

# Mechanical Ventilators

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## ▲ Introduction

There are three fundamentally different modes of ventilation available in the NICU: "pressure ventilators", "volume ventilators", and high frequency ventilators. They all serve to support adequate **ventilation** and **oxygenation**, but each has its own particular niche.

**Ventilation** (CO<sub>2</sub> removal) is a function of minute ventilation which is respiratory rate (RR) multiplied by tidal volume (Vt).

**MINUTE VENTILATION = RATE x TIDAL VOLUME**

**Arterial Oxygenation** improves when either the fraction of inspired oxygen concentration (FiO<sub>2</sub>) and/or mean airway pressure (MAP) are increased.

The first step in managing a patient on a ventilator is to choose appropriate goals for **ventilation** and **oxygenation** (i.e. blood gases). These goals depend on the patient's disease state. An otherwise healthy term infant intubated for choanal atresia might have as a goal pH = 7.40, PaCO<sub>2</sub> = 40, PaO<sub>2</sub> = 60. In a small preterm infant (<1000g), to minimize lung injury due to mechanical ventilation, a strategy of mild permissive hypercapnea may be followed. In a patient with severe chronic lung disease gases with PaCO<sub>2</sub> of 60-65 torr and SaO<sub>2</sub> >88% may be acceptable. In

contrast, a patient with persistent pulmonary hypertension of the newborn might have as a goal  $\text{pH} > 7.45$ ,  $\text{PaCO}_2 < 30$ ,  $\text{PaO}_2 > 100$  in an attempt to attenuate hypoxic pulmonary vasoconstriction.

**Ventilation** goals can be a range of pH values and/or a range of  $\text{PaCO}_2$  values.

Extreme acidosis ( $\text{pH} < 7.10$ ) is to be avoided but otherwise mild acidosis alone appears to be relatively well tolerated. Of greater concern are wide swings in  $\text{PaCO}_2$  which can have significant effects on cerebral blood flow. Also of concern is identifying and, if appropriate, treating the underlying cause of the acidosis. Ventilation can best be monitored using arterial blood gases. Capillary blood gases (and even more so venous) tend to give low values for pH ( $\sim 0.05$ - $0.1$  lower depending on perfusion). The difference between arterial and capillary or venous pH is variable over time and between patients. As an estimate of ventilation, it does not work well in older infants with BPD, infants with hydrops, and other conditions that impair transcutaneous passage of capillary gas. If using a conventional ventilator (not High Frequency), end tidal  $\text{CO}_2$  monitoring (capnography) is another valuable non-invasive method of **estimating** ventilation though it may give inaccurate readings with chronic lung disease (e.g. BPD).

**Oxygenation** goals can either be a range of arterial oxygen saturation or  $\text{PaO}_2$  values. Oxygen saturation ( $\text{SaO}_2$ ) best reflects arterial blood oxygen content ( $\text{SaO}_2 \times \text{Hemoglobin} \times 1.34$ ) and thus is of direct physiologic interest.  $\text{PaO}_2$  better reflects degree of shunt, and is more accurate than  $\text{SaO}_2$  at the lower range. Oxygenation can best be monitored by pulse oximetry or arterial blood gases. Capillary and venous blood gases are never useful measures of arterial  $\text{PaO}_2$ .

The appropriateness of initial ventilator support needs to be **rapidly** confirmed by checking a blood gas (within 15-20 minutes if possible) and making adjustments accordingly. Initial ventilator settings for pressure ventilators are typically chosen based on what types of pressures and rates were required when hand bagging. Initial settings on volume ventilators are usually chosen based on typical minute ventilation requirements (e.g. rate of around 20-30 breaths per minute with tidal volume of  $\sim 4$ - $6$  mL/kg). When switching from conventional ventilation to high frequency ventilation, a rule of thumb is to choose a mean airway pressure (MAP) for the high frequency ventilator that is 2  $\text{cmH}_2\text{O}$  greater than the MAP on the conventional ventilator. Amplitude starting point is chosen such that there is adequate shake (a rule of thumb being the umbilical line should be shaking slightly; alternative rule of thumb is to start at twice the MAP and back down from there until shake appears appropriate).

**Blood Gases:** When evaluating a blood gas, first determine your goals for pH,  $\text{PaCO}_2$ , and  $\text{PaO}_2$ . Secondly, determine the type of specimen to decide if any correction for capillary or venous specimen is in order. Finally, evaluate the blood gas to see if any changes in inspired oxygen concentration or ventilator settings are needed. Before analyzing the blood gas it is worth determining whether the gas is significantly different from previous gases and, if so, why (i.e. was a ventilator wean made, is the patient extubated, is there a pneumothorax, is the patient showing

signs of sepsis, are there signs of persistent pulmonary hypertension of the newborn, is this an expected change given the patients diagnosis). If  $\text{PaO}_2$  is low then  $\text{FiO}_2$  or MAP need to be increased. If the pH is low, one should determine if the acidosis is respiratory ( $\text{PaCO}_2$  high) and/or metabolic (calculated  $\text{HCO}_3$  low). Increasing ventilation is merely a temporizing act **until the cause of the acidosis is determined**. If the pH is low and/or the  $\text{PaCO}_2$  is high, indicative of a respiratory acidosis, then ventilation needs to be increased by increasing rate and/or tidal volume - how this is accomplished again varies from ventilator to ventilator.

Abbreviations:

ETT: Endotracheal Tube

PEEP: Positive End Expiratory Pressure

CPAP: Continuous Positive Airway Pressure, PEEP with no rate

PIP: Peak inspiratory pressure

MAP: Mean Airway Pressure

RR: Respiratory Rate

$T_i, T_e$ : Inspiratory and expiratory times

I:E: Ratio of inspiratory to expiratory time

$V_t$ : Tidal Volume, volume of each breath

$\text{SaO}_2$ : arterial oxygen saturation determined by arterial blood gas analysis

$\text{SpO}_2$ : arterial oxygen saturation determined by pulse oximetry

$\text{FiO}_2$ : Fractional inspired oxygen

HFV: High Frequency Ventilation

HFOV: High Frequency Oscillatory Ventilator/Ventilation

Amplitude: (aka Delta P) Setting on HFV. Difference between maximum and minimum airway pressure

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## ▲ "Volume Ventilators"

Historically, volume ventilators (time cycled, volume regulated, volume limited) were used in anesthesia (a bellows of defined tidal volume pumped at a given rate) and as pediatric and adult intensive care evolved. Initially these ventilators were not used in the NICU due to the difficulty achieving consistent small volumes (5-7 mL/kg in a 1200g infant!). Current volume ventilators are able to deliver small volumes consistently. In the past, triggering was inconsistent and increased the work of breathing. The latest generation (Siemens 300) has resolved these problems. In the NICU their use has been primarily in larger infants with chronic lung disease (partly because SIMV was only available on volume ventilators until recently) or perioperatively (tradition - likely related to familiarity of operating room personal with volume ventilators). Their use in the acute NICU setting has extended into the micropremie population.

**PROS:** Stable minute ventilation with known tidal volume. Simpler models available for use outside hospital setting. Control or SIMV modes are available. Home ventilators currently available are typically "volume ventilators".

**CONS:** Tidal volume is maintained at the expense of peak airway pressure. If lung

compliance falls by 50% (i.e. ETT slipping down right mainstem) then to maintain tidal volume, peak airway pressure doubles, possibly increasing the risk of volutrauma or barotrauma. Since these ventilators do not have constant flow, to breathe spontaneously the infant always has to trigger a valve to allow air flow. Large leaks around the ETT can be problematic due to difficulty maintaining tidal volume and "triggering" (patient cycling) of the ventilator causing frequent alarming.

### Adjusting ventilation/oxygenation:

To increase alveolar ventilation: **Increase Rate** or **Increase Tidal Volume**

$$\text{MINUTE VENTILATION} = \text{RATE} \times \text{TIDAL VOLUME}$$

To increase oxygenation: **Increase FiO<sub>2</sub>**, or **Increase PEEP**, or **Increase Tidal Volume**

$$\text{OXYGENATION is improved by increasing MAP and/or FiO}_2$$

/ \

Vt    PEEP

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### ▲ High Frequency Ventilators

This is a radical innovation in ventilator design. The rate in "high frequency" is the Hz (range 3-15 Hz) (i.e. 180-900 breaths per minute). Since the tidal volume generated by these ventilators approximates dead space, simple pulmonary mechanics, physics, and physiology are inadequate to explain their operation. Gas exchange occurs by enhanced diffusion.

**HFOV (High Frequency Oscillatory Ventilation):** (Sensormedics 3100A) uses a piston with a diaphragm unit to actively move gas in and out of the lung. This type of ventilator requires a special non-compliant breathing circuit. Indications for use of high frequency ventilation are unclear but include:

1. Initial and subsequent ventilatory support in very low birth weight infants with respiratory distress syndrome.
2. Air leak (pneumothorax, pulmonary interstitial emphysema).
3. Failure of conventional ventilation (pre-ECMO step) particularly in persistent pulmonary hypertension of the newborn, meconium aspiration syndrome, pneumonia, pulmonary hemorrhage.
4. To reduce the risk of volutrauma and barotrauma when conventional ventilator settings are very high.

**PROS:** May allow gas exchange when conventional ventilation has failed.

**CONS:** Unclear which patients will respond and there is some risk involved in "just trying". Switching ventilators on an unstable patient who is failing conventional ventilation may result in clinical deterioration. The high airway pressures often seen with high frequency ventilation can be transmitted to the heart (particularly with

compliant lungs) and result in impaired cardiac output requiring inotropes and/or volume boluses. HFOV makes turning patients, taking x-rays, or performing ultrasounds more complex due to the heavy, non-flexible tubing. Stopping HFOV for suctioning or administering nebulized medications may negate its benefit.

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**Adjusting ventilation/oxygenation:** Ventilation is dependent on amplitude much more than rate. In larger infants paradoxically lowering Hz improves CO<sub>2</sub> removal on the Sensormedics. This is *postulated* to occur by increased tidal volume (more inspiratory time) and better gas escape (more expiratory time). Mean airway pressure primarily effects oxygenation. MAP can also influence ventilation: too high a MAP and ventilation may drop due to decreased compliance from overdistention, too low a MAP and hypoventilation may occur secondary to atelectasis.

To increase minute ventilation: **Increase Amplitude**, (although changes in MAP and Hz can *sometimes* have significant effects on CO<sub>2</sub> also)

$$\text{MINUTE VENTILATION} = \frac{\text{RATE}}{\text{Hz}} \times \frac{\text{TIDAL VOLUME}}{\text{AMPLITUDE} \backslash \text{MAP}}$$

To increase oxygenation: **Increase FiO<sub>2</sub>**, or **Increase MAP**, (change in Hz may *sometimes* effect oxygenation also). Note, however, overdistention can impair oxygenation. When in doubt, a chest x-ray is indicated.

OXYGENATION is proportional to **MAP x FiO<sub>2</sub>**

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### ▲ "Pressure Ventilators"

These are the most frequently used ventilators in the NICU. Traditional "pressure ventilators" are constant flow, time cycled, pressure limited devices. Constant flow implies that there is a constant flow of gas past the top of the endotracheal tube. Pressure limited means that once the pre-set PIP has been reached, it is maintained for the duration of the inspiratory cycle. Time cycled implies that breaths are given at fixed intervals, independent of the infants respiratory efforts. Newer "pressure ventilators" can sense infants breaths and synchronize to them. There may be some added work of breathing due to the need to trigger breaths - this has been hard to quantify and remains controversial.

**PROS:** The constant flow permits the infant to easily take spontaneous breaths. Simple, reliable mechanical design. Pressure limitation prevents sudden changes in PIP as compliance changes (i.e. on a pressure ventilator if compliance falls by 50% PIP does not change - though tidal volume drops, for example ETT slipping down right mainstem).

**CONS:** Variable tidal volume as lung compliance changes. Should lung compliance

worsen then Vt will drop (if the ETT plugs Vt drops to zero, but the ventilator does not sense it). Should compliance improve (following surfactant for example) this may result in overdistention. If the child is exhaling during a non-synchronized ventilator breath, then the breath is ineffective.

**Adjusting ventilation/oxygenation:** Key determinants of oxygenation (MAP) and ventilation (tidal volume) are not directly adjustable, but are derived from related parameters (Bold faced). Adjustments are thus less straightforward than with either "High Frequency" or "Volume Ventilators". Furthermore, there are interactions between the various parameters. Driving pressure conceptually is similar to "amplitude" on high frequency ventilation, but is not directly adjustable: it is proportional to the difference between PIP and PEEP.

To increase ventilation: **Increase Rate**, or **Increase PIP**, or **Increase Inspiratory Time**, or **Decrease PEEP** (rarely done)

$$\begin{array}{rcccc}
 \text{MINUTE VENTILATION} = & & \text{RATE} & \times & \text{TIDAL VOLUME} \\
 & / & | & \backslash & / & \backslash \\
 & T_i & T_e & I:E & \text{Driving} & \text{Time} \\
 & & & & \text{Pressure} & \text{Constant} \\
 & & & & | & / & \backslash \\
 & & & & \text{PIP-PEEP} & \text{Resistance} & \text{Compliance}
 \end{array}$$

To increase oxygenation: **Increase FiO<sub>2</sub>**, or **Increase MAP** (see below)

OXYGENATION is proportional to MAP x **FiO<sub>2</sub>**

$$\text{MAP} = \frac{(T_i \times \text{PIP}) + (T_e \times \text{PEEP})}{T_i + T_e}$$

This equation **assumes** Pressure vs. Time is a square wave.

Ways to increase MAP (See figure 1):

1. Increase PEEP
2. Increase PIP
3. Increase T<sub>i</sub>
4. Increase RR
5. Increase Flow

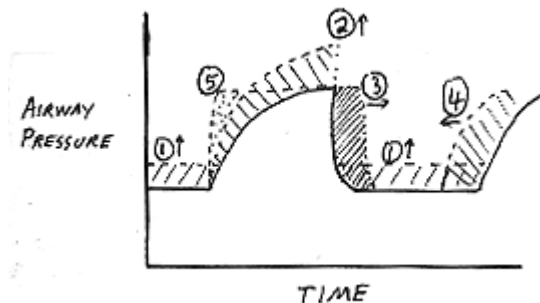


Figure 1: Pressure vs. time

**IMV:** Intermittent Mandatory Ventilation. Intermittent breaths (fixed PIP or Vt) at a fixed rate. **Not synchronized** to patient. Beyond the set rate, the infant is on his/her own. (See figure 2-IMV) Standard on most ventilators, but infrequently used. Generally good for small premature infants but when rates are high (>60) or large infant "fighting" ventilator (exhaling during ventilator's inspiratory cycle), the lack of synchronization may impair ventilation.

**CON:** No synchronization.

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**SIMV:** Synchronous Intermittent Mandatory Ventilation. Like IMV but **synchronized** (senses infant's spontaneous breaths). Beyond the set rate the infant is on his/her own (See figure 2-SIMV). Since it is synchronized to the patient's effort, it is the preferable mode. It will function exactly like IMV if the infant is apneic or the trigger/synchronization fails. Typically used in infants who can reliably trigger demand valve and those fighting a preset rate. Usually lower rates/pressures since at higher spontaneous rates (>60) may get inadvertent PEEP and air trapping. Also good for older ventilator dependent patients.

**PRO:** Synchronized to patient effort.

**CON:** None, at worst is like IMV.

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**AC:** Assist/Control. **Synchronized** (senses infant's spontaneous breaths) but with **mandatory minimum set rate, all breaths** the infant takes are a **full assisted ventilator breaths** (See figure 2-AC). Used in more active ventilator dependent infants not aggressively being weaned.

**PRO:** Infant can increase minute ventilation easily on demand, based on need.

**CON:** When weaning can't wean rate, only PIP or Vt.

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**SIMV-PC with PS (Pressure Support):** Term used on Servo 300 ventilators to describe an SIMV "pressure ventilator" with set PIP/PEEP. Beyond a set background ventilator rate, spontaneous breaths are augmented (supported) with pressure - usually relatively low values (+4 to +8 cmH<sub>2</sub>O) (See figure 2-PC/PS).  
Uses: 1) To provide mandatory backup breaths (conceptually large sighs to prevent gradual progressive atelectasis) while allowing amount of PS to be weaned slowly to "train" respiratory muscles 2) As a means of providing intermediate respiratory support (less than conventional modes but more than CPAP or extubation) 3) Pressure support just enough to overcome resistance of ETT and ventilator circuit and maintain minimum adequate spontaneous ventilation. Uses as above, but in "pure pressure" support mode. (If set PIP and PS pressures are the same then essentially you have pressure AC mode).

**NOTE ON WRITING PS: Pressure support is above PEEP.** At the University of Washington NICU, writing an order for "PS 5, PEEP of 4" yields inspiratory pressures for assisted breaths of 5+4=9.

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**SIMV-VC with PS (Pressure Support):** Term used on Servo ventilators to describe SIMV with set Vt. Beyond the set rate, spontaneous breaths are augmented (supported) with pressure - usually relatively low values. The difference between this mode of ventilation (VC/PS) and the mode described above (PC/PS) is that in VC/PS the SIMV breaths are volume breaths and in PC/PS mode the SIMV breaths are pressure breaths.

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**PC:** Pressure Control. Term used on Siemens Servo ventilator to describe AC mode with a set PIP/PEEP ("pressure ventilator" AC mode).

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**VC:** Volume Control. Term used on Siemens Servo ventilator to describe AC mode with a set Vt ("volume ventilator" AC mode).

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**PRVC:** Pressure regulated volume control. In this mode, the tidal volume and rate are preset. The minimum inspiratory pressure necessary to provide the ordered tidal volume will be delivered. The initiation of the first breath will start with a pressure 10 cmH<sub>2</sub>O above PEEP. With the Servo 300, the pressure will staircase up over 5 breaths until the set volume is met. If the measured tidal volumes increase or decrease, the pressure levels will make small adjustments, in increments of 3 cmH<sub>2</sub>O, to maintain the preset tidal volume.

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**PSVG:** Pressure support volume guarantee. This mode is available on the Drager Babylog 8000. This mode is pressure limited with a set tidal volume. The pressure will staircase up to meet the set tidal volume. There are two sets of values: Set (ordered) and Measured (spontaneous). Set values include tidal volume (4-8 mL/kg), inspiratory time, inspiratory pressure limit (PIP), rate, and PEEP. The set values are utilized when the infant is apneic. Otherwise, the infant regulates their own PIP to meet the set tidal volume. As infant's compliance improves, the PIP needed to deliver set tidal volume decreases.

**Pro:** Adjusts for compliance automatically, compensates for ETT leaks, no need to correct for tubing volume

**Con:** Weaning mode only. If infant needs increasing support, switch to another mode on ventilator.



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**SIMV + VG:** With the Drager Babylog 8000, the addition of VG (volume guarantee) to SIMV allows one to control the inspiratory time. The PIP still adjusts to meet the set tidal volume, but the inspiratory time is set by the therapist.

**Pro:** More supportive and more control of ventilation than with PS + VG.

**Con:** Less control over PIP, infant is still doing most of the work of breathing.

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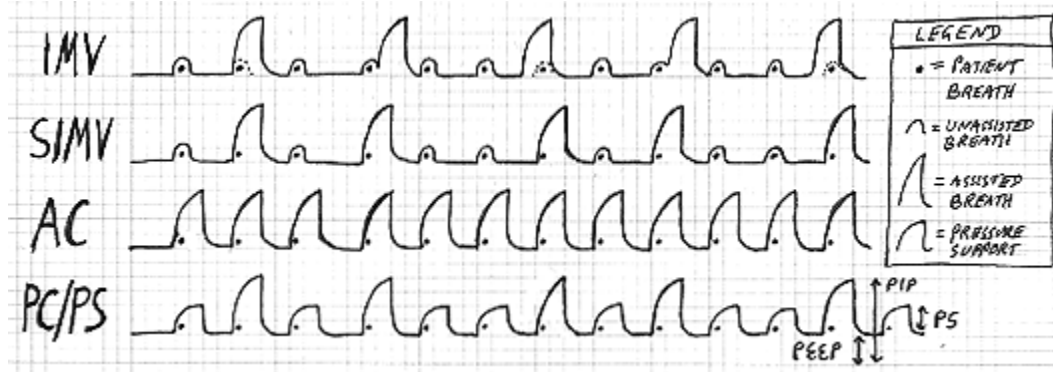
**CPAP:** Continuous Positive Airway Pressure (like PEEP). Primarily used to maintain airway distending pressure; major effect is to help to maintain lung volume and improve oxygenation. Can be administered via ETT or nasal prongs. Uses: 1) To prevent alveolar collapse in mild HMD (perhaps avoiding intubation) 2) In mild chronic lung disease (perhaps avoiding reintubation) 3) In severe apneic spells to avoid reintubation. Sometimes used in infants as prelude to extubation to ensure adequate respiratory drive. If done for a prolonged time, infants tire out breathing through the relatively high resistance of a 2.5-3.5 ETT.

**PRO:** Improve oxygenation by maintaining functional residual capacity.

**CON:** Impair ventilation by increasing FRC and increasing work of breathing (exhaling against pressure).

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**FIGURE 2: RESPIRATORY PATTERN UNDER DIFFERENT MODES**



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### ▲ Specific Ventilators

**NOTE:** Each ventilator manufacturer has utilized specific names for mode functions of their specific machine that may not be identical with other machines. For example, PSV of the Servo 300 is not the same as PSV of the Drager Babylog 8000.

**Drager Babylog 8000:** This ventilator is specifically designed for infants up to 10 kilograms (22 pounds). It is capable of both volume and pressure ventilation. A flow

sensor at the patient wye accurately measures tidal volume and senses air flow initiated by the patient allowing triggering of the ventilator cycle. The sensor is able to compensate for small ETT leaks. The Drager Babylog 8000 provides the following modes: AC, SIMV, PSV (pressure support ventilation), Volume guarantee (VG), and independent Expiratory Flow (VIVE). VG is often used with SIMV, PS, and AC. The most important and commonly used modes are SIMV, PSV, VG, and CPAP.

**Sensormedics 3100A:** High frequency oscillatory ventilator with active inhalation/exhalation driven by a moving piston and diaphragm. Requires special stiff non-compliant ventilator circuit. Can be utilized for a wide weight range of infants. Some preliminary work using it in smaller infants suggests that it may result in less barotrauma than conventional ventilation.

**Siemens Servo 900C:** Either a volume or pressure ventilator, **no gas flow from ventilator between breaths**. Volume ventilator with IMV, SIMV, AC and pressure modes PC/PS. Has pediatric settings for alarm limits, but no specific **infant** modes. Used when primarily volume ventilator needed in larger term infant and often for home ventilatory support. Currently, used only in the ICU.

**Siemens Servo 300:** Either a volume or pressure ventilator, **low bias flow from ventilator between breaths**. Does not have continuous high flow through circuit and requires some effort on the part of the infant to trigger significant flow. In the Neonatal Mode, there is a low continuous flow of 0.5 LPM through the circuit. A disruption or change in this flow caused by the infant's breathing is required to initiate/trigger an assisted breath. The major advantage over Siemens 900C is that it has **infant** ranges for Vt, flow, pressures, and alarms. Has extensive list of modes: PC, VC, SIMV-VC+PS, SIMV-PC+PS, CPAP and PRVC (pressure regulated volume controlled). Uses include 1) Volume ventilation of small infants, 2) Synchronized/mixed modes, 3) Overcoming resistance of circuit & ETT with PS, 4) Facilitation of weaning by allowing gradual entrainment.

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