Modern Anesthesia Ventilators and the Pediatric Patient

Topics: Controlled Modes of Ventilation
Supported Modes of Ventilation
Respiratory Monitoring to Optimize Ventilator Strategy

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Mechanical ventilation of pediatric patients in the operating room can be challenging. Even small changes in delivered volume can be a significant percentage of the desired volume and lead to unintended hyper- or hypoventilation, or even barotrauma. Modern anesthesia ventilators offer a selection of ventilation modes that approach the capabilities of an intensive care ventilator. Although the ICU experience can be helpful to guide the use of these modern anesthesia ventilators, clinical problems in the operating room are different from those in the ICU. Effective use of the modern anesthesia ventilator requires a clear understanding of the advantages and disadvantages of the available ventilation modes for solving the ventilation challenges which confront the pediatric anesthetist. Optimizing the ventilation strategy for an individual patient requires effective use of bedside respiratory monitoring technology. The following information will review the use of both controlled and supported modes of ventilation for the anesthetized pediatric patient. An approach to using respiratory monitors to optimize the ventilation strategy is also discussed.

Advantages of Modern Anesthesia Ventilators

Traditional anesthesia ventilators combined with a circle anesthesia system have limitations which make it challenging to ventilate pediatric patients accurately. (1,2) The compliance of the breathing system and changes in fresh gas flow interact in a subtle but significant fashion to influence the volume delivered to the patient. When caring for anesthetized pediatric patients, clinicians have used different strategies to ventilate their patients despite the limitations of traditional technology. A common approach is to adjust the ventilator settings based upon a clinical assessment which includes observation of chest expansion during inspiration and measurement of inspiratory pressure, as well as monitoring the effectiveness of ventilation with capnography and pulse oximetry or blood gas analysis. Clinical assessment is always important and new anesthesia ventilators are designed to make it even easier to satisfy the ventilation requirements of even the smallest patients. Depending upon the device and the manufacturer, different strategies are employed to overcome the influence of compliance and fresh gas flow on delivered volume.

When using volume controlled ventilation, the goal of modern ventilator designs is to deliver a volume to the patient that is as close as possible to the volume set to be delivered. To achieve this goal, the ventilator must be able to compensate for both the compliance of the breathing system and the influence of fresh gas flow on tidal volume independent of changes in lung compliance. Modern bellows

ventilators (eg. GE Healthcare) utilize a flow sensor at the inspiratory limb to control the volume delivered by the ventilator. The ventilator output is controlled by the flow sensor such that the set volume is delivered to the breathing circuit independent of changes in fresh gas flow or the compliance of the system between the ventilator and the flow sensor. Piston anesthesia ventilators (eg. Draeger Medical) measure the compliance of the breathing system during the preuse checkout. The compliance measurement is then used to determine how much additional volume must be added to each breath to deliver the set volume to the patient. The influence of fresh gas on delivered volume is eliminated in the piston design by altering the configuration of the circle system and including a valve which prevents fresh gas from entering the patient circuit during mechanical inspiration. In addition, the exhaled volume measurement is corrected using the circuit compliance measurement.

Efforts to improve the design of anesthesia ventilators have been directed towards improving the accuracy of volume ventilation so that the patient reliably receives a tidal volume that is as close as possible to the set tidal volume. (3,4,5) Another important improvement in anesthesia ventilator design has been to make multiple modes of ventilation available to the clinician in the operating room.

Selecting the Ventilation Mode: Controlled Modes of Ventilation

Volume controlled ventilation (VCV) by definition is designed to deliver a constant tidal volume despite changes in the patient's total pulmonary compliance. During volume controlled ventilation, inspiratory pressure varies and is dependent on the set tidal volume, PEEP, gas flow rate, gas flow resistance and respiratory system compliance. Increasing inflation pressure signals decreased pulmonary compliance or conductance (e.g., offset of neuromuscular blockade, bronchospasm) or obstruction of the breathing circuit (e.g., occluded ETT). The disadvantages of VCV include the potential to produce very high inflating pressures with the associated risk of barotrauma. With proper monitoring of inspiratory pressure, including the use of appropriate limits and alarms, changes in the patient's pulmonary mechanics can be observed and the risk of barotrauma minimized. When an uncuffed endotracheal tube is used, VCV may not be desirable since any leaks that occur during inspiration will reduce the volume delivered to the patient.

During volume controlled ventilation, the target tidal volume is preset and the pressure which results will vary. The pediatric patient can be exposed to high airway pressures for any number of reasons from a surgeon leaning on the patient’s chest, to a mainstem intubation, to a cough which coincides with the inspiratory cycle of the ventilator. In all of these cases, in volume mode, the ventilator will continue to deliver volume until it reaches either the target volume or the maximum pressure setting. Some modern anesthesia ventilators offer the ability to preset the maximum pressure when using volume controlled ventilation. If the inspiratory pressure limit is set to 40 cmH2O, the ventilator will maintain pressure for the duration of inspiration, but cease to deliver gas once the pressure limit of 40 cmH2O is reached. **It is important to note that if the pressure limit is reached before the end of inspiration, the set tidal volume will not be delivered.** The pressure limit should therefore be used as a safety net to avoid excessive pressure due to transient causes, and not as a routine part of the ventilation strategy to limit the pressure of each breath.

Pressure controlled ventilation (PCV) has become popular for ventilating children in the operating room since it has been difficult to deliver tidal volume accurately to children using the traditional anesthesia ventilator. When using PCV with a traditional anesthesia ventilator, the patient can receive an appropriate volume independent of circuit compliance, changes in fresh gas flow or leaks around the endotracheal tube. Furthermore, inspiratory pressure is set so that excessive inflating pressures and barotrauma are avoided. In contrast to volume controlled ventilation, during PCV, the pressure remains constant and the volume delivered varies depending primarily upon lung compliance. As a result, a

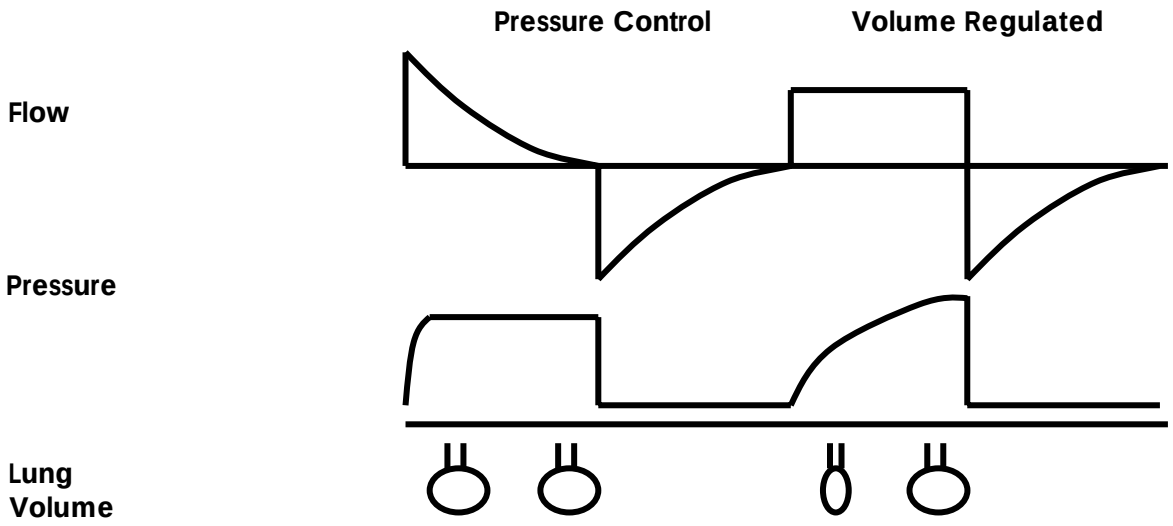

Figure 2: Pressure versus Volume Controlled Ventilation. Pressure controlled ventilation provides constant pressure and flow/volume vary with lung compliance. Volume controlled ventilation provides constant volume and pressure varies with compliance.

established at a set inspiratory pressure, upper and lower limits for tidal volume or minute ventilation alarms can be set close to the current baseline value. Any significant variation in lung compliance will cause a change in delivered volume and trigger the associated alarm.

Pressure control ventilation (PCV) is frequently applied to infants and children receiving mechanical ventilatory support in whom severe pulmonary pathology dictates the need for rapid respiratory rates or high inflating pressures. Advantages of this mode of ventilation include limiting the peak inflating pressure delivered by the ventilator, thereby limiting the transalveolar pressure and potential for ventilator-induced lung injury. Since the set inspiratory pressure is maintained throughout the entire inspiratory cycle, volume is delivered at a lower peak pressure than during VCV. The decelerating flow used to produce PCV is thought to improve the distribution of gas flow to the lungs and result in more effective gas exchange. (6) In patients with underlying lung pathology, PCV may provide better gas exchange with a more rapid improvement in lung compliance and oxygenation than when using VCV.

Whereas PCV has become a widely accepted approach to ventilating the pediatric patient during anesthesia, changes in ventilator technology and clinical practice could stimulate increasing use of VCV. Modern anesthesia ventilators are designed to deliver the set tidal volume to the patient's airway independent of compliance and fresh gas flow effects. In addition, uncuffed endotracheal tubes are no longer used exclusively even in small children. Cuffed endotracheal tubes are gaining popularity since they offer the ability to adjust the degree of leak, and long held concerns about morbidity related to endotracheal tubes have not been proven. VCV offers the advantage of a volume guarantee but the disadvantage of variable pressure. When using a newer anesthesia ventilator capable of accurate volume delivery and a cuffed endotracheal tube, VCV with a preset pressure limit may be a very useful approach to ventilation. Furthermore, evidence is accumulating that carefully controlled tidal volume (which is best achieved using a volume controlled mode of ventilation) can reduce morbidity and mortality in certain populations. (7)

Selecting the Ventilation Mode: Supported Modes of Ventilation

Pressure support ventilation (PSV) is widely used in the intensive care unit to support spontaneous ventilation for intubated patients. The primary advantage of PSV is the ability to use varying degrees of pressure support to reduce the work of breathing for the intubated patient. Indeed, the work of breathing imposed by an endotracheal tube or laryngeal mask airway and a circle system is an obstacle to allowing children to breathe spontaneously during anesthesia. Anesthesia ventilators are now available with the capability to provide PSV. Data on the benefits of PSV during anesthesia in children are very limited. One study compared PSV to CPAP used to ventilate anesthetized children under general anesthesia using the Proseal LMA and found that PSV produced lower end-tidal CO2, respiratory rate, and work of breathing with greater exhaled tidal volumes. (8) Although scientific data documenting the benefits of PSV during anesthesia are limited, one can argue on a clinical basis that PSV may be quite useful. As long as a patient is making spontaneous breathing efforts, PSV can support safe spontaneous ventilation despite the imposed work of breathing by the circle system and the respiratory depressant effects of anesthetic agents. Clinical advantages may be better gas exchange, ability to titrate anesthetic depth (especially narcotics) based upon respiratory efforts and facilitating the emergence process. An important caveat is to remember the influence of anesthetic agents on the carbon dioxide response curve. Anesthetized patients, especially those given opioids, typically require an elevated PCO2 to stimulate spontaneous ventilation. **PSV may be useful to increase the volume and effectiveness of individual breaths thereby improving oxygenation and offsetting the impact of work of breathing on PCO2, but the minimum PCO2 that can be attained will be limited by the apneic threshold as spontaneous breathing efforts must be maintained.**

Modern anesthesia ventilators provide backup ventilation features that can be utilized if there is a risk of apnea during PSV. Synchronized Intermittent Mandatory Ventilation (SIMV) can be combined with PSV to insure that a minimum amount of minute ventilation will be provided. Depending upon the capabilities of the ventilator, SIMV can be used as either a volume or pressure controlled synchronized mode. When SIMV and PSV are used together, the patient will receive the preset SIMV breaths in synchrony with spontaneous efforts and will receive pressure support for additional breaths that exceed the SIMV rate. Should the patient cease to breathe, the SIMV breaths will continue to be delivered. Another backup mode that is available uses the Pressure Support settings to generate positive pressure breaths. Breaths are delivered at a preset minimum rate using the pressure support settings for both inspiratory and expiratory breaths. Although pressure support settings can be used as a safety net if apnea should occur during PSV, these backup modes should not be relied upon as a primary mode of controlled ventilation. In general, pressure support settings provide adequate tidal volumes when the patient is making spontaneous efforts. Pressure support settings will generate tidal volumes but the total volume may not be adequate in the absence of a patient effort.

Respiratory Monitoring: Finding the Optimal Ventilation Strategy

Respiratory monitoring during anesthesia serves a variety of functions. Patient safety has been the motivation for mandating the use of certain respiratory monitors during anesthesia care. Certainly it is essential to be able to detect problems with the integrity of the airway and breathing circuit as well as to document that the ventilator is performing in the intended fashion. Modern anesthesia ventilators offer multiple modes of ventilation with very flexible settings so it is possible to tailor the ventilation strategy to the needs of the individual patient. The clinician now needs tools to evaluate and optimize the effectiveness of the ventilator mode and settings. Arterial blood gas analysis is the gold standard for assessing gas exchange but is not practical for routine use on most anesthetized patients. Bedside respiratory monitors can be used to guide the ventilation strategy if one understands the capabilities and limitations of the available respiratory monitors.

The ultimate goals of an optimal ventilation strategy are to obtain the greatest arterial oxygen tension (PaO2) at the lowest inspired oxygen concentration (FiO2), the desired tidal volume at the least inspiratory pressure and an acceptable arterial carbon dioxide tension (PaCO2). Commonly available bedside respiratory monitors can help to guide the clinician to achieve these goals.

Pulse Oximetry: There is little debate about the importance of the pulse oximeter to bedside respiratory monitoring during anesthesia. Although the value of this monitor cannot be disputed, it is not a useful tool to optimize the ventilation strategy unless the inspired oxygen concentration (FiO2) is limited. The pulse oximeter estimates arterial oxyhemoglobin saturation (SpO2) not the partial pressure of oxygen in arterial blood. Oxyhemoglobin is completely saturated when the FiO2 is 21% when gas exchange is normal. When an enriched FiO2 is used, the oxygen saturation can be 100% in the presence of a significant alveolar to oxygen tension difference. **To use the pulse oximeter to optimize the ventilation strategy, the inspired oxygen concentration should be kept to a minimum.** If the FiO2 is limited, a reduced SpO2 may indicate an oxygenation problem that can be improved by adjusting the ventilator. Atelectasis is well known to be the most common cause of impaired oxygenation during anesthesia and can be reduced or eliminated by optimizing tidal volume, the use of PEEP and application of recruitment maneuvers. One must always consider the important correctable causes of an oxygenation problem such as endobronchial intubation before focusing on ventilator settings. Although the SpO2 can typically be improved by increasing the inspired oxygen concentration, that should not be the first step unless there is serious hypoxemia (SpO2 < 90%) as it will hide the underlying oxygenation problem.

Capnography: The value of capnography to monitor the integrity of the airway is indisputable. Virtually all capnographs provide a continuous waveform of carbon dioxide concentration in the inspired and exhaled gas. Numerical values for inspired and end-tidal CO2 (ETCO2) are displayed, and both trend and alarm capabilities are built in to most devices. When the value of capnography for optimizing ventilation is considered, the focus is on the use of capnography to estimate PaCO2. ETCO2 is the concentration of CO2 in the gas at the end of exhalation and is the closest estimate of PaCO2. **Although ETCO2 is often a close approximation of PaCO2, it is not reliable. There is always a gradient between end-tidal and arterial CO2 and the magnitude of that gradient cannot be predicted.** In particular, as the tidal volume falls, the gradient between end-tidal and arterial CO2 increases so that is possible to have a normal ETCO2 along with significant hypoventilation. Furthermore, it is well known that ETCO2 increases in neonates when CO2 is sampled distal in the endotracheal tube. (9) For these reasons, when accurate control of PaCO2 is required (eg. Elevated ICP), arterial blood gas analysis is required to document effective ventilation.

Pressure Monitoring: Every anesthesia delivery system is equipped with some form of airway pressure monitoring. At a minimum, a mechanical pressure manometer is affixed to the breathing system. One can use this mechanical manometer to observe changes in airway pressure. Peak airway pressure and PEEP can be determined from the manometer, but it is difficult to determine plateau and mean airway pressures. Furthermore, there is no trend information or pressure alarms available from this mechanical device.

Most 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. Pressure trend information is also often available and alarms are tailored to warn the user of excessive pressure or too little pressure in the event of a leak or disconnect.

Pressure monitoring can only be used to optimize the ventilation strategy during volume controlled ventilation. During pressure controlled ventilation, the pressure waveform does not change with each breath. During volume controlled ventilation, the goal is to provide the desired

tidal volume at the minimum airway pressure. **If ventilator settings are effective at recruiting alveoli and maintaining lung volumes, the lung compliance will increase and the pressure required to deliver a set tidal volume will diminish.**

Which airway pressure should be followed to optimize ventilation? Peak, Mean, Plateau, PEEP? **The relationship between the volume delivered to the lung and the pressure required to deliver that volume is of most interest. Plateau pressure is most useful to assess that relationship as it is the pressure when flow has ceased and the volume has been delivered.** To obtain a plateau pressure measurement, it is important to set the ventilator with an inspiratory pause. Peak pressure reflects both lung compliance and the resistance to gas flow. Since most of the resistance to gas flow, especially in the pediatric population is the small diameter of the endotracheal tube, the pressure in the lungs is always less than the peak pressure. The difference between peak and plateau pressure can be useful to identify obstructions (changes in resistance) within the airway.

Volume Monitoring: 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. This volume sensor can be used to optimize the ventilation strategy during pressure controlled ventilation. **If ventilator settings are effective at recruiting alveoli and maintaining lung volumes, the lung compliance will increase and the volume delivered at a certain pressure setting will increase.** By following exhaled volume during PCV, improvements in lung compliance will be reflected by an increase in exhaled volume and inspiratory pressure can be reduced.

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 due to the compliance of the breathing circuit at the start of exhalation. The result is an overestimation of the volume the patient actually received. The magnitude of the difference can be significant especially for small tidal volumes and high airway pressures.

Continuous Spirometry: The monitoring modality has been available for many years but has not been widely utilized for respiratory monitoring outside of the intensive care unit. Nevertheless, this monitoring tool offers significant advantages over traditional respiratory monitors especially for neonates and small children. Spirometry relies upon a sensor placed at the airway which measures both flow and pressure. This sensor adds some bulk and dead space to the airway but sensors are now available for even the smallest patients. From this sensor, pressure and flow are measured continuously during both inspiration and exhalation. **One major advantage of this technology for small patients is direct measurement of volume at the airway.** The measured volume is the volume the patient received. Another major advantage of this technology is the plot of volume versus pressure that is typically generated, the so-called pressure-volume (PV) loop. **The PV loop is a continuous, dynamic indicator of lung compliance.** During volume controlled ventilation, horizontal stretching of the loop to the right indicates a reduced lung compliance. During pressure controlled ventilation horizontal depression of the loop indicates a reduced lung compliance. Most spirometry devices allow one to save a reference loop and evaluate subsequent breaths against this reference. This is an ideal tool for assessing the impact of changes in ventilation.

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