Optimal Ventilation of the Anesthetized Pediatric Patient

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Mechanical ventilation of the pediatric patient is challenging because small changes in delivered volume can be a significant fraction of the intended tidal volume. Anesthesia ventilators have traditionally been poorly suited to delivering small tidal volumes accurately, and pressure-controlled ventilation has become used commonly when caring for pediatric patients. Modern anesthesia ventilators are designed to deliver small volumes accurately to the patient’s airway by compensating for the compliance of the breathing system and delivering tidal volume independent of fresh gas flow. These technology advances provide the opportunity to implement a lung-protective ventilation strategy in the operating room based upon control of tidal volume. This review will describe the capabilities of the modern anesthesia ventilator and the current understanding of lung-protective ventilation. An optimal approach to mechanical ventilation for the pediatric patient is described, emphasizing the importance of using bedside monitors to optimize the ventilation strategy for the individual patient. (Anesth Analg 2015;120:165–75)

HISTORICAL PERSPECTIVE

In 1963, Bendixen et al. published a study in the New England Journal of Medicine that set the stage for the approach to mechanical ventilation in surgical patients for the next 40 years. Those authors studied oxygenation during surgery in 18 adult patients undergoing laparotomy procedures. The patients received pressure-targeted ventilation between 15 and 20 cm H2O, and the authors found that both arterial Po2 and lung compliance decreased over time, but the changes could be reversed with hyperinflations up to 40 cm H2O sustained for 15 seconds. The authors concluded, “Large tidal volumes appear to protect against falls in oxygen tension, presumably by providing continuous hyperinflation.” In retrospect, it is clear that this was one of the earliest studies on the use of a recruitment maneuver to reverse atelectasis and improve gas exchange. However, at the time, the study served as the basis for the longstanding recommendation to use larger-than-normal tidal volumes in the range of 10 to 12 mL/kg when ventilating the lungs of the anesthetized patient. Indeed, using a larger-than-normal tidal volume when ventilating the anesthetized patient’s lungs has only recently been called into question.

Pediatric anesthesiologists embraced the concept of a volume target but found it difficult to achieve in pediatric patients with existing anesthesia ventilator technology. Circuit compliance and fresh gas flow both influenced tidal volume delivered by an anesthesia ventilator, preventing consistent delivery of a precise volume (Fig. 1). It became common to adjust the ventilator by observing the chest excursion until the delivered volume looked proper, or using an “educated hand” on the bag to manually assess the relationship between pressure and tidal volume. This approach to ventilation in the operating room using clinical assessment recognized the fact that the tidal volume set to be delivered to the patient by the ventilator would not necessarily be the tidal volume delivered to the airway, and further, that it was difficult to measure small tidal volumes accurately.

Because the traditional anesthesia ventilator was not designed to be able to deliver small tidal volumes to the patient’s airway accurately, pediatric anesthesiologists ultimately adopted pressure-controlled ventilation (PCV) rather than volume-controlled ventilation (VCV). PCV was...
advantageous because the factors that made it difficult to deliver a small tidal volume accurately no longer mattered. The tidal volume that results from a pressure-targeted breath is purely attributable to the set inspiratory pressure and the patient’s lung–thorax compliance. Circuit compliance, fresh gas flow changes, and even small leaks around an uncuffed endotracheal tube do not alter the delivered tidal volume. Although PCV addresses many limitations of the typical anesthesia ventilator and breathing circuit, the problem with PCV is that consistent tidal volumes are not guaranteed. Any change in lung–thorax compliance alters tidal volume. Surgical procedures in the abdomen or thorax and especially laparoscopic procedures are likely to be associated with changes in effective lung–thorax compliance and therefore fluctuation in delivered tidal volumes. In small patients, these tidal volume fluctuations can be a significant deviation from the intended tidal volume. Fortunately, the technology available to support mechanical ventilation in the operating room is much better suited to accurate small volume delivery than ever before, and it is capable of supporting patients with significant comorbidities undergoing complex procedures.

THE MODERN ANESTHESIA VENTILATOR

As a component of the anesthesia machine, the anesthesia ventilator must be able to support both mechanical ventilation and anesthetic drug delivery. Although there has been little change in the manner in which anesthetic drugs are delivered, the mechanical ventilation capabilities have evolved significantly in recent years. The focus of design changes to the anesthesia ventilator has been to improve the accuracy and precision of volume delivery so that the set tidal volume is delivered to the patient’s airway. Manufacturers have also focused on providing a selection of ventilation modes in an effort to reproduce the functionality of an intensive care unit (ICU)-type ventilator.

As noted previously, the biggest obstacles to delivering the set tidal volume to the patient’s airway accurately are the compliance of the breathing system and the interaction between fresh gas flow and tidal volume. Technology advances have been focused on methods that allow the ventilator to compensate for the compliance of the breathing system, and also to eliminate the interaction between fresh gas flow and delivered tidal volume. The manner in which each ventilator achieves these goals varies depending upon the underlying technology. The currently available anesthesia ventilators include pneumatically powered ventilators, for example, the classic bellows designs and the volume reflector, and also electrically powered ventilators using either a piston or a turbine. It is beyond the scope of this review to detail the engineering solution to compliance and fresh gas compensation for each type of ventilator. There are no studies comparing the performance of each ventilator in pediatric surgical patients, but published specifications are a guide to the capabilities of the device. All of the major manufacturers of anesthesia ventilators for sale in the United States offer devices with specifications suitable for pediatric patients.

For purposes of this review, and to illustrate the concepts underlying compliance and fresh gas flow compensation, one example will be reviewed. Again, the primary goal of these design features is to ensure that the volume set to be delivered is delivered to the patient’s airway. The breathing circuit compliance is expressed in mL/cm H₂O and can be multiplied by inspiratory pressure to quantify the influence of system compliance on delivered tidal volume. For example, in a typical anesthesia machine, the compliance of the system between the ventilator and the patient might be 5 mL/cm H₂O and can be multiplied by inspiratory pressure to quantify the influence of system compliance on delivered tidal volume. For example, in a typical anesthesia machine, the compliance of the system between the ventilator and the patient might be 5 mL/cm H₂O. If the inspiratory pressure is 20 cm H₂O, 100 mL of volume will not reach the patient. In an adult patient, this approaches 20% of the intended volume and significantly more in smaller patients. Overall breathing circuit compliance is attributable to the compression of gas within the breathing system and the distensibility of the circuit tubing. The compliance related to gas compression depends upon the volume of gas between the ventilator and the patient and the peak inspiratory pressure. As pressure increases during inspiration, gas is compressed within the breathing circuit, and a portion of the volume delivered by the ventilator does not reach the patient. Gas composition, altitude, and temperature also influence the amount of gas
compression, but to a much smaller degree than the internal volume of the circuit. With most modern breathing circuits, tubing distensibility is a much smaller factor influencing tidal volume than gas compression.

Compliance compensation is the feature that allows the modern anesthesia ventilator to compensate for breathing circuit compliance. The pre-use leak and compliance test is essential to compliance compensation. During that test, the end of the breathing circuit is occluded while the ventilator delivers enough volume to increase the pressure within the circuit to a specific value. The volume required to achieve the specific pressure is measured, and the compliance factor becomes the ratio of that volume to the pressure achieved. Once the compliance factor is measured, it is used during volume-targeted ventilation modes to allow the ventilator to provide additional volume to compensate for volume losses such that the set volume is delivered to the patient's airway (Fig. 2). Once measured, the compliance factor is not determined again until the next pre-use compliance test is performed.

Independence of tidal volume from fresh gas flow is accomplished differently by each manufacturer. In some cases, a valve closes during inspiration between the ventilator and the fresh gas inflow, preventing fresh gas from entering the breathing circuit during inspiration. In other cases, a flow sensor detects changes in fresh gas flow and can provide that information to the ventilator to adjust delivered volume accordingly. In general, anesthesia ventilators that require a pre-use leak and compliance test during which the end of the circuit is occluded for the test are designed to provide compliance and fresh gas flow compensation in an effort to ensure accurate volume delivery. Although testing has not been performed on all available anesthesia ventilators, data suggest that different designs are equally effective for ensuring that the set tidal volume is delivered to the patient's airway even at smaller tidal volumes. Most modern anesthesia ventilators have minimal tidal volume specifications of 20 mL, and the exact value is published by each manufacturer for each device.

Compliance compensation is, without question, a major advance in the ability of anesthesia ventilators to deliver the set tidal volume to the patient's airway. However, it is essential that the pre-use test be done each time the circuit is changed or altered and that the breathing circuit be configured before the pre-use test in the exact configuration that it will be used for the procedure. All components (e.g., humidifiers) must be in the circuit, and if the circuit is expandable, the length required for the procedure should be set before the leak and compliance test is completed. Alterations in the breathing circuit after the leak test will influence the accuracy of volume delivered to the patient's airway. Any increase in circuit compliance, such as expanding the circuit or adding a humidifier after the pre-use test, will lead to smaller volumes delivered than expected. Any decrease in circuit compliance that occurs after the pre-use test, such as replacing an adult circuit with a lower compliance pediatric circuit without redoing the test, will lead to larger volumes delivered to the patient than expected. There are some safeguards to prevent patient injury from excessive tidal volume if the circuit compliance is less than the value determined during the pre-use check. Setting a pressure limit on the ventilator will also help to protect the patient from excessive volumes. Ventilators designed with compliance compensation will also typically have some limitation on the total volume that can be added to compensate for compliance.

The ability to provide small tidal volumes to the patient's airway accurately and reliably is a major improvement in the ventilators available to the pediatric anesthesiologist. This technological advance comes at a good time because we are learning that control of tidal volume is important for preventing ventilator-induced lung injury.

**LUNG-PROTECTIVE VENTILATION AND THE PEDIATRIC SURGICAL PATIENT**

Lung-protective ventilation refers to a strategy whereby positive end-expiratory pressure (PEEP) is used to prevent...
atelectasis and tidal volume is limited to avoid overdistending the lung. There are no studies documenting the relationship between the approach to mechanical ventilation in the operating room and outcome specifically in pediatric patients. As is often the case, the adult literature serves as a guide to pediatric practice, and current evidence supports the use of a lung-protective ventilation strategy, especially in patients at risk for postoperative complications.

Although lung-protective ventilation has been studied for some time, the relationship with improved outcome was clearly established in adult ICU patients with acute respiratory distress syndrome (ARDS). In this prospective study, patients meeting criteria for ARDS were randomized to traditional tidal volumes of 12 mL/kg or small tidal volumes of 6 mL/kg. The study was stopped after it was clear that patients in the lower tidal volume group had improved mortality at 28 days and fewer days requiring mechanical ventilation. Additional studies have confirmed the improved mortality at 28 days, and despite the lack of long-term outcome data, the practice of low-volume lung-protective ventilation has become well established in the treatment of ARDS.

How can we relate the data from adult ICU patients with ARDS to pediatric surgical patients? Evidence from adult surgical patients has been accumulating to indicate that in certain high-risk populations, a lung-protective ventilation strategy in the operating room can reduce the risk of postoperative complications. A review of all the studies in this area is beyond the scope of this article, but once again, a recent publication in the *New England Journal of Medicine* is useful to guide our practice in the operating room. In this study, Futier et al. randomized patients undergoing abdominal surgery to tidal volumes of 12 mL/kg of predicted body weight without PEEP or 6 to 8 mL/kg with PEEP and recruitment maneuvers. Patients in the small tidal volume group experienced fewer postoperative complications and shorter length of stay than the patients in the other group. In the absence of similar data in pediatric surgical patients, we must turn to evidence from other pediatric populations to gain insight into the role of lung-protective ventilation for pediatric patients in the operating room.

Neonatologists have a significant investment in preventing lung injury, yet definitive evidence from the neonatology literature on the best approach to lung-protective ventilation remains elusive. Extremely premature infants have lungs that are both structurally and biochemically immature and therefore particularly vulnerable to injury. In a recent review of ventilation in extremely premature infants, Dargaville and Tingay stratified these patients into: those with vulnerable lungs but no respiratory distress syndrome (RDS); those with RDS; and those with sufficient pulmonary hypoplasia for which gas exchange is barely compatible with life. Often, the RDS and pulmonary hypoplasia patients are managed with high-frequency oscillatory ventilation so that when anesthesia care is required, the mechanical ventilation strategy is already determined. Those infants with vulnerable lungs but no RDS who require anesthetic care need special attention to mechanical ventilation. Even short periods of overdistention are likely to cause lung injury and increase the likelihood of RDS and long-term bronchopulmonary dysplasia. The lung-protective ventilation strategy advocated by Dargaville and Tingay is analogous to strategies advocated for adult patients, namely, “setting end-expiratory pressure at the lowest value that maintains oxygenation and restricting tidal volume using a volume targeted mode of ventilation.” Principles include using PEEP to prevent atelectasis and limiting tidal volume to avoid overdistention. Although there remains some controversy over the best tidal volume and PEEP to use for lung protection, a meta-analysis concluded that lung-protective ventilation using volume-targeted ventilation for infants younger than 28 days corrected age can reduce the incidence of bronchopulmonary dysplasia and death compared with pressure-limited ventilation.

Although we are missing data in pediatric surgical patients that relate the approach to mechanical ventilation to outcome, evidence from adult surgical patients and neonates suggests that a lung-protective ventilation strategy is beneficial. A strategy relies upon a tidal volume target in the range of 6 to 7 mL/kg of predicted body weight, the use of PEEP to prevent atelectasis, and recruitment maneuvers as needed to reverse atelectasis. Modern anesthesia ventilators make it possible for clinicians to deliver small tidal volumes accurately and therefore implement a lung-protective, volume-targeted ventilation even for pediatric patients. Implementing such a strategy safely and effectively requires selecting the ventilation mode and monitoring the interaction between the ventilator and the patient to optimize the ventilator settings.

**SELECTING THE VENTILATION MODE**

Modern anesthesia ventilators offer a variety of ventilation modes. One can select pressure or volume-controlled modes, pressure support when the patient is breathing spontaneously, and hybrid modes that provide a synchronized mandatory minute ventilation in addition to pressure support. All of these modes are potentially useful for the pediatric surgical patient, but one must understand the benefits and limitations of each when selecting a ventilation mode and adjusting the ventilator settings.

**Controlled Ventilation Modes**

PCV is commonly used in pediatric anesthesia practice. In this mode of ventilation, once the inspiratory pressure, inspiratory time (i-time), and respiratory rate (RR) are set, the ventilator will deliver a constant pressure for the entire i-time and repeat that waveform at the set RR. As noted previously, PCV has been adopted for pediatric patients in part because delivered volume is independent from circuit compliance and fresh gas flow. PCV offers 3 other advantages when compared with VCV.

1. The resulting square wave pressure waveform provides the maximum inspiratory pressure for the entire i-time favoring lung recruitment. Said another way, when compared with VCV, the pressure required to overcome resistance is rapidly generated by the high inspiratory flow and most of the area under the pressure-time plot is available to fill the lung (Fig. 3A).
2. The maximum volume of the ventilator (typically 1.5 L) is available to develop the set pressure so that
even in the presence of small leaks (e.g., around an uncuffed endotracheal tube or bronchopleural fistula), the desired tidal volume can be delivered.

3. The maximum inspiratory pressure is limited, thereby preventing barotrauma.

The primary disadvantage of PCV is the lack of a volume guarantee. Any changes in lung–thorax compliance will alter tidal volume. The lack of a volume guarantee is a decided disadvantage to PCV when pursuing a lung-protective ventilation strategy, especially in small patients. Because the desired tidal volume range is narrow, it does not take much tidal volume change in a small patient to either exceed or fall below the desired tidal volume.

Classic VCV involves setting the desired tidal volume, the i-time (or I:E ratio), and RR. The ventilator then provides a square wave flow waveform, with flow rate determined by the ratio of the set tidal volume to the i-time. Because flow is constant, the peak pressure is achieved at the end of inspiration when the total tidal volume is delivered (Fig. 3B). Although volume is guaranteed during VCV, pressure will vary with lung compliance. Preventing the potential for barotrauma can be accomplished by setting a maximum pressure limit. As the breath is delivered, if the maximum pressure limit is reached, the ventilator will cease to deliver volume so that the set tidal volume will not be delivered. Therefore, the pressure limit is useful for preventing transient increases in pressure beyond the set limit from an abrupt change in lung compliance (e.g., cough), but it is not useful as a breath-to-breath ventilation strategy.

The good news is that volume specifications for modern anesthesia ventilators allow for providing small tidal volumes, typically 20 mL, and in some cases, as low as 5 mL. Specifications for minimum tidal volumes of 20 mL allow for lung-protective VCV in patients as small as 3 kg.

In both PCV and VCV, the ventilator only responds to the settings selected by the user, and changes in lung compliance are not accommodated by the ventilator and result in changes in volume and pressure. An alternate mode of ventilation available on some ventilators allows the ventilator to measure the patient’s lung compliance on a breath-to-breath basis and determine the pressure required to be given for the set i-time to achieve the set tidal volume. As a result, the ventilator can deliver a square wave pressure waveform like PCV (Fig. 3A), but also ensure that a constant tidal volume is delivered to the patient like VCV. Because there is a volume target, pressure
will change if lung compliance changes. This mode has different terminology depending upon the manufacturer. Some examples include Pressure Controlled Ventilation–Volume Guarantee (PCV-VG; GE; Madison, WI), Autoflow (Draeger Medical; Luebeck, Germany), Pressure-Regulated Volume Control (Maquet; Rastatt, Germany), and Pressure-Regulated Volume-Targeted Ventilation (PRVT; Spacelabs; Redmond, WA). Unfortunately, this mode lacks a generic descriptive terminology, therefore, for purposes of discussion, we will call it “best-of-both-ventilation” because it incorporates the advantages of VCV and PCV in a single ventilation mode. Because this mode requires that the ventilator measure lung compliance, it may take a few breaths to reach the set tidal volume when first initiated, and delivered volume may fluctuate for a few breaths when lung compliance changes.

The flexibility of ventilator settings can lead to confusion when trying to select the optimal ventilator setting for each patient. The available evidence supports the use of a lung-protective ventilation strategy for patients at risk for postoperative pulmonary complications. It is also a strategy that will be effective for patients with healthy lungs. Control of tidal volume and use of PEEP are key to proper lung-protective ventilation. The smaller the patient, the more important it becomes that tidal volumes be delivered accurately because the target tidal volume is small, and errors can easily lead to inadequate gas exchange. Uncuffed endotracheal tubes can be an impediment to delivering a consistent small tidal volume if some of the delivered volume leaks around the tube, especially if the magnitude of the leak is not constant. Anesthesia ventilators are not designed to detect or compensate for leaks around the endotracheal tube, and a lung-protective ventilation strategy will be easiest to implement using a cuffed tube or an uncuffed tube that does not leak at the inspiratory pressures required for the patient.

When using an anesthesia ventilator with compliance compensation and PEEP capability, VCV or best-of-both-ventilation will support a lung-protective ventilation strategy for pediatric surgical patients. When available, best-of-both-ventilation may be preferred to gain the benefit of the maximum inspiratory pressure for the entire i-time; however, studies of best-of-both-ventilation in neonatal ICU ventilators indicate significant fluctuation in tidal volume if lung compliance or airway resistance changes abruptly. If there is a leak that cannot be eliminated (e.g., uncuffed endotracheal tube), or the desired tidal volume is below the specifications of the ventilator (20 mL for most ventilators), PCV with PEEP would be the better choice, but the delivered volume should be monitored carefully.

**Supported Modes of Ventilation**

The ability to provide pressure support ventilation (PSV) either as an independent mode or mixed with one of the controlled modes noted above is another useful advance available in the modern anesthesia ventilator. The primary advantage is the ability to support spontaneous ventilation with the anesthesia ventilator either alone or in combination with one of the controlled modes of ventilation.

PSV has become well established in the ICU environment as a means to make the ventilator more comfortable, allow for spontaneous ventilation of the intubated patient, and facilitate weaning. The clinical challenges are different in the operating room, yet PSV offers significant clinical advantages for the surgical patient as well. Although there are not many studies of PSV in surgical patients, available evidence in both adults and children indicates that gas exchange is better when PSV is used compared with continuous positive airway pressure. These data speak to the value of PSV to allow patients to breathe spontaneously during anesthesia. Spontaneous ventilation has many clinical advantages, not all of which are yet proven but are physiologically sound. The potential advantages include:

- **Facilitating emergence**: When potent anesthetic vapors are used, minute ventilation is required to eliminate the vapors at the end of the anesthetic. PSV provides greater minute ventilation than spontaneous ventilation alone. Also, continued spontaneous ventilation after extubation is an important goal of safe care. PSV supports spontaneous ventilation while the patient is still intubated by reducing the work of breathing through the endotracheal tube and circuit. If the patient breathes spontaneously for a period of time before extubation, it is more likely that the patient will continue to breathe after the tube is removed.
- **Improved hemodynamics**: This remains to be proved, but because the patient is helping to develop the desired tidal volume, less positive pressure is needed, and venous return should be improved.
- **Assessing depth of anesthesia**: The response of RR to changes in surgical stimulus is one indicator of anesthetic depth/adequacy of analgesia and can be assessed when patients are breathing spontaneously.
- **Titration of opioid analgesia**: Opioids shift the CO2 response curve to the right. During PSV, the patient will breathe at the CO2 threshold for spontaneous ventilation. End-tidal CO2 measurement can indicate this threshold during PSV. A normal or low end-tidal CO2 can indicate inadequate analgesia assuming tidal volume is adequate. An adequate opioid dose for managing moderate to severe pain will shift the CO2 threshold, leading to moderate hypercarbia.

PSV can be used in almost any size patient. Although there are limited data in pediatric surgical patients on the use of PSV, data from the neonatal ICU indicates that up to 60% of patients receive some form of supported ventilation. Because most anesthesia ventilators mimic the specifications of ICU ventilators, PSV, as implemented in many anesthesia ventilators, is suitable for infants. The trigger setting needs to be decreased for small infants, and settings of 1 L/min are typically adequate. There is some risk of auto-triggering at these low settings. Because most PSV modes have the ability to select a backup rate, ensuring that the measured RR exceeds the set backup rate can help to indicate whether the patient is making spontaneous efforts.

**Optimal PEEP**

In general, lung-protective ventilation dictates that sufficient PEEP be administered to prevent atelectasis. During mechanical ventilation in the operating room, atelectasis is a common problem, and it is prudent to use PEEP in
most patients. One recommendation is to set PEEP to 5 cm H2O routinely. In anesthetized patients with healthy lungs, PEEP of 5 cm H2O was successful for preventing the return of atelectasis after an alveolar recruitment maneuver. Studies in anesthetized adults with normal lungs that have shown benefit to lung-protective ventilation have used PEEP settings between 5 and 10 cm H2O. Settings in this range should be safe and prevent atelectasis in most surgical patients. Finding the optimal PEEP can be challenging in patients with RDS. PEEP levels beyond 10 cm H2O are often required, but the actual setting should be dictated by an assessment of oxygenation such as the Pao2/Fio2 ratio or alveolar to arterial oxygen gradient.

If an oxygenation problem develops that is not easily corrected with a recruitment maneuver, PEEP should ultimately be titrated to the patient’s needs by assessing the relationship between inspired oxygen concentration and arterial oxygenation. Although PEEP is well tolerated by most patients, relative contraindications to the use of PEEP include intracranial hypertension, hypovolemia, and bronchopleural fistula.

**Dead Space and the Pediatric Patient**

No discussion of mechanical ventilation for the pediatric patient would be complete without some attention to the implications of equipment dead space. For practical purposes, the dead space volume can be considered as any portion of the breathing circuit or lungs in which there is bidirectional gas flow without gas exchange. Dead space within the lungs consists of anatomic dead space, which is fixed, and alveolar dead space, which may change with alterations in perfusion and ventilation. When using a circle anesthesia breathing circuit, any apparatus connected on the patient side of the y-piece adds to the overall dead space.

Every effort should be made to minimize apparatus dead space, especially when caring for small patients. Mathematical models predict an exponential increase in Paco2 as the dead space to tidal volume (Vd/Vt) ratio increases. Furthermore, as Vd/Vt increases, the gradient between end-tidal and arterial CO2 will increase, and hypercarbia may go undetected.

It has been demonstrated in neonates that end-tidal CO2 increases when CO2 is sampled distal in the endotracheal tube, underscoring the impact of dead space on the end-tidal Paco2 gradient in small patients.

For pediatric patients, small increases in dead space can substantially increase the Vd/Vt ratio. Therefore, attention to the volume added to the circuit is important. Common additions to the circuit include the elbow connector, heat and moisture exchanger (HME), and flexible tubing extensions. These devices have different internal volumes depending upon the devices selected, and when connected together, the aggregate dead space volume can be substantial (Fig. 4). Adding an HME to the circuit has been shown to increase the minute ventilation required to maintain normocarbia in patients younger than 2 years of age. When a patient is anesthetized, it is considered safe practice to sample inhaled and exhaled gas from the breathing circuit to support monitoring gas (O2 and CO2) and vapor concentrations. Therefore, a device that provides a gas sampling connection is required but will add to the dead space. For the smallest patients, if an HME is used to support gas analysis, it is recommended that the most compact HME be used. If a circuit heater humidifier is used, it is typically placed in line with the inspiratory limb, and therefore does not increase dead space. However, the humidifier will increase the internal compliance of the breathing circuit and must be in place when the pre-use compliance test is performed to ensure accurate tidal volume delivery.

**Monitoring to Achieve Optimal Ventilation**

Patient monitors serve a variety of functions, including patient safety, helping to detect undesirable physiologic changes, and supporting titration of therapeutic interventions. The “gold standard” for assessing the efficacy of mechanical ventilation is arterial blood gas analysis. Because of the intermittent nature of arterial blood gas analysis, it cannot be used as a continuous monitor, and because most patients do not have an arterial catheter, it is often simply not available. The commonly used bedside devices germine to respiratory monitoring include pressure and flow sensors for assessing respiratory mechanics and respiratory gas monitors and pulse oximeters for evaluating gas exchange.

Although not as reliable as blood gas information, bedside monitors can be used to guide the clinician to the optimal ventilation strategy. A lung-protective ventilation strategy requires that tidal volume be limited, creating a risk of atelectasis and hypercarbia. The recommended tidal volume is typically 6 to 7 mL/kg of predicted body weight, and PEEP is typically used to reduce the likelihood of atelectasis. Following these recommendations in pediatric patients can be challenging because the exact body weight and the optimal level of PEEP may not be obvious. Bedside monitors are essential for finding an optimal ventilation strategy for an individual patient because ventilator variables can be adjusted based on real-time assessment of ventilation effectiveness and gas exchange.

There are 3 goals for an optimal ventilation strategy, and in each case, bedside monitors can be used to guide the clinician to a ventilation strategy consistent with each goal.
Goal 1: The Optimal Arterial Oxygen Tension (Pao₂) at the Lowest Inspired Oxygen Concentration (FiO₂)

When arterial blood gas analysis is available, this goal is achieved by measuring the Pao₂ and comparing the result with the FiO₂ so that the alveolar to arterial oxygen (A-a) gradient can be assessed and adjustments made to the ventilation strategy as needed. In the absence of blood gas information, the pulse oximeter (Spo₂) becomes the next best tool for assessing oxygenation. Although the value of this monitor cannot be disputed, it is not a useful tool for detecting problems with oxygen exchange in the lung unless the FiO₂ is limited. The pulse oximeter estimates arterial oxyhemoglobin saturation (Spo₂), not the partial pressure of oxygen in arterial blood. When gas exchange is normal, oxyhemoglobin is 100% saturated at an FiO₂ of 21%. If FiO₂ is enriched above 21%, the oxygen saturation can be 100% in the presence of a significant A-a gradient. To use the pulse oximeter to assess the effectiveness of oxygenation, the inspired oxygen concentration must be either limited or periodically reduced. Although there is little need to increase the FiO₂ much more than 21% in many patients, there are clinical situations in which a significantly greater FiO₂ may be desirable. However, it is not necessary to maintain an enriched FiO₂ consistently unless there is a significant ventilation/perfusion abnormality that cannot be reversed. Periodically reducing the FiO₂ to assess the impact on Spo₂ can help to reveal an A-a gradient that could be reduced with lung recruitment and a change in the ventilation strategy. The utility of the relationship between FiO₂ and Spo₂ for finding the best strategy to optimize oxygenation has been demonstrated in clinical studies in adults (Fig. 5). Furthermore, minimizing the FiO₂ based on an Spo₂ target is commonly used in the neonatal ICU to mitigate the adverse effects of enriched oxygen.

If the FiO₂ is limited to 25% or below, a reduced Spo₂ may indicate an oxygenation problem that can be improved by adjusting the ventilator. Atelectasis is the most common cause of impaired oxygenation during anesthesia and can be reduced or eliminated by adjusting tidal volume and/or PEEP and using recruitment maneuvers. Recruitment maneuvers have been implemented with manual positive inspiratory pressure up to 30 or 40 cm H₂O sustained for up to 40 seconds, or using the ventilator to increase inspiratory pressure and PEEP in stepwise fashion. In practice, the relationship between FiO₂ and Spo₂ can be used to guide the recruitment process if FiO₂ is limited. Stepwise increases in inspiratory pressure sustained for progressively longer intervals can be used until the desired increase in Spo₂ is observed. This process of "pressure titration" can often achieve the desired effect without having to sustain the pressure for as long as 30 seconds. One must always consider other important causes of an oxygenation problem, such as endobronchial intubation, before focusing solely on ventilator settings. Maintaining the PEEP setting at 5 cm H₂O or more after successful recruitment is important to sustain the improved oxygenation. Although the Spo₂ can be improved by increasing the inspired oxygen concentration when the underlying problem is ventilation perfusion mismatching, increased oxygen should not be the first step unless there is concern for serious hypoxemia because increasing the FiO₂ will obscure the underlying oxygenation problem.

Figure 5. Relationship between oxygen saturation and FiO₂ during different phases of a thoracotomy procedure. Saturation curves move to the right as ventilation/perfusion relationships become impaired. Shunt reduces the maximum saturation possible because increasing FiO₂ cannot improve shunt. (From Jones JG, Jones SE, Discriminating between the effect of shunt and reduced VA/Q on arterial oxygen saturation is particularly useful in clinical practice, J Clin Monit Comput 2000;16:337–50.)

Goal 2: An Acceptable Arterial Carbon Dioxide Tension (Paco₂)

Absent blood gas analysis, capnography is the most available bedside surrogate for assessing the arterial carbon dioxide tension (Paco₂). Although end-tidal CO₂ is often a close approximation of Paco₂, it cannot be used as a reliable quantitative indicator. There is always a gradient between end-tidal and arterial CO₂ and the magnitude of that gradient cannot be predicted with certainty. In particular, as the tidal volume decreases, or dead space increases, the gradient between end-tidal and arterial CO₂ will increase so that it is possible to have a normal end-tidal CO₂ along with significant hypercarbia.

When using lung-protective ventilation in small patients, there is a risk of inadequate tidal volume or an unfavorable VD/Vt ratio, causing a larger than normal difference between Paco₂ and end-tidal CO₂. A larger manual breath will typically yield an increase in end-tidal CO₂ if that is the case and indicate the need to alter the ventilation strategy by either increasing the set tidal volume or reducing apparatus dead space. As mentioned previously, when caring for patients with immature lungs, large tidal volumes should be avoided, and it can be difficult to assess ventilation definitively based upon end-tidal CO₂ alone. Fortunately, hypercarbia is typically well tolerated, and accepting hypercarbia can be part of the lung-protective ventilation strategy. When accurate control of Paco₂ is required (e.g., increased intracranial pressure), arterial blood gas analysis is necessary to document effective ventilation.

Goal 3: The Desired Tidal Volume at the Least Inspiratory Pressure

During positive pressure ventilation, the relationship between inspired tidal volume and the pressure generated
is otherwise known as lung compliance. Adverse changes in the lung typically result in reduced lung compliance. In cases of chronic lung disease (e.g., ex-preemies with bronchopulmonary dysplasia), the reduced lung compliance cannot be improved. However, there are reversible causes of reduced lung compliance, most commonly atelectasis, which can be improved upon by optimizing the ventilation strategy. Both pressure and volume monitoring are considered standards of care, and these bedside monitors are useful for assessing the impact of the ventilation strategy on lung compliance.

Modern anesthesia ventilators are equipped with electronic pressure manometers to measure airway pressure. The airway pressure is typically displayed as a continuous waveform. Peak, plateau, and mean airway pressures as well as PEEP are derived from the pressure measurements and displayed to the user (Fig. 6). Pressure in the breathing circuit results from the flow of gas through the resistance of the endotracheal tube plus the volume of gas filling the lung compliance. The true lung compliance, so-called static compliance, can be assessed only in the absence of flow, and as a result, the pressure measurements are influenced by the ventilation mode. When using VCV, an inspiratory pause is required to ensure that flow ceases during the inspiratory cycle. The relationship between plateau pressure and exhaled volume then becomes useful to assess lung compliance. When using a PCV or best-of-both-ventilation with a decelerating flow waveform, most of the volume is delivered in the first part of the breath, and flow is zero by the end of inspiration, therefore, peak and plateau pressure will be identical, and either can be used relative to exhaled volume to assess lung compliance.

The most common approach to volume monitoring in the anesthesia delivery system is to place a flow sensor adjacent to the expiratory valve on the breathing system. There is an important limitation inherent in measuring exhaled volume at the expiratory valve on the anesthesia machine. The flow sensor at that location will measure both exhaled volume from the patient as well as the gas that is released or decompressed resulting from the compliance of the breathing circuit. The result can be an overestimation of the volume the patient actually received. Fortunately, modern anesthesia machines equipped with compliance compensation can use the circuit compliance information to correct the exhaled volume measurement to more closely approximate the volume exhaled by the patient. Lung compliance is calculated as the ratio of exhaled volume to inspiratory pressure. Dynamic compliance is calculated as the exhaled volume divided by the peak pressure. Static compliance is measured in the absence of flow as the ratio of exhaled volume to plateau pressure and is the most accurate reflection of true lung compliance.

Continuous spirometry has been available for many years and has become a more common feature of the modern anesthesia machine. Again, compliance compensation has allowed manufacturers to implement this feature using pressure and flow sensors built into the machine rather than mounted at the patient’s airway. This technology provides a plot of volume versus pressure or the so-called pressure-volume (PV) loop. The PV loop is a continuous, dynamic indicator of lung compliance. Using this bedside technology, it is easier for the clinician to assess changes in lung compliance. A reference or baseline loop can be set, and then, as PEEP is adjusted or recruitment maneuvers used, the resulting impact on lung compliance can be assessed. It is important to recognize that the mode of ventilation will influence how the compliance changes will be reflected in the PV loop (Fig. 7). During VCV and best-of-both-ventilation, because volume is constant, horizontal stretching of the loop to the right indicates reduced lung compliance. During PCV, because pressure is constant, vertical decreases in the loop indicate reduced lung compliance. The PV loop is a useful tool for assessing the impact of changes in ventilation on lung compliance on a breath-to-breath basis in the operating room.

**CONCLUSIONS**

The goal of this review has been to critically evaluate the approach to mechanical ventilation in the pediatric surgical patient in light of advances in modern anesthesia ventilators, current thinking about lung-protective ventilation, and monitoring devices available at the bedside to evaluate the effectiveness of the ventilator settings. There are other relevant topics that were not discussed in detail. Recruitment maneuvers were mentioned briefly and are an important tool for improving gas exchange. Absorption atelectasis was also not discussed, but the literature clearly demonstrates that when 100% oxygen is used, atelectasis will occur, bringing into question the long-established practice of using 100% oxygen during induction and emergence. Finally, the question of whether an ICU ventilator is needed in the
operating room was not explored in detail. Suffice it to say that modern anesthesia ventilators have specifications that approach or equal their ICU ventilator counterparts, and furthermore, anesthesia ventilators have the added advantages of delivering anesthetic drugs and allowing for a rapid transition to manual ventilation at any time without disconnecting the ventilator.

The technological limitations in ventilator design that have historically made it difficult to deliver small tidal volumes accurately and made PCV compelling for pediatric patients are no longer present. The pediatric anesthesiologist using an anesthesia ventilator equipped with compliance and fresh gas compensation can use a volume-targeted mode of ventilation with confidence. Minimal tidal volume specifications as low as 20 mL are common, but the minimal volume should be confirmed for the equipment being used. We are also learning that lung-protective ventilation, consisting of limited tidal volume with PEEP, can improve outcomes in some patient populations, although whether to implement this strategy for all patients remains controversial. We have yet to define the pediatric surgical patients who will benefit from lung-protective ventilation, but it is likely to be useful for patients at risk of lung injury and benign for those who are not. Careful attention to bedside monitors, in particular, the relationship between $F_iO_2$ and $S_pO_2$, will allow the clinician to implement an optimal lung-protective ventilation strategy safely and effectively for all patients.

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REFERENCES
15. Jaber S, Tassaux D, Sebbane M, Dzoljic M, Vroom MB, Schultz MJ. Pressure support ventilation versus continuous positive airway pressure ventilation with the ProSeal laryngeal mask airway: a randomized controlled study in adult and pediatric patients. Anesthesiology 2008;109:494–52
24. McSwain SD, Hamel DS, Smith PB. End-tidal and arterial carbon dioxide measurements correlate across all levels of physiologic dead space. Respir Care 2010;55:288–93