NeoReviews™
AN OFFICIAL JOURNAL OF THE AMERICAN ACADEMY OF THE PEDIATRICS

Volume-targeted Ventilation

Martin Keszler

Neoreviews 2006;7;e250
DOI: 10.1542/neo.7-5-e250

Volume-targeted Ventilation

Martin Keszler, MD*

Author Disclosure
Dr Keszler disclosed the he has served as a consultant to and received a research grant from Draeger Medical, Lubeck, Germany, and is an unpaid consultant to Bunnell, Inc, Salt Lake City, Utah.

Objectives

After completing this article, readers should be able to:

1. Understand the importance of controlling tidal volume and avoiding hyperventilation/excessive tidal volume.
2. Recognize the importance of optimizing lung inflation and avoiding atelectasis.
3. Delineate the limitations of traditional volume-controlled ventilation in newborns.
4. Describe the various modes of volume-targeted ventilation and their advantages and disadvantages.
5. Describe the key steps in the clinical application of volume guarantee ventilation.

Introduction

Mechanical ventilation has improved to the point where few infants die because of acute respiratory failure. Mortality now is predominantly from other complications of extreme prematurity, such as infection, necrotizing enterocolitis, and intracranial hemorrhage. Consequently, focus has shifted from merely reducing mortality to reducing the incidence of chronic lung disease, which has increased in recent years with improved survival of extremely preterm infants.

Although high-frequency ventilation has shown promise, results of clinical trials have been inconsistent, and continued concerns about the hazards of inadvertent hyperventilation have limited its acceptance as first-line therapy in infants who have uncomplicated respiratory distress syndrome (RDS). At the same time, technologically advanced synchronized ventilation has become widely available. The most exciting development in neonatal respiratory support, however, is the advent of volume-targeted modalities of conventional ventilation that, for the first time, allow effective control of delivered tidal volume for neonatal ventilation.

Rationale for Volume-targeted Ventilation

Pressure-limited, time-cycled, continuous flow ventilation has been the standard of care in neonatal ventilation for more than 30 years. One of the advantages cited for the preference for pressure-limited over volume-controlled ventilation has been the ability to control the inspiratory pressure directly. Preoccupation with high inspiratory pressure as the chief culprit in lung injury and air leak has been a constant theme in neonatal respiratory support until recently, despite accumulating evidence over more than a decade that volume, rather than pressure, is the critical determinant of ventilator-induced lung injury. Dreyfuss and colleagues demonstrated as early as 1988 that severe acute lung injury occurred in animals ventilated with large tidal volume, regardless of whether that volume was generated by positive or negative inspiratory pressure. On the other hand, animals whose chest walls and diaphragmatic excursions were limited by external binding, but who were exposed to the same high inspiratory pressure, experienced much less lung damage. Results from this and other experiments clearly show that excessive tidal volume, not pressure per se, is chiefly responsible for lung

Abbreviations

AC: assist control
PEEP: positive end-expiratory pressure
PIP: peak inspiratory pressure
PSV: pressure support ventilation
PRVC: pressure-regulated volume control
RDS : respiratory distress syndrome
SIMV: synchronized intermittent mandatory ventilation
VAPS: volume-assured pressure support
VG: volume guarantee

*Professor of Pediatrics, Georgetown University, Washington DC.

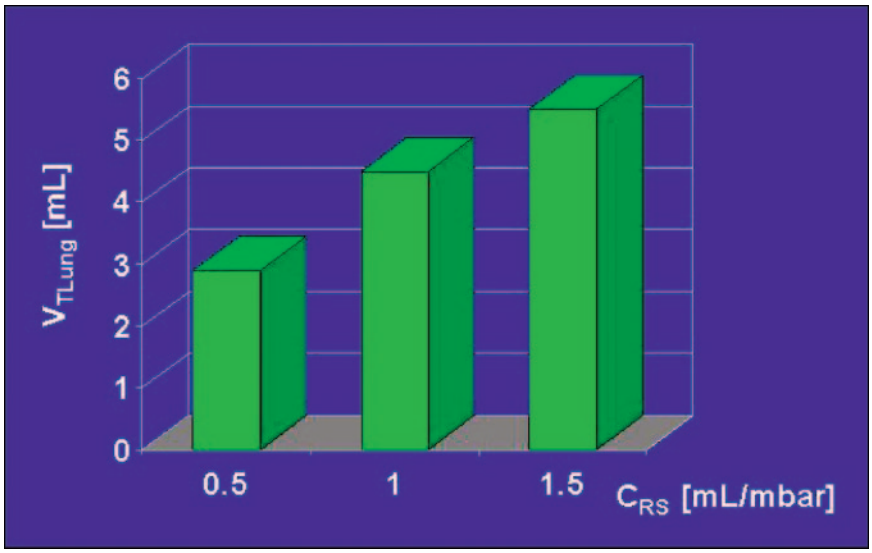

Figure 1. Effect of compliance on delivered tidal volume with traditional volume-controlled ventilation using a standard neonatal circuit. Tidal volume was set at 10 mL. Volume entering the lungs ranged from 5.5 mL with fairly normal lung compliance to less than 3 mL with severely decreased compliance, such as typically is seen with respiratory distress syndrome.

injury. However, only recently has full recognition of the importance of volutrauma rekindled interest in directly controlling tidal volume.

An equally compelling reason for volume-targeted ventilation is the extensive body of evidence documenting that hypocarbia is associated with neonatal brain injury. Despite increasing awareness of the dangers of hypocarbia, inadvertent hyperventilation remains a common problem with pressure-limited ventilation, especially early in the clinical course when lung compliance is changing rapidly in response to clearing of lung fluid, surfactant administration, and optimization of lung volume. A recent study, for example, demonstrated that 30% of ventilated infants had at least one blood gas result with a $PaCO_2$ of less than 25 torr during the first day after birth.

Limitations of Traditional Volume-controlled Ventilation

Traditional volume-controlled ventilation was attempted in newborns in the early 1980s, but quickly proved to be impractical and soon was abandoned. In volume-controlled ventilation, the device delivers a set volume of gas into the ventilator circuit. Pressure rises passively, in inverse proportion to lung compliance, as the tidal volume is delivered. A portion of the tidal volume is lost to compression of gas in the circuit and humidifier and to stretching of the elastic ventilator circuit. When the circuit volume and compliance are low in relation to the patient's lungs, this is a relatively minor problem and can be compensated using standard normograms. However, in small neonates who have poorly compliant lungs, the volume loss to the circuit/humidifier is proportionally much larger and more difficult to compensate (Fig. 1). More importantly, there is large and unpredictable loss of tidal volume to the ubiquitous and highly variable leak around uncuffed endotracheal tubes, which cannot be adequately compensated. For these reasons, traditional volume-controlled ventilation was abandoned in neonatal intensive care units more than 20 years ago. Nonetheless, it is important to be aware of these serious problems because a number of the newer ventilators that claim to be suitable for both neonates and adults have such traditional volume-controlled ventilation modes available. Unfortunately, such volume-controlled ventilation often is promoted as a mode suitable for small preterm infants without acknowledging these important limitations.

Neonatal Volume-targeted Ventilation

Because of the previously cited problems, a number of modifications of time-cycled, pressure-limited ventilation designed to target a set tidal volume by microprocessor-directed adjustments of peak pressure or inspiratory time have been developed recently. Each of the available modes has advantages and disadvantages. The modes of volume-targeted ventilation most widely available in North America are discussed.

Pressure-regulated Volume Control (PRVC)

PRVC is a pressure-limited, time-cycled mode that adjusts inspiratory pressure to target a set tidal volume, based on the tidal volume of the previous breath. This is solely an assist control (AC) mode. Breath-to-breath change is limited to 3 cm H_2O, up to 5 cm H_2O below the set upper pressure limit. Because pressure adjustment is based on the previous breath, variable or intermittent patient respiratory effort causes fluctuations in tidal volume. The primary problem with the PRVC mode for newborns is the major inaccuracy of tidal volume mea-

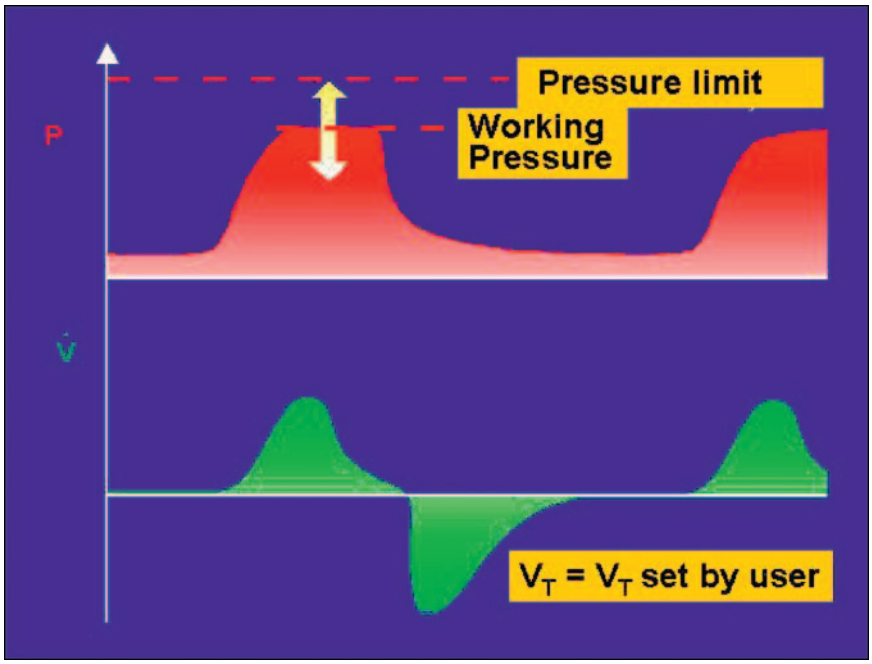

Figure 2. Principles of operation of volume guarantee. The device autoregulates the positive inspiratory pressure (PIP) (working pressure) within a preset limit (pressure limit) to achieve a tidal volume that is set by the user. Regulation of PIP is in response to *exhaled* tidal volume to eliminate artifact due to endotracheal tube leak leak.

surement performed at the ventilator end of the circuit, rather than at the airway opening.

Volume-assured Pressure Support (VAPS)

VAPS is a hybrid mode that seeks to ensure that the targeted tidal volume is reached. Each breath starts as a pressure-limited breath, but if the set tidal volume is not reached, the breath converts to a flow-cycled mode by prolonging the inspiratory time with a passive increase in peak pressure. This may result in a prolonged inspiratory time, leading to expiratory asynchrony. Targeting tidal volume based on inspiratory tidal volume is susceptible to substantial error in the presence of significant endotracheal tube leak. Furthermore, there is no provision for automatically lowering inspiratory pressure as lung compliance improves. Therefore, the focus is on ensuring a sufficiently large tidal volume, but no provision is made to avoid excessive tidal volume and inadvertent hyperventilation or to allow for automatic weaning.

A new generation of this ventilator has the basic features of VAPS, but adds a volume limit function that terminates inspiration if the upper limit of tidal volume is exceeded. The algorithm used to assure tidal volume has been refined to try to avoid excessive inspiratory time. The ventilator calculates the decelerating inspiratory flow required to deliver the set volume in the set inspiratory time. When a pressure control breath is delivered and peak flow decelerates to this calculated peak inspiratory flow, if the set volume has not been delivered, the ventilator automatically transitions to a continuous flow mode until the set volume has been delivered. Once the set volume has been delivered, the ventilator cycles into exhalation. If the set volume is met or exceeded during delivery of the pressure control breath, the ventilator completes the breath as a normal pressure control breath.

The addition of a volume limit should reduce the risk of volutrauma and hyperventilation, but it still does not lead to automatic weaning of inspiratory pressure. No clinical studies at this time validate the performance of this device in newborns. As with the other approaches, the interaction of an actively breathing infant with the device makes achievement of a stable tidal volume much more difficult than in bench tests.

Volume Guarantee (VG)

VG is a volume-targeted, time-cycled, pressure-limited form of ventilation that can be combined with any of the standard ventilator modes (assist control, synchronized intermittent mandatory ventilation, or pressure support ventilation). The operator choses a target tidal volume and selects a pressure limit up to which the ventilator operating pressure (the working pressure) may be adjusted (Fig. 2). The microprocessor compares the tidal volume of the previous breath, using exhaled tidal volume to minimize possible artifact due to air leak, and adjusts the working pressure up or down to try to achieve the set tidal volume. The algorithm limits the amount of pressure increase from one breath to the next to avoid overcorrection leading to excessive tidal volume. This, and use of the exhaled tidal volume of the prior breath, means that very rapid changes in compliance or patient inspiratory effort requires several breaths to reach target tidal volume. To minimize the risk of excessively large tidal volume, the microprocessor opens the expiratory valve, terminating any additional pressure delivery if the delivered tidal volume exceeds 130% of the previous

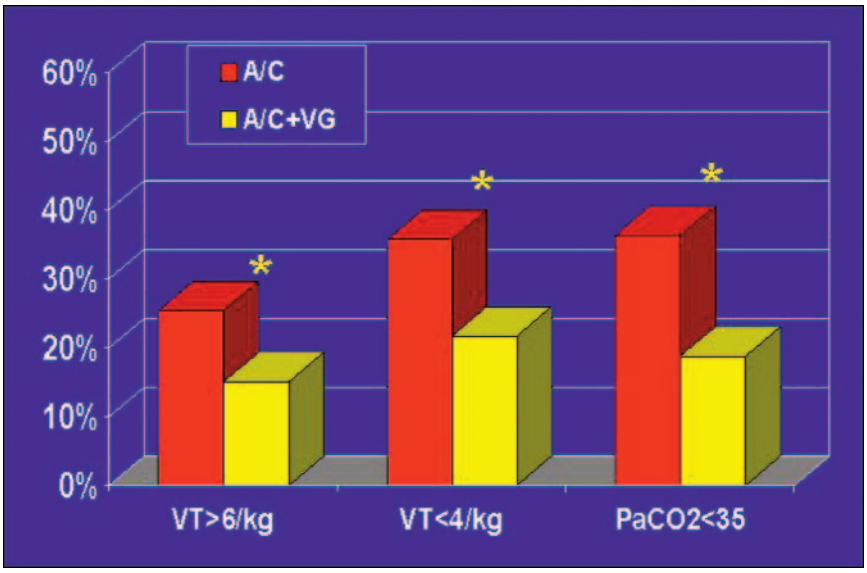

Figure 3. Proportion of breaths with tidal volume above (left panel) and below (middle panel) target range of 4 to 6 mL/kg. The right panel shows proportion of blood gases with $Paco_2$ <35 torr. *=P<0.001. From Keszler M, et al. *Pediatr Pulmonology.* 2004.

breath. By design, the algorithm is geared toward slower adjustment for low tidal volume and more rapid adjustment for excessive, potentially dangerous tidal volume. The autoregulation of inspiratory pressure makes VG a self-weaning mode. Because weaning occurs in real time, rather than intermittently in response to blood gas values, VG has the potential to achieve faster weaning from mechanical ventilation.

Clinical Studies of Volume-targeted Ventilation

PRVC

D'Angio and colleagues studied 212 preterm infants (birthweight of 500 to 1,249 g) requiring mechanical ventilation to test the hypothesis that PRVC would increase the proportion of very low-birthweight infants who were alive and extubated at 14 days of age compared with pressure-limited synchronized intermittent mandatory ventilation (SIMV). Infants received their assigned mode of ventilation until extubation, death, or meeting predetermined failure criteria. Mean birthweights were similar in the SIMV (888±199 g) and PRVC (884±203 g) groups. No differences were detected between SIMV and PRVC groups in the proportion of infants alive and extubated at 14 days (41% versus 37%), length of mechanical ventilation in survivors (median, 24 d versus 33 d), or the proportion of infants alive without a supplemental oxygen requirement at 36 weeks' postmenstrual age (57% versus 63%). The authors concluded that PRVC offered no demonstrable advantage over SIMV.

VG

Cheema and colleagues examined the feasibility and efficacy of VG in 40 preterm newborns. In a 4-hour crossover trial, they compared AC with and without VG in infants who had acute RDS and SIMV with and without VG during weaning. In both VG groups, infants achieved equivalent gas exchange using lower peak airway pressure. There were fewer excessively large tidal volumes during the VG periods. The authors concluded that the VG mode was feasible and may offer the benefit of lower airway pressures. Due to the short duration of the study, no major conclusions could be drawn, other than that the ventilator performs as intended and no short-term adverse effects were evident.

Herrera and associates compared the effects of SIMV+VG with conventional SIMV on ventilation and gas exchange in a group of very low-birthweight infants recovering from acute respiratory failure. Short-term use of SIMV+VG resulted in automatic reduction of mechanical support and enhancement of spontaneous respiratory effort while maintaining gas exchange relatively unchanged compared with conventional SIMV. Further shifting of the work of breathing to the patient was observed when the target tidal volume was reduced from the normal 4.5 mL/kg to 3 mL/kg. The proportion of excessively large breaths more than 7 mL/kg was reduced from 16% with SIMV to 6% with VG. The study further confirmed the short-term benefit and potential of VG. It should be pointed out that excessive reduction of target tidal volume below a physiologically appropriate value is likely to impose excessive work of breathing on the infant, eventually leading to fatigue and atelectasis. As long as the target tidal volume is low enough to stimulate the infant's respiratory drive, self-weaning of inspiratory pressure will occur.

In a small prospective clinical trial involving 34 relatively large preterm infants (mean birthweight, 1,122 g), Nafday compared SIMV and PSV+VG over the first 24 hours after birth. There was no difference in time to

extubation or other important clinical outcomes, but this "pilot" study lacked adequate statistical power. The authors noted that mean airway pressure declined more rapidly in the SIMV group, but this is simply the result of lowering the ventilator rate with SIMV. There was no difference in the rate of decline of peak pressure. Significantly fewer blood gas measurements were needed in the VG group.

We earlier showed that VG combined with AC, SIMV, or pressure support ventilation (PSV) in a short-term crossover study led to significantly lower variability of tidal volume with VG compared with AC or SIMV alone and that peak inspiratory pressures (PIPs) were similar. In a small, randomized clinical trial, we subsequently demonstrated that VG combined with the AC mode maintained $PaCO_2$ and tidal volume within a target range more consistently than AC alone during the first 72 hours after birth in preterm infants who had uncomplicated RDS (Fig. 3). The first study documented that the VG mode functions as intended in the clinical setting, with the anticipated reduction of tidal volume variability. The prospective trial demonstrated that excessively large tidal volume and hypocarbia could be reduced, although not eliminated, with the use of VG, which suggests the potential of VG to reduce many of the important adverse effects of mechanical ventilation.

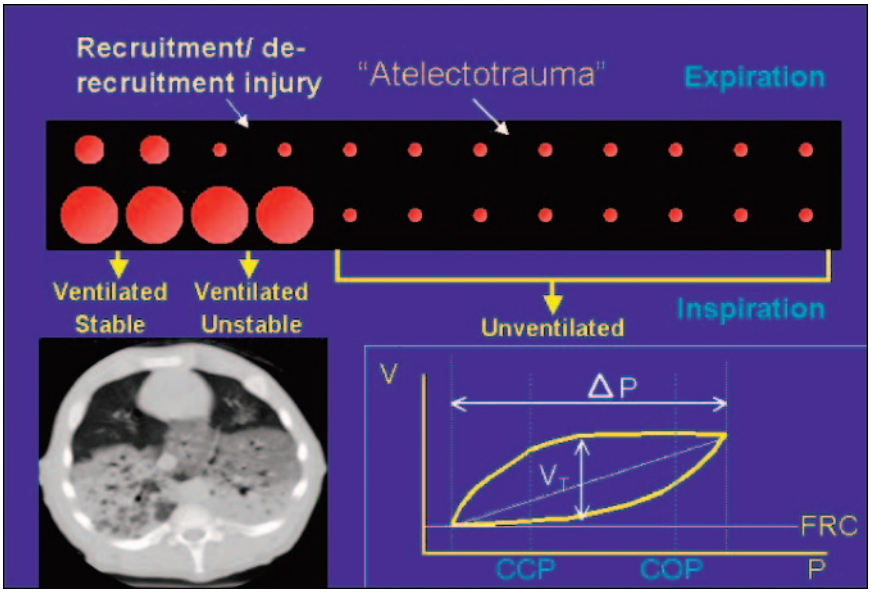

Figure 4. Nonhomogeneous aeration in respiratory distress syndrome. Extensive atelectasis often is present in surfactant-deficient lungs, as illustrated on the computed tomography scan in lower left corner. This situation is represented diagrammatically in the middle panel. The corresponding pressure-volume loop is shown in the lower right portion of the figure. Inadequate oxygenation strongly suggests that atelectasis is present. If this situation is allowed to persist, even a normal, physiologic tidal volume entering the small proportion of open alveoli inevitably leads to overexpansion and damage.

In a short-term crossover trial involving extremely low-birthweight infants (679±138 g), we addressed the question of whether VG is more effective when combined with AC or SIMV. As anticipated, the tidal volume was more stable when VG was combined with AC because fewer mechanical breaths are volume regulated during SIMV. An unanticipated finding was that during SIMV, the infants had lower and more variable oxygen saturation as well as more tachycardia and tachypnea. By design, the tidal volume was identical, but significantly higher PIP was required during SIMV to achieve the same tidal volume. The tachypnea, tachycardia, and lower oxygen saturation suggest that the higher machine PIP was required because the infants were tiring during the SIMV period and contributing less to their ventilation by the end of the 2-hour period when the measurements were obtained. (During synchronized ventilation, the tidal volume is the result of the combined effort of the baby and the ventilator pressure; if the baby contributes less, the ventilator needs to generate higher PIP to deliver the tidal volume.)

Finally, in a small, randomized trial of 53 preterm infants who had RDS, Lista and coworkers demonstrated decreased concentrations of proinflammatory cytokines and a trend toward shorter duration of mechanical ventilation with VG combined with PSV compared with PSV alone when using a target tidal volume of 5 mL/kg. These data clearly support the hypothesis that volume-targeted ventilation is capable of reducing ventilator-induced lung injury, which is believed to be mediated by the release of proinflammatory cytokines in a process known as biotrauma.

Interestingly, a subsequent similar study by the same authors using a target tidal volume of 3 mL/kg showed an *increase* in proinflammatory cytokines, most likely as a consequence of atelectasis that resulted from the combination of low tidal volume and low end-expiratory pressure of 3 to 4 cm H_2O that was used.

Table. Volume Guarantee: Clinical Guidelines

Initiation:

- Volume guarantee should be implemented as soon as possible after initiation of mechanical ventilation because this is the time when most rapid changes in lung compliance occur.
- Assist control or pressure support are preferred as the basic mode rather than synchronized intermittent ventilation.
- The usual starting target tidal volume is 4.5 mL/kg during the acute phase of respiratory distress syndrome in most infants. Babies whose birthweights are less than approximately 750 g require 5 to 6 mL/kg because the modest additional dead space of the flow sensor becomes proportionally more important in the smallest infants.
- Larger tidal volume is needed in older infants who have chronic lung disease because of increased anatomic dead space due to stretching of the trachea (acquired tracheomegaly) and increased physiologic dead space (wasted ventilation due to poor ventilation/perfusion matching).
- The peak inspiratory pressure (PIP) should be set initially at about 5 cm H_2O above that estimated to be sufficient to deliver a normal tidal volume. If the target tidal volume cannot be reached with this setting, increase the pressure limit until the desired tidal volume is generated. (Be sure the endotracheal tube is not in the mainstem bronchus or obstructed on the carina!)
- Once the working pressure stabilizes, set the pressure limit 15% to 20% above the working pressure displayed on the front panel to give the device adequate room to adjust PIP.
- It is important to chart not only the PIP limit, but also the working pressure, so the level of support the infant actually is receiving is clear.

Subsequent Adjustments:

- Subsequent adjustment to target tidal volume may be needed, based on $Paco_2$. (This is seldom necessary). The usual increment is 0.5 mL/kg.
- The PIP limit needs to be adjusted occasionally (usual increment, 2 to 3 cm H_2O) to keep the PIP limit sufficiently close to the working pressure while avoiding frequent alarms.
- **Note:** If the flow sensor is temporarily removed (such as around the time of surfactant administration or delivery of nebulized medication), if its function is affected by reflux of secretions or surfactant, or if it malfunctions for any reason, the working pressure defaults to the PIP limit. Therefore, it is important to keep the PIP limit sufficiently close to the working pressure to avoid volutrauma. Ideally, when removing the flow sensor for significant periods, such as when nebulizing medications, the PIP should be adjusted to match the average or recent working pressures.
- If tachypnea persists (respiratory rate, >80 breaths/min), consider increasing the tidal volume target, even if the $Paco_2$ and pH are normal, because the tachypnea suggests that the infant's work of breathing is excessive. In this situation, the infant often generates a tidal volume greater than the set target. (However, if the $Paco_2$ is low and the respiratory rate is high, sedation may be indicated).
- If the pressure limit must be increased substantially or repeatedly, verify that the tidal volume measurement is accurate (assess chest rise, obtain a blood gas measurement), and if true, seek the cause of the change in lung mechanics (examine the patient, obtain chest radiograph).

Alarms/Troubleshooting:

- The volume guarantee option may generate additional arms, which may prove annoying if excessive. Unnecessary alarms can be avoided by optimizing settings and alarm limits. The alarms are generated because the device, in volume guarantee mode, provides feedback as to whether the patient is receiving the desired level of ventilator support. Significant fall in lung compliance, decreased spontaneous respiratory effort, impending accidental extubation, and forced exhalation episodes all generate "low tidal volume" alarms. When used properly, such information should improve care in the most vulnerable infants. It is important to evaluate the cause of the alarms and correct any correctable problems. A large leak results in underestimation of delivered tidal volume and triggers the low tidal volume alarm when the device is unable to reach the target tidal volume at the set PIP limit. When the leak exceeds about 40%, the volume guarantee mode no longer functions reliably due to inability to measure tidal volume accurately.
- **Use of longer alarm delay settings, appropriate pressure limit settings, avoidance of large leak around endotracheal tubes, and adequate physical comfort measures or sedation minimize alarms.**
- If the low tidal volume alarm sounds repeatedly in the absence of excessive leak, increase the pressure limit and investigate the cause of the change in lung mechanics (eg, atelectasis, pneumothorax, pulmonary edema).

(continued)

Table. Volume Guarantee: Clinical Guidelines—Continued

Weaning:

- When the target tidal volume is set at the low end of the normal range (usually 4 mL/kg) and $Paco_2$ is allowed to rise to the low to mid-40s, weaning occurs automatically ("self-weaning").
- For infants who have chronic lung disease, a higher tidal volume should be used even during weaning. Self-weaning occurs as long as the pH is low enough to give the infant respiratory drive.
- If the tidal volume is set too high or the $Paco_2$ is too low, the baby will not have a respiratory drive and will not "self-wean." Instead, the baby will become dependent on the ventilator due to lack of respiratory muscle training.
- Avoid oversedation during the weaning phase.
- If an infant appears not to be weaning as expected, despite apparently improving lung disease, try lowering the tidal volume to 3.5 mL/kg, as long as blood gases are adequate and the work of breathing does not appear excessive.
- If significant oxygen requirement persists, positive end-expiratory pressure may need to be increased to maintain mean airway pressure as PIP is automatically lowered.
- Most infants can be extubated when they consistently maintain tidal volume at or above the target value with delivered PIP <10 to 12 cm H_2O (<12 to 15 cm H_2O in infants >1 kg), with Fio_2 <0.35 and good sustained respiratory effort.
- Observing the graphic display of the delivered PIP is helpful in assessing for periodic breathing (variable respiratory effort) that may require methylxanthine administration to facilitate extubation.

Importance of Open Lung Strategy

As a result of the overwhelming evidence that excessive tidal volume, rather than high inspiratory pressure, is the primary determinant of lung injury, most clinicians now at least monitor the delivered tidal volume when using pressure-limited ventilation or one of the forms of volume-targeted ventilation. The critical importance of distributing the tidal volume evenly into an optimally aerated lung has not been as widely appreciated and requires special emphasis. As can be seen in Figure 4, if extensive atelectasis is allowed to persist, the normal, physiologic tidal volume entering the small proportion of open alveoli inevitably leads to overexpansion of the relatively healthy portion of the lung, with subsequent volutrauma/biotrauma. The collapsed portion of the lung is also damaged with a process for which the term "atelectotrauma" has been coined. Exudation of protein-rich fluid with increased surfactant inactivation and release of inflammatory mediators has been documented. The benefits of volume-targeted ventilation cannot be realized without ensuring that the tidal volume is distributed evenly throughout the lungs.

In practical terms, optimization of lung inflation, referred to as the "open lung concept," is achieved by applying adequate positive end-expiratory pressure (PEEP). For a variety of reasons, including poorly conceived animal studies in which moderate-to-high levels of PEEP were applied to animals that had normal (ie, very compliant) lungs, resulting in significant hemodynamic impairment, there is widespread fear of using adequate levels of PEEP. This fear has been difficult to overcome and may be one of the most important obstacles to optimization of ventilatory support. It is important to understand that there is no single "safe" PEEP level. Rather, optimal end-expiratory pressure must be tailored to the degree of lung injury (ie, lung compliance). For infants who have no lung disease and, thus, normal lung compliance, a PEEP of 3 cm H_2O is probably appropriate, and a PEEP of 5 cm H_2O may result in overexpansion of the lungs, with impairment of venous return, elevated cerebral venous and systemic venous pressures, and decreased cardiac output. On the other hand, severely atelectatic, poorly compliant lungs may require PEEP levels as high as 8 to 10 cm H_2O or more to achieve adequate lung volume and improve the ventilation/perfusion ratio. Because we seldom ventilate infants with healthy lungs, a PEEP of less than 5 cm H_2O should be the exception rather than the rule.

Clinical guidelines for use of the VG mode used in our institution are provided in the Table. These guidelines are based on sound pathophysiologic principles, our clinical experience with this mode of ventilation in hundreds of patients over more than 5 years of use, and available clinical research. However, these are only guidelines; individual patients may require modification of this approach to tailor the treatment to their specific needs and circumstances.

Conclusion

VG ventilation has been demonstrated to function as intended and to lead to more stable tidal volume, with a lower incidence of hypocarbia and excessively large tidal volumes. When combined with other lung-protective strategies aimed at optimizing lung volume and ensuring

even distribution of tidal volume, the technique appears to offer the best hope of making a significant impact on ventilator-induced lung injury. However, the development of chronic lung disease in extremely preterm infants is multifactorial. The degree of prematurity and presence of intrauterine inflammation have a very large effect that is likely to dwarf any impact of ventilation strategy. Thus, it will be difficult to demonstrate substantial differences in chronic lung disease; large multicenter studies involving 500 to 800 infants are needed to have sufficient statistical power. Because of the self-weaning nature of VG, more rapid weaning from mechanical ventilation is likely to be an easier endpoint to demonstrate.

Suggested Reading

Abubakar K, Keszler M. Effect of volume guarantee combined with assist/control vs synchronized intermittent mandatory ventilation. *J Perinatol*. 2005;25:638–642

Abubakar KM, Keszler M. Patient-ventilator interactions in new modes of patient-triggered ventilation. *Pediatr Pulmonol*. 2001; 32:71–75

Cannon ML, Cornell J, Tripp-Hamel DS, et al. Tidal volumes for ventilated infants should be determined with a pneumotachometer placed at the endotracheal tube. *Am J Respir Crit Care Med*. 2000;162:2109–2112

Cheema IU, Ahluwalia JS. Feasibility of tidal volume-guided ventilation in newborn infants: a randomized, crossover trial using the volume guarantee modality. *Pediatrics*. 2001;107: 1323–1328

Chow LC, Vanderhal A, Raber J, Sola A. Are tidal volume measurements in neonatal pressure-controlled ventilation accurate? *Pediatr Pulmonol*. 2002;34:196–202

Clark RH, Slutsky AS, Gertsmann DR. Lung protective strategies of ventilation in the neonate: what are they? *Pediatrics*. 2000;105: 112–114

Dreyfuss D, Saumon G. Ventilator-induced lung injury: lessons from experimental studies. *Am J Respir Crit Care Med*. 1998; 157:294–323

Dreyfuss D, Soler P, Basset G, et al. High inflation pressure pulmonary edema: respective effects of high airway pressure, high tidal volume, and positive end-expiratory pressure. *Am Rev Respir Dis*. 1988;137:1159–1164

Fujimoto S, Togari H, Yamaguchi N, et al. Hypocarbia and cystic periventricular leukomalacia in premature infants. *Arch Dis Child*. 1994;71:F107–F110

Graziani LJ, Spitzer AR, Mitchell DG, et al. Mechanical ventilation in preterm infants. Neurosonographic and developmental studies. *Pediatrics*. 1992;90:515–522

Herrera CM, Gerhardt T, Claure N, et al. Effects of volume-guaranteed synchronized intermittent mandatory ventilation in preterm infants recovering from respiratory failure. *Pediatrics*. 2002;110:529–533

Keszler M, Abubakar KM. Volume guarantee: stability of tidal volume and incidence of hypocarbia. *Pediatr Pulmonol*. 2004; 38:240–245

Lista G, Colnaghi M, Castoldi F, et al. Impact of targeted-volume ventilation on lung inflammatory response in preterm infants with respiratory distress syndrome. *Pediatr Pulmonol*. 2004;37: 510–514

Slutsky AS. Ventilator-induced lung injury: from barotrauma to biotrauma. *Respir Care*. 2005;50:646–59

Wiswell TE, Graziani LJ, Kornhauser MS, et al. Effects of hypocarbia on the development of cystic periventricular leukomalacia in premature infants treated with high-frequency jet ventilation. *Pediatrics*. 1996;98:918–924

Additional Reading

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

Lista G, Castoldi F, Fontana P, et al. Lung inflammation in preterm infants with respiratory distress syndrome: effects of ventilation with different tidal volumes. *Pediatr Pulmonol*. 2006;41: 357–363

Nafday SM, Green RS, Lin J, Brion LP, Ochshorn I, Holzman IR. Is there an advantage of using pressure support ventilation with volume guarantee in the initial management of premature infants with respiratory distress syndrome? A pilot study. *J Perinatol*. 2005;25:193–197

NeoReviews Quiz

7. With advances in neonatal care, including technologic advances related to mechanical ventilation, the survival of extremely preterm neonates has improved in recent years. However, chronic lung disease has emerged as a major cause of morbidity among the preterm survivors, which has led to innovations in mechanical ventilation as a means of reducing lung injury. Of the following, the *most* critical determinant of ventilator-induced lung injury in preterm neonates is excessive:

   A. Airway pressure.
   B. Gas flow.
   C. Oxygen concentration.
   D. Tidal volume.
   E. Time constant.

8. A 2-week old preterm neonate, whose estimated gestational age at birth was 30 weeks, is experiencing recurrent episodes of apnea. The infant is well-oxygenated in room air between episodes and has no clinical or radiographic evidence of lung disease. Mechanical ventilation using the strategy of volume guarantee is started. Of the following, the *most* appropriate positive end-expiratory pressure in this infant who has normal lung compliance is:

   A. 0 cm H_2O.
   B. 3 cm H_2O.
   C. 5 cm H_2O.
   D. 8 cm H_2O.
   E. 10 cm H_2O.

Volume-targeted Ventilation

Martin Keszler

Neoreviews 2006;7;e250
DOI: 10.1542/neo.7-5-e250