manipulating CO_2 elimination		
Minute volume (Vmin) controls CO_2 elimination. CO_2 levels will be influenced by any changing measure affecting Vmin; that is, manipulating the rate, V_T, or both will alter the Vmin.		
To clear more CO_2 CO_2 elimination will be improved by any measure that increases respiratory Vmin (i.e., increasing the rate, V_T, or both will increase the Vmin).	Increase rate (in increments of 5–10 BPM) to increase Vmin and remove more CO_2. OR increase PIP (in steps of 1–2 cm H_2O) with caution, which will increase V_T for each breath and increase Vmin. Decrease PEEP; however, this may cause a reduction in oxygenation which needs to be observed. In addition, if CO_2 is increased because of atelectasis, decreasing the PEEP may worsen the situation and increase CO_2; again this needs to considered. If on VG (TTV), increase set or desired V_T.	Observe measured V_T and Vmin on the ventilator Check CO_2 on blood gas analysis and/or Tc monitoring
To clear less CO_2 when weaning—CO_2 elimination will be reduced by any measure that decreases respiratory Vmin (i.e., decreasing the rate, V_T, or both will decrease the Vmin).	Reduce rate in increments of 5–10 BPM and/or reduce PIP (in steps of 1–2 cm H_2O). Consider reducing PEEP as the PIP is reduced. Reduce set/desired V_T if VG (TTV) is being used.	As above
High-Frequency Oscillatory Ventilation		
Desired Outcome	**Aim and Possible Actions**	**Evaluation**
To increase oxygenation	Increase FiO_2 in increments of 5%–10%. Increase MAP in increments of 1–2 cm H_2O.	As for conventional ventilation. Ensure chest x-ray (CXR) is done after being put onto HFOV.
To decrease oxygenation when weaning	Aim to get FiO_2 to an acceptable level. Reduce MAP in increments of 1–2 cm H_2O.	As for conventional ventilation
To clear more CO_2	Increase amplitude (Delta P) in increments of 2–5 cm H_2O according to blood gas (CO_2) and chest wiggle OR decrease frequency (Hz), allowing greater efficiency of oscillations to reach the peak and trough of the pressure wave.	As for conventional ventilation Observe for adequate chest wiggle/bounce.
To clear less CO_2 when weaning	Reduce amplitude in increments of 1–2 cm H_2O according to CO_2 and chest wiggle.	As above

Suggested actions and changes should be based on assessment of the individual neonate.

Abbreviations: E_T = expiratory times; FiO_2 = fractional concentration of oxygen; HFOV = high-frequency oscillatory ventilation; I_T = inspiratory time; MAP = mean arterial pressure; PEEP = positive end-expiratory pressure; PIP = peak inspiratory pressure; PSV = pressure support ventilation; SIMV = synchronized intermittent mandatory ventilation; TTV = target tidal volume; VG = volume guarantee; V_T = tidal volume.

TABLE 3 ■ Setting the Rate Using Inspiratory and Expiratory Times

Confirm desired rate	
Divide this into 60	
From this number, subtract the inspiratory time (I_T)	
This gives you the expiratory time (E_T) that you need to set to get the desired rate	
Example 1—	You want a rate of 60 and I_T of 0.4 second
	60 divided by 60 = 1 second
	1.0 minus 0.4 = 0.6 (set the E_T at 0.6 second)
	This will give you a rate of 60
Example 2—	You want a rate of 40 and I_T of 0.5 second
	60 divided by 40 = 1.5 second
	1.5 minus 0.5 = 1 second (set the E_T at 1 second)
	This will give you a rate of 40

OSCILLATION SETTING

For HFOV, the frequency of oscillations is expressed in Hertz. There are 60 breaths in 1 Hz. This mode will deliver very small V_T at very high rates, for example, 600 BPM. The MAP is set within this mode and manipulated to control oxygenation, and this is usually set above the MAP that was given for conventional modes (e.g., 2 cm H_2O higher). Pressure amplitude (Delta P) is the "power" setting and determines the strength of the oscillations (and so the extent of "chest wiggle" in the neonate).

Increasing the Delta P will increase chest wiggle and increase the height of the pressure trace as displayed in Figure 3B. This controls the volume entering the lungs and so controls CO_2 elimination. Oxygen, high and low alarm pressure, V_T alarm threshold, and Vmin high and low alarm thresholds are also set.

Humidification is also an essential element of normal respiratory function. *Any mode*, be it noninvasive or full ventilation, should deliver warm, humidified gases by a humidifier within the inspiratory limb of the ventilator circuit. A humidifier should ensure an airway temperature of as close to 98.6°F (37°C) as possible.

UNDERSTANDING MEASUREMENTS IN VENTILATION

All *measured* readings of the dynamics of the neonate's lungs are taken by the flow sensor situated on the connection between the ventilation tubing and the endotracheal tube. This sensor is designed to measure certain parameters, which are then displayed in various forms. The ventilator screen panel displays the measured and calculated parameters. It is important to calibrate the flow sensor prior to use (flow calibration) and to prevent damage or disruption of the measuring capability because of excessive condensation from the tubing. In the absence of a flow sensor, dynamic measurements are not possible. The ventilator will still be able to deliver the desired settings; however, the breaths will not be synchronized with the neonate's respiratory efforts.

The following measurements can be recorded by the neonatal nurse at the bedside. The MAP is the total pressure within the lungs throughout the respiratory cycle as determined by PIP, PEEP, I_T, and E_T. The MAP has a direct influence on oxygenation—for example, if you need to increase oxygenation, the MAP must be increased by manipulation (increasing) of one or more of the PIP, PEEP, and I_T. If oxygenation is adequate or high, then the values can be *decreased* to reduce MAP. Although MAP is a *measured* value in conventional modes, it *can* be manipulated by changing the parameters that determine MAP (see Table 1). Oscillation measurements comprise the total rate or frequency (BPM), V_T, Vmin, leak, MAP, and oxygen.

The relationship between the I_T and E_T is expressed as the I:E (inspiratory to expiratory) ratio. For example, if the I_T is 0.5 seconds and the rate is 60, the E_T will also be 0.5 seconds. The I:E ratio will therefore be 1:1.0. With a lower I_T of 0.4, a rate of 60 will mean an E_T of 0.6 with an I:E ratio of 1:1.2 (see Table 3).

The ventilator will measure the total number of breaths detected and delivered by the ventilator (mechanical and patient triggered). The number of patient-triggered breaths is usually displayed separately and is an indication of neonatal respiratory effort.

Volume is also measured and gives us valuable information about the dynamics of ventilation. The V_T is the volume of gas delivered to the lungs in one breath and is measured as the expired V in milliliters (mL).

Vmin (liter) is the accumulated expiratory V_T over a one-minute period. V_T multiplied by the rate gives the Vmin; this has a direct influence on CO_2 clearance in that increasing either the rate or V_T (or both) will increase removal of CO_2. However, this will not work if the CO_2 is high because of overdistension or impeded pulmonary venous return. Such actions could in these cases hamper CO_2 removal. In general, decreasing the rate, V_T or both will slow CO_2 removal. Being mindful of the neonate's underlying pathophysiology is essential in selecting optimal ventilator settings.[45]

The difference between the I:E flow expressed as a percentage leak can indicate the need for endotracheal tube change. Further lung dynamics are also monitored by measuring the resistance; the total change in the applied pressure to the lung divided by the maximum flow into the lung (resistance to flow); and compliance, the ratio of the change in lung volume to the change in the applied pressures.

Graphical representations of the dynamics of the neonate's breathing pattern can be seen on the ventilator display screen. Figure 3 (A and B) shows pressure graphs for both conventional and high-frequency ventilation.

A summary of all modes discussed including what is both set and measured can be seen in Table 4.

TABLE 4 ■ Summary of Settings and Measurements for Ventilation Modes[6]

Mode	Settings	Measurements
CMV	Rate (BPM), PEEP, PIP, I_T, oxygen, high and low alarm pressure thresholds, V_T alarm threshold, Vmin high and low alarm thresholds	I:E ratio, E_T measured, rate (BPM), V_T, Vmin, leak, resistance, compliance, PIP/PEEP, and MAP. Recorded breath rate is what is set, not what the neonate does.
SIMV	Rate (BPM), apnea time (if backup breath rate is less than 20 breaths) per minute or lower, PEEP, PIP, I_T, oxygen, trigger threshold, high and low alarm pressure thresholds, V_T alarm threshold, Vmin high and low alarm thresholds	I_T measured, total rate (BPM), trigger (number of neonate's triggered breaths), V_T, Vmin, leak, resistance, compliance, PIP/PEEP, and MAP
PTV/ A/C	Backup rate (BPM), apnea time (if backup breath rate is less than 20), PEEP, PIP, I_T, oxygen, trigger threshold, high and low alarm pressure thresholds, V_T alarm threshold, Vmin high and low alarm thresholds	I_T measured, total rate (BPM), trigger (number of neonate "triggered" breaths), V_T, Vmin, leak, resistance, compliance, PIP/PEEP, and MAP
PSV	Backup rate (BPM), apnea time (if backup breath rate less than 20), PEEP, PIP, maximum I_T, oxygen, flow termination sensitivity, trigger threshold, high and low alarm pressure thresholds, V_T alarm threshold, Vmin high and low alarm thresholds	I_T measured, total rate (BPM), trigger (number of neonate's triggered breaths), V_T, Vmin, leak, resistance, compliance and PIP/PEEP, MAP, oxygen
SIMV + PS	As for SIMV above but turn PS to "on" and set % of pressure support plus flow termination sensitivity	I_T measured, total rate (BPM), trigger (number of neonate's triggered breaths), V_T, Vmin, leak, resistance, compliance, PIP/PEEP, MAP, and oxygen
VG/TTV	As for these modes above but turn on TTV and set V_T required for each breath.	As for each mode above plus "measured" PIP (will vary)
HFJV	Set short bursts with short I_T, frequency, and flow	See below as for HFOV
HFOV	HFO rate (in Hz), mean pressure, pressure amplitude (or Delta P), oxygen, high and low alarm pressure thresholds, V_T alarm threshold, and Vmin high and low alarm thresholds	Rate (BPM) total, V_T, Vmin, leak, MAP and oxygen
CMV PLUS HFOV	BPM, I_T, PIP, PEEP, HFO rate, HFO activity (oscillations in inspiratory and expiratory phases or expiratory phase only), pressure amplitude (Delta P), oxygen, high and low alarm pressure thresholds, V_T alarm threshold, Vmin high and low alarm thresholds	I:E ratio, E_T measured, rate (BPM) and HFO rate, PIP/PEEP, MAP, and oxygen
NAVA	Trigger threshold to pick up electrical diaphragmatic activity. Adapt NAVA level to regulate pressure support.[6]	As for above

Note: Other modes of ventilation are less commonly cited in the literature and so are not included in this article; for example, volume-controlled ventilation, volume-limited ventilation, pressure-regulated volume control, volume-assured pressure support (VCV, VLV, PRVC, VAPS, respectively) and high-frequency flow interruption (HFFI); refer to key literature for more information.[4,6]

Abbreviations: A/C = assist control; BPM = breaths per minute; CMV = continuous mandatory ventilation; HFJV = high-frequency jet ventilation; HFO = high-frequency oscillation; HFOV = high-frequency oscillatory ventilation; I:E ratio = inspiratory and expiratory ratio; I_T = inspiratory time; MAP = mean airway pressure; NAVA = neurally adjusted ventilatory assist; PEEP = positive end-expiratory pressure; PIP = peak inspiratory pressure; PS = pressure support; PSV = pressure support ventilation; PTV = patient trigger ventilation; SIMV = synchronized intermittent mandatory ventilation; TTV = target tidal volume; VG = volume guarantee; Vmin = minute volume; V_T = tidal volume.

DECISION MAKING IN NEONATAL VENTILATION

Selecting or Switching Modes of Ventilation

The decision to move a neonate from one strategy to another is influenced by the severity and progression of the neonate's underlying condition, lung pathology, and the response to ventilation changes and attempts at weaning. Gestation, birth weight, and age should also be considered. This emphasizes the importance of matching ventilation strategies to the underlying pathophysiology[45] and individualized factors applicable to each neonate. The type or level of a specific unit in which a neonate is delivered or admitted also needs are considered as this will determine the level of support and strategies available. A United Kingdom–wide survey of ventilation strategies within 54 tertiary-level neonatal units was undertaken[46] and found that the use and availability of modes are variable. Ninety-eight percent response to a structured questionnaire found that pressure-controlled ventilation was most frequently used as the primary form of ventilator support (69.8 percent) compared with volume targeted (24.5 percent) and HFOV (5.7 percent). Similarly, an international survey of 50 tertiary units in Australia, New Zealand, Sweden, Denmark, Finland, and Norway evaluating the use of volume-targeted ventilation again found that use was variable,[47] ranging from 40 to 60 percent of units. The most common reason cited for its use was the reduction in BPD. Overall, it is clear that no single ventilation mode or strategy has shown to have a truly significant benefit in terms of mortality or CLD.[19,48] Moreover, although there is a wealth of research on ventilation strategies, each individual neonatal unit will be unique in its application of research data, preferences, patient-specific population, and unit outcomes.

However, for any neonatal unit, accurate patient assessment is of vital importance for the decision-making process. This is a key element in coming to a diagnosis but also to gain a full picture of how compromised the respiratory system and other related systems are and which actions to take or whether to transfer appropriately if necessary.

Decision-Making Tools for Neonatal Ventilation Practice

Various tools exist in neonatal ventilation practice to guide and inform decision making in practice. However, they should never replace a holistic approach to care of the neonate and family. Nurses can be assisted in their practice by tools that can facilitate understanding of interventions their neonates undergo. Tools may provide clarification and guidance at a novice level which may serve to facilitate safer practice (Tables 3–5); however, whichever tool is employed, assessment is central when deciding what modes and parameters are suitable for any specific neonate.

Making Changes to Ventilation Parameters

Overall, changing ventilation parameters is based on assessment in the first instance of both blood gas analysis and clinical picture. Then, the initial question to ask is "What am I trying to achieve?": Is it the need to change oxygenation, CO_2 or both? Other questions may be: "What is the target oxygen saturation? What does the neonate look like—for example, chest movement and synchrony? Do ventilation requirements need increasing or decreasing or remain static?" Balance is important, or, in other words, in line with protecting the lungs, there is a need to balance the ventilator settings. For example, if a neonate is in 100 percent oxygen but with low pressures settings, it may be preferable to reduce the FiO_2 but increase the pressures. Similarly, if the neonate is on high pressure settings but a low rate, it may be better to give a faster rate and lower pressures.

A full summary of the principles behind changing ventilation can be seen in Table 5. The clinical application of how changes are made in practice can be seen in Case Studies 1, 2, and 3.

One important change in ventilation practice is the weaning of support. In essence, weaning a neonate from a ventilator should be a central objective at the point of intubation and should be commenced as soon as possible in line with a protective lung strategy. However, it is reported that approximately 30 percent of intubated neonates may fail attempted extubation,[51] and so, bearing in mind the clinical implications of this, appropriate decision making for weaning must be employed. Strategies for weaning include any change to any parameter that facilitates the neonate taking control of his own ventilation. Weaning can be done on any mode mentioned thus far, with the exception of CMV which should be changed to a synchronized or trigger mode as soon as possible. Oxygen should certainly be weaned down within any mode of ventilation to the minimum requirement needed for adequate oxygenation of the neonate. The I_T should be bought down to the minimum, to be as close as possible to the neonate's own physiologic time. SIMV has been found to be the most common mode in practice, and, therefore, it follows that this mode is most commonly used for weaning.[5] In this mode, rate, pressure, or both are reduced in increments depending on individual assessment of blood gas analysis and clinical picture. If PS is turned on, the percentage of pressure support is gradually reduced until this is eventually switched to off, so that the neonate's breaths are no longer supported. Some clinicians prefer to wean from PTV or A/C mode as this has been found to be associated with a shorter duration of weaning.[14] In this mode, pressure alone is reduced. If PSV is used, similarly the level of pressure support is reduced gradually. In A/C or PSV, because the neonate controls the ventilator rate, reducing this rate has no effect on delivered rate unless respiratory effort is poor or the backup rate is greater than the spontaneous breathing rate.

The VG mode of ventilation results in automatic weaning of the PIP as lung function improves.[3–5] The only parameters that should be altered during weaning are the FiO_2 and the set V_T. When the set V_T is below the neonate's spontaneously generated V_T, the PIP will be reduced. Extubation should be considered when the PIP reaches minimal levels.[7,52,53] Extubation is considered if the MAP is consistently <8 to 10 cm H_2O with set V_T T 3.5 to 4.5 mL/kg with satisfactory blood gases.[8] Readiness for extubation can also be ascertained by assessing the neonate's spontaneous breathing.[54]

To serve as a guide, protocol-led care has been recommended.[11,55] Overall, however, there does not seem to be any one strategy that is recommended for weaning.[55–57] In relation to any weaning strategy, key questions should be considered as seen in Figure 4. It is always important to emphasize here that, whatever strategy is chosen, each change must have rationale. Moreover, the individualized evaluation of any change made is vital to know if this has been effective in the best interest of the neonate.

CASE STUDY 1: CMV, SIMV, SIMV PLUS PSV, AND PSV

Baby John was a preterm neonate born at 27 weeks gestation (birth weight 1 kg) by spontaneous vaginal delivery. The neonate's mother received a course of antenatal steroids on admission to hospital; the aim was to enhance surfactant maturation and reduce the severity of respiratory distress syndrome (RDS). The neonate was rigorous and active at birth, spontaneously breathing and required no resuscitation except for some stimulation and prevention of heat loss. He was placed onto binasal CPAP with a pressure of 5 cm H_2O and 35 percent oxygen to maintain an oxygen saturation (SaO_2) target of 89–93 percent. An initial arterial blood gas (ABG) showed; pH 7.3, PaO_2 64 mmHg (8.5 kPa [kilopascal]), CO_2

TABLE 5 ■ Interpretation of Blood Gases in the Neonatal Unit

A. BLOOD GAS VALUES[61–66]

In relation to values, different sources may cite slight variations.

	pH	CO_2	O_2	Bicarbonate	Base	References
CORD (arterial)	7.25–7.28	48 mmHg 6.5 kPa	18–22.5 mmHg 2.4–3 kPa	n/a	−4	35, 36
CORD (venous)	7.28–7.35	35–45 mmHg 5–6 kPa	27–38 mmHg 3.8–5 kPa	n/a	−4	35, 36
NEONATAL (arterial)*	7.35–7.45	35–45 mmHg[38] 4.6–6.0 kPa	50–90 mmHg 7.0–12.0 kPa Term 50–80 mmHg 6.5–10.5 kPa Preterm	22–26 mEq/liter Term 20–24 mEq/liter Preterm[38] Or 22–26 mmol[39]	+2 to −2	37, 38, 39

For "Uncompensated" gas (i.e., pH is abnormal)

Low pH and high CO_2 = respiratory acidosis

Low pH and large base deficit/low bicarbonate = metabolic acidosis (Note: Mixed acidosis = low pH, high CO_2 & large base deficit)

High pH and low CO_2 = respiratory alkalosis

High pH and large base excess/high bicarbonate = metabolic alkalosis

For "compensated" gas (i.e., pH is normal, but other values are out of range)

pH	CO_2	Bicarbonate	Problem
Low normal	High	High	Compensated respiratory acidosis
High normal	Low	Low	Compensated respiratory alkalosis
Low normal	Low	Low	Compensated metabolic acidosis
High normal	High	High	Compensated metabolic alkalosis

Permissive hypercapnia

To avoid overventilating the lungs, keep pH >7.25

Watch base deficit and keep between −4 and +4[50]

*Capillary venous neonatal sampling can also be considered for all values (pH, CO_2, base, and bicarbonate) except oxygenation status.

B. BLOOD GAS ALGORITHM[65,66]

1. Assess pH

(Is the pH normal? If not, is it acidotic or alkalotic?—see values)

↓

2. Assess respiratory component

Is CO_2 within normal range? See A, above.

↓

3. Assess metabolic component

Is the bicarbonate within normal range and is there a large base deficit (a negative (−) number) or base excess (a positive (+) number)? See A, above.

↓

4. Assess if compensation has occurred

(i.e., The pH has normalized, but the other values are out of normal range.)

↓

5. Assess oxygenation (PaO_2)

A low PaO_2 can contribute to a metabolic acidosis by anaerobic respiration by cells and lactic acidosis accumulation.

Plus

Consider lactate levels

↓

6. Interpret and make plan of action

↓

7. Evaluate/Reassess

When to evaluate/recheck a blood gas depends on how abnormal the values are.[50] If they are very abnormal OR a significant change has been made (e.g., surfactant, high-frequency oscillatory ventilation has been commenced), the blood gas may need rechecking within 30 minutes. If the neonate is stable, then it will need rechecking less frequently.

Decide on an individual basis following discussion with the clinical team.

Abbreviation: HFOV = high-frequency oscillatory ventilation.

FIGURE 4 ■ Considerations when weaning ventilation.

As before, suggested actions should be based on assessment of the individual neonate, and evaluation of any change made is a key part of the weaning process.

AIM: To wean any neonate from positive pressure ventilation as soon as possible in line with protective lung strategies, to avoid potential damage from long-term or unnecessary ventilation

If a mandatory mode (CMV) is in use, is the neonate making spontaneous efforts to breathe relative to the ventilator-supported breaths so that a synchronized/trigger mode can be employed (e.g., SIMV, PTV, TTV, PS)? Determine this by observing breath rate noting the ventilator breaths versus the neonate's own breaths. In addition, one can observe the number of measured "triggered" (baby-controlled) breaths on the ventilator.

If no, the neonate may not be ready to wean.

If yes

CONSIDER:

- Have the blood gas values normalized? See Table 2 for possible changes to ventilation during weaning in line with oxygenation or CO_2 elimination or both. Wean whichever parameter is appropriate.
- Has the oxygen requirement improved, preferably below a FiO_2 of 0.6 (60%)? Wean the oxygen as tolerated.
- Has the compliance of the lungs improved, determined by observing chest expansion and expanded lung fields on the CXR?

If on VG, is the PIP needed to reach the target volumes decreasing?

- Have any opiates or sedatives that could affect respiratory drive been stopped?
- Has the neonate been started on respiratory stimulants (e.g., caffeine) to increase his respiratory drive, according to his gestation and individual unit policy?

If no to any of these questions, the neonate may not be ready to wean.

If yes

Continue to wean pressure, rate, or other parameters in stages appropriate to the mode of ventilation.

Evaluate the effect of each change.

Prior to extubation, are the ventilator settings low enough to be close to the neonate's physiologic parameters (PIP 16–18 cm H_2O/PEEP 4–5 cm H_2O: MAP <10, and minimal oxygen requirement, preferably able to ventilate in air)?

Extubate when appropriate based on the aforementioned requirements.

Following extubation, continue to assess and evaluate regularly.

45 mmHg (6.0 kPa), Base −2, and bicarbonate 22 mEq/liter (mmol/liter); all within satisfactory limits (Table 5).

However, six hours later, the neonate started to show signs of tachypnea, chest recession, and nasal flaring with poor saturations and an increasing oxygen requirement. The ABG showed a respiratory acidosis pH 7.2, PaO_2 57 mmHg (7.6 kPa), CO_2 67 mmHg (8.9 kPa), Base −3, and bicarbonate 21 mEq/liter (mmol/liter). Therefore, the CPAP pressure was increased to 7 cm H_2O with a biphasic level added after the ABG an hour later failed to show any significant improvement. This continued and along with both the clinical assessment and a CXR led to a diagnosis of RDS.

The decision was made to intubate and ventilate the neonate to provide respiratory support and to enable surfactant to be administered. Following intubation, Baby John made little spontaneous effort, and CMV was commenced (PIP 22, PEEP 5, I_T 0.4, rate 60). The ABG improved an hour later: pH 7.31, PaO_2 60 mmHg (8.0 kPa), CO_2 42 mmHg (5.6 kPa), Base −2, and bicarbonate 22 mEq/liter. After eight hours, the CXR appearance, lung expansion, and ABG values showed improvement. Baby John was also spontaneously breathing but appeared to be in asynchrony with the ventilator breaths and exhibiting signs of discomfort. The mode was therefore switched to SIMV to allow the ventilator breaths to be synchronized to his breaths. He remained stable on this mode through the night, enabling the pressures and I_T to be reduced in increments to avoid any undue excessive expansion of the lungs. By the morning, the settings were PIP 20, PEEP 4, I_T 0.35, and rate 55. The measured V_T was adequate at 4–6 mL/kg; spontaneous breathing was approximately one-third of the total breaths with synchrony evident on clinical assessment.

By the afternoon, two doses of surfactant had been administered, and he was stable on SIMV; the rate was turned down to 40 as the CO_2 on the blood gas was satisfactory and Baby John was making good spontaneous efforts between the ventilator breaths. Later, the pressure settings were reduced to 18/4 cm H_2O to limit the applied pressure to the lungs as much as possible. There was good chest expansion and sound clinical assessment at this time with adequate oxygenation (SaO_2 and PaO_2).

Later that day, however, a follow-up gas was not acceptable, with a developing mixed acidosis evident. Therefore, rather than increasing the SIMV rate, the decision was made to turn on PSV with SIMV to support Baby John's breaths at 100 percent of the set PIP. In other words, the ventilator was set to deliver 40 breaths at 18/4 cm H_2O with all Baby John's own breaths supported at this pressure and I_T. This was effective as the blood gases stabilized.

PSV allowed additional support for this neonate who appeared to be becoming tired on SIMV alone. Rather than increasing the settings, adding this additional mode allowed such support without having to increase pressures again. The oxygen requirement throughout the previous period had been between 45 and 55 percent, and, after eight hours on SIMV with PSV, the oxygen requirement was reduced and stable at 40–45 percent.

Over the course of the next two days, the PSV level was slowly reduced in increments to 50 percent of the set PIP; that is, the neonate's breaths were supported to 50 percent of the PIP set in the ventilator. Assessment was satisfactory, and, when the neonate was five days old, he was able to be weaned further from the ventilator settings. Because he was making a good spontaneous effort, the decision was made to wean on full PSV; this meant that Baby John controlled his own rate and I_T, and the ventilator supported every triggered breath with pressures of 18/4 cm H_2O. This pressure was slowly weaned down to 16/4 cm H_2O with an oxygen requirement of 35–40 percent until he was ready to be extubated to CPAP at 6 days of age.

CASE STUDY 2: SIMV WITH VG AND A/C

Baby Faye was born spontaneously at 25 weeks gestation to an unbooked mother who presented in precipitous labor and did not receive any antenatal steroids. The neonate had then spent a difficult period on high ventilation requirements leading to a diagnosis of CLD of prematurity with patchy appearance of PIE throughout both lungs. She was now 4 weeks old, weighing 900 g, and continued to be ventilated on SIMV—PIP 23, PEEP 5, I_T 0.36, and a rate of 50. The capillary blood gas showed a picture of permissive hypercapnia accepting a higher-than-normal CO_2 with a pH maintained higher than 7.25 and preventing overventilating the premature lung: pH 7.28, PaO_2 37.5 mmHg (5 kPa; capillary), CO_2 66 mmHg (8.8 kPa), Base +5, and bicarbonate 32 mEq/liter. In addition, this gas shows compensation had occurred.

However, it was not possible to wean any further than this because Baby Faye became unstable after any attempts to change the ventilator settings. The last attempt to wean down the pressures led to a drop on SaO_2 and a worsening pH of 7.22, lower than the acceptable range. It was also noted that the measured V_T was quite variable and often much lower than 4 mL/kg even when the PIP was increased. Therefore, the decision was made to switch on VG, and a target V_T was set at 4 mL/kg (3.6 mL); the aim was to achieve a balance between ensuring delivery of an adequate volume while also being mindful of limiting the V_T to prevent any further damage from volutrauma. This also allowed the lung volumes to be optimized but at the lowest possible pressures, thus reducing the incidence also of barotrauma.

On assessment, measured PIP was 18–20 cm H_2O, lower than the previous settings on SIMV. However, the pH and $PaCO_2$ did improve to some degree and did not revert back to the previous acceptable values; pH hovered around 7.24–7.25. Therefore, to optimize the V_T further, the target V_T was increased to 5 mL/kg (4.5 mL). The measured PIP continued to remain acceptable, and blood gases then improved with greater clearance of CO_2. pH was then stable at 7.25–7.28.

Over time, the previous situation continued, and Baby Faye was then able to be weaned with a gradual reduction of the ventilator rate in increments of 5 cm H_2O.

After two weeks, the mode was changed to A/C (PTV) allowing her to control her own rate since she was now 6 weeks old. Overall, this case study shows how the complexity of the lung condition and the associated chronic changes in the preterm neonate necessitate significant support over a lengthy period. However, to synchronize and tailor the ventilation to a neonate's own efforts while optimizing V_T, using a trigger or synchronized mode along with VG can allow this.

CASE STUDY 3: SIMV, HFOV, A/C (PTV)

A term neonate (birth weight 4 kg) was born in poor condition in thick meconium following a prolonged and difficult labor. The neonate, Baby Ahmed, required full resuscitation measures at birth and was intubated and ventilated in the delivery suite with a subsequent transfer to the neonatal unit. He was ventilated on CMV mode requiring PIP 26 cm H_2O, PEEP 5 cm H_2O, I_T 0.4, and a rate of 45. The ABG showed a severe mixed acidosis: pH 7.1, PaO_2 37 mmHg (4.9 kPa), CO_2 70 mmHg (9.3 kPa), Base −8, and bicarbonate 16 mEq/liter (mmol/liter). The PIP was therefore increased to raise the MAP, aiming to increase oxygenation. However, no change was observed to Baby Ahmed's condition or oxygenation, and the measured V_T did not improve regardless of any change in PIP. All parameters continued to be increased until the settings were PIP 30, PEEP 6, I_T 0.5, and a rate of 45. The required FiO_2 was 0.8 (80 percent) to maintain SaO_2 at a range of 95–100 percent for a term neonate. The measured MAP was 16 cm H_2O, and V_T was 12 ml (i.e., only 3 mL/kg). Therefore, the decision was made to switch Baby Ahmed to HFOV to enable a higher MAP while avoiding excessive lung expansion from any higher PIP and shearing forces of conventional ventilation at high pressures and I_T. Settings were MAP 18 cm H_2O, amplitude 40, frequency 10 Hz, FiO_2 0.75 (75 percent); set to maintain a MAP 2 cm H_2O higher than the previous conventional ventilation and to observe adequate chest wiggle or bounce.

This continued for an eight-hour period during which the clinical picture and the blood gases started to improve. The CXR showed good lung expansion. The amplitude was able to be reduced as chest wiggle was pronounced and CO_2 started to decrease. Oxygenation was slower to improve, but, after a 24-hour period on MAP of 18, the FiO_2 could be reduced to 0.6 (60 percent). The PaO_2 then also started to increase in value and continued to do so over the next 24 hours. During this time, the MAP was slowly reduced by increments of 1–2 cm H_2O until this reached 14 cm H_2O. The oxygen requirement was now 50–60 percent.

Baby Ahmed started to attempt to take spontaneous breaths on Day 3 of life—therefore, the decision was made to switch from HFOV to a conventional but trigger (synchronized) mode of ventilation. A/C (PTV) was given as a weaning mode for Baby Ahmed who, from this point, started to clinically improve. The pressure was reduced in increments because it was futile to reduce the rate because he was breathing above the backup rate. On Day 5 of life, Baby Ahmed was able to be extubated onto a short period of nasal CPAP until his lungs has significantly improved and all meconium had cleared. By Day 6, he was self-ventilating in air.

Current Strategies to Reduce Lung Injury

The importance of a protective lung strategy has been highlighted throughout the article. It is worth reiterating this fact as an integral component of ventilation practice. Ultimately, we must achieve a *balance* between providing optimum respiratory status and support while avoiding overventilation or an unnecessary length of time on mechanical ventilation and the associated effects on the neonate. When deciding how to deliver optimum ventilator support to neonates, it is important to be aware of these potential negative effects of ventilation and place emphasis on preventing them. They include lung injury from barotrauma (pressure) and/or volutrauma (volume) leading to CLD, oxygen toxicity, hypotension, lung hyperinflation, air leak, and nosocomial respiratory infection. Bedside assessment and monitoring are the keys to ensuring any negative effect is identified as soon as possible, for example, changes in CXR findings, blood pressure, oxygen concentrations, and oxygen saturations. Current strategies must also have these dangers as a central consideration. As stated earlier, CLD or BPD is one of the most common long-term complications in very premature infants.[50,58] There has been a revolution in the therapies that are used, either to manage initial RDS with an aim to prevent CLD or to manage the established condition, and several devices and strategies have been developed to provide respiratory support with reduced risk of lung injuries. These protective lung strategies include the use of noninvasive ventilation modes such as CPAP and biphasic CPAP and minimizing both oxygen delivery along with pressure and volume from the point of birth and beyond. Brown and DiBlasi[19] state that the keys to protecting the neonatal lung during mechanical ventilation are to optimize lung volume, limit excessive expansion, apply appropriate end pressure, use shorter inspiratory times and smaller V_T, and allow permissive hypercapnia appropriately. All these protective lung strategies are clearly seen within Case Studies 1, 2, and 3 highlighting, within each of the modes included, the differences in management and decision making between conditions but also the vital considerations around minimizing lung damage as much as possible.

CONCLUSION

Technological advances have resulted in improvements in ventilators and strategies that are more sophisticated to be in synchrony with the neonate's own efforts, aiming to limit the damaging effects by pressure and/or volume trauma. Those caring for such sick and vulnerable neonates owe it to them and their families to have a full understanding of common but often-complex practices such as ventilation practice while at the same time working toward minimizing any resultant damage and respiratory morbidity. Knowledge of the modes and terms used in neonatal ventilation practice is valuable because this practice comprises a significant proportion of care given to sick neonates and their families within the neonatal unit. It has not been possible to discuss the *care of* neonates in relation to ventilation modes or to discuss the details of underlying neonatal physiology. Rather, the aim is for the reader to have a basic underlying foundation of knowledge in ventilation practice so she has the rationale for the care she learns about within the clinical area and also to gain a basis for further learning. The decision to place a neonate onto a specific type of ventilation strategy and/or to change a mode or parameter depends on a complex interplay of factors. It is vital that effective clinical decisions are based on valid, sound judgments that consider the neonate's clinical assessment cues including sound evaluation on an ongoing basis. Finally, ventilation practice and decision making must be supported by best evidence-based rationale not only so that health professionals can learn and progress but also so that parents are given information about the treatments their neonates receive and the outcomes they might expect, a vital component of true family-centered neonatal care.

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