

CURRENT TOPIC

Advances in neonatal conventional ventilation

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Despite the implementation of several alternative strategies for management of respiratory failure in neonates, such as extracorporeal membrane oxygenation, high frequency ventilation, and nitric oxide, conventional assisted ventilation remains the mainstay of treatment. This has traditionally been accomplished by time cycled, pressure limited ventilators over the past three decades primarily because of its ease of application and relative safety. However, several recent advances, both in the concept and the application of conventional ventilation, have been introduced for use in neonates. The introduction of newer, state of the art, microprocessor controlled ventilator systems provides clinicians with opportunities to apply a number of advanced ventilatory modalities not previously available for treating newborns.

Some of these techniques will need further scientific evaluation in controlled trials, but this should not preclude their use in clinical settings, as their safety has already been proved by "standard setters" for use in neonates. There is a firm physiological rationale for their use, and individual centres have already acquired substantial experience in the application of these modalities.

In this paper scientific information and technological advances leading to the newer concepts of ventilatory management in neonates will be addressed, and clinical perspectives based on personal experience will be discussed. Each section includes background information, technical details, clinical application and experience, advantages and limitations, and future perspectives.

Equipment

Recent advances in microprocessor based, respiratory technology have transformed standard mechanical ventilators. These are now highly sophisticated machines which offer the unique ability to provide rapid and precise control of gas delivery and ventilatory support in various different ways, while allowing for the monitoring and alarming of virtually every aspect of the procedures involved.

Detailed technical description of these mechanics is complex and beyond the scope of this article, but salient features relating to individual components of ventilator machinery are

described. As these features may be unique to specific ventilators, it is imperative that the user familiarises him or herself with the individual ventilator specifications, while selecting the appropriate device. For this reason, it is always helpful to consider the individual ventilator's mechanics in the following sequence: (a) user interface; (b) gas flow patterns; and (c) the various approaches used to monitor and alarm patient-ventilator functions. This format allows the various devices to be compared in a uniform manner.

The user interface is the interaction between the clinician and the ventilator. Unlike the previous machines, which only displayed data relating to ventilator function as set by the clinician, the current generation of microprocessor controlled ventilators can display output data from the patient, thus making the assisted ventilation much more precise. The system that governs the kinetics of gas flow in the ventilator circuit from the point of its entry, through the breathing circuit, and to its exit through the exhalation system, is an important consideration in terms of ventilator performance and patient safety.

The recent generation of ventilators use a number of methods to regulate inspiratory flow and manipulate the inspiratory flow pattern. Besides automatic adjustment of flow delivery to meet the patient's need, features available on these newer ventilators include "educated" inspiratory flow delivery, improved breath termination criteria, guaranteed tidal volume delivery, availability of bias flow to maintain stable PEEP, air leak compensation, and built-in system adjustments to prevent pressure overshoot. (Product information, VIP-BIRD Product Corp., Palm Springs, California, USA)¹

With the increasing trend toward coordinating mechanical breaths with the patient's own inspiratory effort (synchronised or patient triggered ventilation) (PTV), ventilators must respond effectively at minimal effort from the patient, especially if they are to be effective in very low birthweight babies. Most of the ventilators are triggered by signals measured within the ventilator circuit, but the particular point of measurement varies. Ideally, these sensors should be nearer to the patient's airway—at the proximal endotracheal tube, for example—at the potential for dyssynchrony increases the fur-

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ther away the sensor is from the patient.² The trigger signal can be impedance (thoracic or abdominal), pressure, or flow. The two important ingredients of successful triggering are "magnitude" (the amount of patient effort required to trigger) and "delay" (the time in between the initiation of patient effort and the rise in pressure at the proximal airway). Flow triggering seems to be more efficient than pressure triggering.² Flow derived signals also allow for complete synchronisation in both inspiratory and expiratory phases of breathing. Newer machines, such as the VIP BIRD ventilator, have a device called "termination sensitivity" which stops the inspiratory phase of mechanical breath when inspiratory flow decreases to 5-25% of peak flow, thus triggering the expiratory phase. When this mode is used, the baby customises his/her own inspiratory time. This is particularly helpful in smaller babies who exhibit relatively short inspiratory times while breathing at a fast rate. A fixed longer inspiratory time in such cases is likely to cause inversion of the inspiratory:expiratory ratio, and hence increase the risk of air trapping. One of the problems with measuring flow at the proximal endotracheal airway is the risk of false triggering (autocycling). This is caused by the accumulation of water in ventilatory circuit, or a leak around the endotracheal tube which is incorrectly "sensed" as patient effort. To eliminate this, a number of newer ventilators use "automatic purge" or "leak compensation" systems (VIP BIRD Corp).

Important applications of microprocessor technology to current ventilators are the processing of pressure, flow, and volume signals; calculation of lung mechanics; and presentation of the results in numerical, graphical, analog, or digital displays. Several commercially available ventilators have optional monitoring packages which display waveforms and pulmonary mechanics (loops). However, those devices with integrated, on-line capabilities for breath-to-breath continuous analysis and display have the advantage.³ These measurements, also available as trends over a longer period of time, facilitate ventilatory management and will be described in a separate paper.

Thus the latest generation of ventilators offers a new breed of sophisticated machines which have the flexibility of multiple mode selection, more effective methods of allowing the patient to work in synchrony with the machines, and improved safety compared with traditional pressure ventilators. This trend

Table 1 Summary of improvements in design of newer ventilators

<i>Flexibility of mode selection on a single ventilator:</i>	
Pressure limited, time cycled (PTV or SIMV/CPAP)	
Volume cycled (PTV or SIMV/CPAP)	
Pressure support ventilation	
Pressure limited, time cycled, and high frequency oscillation	
<i>Improved pneumatics and triggering:</i>	
Sensitive triggering devices for both inspiration and expiration	
Leak compensation system and auto-purging to eliminate auto-cycling	
"Educated" inspiratory flow delivery	
Improved breath termination criteria	
Availability of demand and bias gas flow	
Guaranteed tidal volume delivery	
Maintenance of stable PEEP/CPAP	
<i>Safety features:</i>	
Built-in algorithms to self-correct "inappropriate" settings	
Integrated alarm and safety valve system	
System accuracy by built-in automatic zero calibration function	
<i>On-line pulmonary function monitoring:</i>	
Inspiratory and expiratory tidal volume monitoring	
Graphic displays of volume, pressure, and flow waveforms	
Pressure volume and flow volume loops	

toward increasing sophistication is likely to continue and clinicians would be well advised to familiarise themselves with these changes. The salient features of these newer devices are summarised in table 1, and a brief comparison of the commonly used neonatal ventilators is given in table 2.

Strategies for mechanical ventilation in newborns

TIME CYCLED PRESSURE LIMITED VERSUS VOLUME CYCLED VENTILATION

Because of newer designs and concepts, it is useful to understand some specific nomenclature currently used to present and interpret the data relating to ventilatory management. Positive pressure breaths delivered by a mechanical ventilator are described by three variables: *trigger variable* (pressure, flow), which initiates inspiration;

limit variable, which governs gas delivery (pressure, flow, or volume target that cannot be exceeded during inspiration);

cycle variable (pressure, flow, volume, or time) which terminates the breath.

Thus in pressure limited (targeted) modes, a peak inspiratory pressure is set, and during inspiration gas flow is delivered to achieve that target pressure. After the target is reached flow decelerates in an exponentially reducing manner to maintain pressure at the target until the inspiratory phase is complete. If the patient

Table 2 Comparison of some commonly used neonatal/infant ventilators

Ventilator	Manufacturer	Modes	Signal	Comments
Babylog 8000	Dräger (Lübeck, Germany)	PTV SIMV	Airway flow	Hot wire anemometer Graphic displays, combined HFOV
Sechrist/SAVI	Sechrist Industries (Anaheim, CA)	PTV	Thoracic impedance	Real time analogue output
SLE HV2000	Specialised Laboratory Equipment (Surrey, UK)	PTV SIMV	Airway pressure	Combined HFOV Graphic display
VIP-BIRD	Bird Products Corporate (Palm Springs, CA)	PTV SIMV PSV	Airway flow Airway pressure	Variable orifice differential pressure transducer Volume cycled or time cycled ventilation Partner volume monitor and on-line graphic display monitor

Table 3 Suggested ventilatory management protocol

Volume cycled	Time cycled pressure limited
<p>Start in PTV mode</p> <p>Provide proximal inspiratory tidal volume of 5-8 ml/kg to maintain "target" ABGs</p> <p>Wean by reducing rate but continue to deliver tidal volume of 5-8 ml/kg. When rate \leq 40 bpm, switch to SIMV with PS (minimum 10 cm H₂O)</p> <p>Use flow to adjust inspiratory time of 0.3-0.5 seconds</p>	<p>Start in PTV mode</p> <p>Adjust PIP to provide 5-8 ml/kg of inspiratory tidal volume to maintain "target" ABGs</p> <p>Wean by reducing PIP as tolerated, but continue in PTV with control rate of at least 20-40 bpm</p> <p>Inspiratory time 0.3-0.5 seconds use breath termination "criteris" to achieve full synchronisation in inspiratory and expiratory phase</p>

should inspire more forcefully, flow accelerates to maintain target pressure. This "adjustable" flow feature of pressure limited breaths may seem advantageous in terms of improved patient ventilator synchrony, but because of this gas delivery format, tidal volume is variable on a breath-to-breath basis.

In contrast, with volume limited modes, the primary gas delivery target is tidal volume, and peak inspiratory pressure may vary from breath to breath.⁴ This has been a source of concern to clinicians in the past, but it should be realised that peak pressure measurements are a reflection of airway flow (and resistance) and not necessarily the alveolar pressure, which is primarily determined by compliance and alveolar volume.⁵ Thus, in volume modes of ventilation, peak inspiratory pressure may "wean" automatically as the lung compliance improves either spontaneously or in response to surfactant treatment.

Moreover, the presumption that pressure limited ventilation causes less barotrauma than volume ventilation because of the lower peak inspiratory pressure, may be an oversimplification and is not supported by scientific evidence. If ventilator induced lung injury does, in fact, result from "volutrauma,"⁶ it may be argued that control of tidal volume delivery may have an advantage in neonatal ventilation because of rapidly changing pulmonary compliance. Interestingly, the first ventilator designed and built exclusively for neonates was a modified version of an adult volume cycled ventilator, which was eventually discarded because of technological limitations. However, the development of microprocessor technology and availability of precise flow and pressure transducers has produced substantial improvements in ventilator design and performance, allowing its safe application in babies weighing as little as 1200 g. This is based on our own experiences with over 300 neonates treated with volume cycled ventilation in our two neonatal units, using the VIP-BIRD infant/paediatric ventilator (Bird Product Corporation, Palm Springs, California, USA). For those babies receiving time cycled pressure limited ventilation, we adjust and monitor the ventilatory parameters using tidal volume and minute ventilation as two of the index variables. Table 3 describes our unit protocols. Unfortunately, many of the neonatal units still do not use tidal volume monitoring as a part of their ventilatory management protocol despite the fact that it is now widely available.

SYNCHRONISED VENTILATION

Synchronised ventilatory modes are characterised by delivery of mechanical breaths in response to a signal derived from the patient's spontaneous inspiratory effort (patient triggered), and are available in both pressure limited and volume cycled ventilators. Collectively, these modes of ventilation are a form of *partial ventilation* where the patient has to contribute to the work of breathing.

The modes of synchronised ventilation include:

Assist/control ventilation (A/C), also known as PTV, is a combination mode in which the ventilator delivers a positive pressure breath in response to the patient's inspiratory effort (*assist*) provided it exceeds a preset threshold criteria. This mode also provides the safety of guaranteed mechanical breath rate set by the operator (backup rate) if no patient effort is detected (*control*). The backup control rate ensures a minimum mandatory minute ventilation in case the patient stops making inspiratory efforts. It is probably the best mode to use in the premature infant in the acute phase of illness because it requires the least amount of patient effort, and produces improved oxygenation at the same mean airway pressure, as shown in recent studies.⁷⁻⁹ Earlier clinical experience, however, using different ventilators (SLE Newborn 250, Dräger Babylog 8000, and SLE HV 2000), indicated that prolonged support of very low birthweight infants (< 28 weeks) might not be feasible because of patient fatigue.¹⁰⁻¹² Factors adversely affecting patient triggered ventilation in these studies included development of expiratory asynchrony, long trigger delays, very short inspiratory times, low gestational age and use of PTV early in the course of disease. The difference in results from the above studies may be machine specific, as despite improvement in the software, some of the ventilators seem to perform less well in one mode than another. The Babylog 8000, for example, was more likely to trigger in SIMV (synchronised intermittent mandatory ventilation) rather than in assist/control.¹³ The overall evidence, however, suggests that patient triggered ventilation reduces the duration of time from weaning to extubation in mechanically ventilated neonates, and may have a beneficial effect on secondary outcome measures, such as chronic lung disease and intraventricular haemorrhage.^{7,9,12} This, however, requires verification in larger studies.

Synchronised intermittent mandatory ventilation (SIMV) refers to a ventilatory mode where the mechanically delivered breaths are delivered at a fixed rate but are synchronised to the onset of the patient's own breath, resulting in full inspiratory synchrony. However, unless the inspiratory times are identical, the patient may terminate his/her own effort and begin exhalation while the ventilator is still in the inspiratory phase, resulting in partial asynchrony. Unlike A/C, in SIMV the ventilatory support can be varied according to the rate fixed by the clinician from full (higher rate) to partial (lower rate) assisted ventilation. The flexibility of SIMV in providing a range of ventilatory support levels makes it useful, both as a primary means of ventilatory support or as a method for weaning.¹⁴ However, a low set SIMV rate is undesirable when the patient's ventilatory demand is high. Similarly, reducing the SIMV to a very slow rate (less than 20/minute) may be unwise when discontinuation of mechanical ventilation is imminent, as this may impose significant breathing work for an intubated baby, contributing to weaning failure.¹⁵ This disadvantage of slow rate SIMV can be compensated by some further means of breath support such as pressure support ventilation.

Pressure support ventilation (PSV) can be defined as patient initiated, pressure targeted, and patient controlled ventilation which is generally flow cycled.¹⁶ This is designed to assist the patient's spontaneous breathing with an inspiratory pressure "boost." Although mostly used as a weaning mode, this can be used as a primary modality in patients with acute or chronic ventilatory failure if they have sufficient respiratory drive. In such patients, PSV reduces the imposed work of breathing, created by the resistive forces of endotracheal tubes, the ventilatory circuit, and demand valve systems. In PSV, once the breath is triggered by patient inspiratory effort, a preset system pressure is rapidly achieved and maintained throughout inspiration by adjustment of machine inspiratory flow. The inspiration ends when the inspiratory flow falls below a preset value, usually determined as a percentage of delivered volume or flow. Although PSV closely resembles A/C ventilation, it seems that because of its unique design, PSV is better customised to support and synchronise with

patient effort because the patient has the control of both the inspiratory flow rate and inspiratory time.¹⁷ The main role of pressure support ventilation is to assist respiratory muscle activity and so reduce workload. The reduction in the respiratory muscle load is proportional to the level of pressure given. As in any pressure targeted ventilation, tidal volume in PSV depends on respiratory mechanics and may vary. To overcome this disadvantage, some of the newer ventilator designs have combined pressure support with a guaranteed minimum tidal volume—"volume assured pressure support" or "volume support."¹⁸ The use of PSV in neonates and infants is poorly researched, but information from adult studies can be applied. In most cases, PSV is used in conjunction with volume cycled SIMV during the process of weaning. By boosting the spontaneous breaths according to the set pressure level, PSV negates the disadvantages of SIMV at low rate. PSV, when combined with SIMV, lowers oxygen consumption and shortens the duration of weaning.^{19,20} We have reported a series of successful cases of neonatal volume cycled ventilation followed by PSV (abstract presented at Joint meeting of the Irish Perinatal Society and the British Association of Perinatal Medicine, Dublin, October 1994; Sinha *et al.*). In these babies volume cycled ventilation was used as a rescue modality, because conventional time cycled ventilation was proving ineffective in providing optimal oxygenation. We were able to wean each of these babies successfully using PSV in conjunction with SIMV without any air leaks or radiological findings of chronic lung disease.

Another application for it may be in infants who are chronically ventilatory dependent, and in those with bronchopulmonary dysplasia.²¹

The rationale to use any form of assisted ventilation (A/C, SIMV, or PSV) should be to optimise patient/ventilator synchronisation, improve patient comfort, facilitate or reduce the duration of ventilation, and avoid undesirable respiratory/cardiovascular consequences. At present, strict comparisons of the usefulness of the above modalities remain untested. Table 4 compares the features of the newer ventilatory modes.

Continuous positive airway pressure (CPAP) has some major advantages in babies with sufficient drive in that it can improve oxygenation

Table 4 Comparison of newer ventilatory modes

Modes	Time cycled		Volume cycled		
	PTV	SIMV	PTV	SIMV	PSV
*Parameters					
Rate	P	C	P	C	P
PIP	C	C	P	P	C
PEEP	C	C	C	C	C
Ti	P/C	P/C	P/C	P/C	P/C
Flow	C	C	C	C	P
Spontaneous breath	Triggers mechanical breath	Between mechanical breaths	Triggers mechanical breath	Between mechanical breaths	Triggers mechanical breath
Flow	Continuous	Continuous	Demand	Demand	Variable
Best patients	Weight < 1300 g, acutely ill	Weaning	Weight < 1300 g, severe respiratory failure	Weaning	Weaning, chronic lung disease, high inspiratory resistance

* describes whether parameter is controlled by patient (P), clinician (C), or both (P/C).

and reduce breathing work. The first is achieved by improving the functional residual capacity (FRC), which determines the amount of fresh oxygenated gas available to the alveoli during the resting phase of respiration. This is accomplished either by increasing the volume of patent alveoli within their limits of distensibility or by inflation of the previously collapsed alveoli (alveolar recruitment). CPAP also helps to redistribute interstitial water, thus improving the oxygen diffusion across the alveolar-capillary membrane, and is thought to contribute towards maintaining the integrity of pulmonary surfactant. The increase in FRC permits more tidal volume per unit of pressure, which helps to maintain an adequate minute ventilation and reduce the breathing work.²² In some respects the function of CPAP is similar to the action of surfactant, and physiologically efficient application of CPAP makes sense but requires the appropriate machinery to maintain effective and constant pressure control. Design characteristics of a device must, therefore, be carefully considered in terms of their effect on airway anatomy and function, airway resistance, and the work of breathing before deciding to use them clinically.

Although almost all mechanical ventilators designed to provide conventional ventilation provide the option of CPAP in both pressure limited and volume cycled modes, its application through an endotracheal tube may, in fact, be counterproductive in terms of increased work of breathing, unless supported with a pressure "boost" (as in PSV), which is not yet available in pressure cycled ventilators. Newer devices dedicated to CPAP, such as the Infant Flow Nasal CPAP System (EME Ltd, UK), seem to be designed to ensure stable airway pressure and reduced work of breathing which should avoid respiratory fatigue in very small babies. Specially designed nasal prongs seem to reduce irritation and ensure a constant seal; intranasal pressure monitoring provides accurate assessment of airway pressure measurements (product information, EME Ltd, UK).²³

Most studies of CPAP have focused on its physiological effect, but only a few deal with its effect on clinical outcome when used either in therapeutic or supportive roles. Recent randomised trials assessing the role of nasal and nasopharyngeal CPAP in neonates as a weaning mode, by using predetermined criteria, have produced conflicting results. Larger controlled trials are needed to investigate the safety and efficacy of this modality (product information, EME Ltd).²³⁻²⁵

Future directions

Microprocessor based technology has started a new era of mechanical ventilation that allows for the provision of ventilatory support in several ways not previously available for neonates. The trend toward increasing sophistication and greater versatility is likely to continue, and clinicians involved in the care of sick infants must keep abreast of these developments. As for the newer methods of ventilation, their clinical outcomes will require scientific validation

despite inherent difficulties in conducting such controlled trials in critically ill neonates, because the optimal pattern of ventilation varies even in a single infant, presumably reflecting the change in disease process. Moreover, although respiratory failure in neonates represents severe lung injury, it is often associated with a systemic process which may be associated with other organ and tissue injuries. Any new respiratory treatment per se is unlikely to have a total impact on mortality or morbidity. It is also important for the clinicians to realise that despite improvements, conventional ventilation will still fail in certain specific situations where alternative treatments such as ECMO, high frequency ventilation, or nitric oxide administration may have potential benefit.

While mechanical ventilation of the newborn is more complex than it has been before, it has never been safer.

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