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Modalities of Mechanical Ventilation

Volume-Targeted Versus Pressure-Limited

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ABSTRACT
Background: Respiratory distress syndrome remains the most common admission diagnosis in the neonatal intensive care unit. Healthcare providers have a clear appreciation for the potential harm to pulmonary structures that have been associated with mechanical ventilation (MV) in the preterm infant. Although life sustaining, the goal is to optimally ventilate while limiting trauma to the neonatal lung in order to preserve long-term cardiopulmonary and neurodevelopmental outcomes.
Purpose: To describe, compare, and contrast 2 primary methods of neonatal MV, pressure-limited ventilation (PLV) and volume-targeted ventilation (VTV), highlighting key considerations during therapy.
Methods: A comprehensive search of the literature was completed using the following databases: CINAHL, Cochrane, Google Scholar, and PubMed. Research articles that were published in English over the last 10 years were reviewed for key information to describe and support the topic. Expert content review was conducted prior to publication by respiratory care providers, neonatal nurse practitioners, staff nurses, and neonatologist.
Findings: Technology is rapidly evolving, with the newest mechanical ventilators providing the clinician with real-time data not previously available. Advanced microprocessors and feedback mechanisms can better support various ventilatory strategies including PLV and VTV. Renewed interest in volume ventilation has led many clinicians to ask about current evidence to support ventilatory modalities with regard to timing, settings, and short- and long-term effects.
Implications for Practice: The clinician understands that neonatal pulmonary status is frequently changing based on gestational age, current age, and physiologic influences. Evidence supporting recommendations for the described MV modalities of PLV and VTV is provided for both preterm and term neonates.
Implications for Research: Comparison between MV strategies, specifically PLV and VTV, including short- and long-term neurodevelopmental outcomes, is needed. Recommendations regarding physiologic tidal volume for the extremely preterm infant are lacking.
Key Words: bronchopulmonary dysplasia, chronic lung disease, mechanical ventilation, neonate, NICU, pressure-limited, respiratory distress syndrome, ventilation modalities, volume-targeted

Respiratory distress syndrome (RDS) remains the primary diagnosis of neonates admitted to the neonatal intensive care unit (NICU), accounting for 29% of late preterm and nearly 100% of extremely low birth-weight (ELBW) infants.[1] Over the past 50 years, great strides have been made in the knowledge of neonatal pulmonary physiology, the consequences of respiratory distress on other body systems, and the long-term effects of our respiratory modalities, including supplemental oxygen use and mechanical ventilation (MV).[2] This scientific evidence has guided clinicians in delivery room management, recognition of respiratory distress, and MV strategies with a heightened understanding of long-term implications that evolve from neonatal respiratory disorders.

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"Neonatal respiratory distress" is a general term used to describe any neonatal condition that leads to a progressive state of hypoventilation and/or hypoxia.[3] This condition commonly presents with 1 or more physical symptoms that include tachypnea, grunting, retractions, nasal flaring, and cyanosis.[4] "Neonatal RDS" is a specific term that refers to a surfactant-deficient state that is most commonly linked to prematurity. Pulmonary surfactant deficiency secondary to inactivation may also present as RDS in the term infant, although less likely. These conditions include asphyxia, history of maternal diabetes, infection, and/or meconium aspiration.[5]

Clinicians have a clear appreciation for the potential harm to pulmonary structures during MV including bronchopulmonary dysplasia (BPD). Over the last decade, the movement has been toward noninvasive ventilation strategies in an effort to support the functional residual capacity (FRC) and reduce barotrauma, volutrauma, and ventilator-induced lung injury (VILI).[6] However, it remains clear that some infants require MV to survive. Optimizing MV strategies and equipment has the potential to improve outcomes in this population.

The purpose of this article was to describe 2 primary methods of neonatal MV, pressure-limited ventilation (PLV) and volume-targeted ventilation (VTV). These methods are compared and contrasted to provide clinicians a better understanding of these modalities, highlighting key considerations during therapy. Evidence supporting recommendations for implementation of these supportive MV methods is provided for preterm and term neonates.

FETAL LUNG DEVELOPMENT

To best understand the impact of prematurity on the respiratory system, a brief review of fetal lung development is offered. The human lung develops in an organized and predetermined sequence that begins with the outpouching of the foregut at about 4 to 5 weeks of gestation, with lung maturation achieved well into late childhood.[7] Fetal lung development has been categorized into 5 stages, which have been defined according to weeks of gestation. These stages, embryonic, psuedoglandular, canalicular, saccular, and alveolar, represent differences in both structure and function (Table 1).[7] Critical to neonatal survival is the third stage when gas-exchanging acinar units appear. Surfactant becomes detectable in the amniotic fluid at approximately 23 to 24 weeks of gestation as type I and type II pneumocytes differentiate. Type I pneumocytes impact gas exchange, whereas type II cells are primarily responsible for surfactant production.[7] Having a good understanding of maturation of the lung through these stages is imperative to provision of excellent ventilation strategies.

PULMONARY MECHANICS

To provide a basis for the discussion surrounding MV strategies of the neonate, a brief review of respiratory physiology and pulmonary mechanics is provided (Table 2). In its most simplistic form, the respiratory cycle is inhalation and exhalation to provide adequate gas exchange. The neonatal lung at term gestation is made up of millions of air sacs connected by larger airways. Proliferation of these gas exchanging units continues until childhood.

The expansion of the lung is partly controlled by contraction of the diaphragm and intercostal muscles that increases the volume of the thoracic cavity, decreasing the intrapleural pressure, which promotes gas entry into the lung. Exhalation is largely passive but is impacted by the forces of elasticity and surface tension. Connective tissue (elastic recoil) stretches and relaxes during each breath. Elastic recoil is the tendency of stretched objects to return to their primary shape. Elastance, or elastic resistance, is the tendency of a hollow organ to return to its original size/shape when distending or compressing forces are removed and is the reciprocal of compliance. Surface tension is the tendency of a liquid to take up the least surface area possible. As surface tension and elastance increase, the fluid-lined pulmonary surfaces collapse, which is called atelectasis.

The rib cage and chest wall musculature restricts expiration, stinting pulmonary structures in a slightly open position during full expiration (vital capacity) through negative intrapleural pressure. Surface tension, generated by the fluid–air interface

TABLE 1. Stages of Lung Development

Stage of Development	Gestational Age	Primary Pulmonary Characteristics
Embryonic	Weeks 4-6	Branching of the lung buds Proximal airways are forming The trachea and bronchi differentiate
Psuedoglandular	Weeks 7-16	Conducting airways are forming Branches of the bronchial tree begin to develop Respiratory parenchyma begins to develop
Canalicular	Weeks 17-28	Acinar (gas-exchanging) units are forming Early vascularization of the acinar with differentiation between air–blood barrier Surfactant detectable in the amniotic fluid during late canalicular stage Continued peripheral lung development
Saccular	Weeks 29-35	Maturation of the gas-exchanging sites The formation of alveolar saccules Continued vascularization of the acinar Gas exchange enhanced through the thinning of the interstitial space between alveoli and capillaries
Alveolar	Weeks 36 through mid-childhood	Extension and expansion of the gas exchanging units Continued pulmonary growth and maturation Additional alveoli continue to develop

TABLE 2. Definitions of Key Terms for Pulmonary Mechanics

Term	Definition
Tidal volume (Vt)	The amount of air inspired during normal, relaxed breathing
Inspiratory reserve volume (IRV)	The additional air that can be forcibly inhaled after the inspiration of a normal Vt
Expiratory reserve volume (ERV)	The additional air that can be forcibly exhaled after the expiration of a normal Vt
Residual volume (RV)	The volume of air still remaining in the lungs after the expiratory reserve volume is exhaled
Total lung capacity (TLC)	The maximum amount of air that can fill the lungs (TLC = Vt + IRV + ERV + RV)
Vital capacity (VC)	The total amount of air that can be expired after fully inhaling (VC = Vt + IRV + ERV = approximately 80% TLC)
Inspiratory capacity (IC)	The maximum amount of air that can be inspired after normal exhalation (IC = Vt + IRV)
Functional residual capacity (FRC)	The amount of air remaining in the lungs after a normal expiration (FRC = RV + ERV)
Minute ventilation (MV)	The amount of air a person breathes in a minute (MV = respiratory rate × Vt)

within the terminal air spaces, promotes lung deflation (FRC) or full forced exhalation (residual volume). Airway resistance and compliance are influenced by lung size, that is, the smaller the lung, the greater the resistance and lower the compliance (Table 2).

These described factors are significantly impacted by prematurity. The very compliant chest wall of the preterm neonate offers both minimal resistance to overinflation and little opposition to alveolar collapse at the end of expiration (atelectasis). Surfactant deficiency increases surface tension, leading to decreased compliance, increased elastance, increased atelectasis, and suboptimal FRC. To compensate for these factors, the preterm infant increases both respiratory rate and work of breathing with concomitant increased oxygen requirement. Over time, the infant typically demonstrates fatigue with/without episodes of apnea, which can lead to further respiratory compromise and acidosis. Overall, RDS of the preterm infant is related to low compliance secondary to diffuse microatelectasis complicated by a very compliant chest wall and failure to maintain a normal FRC.[2]

MECHANICAL VENTILATION

The practice of MV in the neonatal population began in the 1960s, initially utilizing adapted adult ventilators. This equipment lacked proper technological advances for optimal use on the sick and/or preterm neonates.[8] In addition to restrictive options for ventilator management, knowledge surrounding neonatal lung pathophysiology was rapidly evolving through the use of animal models.[9] Despite these limitations, the introduction of MV proved to be a lifesaving advancement for neonatal care and remains an essential supportive therapy today.[10]

Mechanical ventilators have undergone significant revisions and enhancement over the last several decades. Specifically, neonatal ventilators with advanced microprocessors allow the clinician to adjust ventilator settings based on continuous monitoring of pulmonary mechanics visible on the LED screen. Some of the measured parameters determined via the proximal flow sensor usually located at the Y-piece of the ventilator circuit include inspired and expired tidal volume (Vt), degree of air leak around the endotracheal (ET) tube, and spontaneous respiratory rate and timing.[11] Overall, the newest generation of mechanical ventilators have created an environment of improved treatment capabilities with the ability to customize the treatment plan for each patient.[2]

Currently, there are 2 primary categories of invasive ventilation utilized for the treatment of RDS in the neonate. These include high-frequency ventilation and conventional MV.[12] These 2 categories differ on the basis of how minute ventilation is delivered. Minute ventilation is the amount of air a person breathes in a minute and is calculated by multiplying the respiratory rate and the Vt (Table 2).[2] Conventional MV delivers gas intermittently to the patient with the goal of approximating the physiologic Vt within the lungs. High-frequency ventilation applies rapid rates with small volumes in an effort to provide adequate ventilation with lower airway pressures. This method of ventilation has been used as both primary and rescue strategies for the neonate.[12] Although high-frequency ventilation remains an important strategy for some neonates, this method is outside the comparison aim for this article.

The basic concepts of neonatal MV must be described and considered by the clinician prior to bedside management and to support our comparison between PLV and VTV. Mechanical ventilation can be time-triggered or synchronized with the patient's respiratory effort. *Synchronization* refers to the initiation of scheduled mandatory breaths in coordination with the patient's spontaneous inspiratory effort. Synchronization has been shown to decrease the work of breathing during MV when compared with neonates who were supported with non–patient-triggered or synchronized breaths.[13] The termination of assisted breaths can be either time or flow cycled and may include a volume limitation. Inspiratory time is a clinician-determined time frame that dictates the length of the ventilation cycle, from inspiration to exhalation. The goal is to approximate the physiologic inspiratory time of the infant with necessary adjustment to a shorter or longer time based on the infant's pathophysiology.[11]

Additional modes of ventilation include assist control and pressure support. Assist control is a mode where all breaths are supported by the preset positive inspiratory pressure (PIP), and the ventilation rate is triggered by the patient's respiratory rate.[14] Assist control typically uses a minimal rate to support the infant during periodic breathing or apnea. Pressure support is a mode where the patient controls the rate of breathing, the inspiratory and expiratory time (or termination of breath), and minute ventilation, which has been shown to provide improved patient–ventilator synchrony.[15] This strategy can be beneficial as a method to provide support to the patient's spontaneous breaths with additional pressure or PIP. This mechanism has been effectively used to support and strengthen spontaneous breathing effort by increasing transpulmonary pressure. The difference between the alveolar and intrapleural pressures supports the alveoli and sustains open lungs, decreasing the work of breathing.[14] Pressure support during PLV has been shown to be beneficial, especially during weaning phases, in order to provide added support in overcoming ET tube and circuit resistance.

Understanding the historical prospective and mechanism of MV provides the clinician key information to effectively examine 2 specific methods of neonatal ventilation, PLV and VTV. The traditional time-cycled, pressure-limited method of ventilation (PLV) is also known as intermittent positive-pressure ventilation.[6,16] This mode has a set rate that can be synchronized (inflation is triggered by a patient's respiratory effort) with PIP that is determined by the clinician and is set to not exceed the prescribed level. Through control of these settings, effective neonatal ventilation can be achieved with PLV.

Volume-targeted ventilation is a strategy that modifies PLV through the use of microprocessor-driven algorithms that adjusts PIP, flow, or time to achieve the "targeted" Vt. The ventilator rate can be synchronized with the patient's respiratory effort, and the microprocessor typically adjusts the delivered PIP based on measured Vt over 2 to 4 ventilated breaths. Overall, VTV utilizes a goal Vt through the delivery of a variable PIP in response to those dynamic physiologic changes that occur in the neonate.

The major differences between volume-targeted and pressure-limited strategies surround the delivery of pressure. Flow delivers volume, which produces pressure. Volume-targeted ventilation changes peak pressure from breath to breath, with variable flows. Both modes, PLV and VTV, utilize a set positive end-expiratory pressure (PEEP).[11] Each of these important MV methods is discussed as follows.

PRESSURE-LIMITED VENTILATION

Historically, PLV, which utilized a fixed inflation pressure, was the preferred method of neonatal ventilation due to the challenge of accurately measuring the infant's spontaneous breaths and/or Vt. Through improved technology, today's neonatal ventilators use sensors to more accurately and precisely measure flow and pressure at the proximal airway and deliver this information to the microprocessor, minimizing earlier challenges.[12] In PLV, the clinician sets a prescribed PEEP to maintain FRC and support alveolar recruitment. The Vt of each mechanical breath is determined by the difference between the prescribed PIP, PEEP, characteristics of the respiratory system (compliance, airway resistance, and respiratory effort), and the prescribed inspiratory time.[14]

A key feature of PLV is that delivered volume to neonatal alveoli relies heavily on the patient's lung compliance by utilizing gas flow during the infant's lung inflation. The ventilator is programmed to time cycle in order to discontinue the inflation process once a certain amount of time passes.[17] Pressure-limited ventilation has the ability to overcome the limitation of a large or changing air leak, as the consistent pressure delivery provides an even volume distribution.[6]

This type of neonatal ventilation continues to be mainstream therapy in the NICU today. A reported advantage of PLV is that it is easier to manage in the clinical setting. Another advantage is that the ventilators used during PLV are less costly than those used during VTV or other MV methods. This method (PLV) may also have advantages over VTV in the larger, chronically ventilated patient, as air leaks are typically smaller and pulmonary dynamics are more stable. And, finally, best practices using PLV have been supported with historical evidence stemming from long-term use. Clinicians' personal training coupled with continued use provides a level of comfort with regard to initial settings and weaning parameters.

The disadvantages of PLV include the variation of Vt breath to breath. Ventilator settings support a consistent PIP, which can be problematic during times of dynamic lung changes, such as following surfactant delivery. Evidence points to a risk of VILI and hypocarbia when excessive Vt is achieved during pressure ventilation. Conversely, atelectasis from hypoventilation or suboptimal pressure delivery during PLV may lead to tissue injury and inflammation. Both scenarios have the potential to create pulmonary trauma and inflammation, which have been correlated with negative neurologic sequelae.[18] The patient's increased work of breathing during spontaneous breaths and poor synchrony between spontaneous and mandatory breaths have been reported as a disadvantage during PLV. Both of these clinical issues have been aided through the use of pressure control and/or synchronized modes of MV during PLV.

VOLUME-TARGETED VENTILATION

Volume-targeted ventilation is a method of ventilation that adjusts inspiratory pressure, flow, or time to achieve a preset target Vt to the patient. Following compelling evidence that volume distension of the lung (volutrauma) was more damaging than peak airway pressure (barotrauma), clinicians moved toward methods of neonatal ventilation that produced a more stable Vt to reduce lung injury and stabilize the symptoms of RDS. This effort was supported by technological advancements of neonatal ventilators, which now employ microprocessor-driven algorithms based on detailed information collected at the proximal airway.

During VTV, the Vt is selected for the patient on the basis of normative values identified through the study of spontaneously breathing preterm infants using pneumotachometers that predict goal values per kilogram of body weight.[19] Although normative values of the ELBW infant have not been well established, VTV supports a measured Vt of 4 to 7 mL/kg based on extrapolated data in an effort to provide appropriate ventilation through dynamic lung compliance changes.[19] These values are recommended as starting ranges during VTV.[16]

The overreaching advantage of VTV is the maintained Vt closer to the set volume, which has been associated with a decrease in the incidence of BPD and death.[16] Reduction in the rate of pneumothorax and ventilator-days has also been reported.[16] A disadvantage of this method includes the ventilator expense, which is required to deliver VTV. The machinery is more expensive to purchase and operate, with fragile, sensitive proximal airway sensors necessary to convey needed information to the microprocessor. The complexity of the ventilator is an initial disadvantage, with an expected learning curve for clinical staff to learn setup, methods of operation, and trouble-shooting, which could impact outcomes. Although early evidence is compelling, evidence to support the nuances of VTV use is needed.

COMPARE AND CONTRAST PLV VERSUS VTV

At the same time improvements were being made in neonatal MV technology, key therapeutic recommendations were made and implemented to improve prenatal, antenatal, and postnatal care. These recommendations include the widespread use of antenatal steroids, surfactant, improved prenatal care, and alternative noninvasive forms of ventilation. These strategies have significantly improved both mortality and morbidity rates for neonates, particular those less than 30 weeks of gestation.[10] As a result of these therapeutic and technological advancements, younger preterm infants are successfully resuscitated, making MV a major contributor to NICU care. Walsh and colleagues[20] conducted a large cohort analysis and found that of extremely preterm infants, 89% were mechanically ventilated during the first 24 hours of life and approximately 95% of survivors required MV during their hospitalization.[20] In 2008, the Vermont Oxford Network reported 64% of neonates weighing less than 1500 g required MV during their NICU stay.[21] More recently, the SUPPORT (Study to Understand Prognoses and Preferences for Outcomes and Risks of Treatment) trial reported that 83% of infants who were 24 to 28 weeks of gestation required MV during their hospitalization.[22]

Although lifesaving, infants who require MV may demonstrate evolving chronic lung disease (CLD) called BPD, which is defined as histologic changes that include impaired alveolarization and fibrosis of the pulmonary structures with supplemental oxygen requirement past 28 days of life and/or 36 weeks of corrected age.[16] A precursor for this chronic pulmonary condition often begins as RDS secondary to immaturity or surfactant deficiency in the term infant.[20] It has been demonstrated that even short-term exposure to excessive volume in the pulmonary system has been linked to increased inflammation of the lung, setting the stage for VILI.[23] Lung injury with evidence of continued surfactant inactivation has been demonstrated following as few as 6 "inflations" after birth in animal models.[24]

While MV is partially responsible for BPD, it remains a multifactorial disease process associated with barotrauma, volutrauma, infections, intrauterine growth restriction, oxygen toxicity, oxidant stress, and lung immaturity.[9,12] Given the array of causes of BPD, it is important to identify that MV is one of the few variables that can be altered by the clinician in an effort to improve neonatal outcomes.

The goal of MV of the neonate is to treat RDS through a proven method that protects the neonatal lung, optimizes lung volumes while limiting hyperinflation, and supports FRC through appropriate PEEP, small physiologic delivery of Vt, and permissive hypercapnia.[18] Ventilatory goals can be achieved through multiple delivery strategies that have been supported by clinical and scientific research. As clinicians, we can individualize each patient's care based on the 2 MV strategies discussed, PLV and VTV, to achieve best outcomes.

Pressure-limited ventilation was initially favored by clinicians secondary to early evidence that supported high pressure or barotrauma as the primary cause of neonatal lung damage during MV. In an effort to minimize high pressures utilized during MV, acceptance of permissive hypercapnia became mainstream therapy.[1] Scientific evidence demonstrated no significant negative impact when pH and $Paco_2$ levels were liberalized during MV. Following these recommendations, a lower PIP was utilized during PLV. We now clearly understand that there is more to the story. The relationship between overdistension of alveoli coupled with periods of alveolar collapse called VILI has been implicated as major contributors of inflammation in the preterm lung, which has been linked to BPD.[16] As previously discussed, a major disadvantage of PLV is the variation of Vt breath to breath as the infant's lung compliance changes. The potential for increased volutrauma due to overstretch injury during hyperventilation and atelectasis during hypoventilation secondary to compliance changes during PLV has been well described. Multiple comparison studies between PLV and VTV have been conducted over the last 10 years. For example, D'Angio and colleagues[25] randomized 213 infants to PLV or VTV with BPD as one of the primary outcome measures. Clinically significant findings were reported as BPD was reduced in the VTV group when compared with the PLV group (from 45 to 38, respectively). Sinha and colleagues[26] conducted a similar study with 109 infants randomized to PLV or VTV and found BPD in 27 of those infants treated with PLV versus 21 in the VTV group. Although statistical significance was not reported, individually, a meta-analysis comparing PLV and VTV concluded a statistically significant reduction in the rate of BPD at 36 weeks in the VTV group.[16]

We understand from scientific evidence that VILI can occur during pressure-controlled and/or volume-controlled ventilation scenarios. Therefore, it is imperative that careful attention is paid to the patient's self-generated pressures, prescribed volume settings, and degree of end-expiratory lung volume when using any MV strategy. In addition, links between overstretch injury and the initiation of the proinflammatory cascade in the lung have been demonstrated. These findings have systemic implications with correlation to increased white matter injury and poor neurodevelopmental outcomes.[27] Overall, compelling scientific evidence continues to support a more consistent Vt in an effort to reduce lung and systemic damages.

Multiple studies have cited the many benefits of VTV such as the reduced length of time an infant may require MV, a decreased risk of pneumothorax, and/or severe intraventricular hemorrhage (IVH).[6,10,12,28] Sinha and colleagues[26] conducted a randomized controlled trial (RCT) of preterm neonates with RDS comparing VTV with PLV. During the study, a targeted volume of 5 to 8 mL/kg was used for the Vt group and PIP adjustment of the PLV group was based on clinical status and blood gases. They found that length of ventilation decreased along with the incidence of BPD.[26] A meta-analysis of 12 RCTs supported the use of VTV.[16] Findings from this meta-analysis showed a reduction in BPD, death, reduced number of ventilator days, hypocarbia with decreased incidence of periventricular leukomalacia, and/or grade 3 to 4 IVH during Vt ventilation.[16,18] A recent meta-analysis compared the use of VTV versus PLV in the neonatal population. Conclusions include decreased BPD, shorter ventilation duration, decreased periventricular leukomalacia/IVH, and decreased incidence of pneumothorax in the volume-targeted group.[28]

Careful consideration must been given to the settings one chooses for VTV. Too much or too little inflation of the lungs can lead to lung injury. Insufficient volumes may promote underinflation of the neonatal lung, which can lead to poor gaseous exchange and hypercapnia. Excessive volume initiates the proinflammatory cascade in the lung due to overdistention.[8] Additional risks include that of periventricular leukomalacia related to hypocapnia and, similarly, the risk of IVH related to hypercarbia.[6]

A thorough examination of VTV makes one realize that the single most important indicator in proper management is the ability to accurately measure Vt. Uncuffed ET tubes are typically utilized in the neonatal population, which is appropriate due to the small size of the neonate and goal to reduce the risk of necrosis of tracheal mucosa. However, inconsistent and/or positional air leak around the uncuffed ET tube can be difficult to manage clinically with this ventilation strategy. As the infant grows, reintubation with a larger ET tube may be necessary, especially for infants who require long-term ventilation.[17]

In addition, humidification and neonatal secretions can impact the accuracy of Vt measurements.[18] Fortunately, the advent of new ventilator capabilities has aided in overcoming these complications.

Measured Vt is displayed on the ventilator screen during both inspiration and expiration, although expiration most closely measures the volume actually entering the lungs. The measurement is problematic, however, due to the placement of the flow sensors in relation to the infant. The space between the infant and the ventilator is large may lead to inaccurate Vt measurements when one takes into consideration the amount of gaseous exchange, compression, and leakage around an ET tube that can occur.[17] Newer technology utilizes methods of proximal airway sensors to more accurately determine the patient's Vt. As discussed previously, the great appeal of Vt ventilation is to rapidly and effectively adjust delivered pressure based on the neonate's ever-changing lung compliance. Discrepancies in measurement and the ability of equipment to overcome the challenges of volume targeting have greatly impacted the effectiveness of this MV strategy.

Weaning ventilator settings during treatment with PLV is accomplished by reducing the PIP based on $Paco_2$ levels, which gradually encourages the infant to better support and control the work of breathing. This assumes that the reduced $Paco_2$ level represents the infant's improved lung compliance and spontaneous respiratory effort/rate, which are needed to maintain an adequate Vt.[17]

The weaning process during VTV has not been as well established. The primary control variable during VTV is Vt; therefore, it has been suggested that weaning the Vt in a stepwise fashion would be correct. However, if the infant is believed to have a normal physiologic Vt, which the clinician has determined and set, then the ventilator pressure delivered to the patient should gradually lessen to achieve the set Vt. Therefore, the reduction in delivered pressure to the patient is a method of weaning support.[17] Reducing the rate has also been suggested as a weaning strategy during VTV.[11]

Clearly, neonatal lung disease and pulmonary compliance are rapidly changing after delivery. By identifying the most appropriate mode of ventilation, the clinician can consider volume versus pressure strategies in an effort to stabilize pulmonary function and reduce lung injury.[16] In addition, the accurate prediction and delivery of goal Vt during MV will result in a reduction of combined atelectrauma and volutrauma.[19]

RECOMMENDATIONS FOR FURTHER RESEARCH

Neonatal respiratory support has evolved quickly in the last half-century, with clear improvements in both mortality and morbidity.[2] Interestingly, VTV is not a new strategy and originally was the ventilation strategy of choice until the introduction of pressure ventilation.[18] As neonatal ventilators continue to evolve, clinicians have the ability to observe variable pressure delivery in relation to an infant's pulmonary mechanics and respiratory effort while treated with VTV.

Based on this discussion, the VTV strategy appears to have clear advantages over PLV. In a recent meta-analysis of randomized and quasi-randomized trials that compared PLV with VTV in neonates less than 28 days of life, VTV strategies were shown to have statistically less incidence of CLD and death.[16] Comparison between MV strategies, specifically PLV and VTV and short- and long-term neurodevelopmental outcomes, is needed.

Through the prediction of constant changes in neonatal lung compliance using sensitive flow sensors attached to new-generation mechanical ventilators, clinicians can most accurately ventilate tiny pulmonary structures. Yet, the identification of the most appropriate Vt level in the neonatal population is not well defined.[29] Current consensus is that 4 to 6 mL/kg should be adequate, but caution is certainly warranted before widespread adoption of any one ventilation strategy for the extremely preterm neonate.

FIGURE 1

Skin-to-skin holding to support neurodevelopmental care during mechanical ventilation. Used with permission.

Summary of Recommendations for Practice and Research

What we know:	• MV is necessary to successfully treat RDS in some neonates • CLD is multifactorial with a clear relationship to prematurity • MV has been linked to acute and chronic lung injury in the neonate • New-generation ventilators are capable of providing multiple ventilation modalities, including volume-targeted and pressure-limited
What needs to be studied:	• RCTs comparing ventilation strategies of preterm and term neonates • ELBW normative values for Vt targets • Systemic influence of VTV with regard to cerebral blood flow and neurodevelopmental outcomes • The impact of late initiation of Vt ventilation in infants with RDS and CLD • ET tube air leak, humidification, secretions, and the degree to which Vt ventilation is impacted by these variables
What we can do today to aid caregivers in the practice setting:	• Educate providers on the various modalities available on mechanical ventilators • Foster the change of culture related to initiating VTV surrounding surfactant administration. • Continue to support nonventilatory methods of respiratory support • Create clear guidelines for administration and weaning of MV in both preterm and term infants • Work with manufacturers to improve ventilator features that target Vt ventilation

There are still questions regarding best practices for older ventilated infants and those with significant pulmonary injury or CLD. Considering embryologic lung development, clear differences are evident between the preterm and term lungs at birth. Therefore, it is important to take into consideration the delicacy of the lung tissue of a preterm as compared with a term infant. Furthermore, a term infant's clinical status, blood gases, generated inspiratory pressures, and chest radiographs are important to evaluate when considering appropriate Vt. Current practice is to apply similar settings to term and preterm infants and consider self-generated PIPs and subsequent blood gases.

Comparative research that examines both pulmonary and systemic influences of various MV strategies needs to be conducted. For example, are there differences in the cerebral blood flow and/or cerebral oxygenation of those ELBW infants treated with VTV versus PLV? Does VTV with changing PIP with consistent Vt versus PLV with consistent PIP with changing Vt creating differences in intrathoracic pressure lead to alterations in cerebral blood flow? The use of proximal Vt measurement in this population leading to tighter VTV management has been shown to be beneficial. Additional studies to analyze baseline optimal values for certain pathophysiologic conditions may prove valuable.

Despite many sources pointing toward VTV as the optimal ventilatory strategy, many clinicians fail to implement the practice early on. Whether it is due to unfamiliarity with the modes or habitual practice toward traditional PLV, practice has been slow to change. Exploring the rationale for clinician choice would be a beneficial area of study. Clinicians are encouraged to consider all MV modalities and non-MV alternatives that ultimately protect the patient from VILI and long-term consequences.

CONCLUSION

The successful management of respiratory disease in the NICU is one of our primary goals. This task must be accomplished without acute or chronic damage to pulmonary structures, as well as protection of the neurodevelopmental outcomes of our vulnerable patients. We understand from previous experimental and clinical research that excessive Vt (volutrauma) causes significant lung injury in the neonate. Injury to pulmonary tissue can also lead to a chronic state of inflammation, which has been correlated with increased morbidity in this population.[27]

So, what seems somewhat straightforward on the surface is hardly that. As with many promising therapies in the NICU, multicentered randomized trials are needed to test these ventilation strategies before conclusive recommendations are made. Until then, clinicians will continue to evaluate each infant individually, using all the tools and knowledge available to us and make sound decisions, otherwise known as the art of nursing practice. This art of ventilation strategies can be used to keep infants and families together (Figure 1).

References

1. Stoll BJ, Hansen NI, Bell EF, et al; Kennedy Shriver National Institute of Child Health and Human Development Neonatal Research Network. Neonatal outcomes of extremely preterm infants from the NICHD Neonatal Research Network. *Pediatrics.* 2010;26:443-456.
2. Goldsmith JP, Karotkin EH. *Assisted Ventilation of the Neonate.* 5th ed. Philadelphia, PA: Elsevier Saunders; 2014.

3. Reuter S, Moser C, Baack M. Respiratory distress in the newborn. *Pediatr Rev*. 2014;35(10):417-428.
4. Aly H. Respiratory disorders in the newborn: identification and diagnosis. *Pediatr Rev.* 2004;25(6):201-208.
5. Warren JB, Anderson JM. Newborn respiratory disorders. *Pediatr Rev.* 2010;31(12):487-496.
6. Habre W. Neonatal ventilation. *Best Pract Res Clin Anesthesiol*. 2010;24(3):353-364.
7. Soltau TD, Carlo WA. Respiratory system. In Kenner C, Lott JW, eds. *Comprehensive Neonatal Nursing Care*. 5th ed. New York, NY: Springer Publishing Co; 2014; pp. 133-151.
8. Claure N, Bancalari E. New modes of mechanical ventilation in the preterm newborn: evidence of benefit. *Arch Dis Child Fetal Neonatal Ed*. 2007;92(6):F508-F512.
9. Hernandez LA, Peevy KJ, Moise AA, Parker JC. Chest wall restriction limits high airway pressure-induced lung injury in young rabbits. *J Appl Physiol*. 1989;66(5):2364-2368.
10. Donn SM, Boon W. Mechanical ventilation of the neonate: should we target volume or pressure? *Respir Care*. 2009;54(9):1236-1243.
11. Klingenberg C, Wheeler KI, Davis PG, Morley CJ. A practical guide to neonatal volume guarantee ventilation. *J Perinatol*. 2011;31(9):575-585.
12. Ramanathan R, Sardesai S. Lung protective ventilatory strategies in very low birth weight infants. *J Perinatol*. 2008;28(suppl 1):S41-S46.
13. Greenough A, Dimitriou G, Prendergast M, Milner AD. Synchronized mechanical ventilation for respiratory support in newborn infants. *Cochrane Database Syst Rev*. 2008;23(1):CD000456.
14. Hummler H, Schulze A. New and alternative modes of mechanical ventilation in neonates. *Semin Fetal Neonatal Med*. 2009;14(1):42-48.
15. Sarkar S, Donn SM. In support of pressure support. *Clin Perinatol*. 2007;34(1):117-128.
16. Wheeler K, Klingenberg C, McCallion N, Morley CJ, Davis PG. Volume-targeted versus pressure-limited ventilation in the neonate [review]. *Cochrane Database Syst Rev*. 2010;10(11):CD003666.
17. Keszler MM. Sustained inflation during neonatal resuscitation. *Curr Opin Pediatr*. 2015;27(2):145-151.
18. Brown MK, Diblasi RM. Mechanical ventilation of the premature neonate. *Respir Care*. 2011;56(9):1298-1311.
19. Wen-Chun JL, Bhutani VK. Core concepts: neonatal tidal volume: physiologic, technologic and clinical considerations. *NeoReviews*. 2011;12(11):652-659.
20. Walsh MC, Morris BH, Wrage LA, et al. Extremely low birthweight neonates with protracted ventilation: mortality and 18-month neurodevelopmental outcomes. *J Pediatr*. 2005;146(6):798-804.
21. Soll R. *Vermont Oxford Network Annual Data, Annual Report*. Burlington, VT: Vermont Oxford Network; 2008.
22. Finer NN, Carlo WA, Walsh MC, et al. Early CPAP versus surfactant in extremely preterm infants. *N Engl J Med*. 2010;362(21):1970-1979.
23. Baraldi E, Filippone M. Chronic lung disease after premature birth. *N Engl J Med*. 2007;357(19):1946-1955.
24. Bjorklund LJ, Ingimarsson J, Curstedt T, et al. Manual ventilation with a few large breaths at birth compromises the therapeutic effect of subsequent surfactant replacement in immature lambs. *Pediatr Res*. 1997;42:348-355.
25. D'Angio CT, Chess PR, Kovacs SJ, et al. Pressure regulated volume control ventilation vs synchronized intermittent mandatory ventilation for very low birth weight infants; a randomized controlled trial. *Arch Pediatr Adolesc Med*. 2005;159:868-875.
26. Sinha SK, Donn SM, Gavey J, McCarty M. Randomized trial of volume controlled versus time cycles, pressure limited ventilation in preterm infants with respiratory distress. *Arch Dis Child Fetal Neonatal Ed*. 1997;77(3):F202-F205.
27. Albertine KH. Brain injury in chronically ventilated preterm neonates: collateral damage related to ventilation strategy. *Clin Perinatol*. 2012;39(3):727-740.
28. Peng W, Zhu H, Shi H, Liu E. Volume-targeted ventilation is more suitable than pressure-limited ventilation for preterm infants: a systematic review and meta-analysis. *Arch Dis Child Fetal Neonatal Ed*. 2014;99(2):F158-F165.
29. Grover A, Field D. Volume-targeted ventilation in the neonate: time to change? *Arch Dis Child Fetal Neonatal Ed*. 2008;93(1):F7-F13.

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