

## The Anesthesia Ventilator

### Why is the piston replacing the bellows?

For many decades, and millions of anesthetics, the bellows anesthesia ventilator has been a safe and effective clinical device. Indeed, Draeger anesthesia ventilators based upon the bellows design continue to be used in all parts of the world. More recently, Draeger Medical has been producing anesthesia ventilators using the piston design. Why would a company with decades of investment in bellows ventilation technology decide to base future anesthesia ventilator products on a piston design? The answer lies in the advantages inherent to the piston design for producing a versatile, reliable anesthesia ventilator now and in the future.

#### The Clinical Requirements of an Anesthesia Ventilator

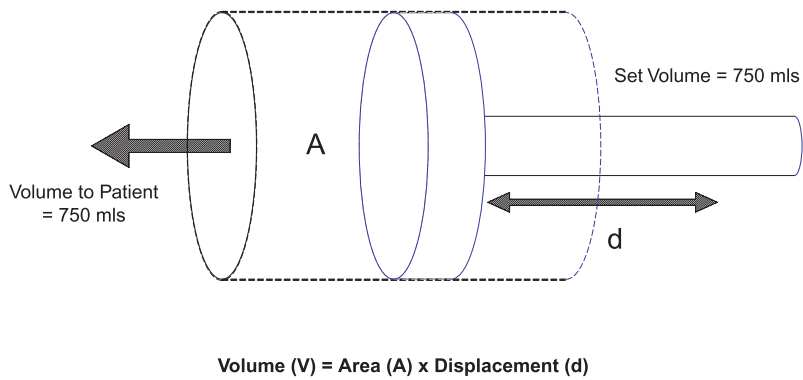
The clinical needs for mechanical ventilation in the operating room have changed significantly over time. The earliest anesthesia delivery systems were open inhalers intended to deliver volatile anesthetics while patients breathed spontaneously throughout the surgical procedure. Breathing circuits with reservoir bags were developed to contain the anesthetic gases and allow clinicians to ventilate patients manually. With the advent of muscle relaxants and narcotics, positive pressure ventilation became essential and was accomplished by manually



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squeezing the reservoir bag, sometimes for several hours. The earliest anesthesia ventilators were bellows designs that essentially automated the process of squeezing the reservoir bag, freeing the anesthesia provider from this repetitive manual activity.

Given the variety of patients that require anesthesia for surgery today, the performance demands on the anesthesia ventilator have increased dramatically. The demand for performance equivalent to that of an intensive care ventilator, while maintaining the ability to deliver



**Fig. 1:** The volume delivered by the piston is determined by the distance the piston moves. When a volume is set to be delivered (eg. 750 mls), the piston is moved the distance required to deliver the set volume to the patient.

anesthetic gases, has been the motivation for redesigning the anesthesia ventilator. The clinical needs for ventilation in the operating room fall into two broad categories: controlled mechanical ventilation and supported spontaneous ventilation. Both bellows and piston ventilators have features designed to serve these needs although the performance of these ventilators is not identical.

The most common mode of controlled mechanical ventilation used in the operating room is volume controlled ventilation whereby a preset tidal volume is delivered by the ventilator to the patient. For a patient of average size with healthy lungs, it is not difficult to deliver the appropriate tidal volume safely. The challenge is to deliver tidal volume accurately when lung compliance is very poor (eg. patients with ARDS) and/or when the patient is very small. **One of the major advantages of the piston ventilator is the ability to deliver tidal volume accurately to all patients under a large variety of clinical conditions.**

Volume controlled ventilation is appropriate for most patients, but pressure controlled ventilation offers advantages to some patients. Pressure controlled ventilation requires that the preset inspiratory pressure is maintained throughout the inspiratory cycle. Proper implementation of pressure controlled ventilation requires

measuring the pressure in the breathing circuit with feedback control of the ventilator during each breath. This feedback control reduces the inspiratory flow as the lungs fill resulting in a decelerating flow pattern. The rigid coupling between the piston and its drive mechanism allows for fine control over the movement of the piston and continuous adjustment of inspiratory flow to maintain the desired inspiratory pressure.

The introduction of the Laryngeal Mask Airway led to a reemergence of spontaneous ventilation during anesthesia. Ventilation modes commonly used in the ICU to augment or support spontaneous ventilation include Synchronized Intermittent Mandatory Ventilation (SIMV) and Pressure Support Ventilation (PSV). Implementation of these modes requires that the ventilator controller sense either a pressure or flow change in the breathing circuit associated with inspiration to trigger ventilator support. Once inspiration is detected, the preset amount of ventilator support begins. In the case of SIMV, a volume or pressure controlled breath is delivered synchronized with the start of inspiration. The breath that is delivered is very similar to the breaths given by the ventilator during controlled mechanical ventilation. In the case of PSV, the trigger is used to adjust the constant pressure in the breathing circuit during inspiration and expiration. The volume that is delivered during PSV will depend upon the magnitude of the patient's effort and the degree of pressure support. When using an



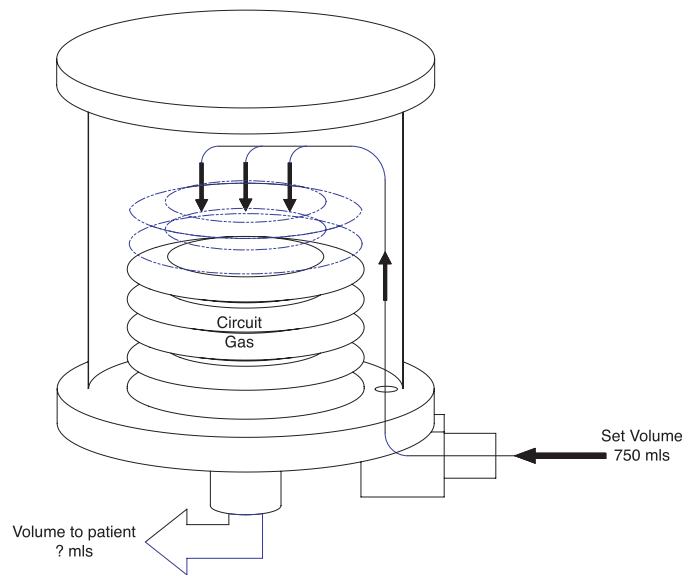
ICU ventilator, the volume that can be delivered is unlimited whereas the volume of both bellows and piston ventilators is limited by the maximum size of the bellows and the piston chambers respectively. Modern bellows and piston ventilators are designed with sufficient volume capacity to meet the needs of virtually all patients.

The clinical need for an anesthesia ventilator that can provide the capabilities of an intensive care unit ventilator, while maintaining the ability to deliver anesthetic gases efficiently, is a major challenge to ventilator designers. Inherent limitations of the bellows design to meet the clinical needs for advanced ventilation in the operating room led to a decision to base future anesthesia ventilator designs on piston rather than bellows technology. The piston design offers advantages of more accurate volume delivery and the ability to serve as a platform for future development. This monograph describes the major advantages of the piston design in detail and addresses frequently asked questions about piston ventilators.

### More Accurate Volume Delivery

The most common mode of ventilation used during anesthesia is volume controlled ventilation where the clinician sets a specific tidal volume to be delivered to the patient. The piston ventilator design is uniquely suited to deliver tidal volume accurately. Since the area of the piston is fixed, the volume delivered by the piston is directly related to the linear movement of the piston. When the user sets a volume to be delivered to the patient, the piston moves the distance necessary to deliver the required volume into the breathing circuit. Furthermore, since the connection between the piston and the drive motor is rigid, the position of the piston is always known and the volume delivered by the piston is also known. (FIGURE 1)

When using a bellows ventilator, the movement of the bellows is controlled by drive gas which enters the bellows chamber and pushes



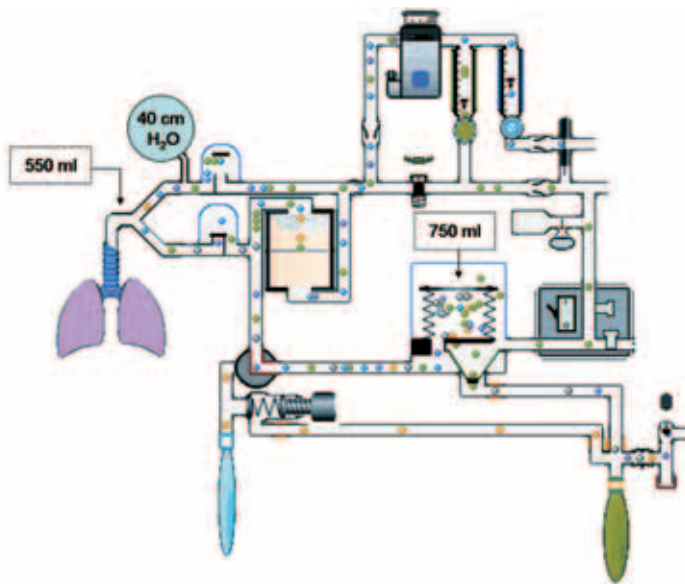
**Fig. 2:** To deliver a certain volume to a patient, the desired volume (eg 750 mls) is delivered into the bellows compartment displacing the bellows and pushing circuit gas to the patient. Since the pressure in the bellows compartment will vary from patient to patient, the volume displaced by the bellows will also vary. Furthermore, since the final position of the bellows is not known, the volume that was delivered by the ventilator is also not known.

circuit gas into the breathing circuit. One common bellows ventilator design begins inspiration with the bellows at its maximum volume and is calibrated to deliver a volume of drive gas into the bellows compartment equal to the volume set to be delivered to the patient. As the volume of drive gas enters the bellows compartment, the bellows moves to displace gas into the breathing circuit. For a given set tidal volume, the pressure that results in the breathing circuit is determined by the resistance and compliance of the breathing circuit and the patient's lungs. Since the pressure in the bellows compartment will vary between patients (or even between breaths), the gas driving the bellows will be subject to varying degrees of compression that cannot be predicted. Variable compression of the drive gas is a fundamental obstacle to accurate volume delivery by a bellows ventilator. This is particularly true for small tidal volumes and high inspiratory pressures. As opposed to the piston design, the position of the bellows in the bellows compartment at the end of inspiration is not known. As a result, volume delivered by the ventilator for a given breath is not known. (FIGURE 2)

### Superior Control of the Ventilator

Irrespective of the type of ventilator being used, the volume delivered by the ventilator into the breathing circuit and the volume the patient receives are not identical. One major determinant of the difference between the two volumes is the compliance of the breathing system. As the ventilator delivers gas to the breathing circuit, the pressure increases. The increased pressure will compress the gas in the system





**Fig. 3: Effect of compliance on delivered tidal volume without compliance compensation. Ventilator set to deliver 750 mls but only 550 mls reaches the patient due to a compliance factor of 5 mls/cmH<sub>2</sub>O and peak pressure of 40 cmH<sub>2</sub>O. (Schematic of Ohmeda Excel)**

\* Modified from the Virtual Anesthesia Machine by permission from the Department of Anesthesiology, University of Florida College of Medicine. For more information, visit [www.simanest.org](http://www.simanest.org)

and also expand the circuit tubing, therefore reducing the volume that reaches the patient. Every breathing circuit has a certain compliance factor which defines the amount of volume stored in the circuit for a given change in pressure. During volume controlled ventilation, the pressure that results when a set volume is delivered by the ventilator will vary between patients. Without some means of compensating for the effect of circuit compliance, as pressure in the circuit increases, the volume the patient receives will decrease. (FIGURE 3)

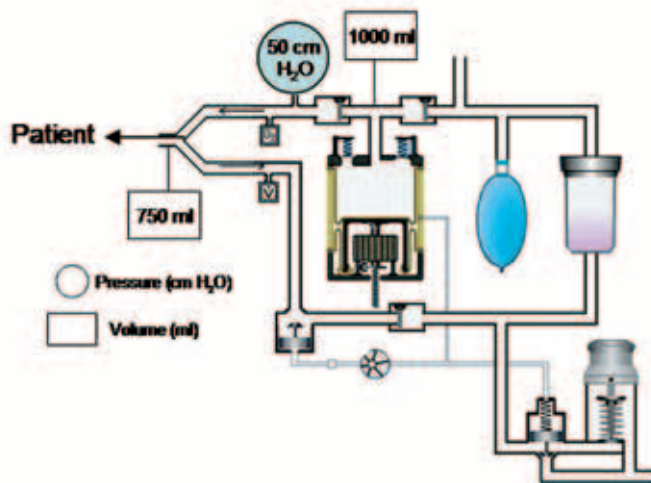
Advanced piston ventilator designs are able to compensate for the compliance of the breathing system by delivering enough additional volume with each breath to ensure that the patient receives the volume set to be delivered. (FIGURE 4) Draeger piston ventilators measure the compliance of the breathing system during the pre-use self-test procedure. Once the compliance factor is determined, only a pressure sensor is needed to determine how much additional volume should be delivered with each breath to compensate for the breathing system compliance. The result is delivery of

the set tidal volume to the patient's airway irrespective of changes in lung compliance. (FIGURE 5) The ability to deliver volume accurately simply based upon a pressure measurement is a unique advantage of the piston ventilator. Pressure sensors are simple devices that are easily calibrated and can be located anywhere in the breathing

system since the plateau pressure is essentially constant throughout. Control of the bellows ventilator based upon pressure is difficult due to variable compression of the drive gas from patient to patient. Bellows ventilators with compliance compensation utilize a flow sensor in the breathing circuit to measure the volume delivered and to tell the ventilator to increase the volume delivered to offset the effects of gas compression. Since flow sensors ultimately measure volume, they work best to ensure delivery of set tidal volume when located at the patient's airway. In this location, flow sensors are prone to inaccuracy due to accumulation of moisture or secretions. If the flow sensor is located at the beginning of the inspiratory limb to reduce the impact of moisture and secretions, the set tidal volume is not delivered to the airway. Furthermore, if the flow sensor should fail or become unreliable, the ventilator must revert to volume controlled ventilation without compliance compensation.

### Facilitate Advanced Ventilation Modes

The trend in anesthesia ventilator technology is to eliminate the disadvantages of traditional anesthesia ventilator technology and to increase the availability of



**Fig. 4: Effect of compliance compensation on delivered tidal volume. Ventilator delivers 1000 mls to insure that 750 mls reaches the patient due to a compliance factor of 5 mls/cmH<sub>2</sub>O. Note that peak pressure has increased to 50 cmH<sub>2</sub>O due to the additional delivered volume. (Schematic of Fabius GS)**

## Compliance Compensation Ensures Constant Volume Delivery

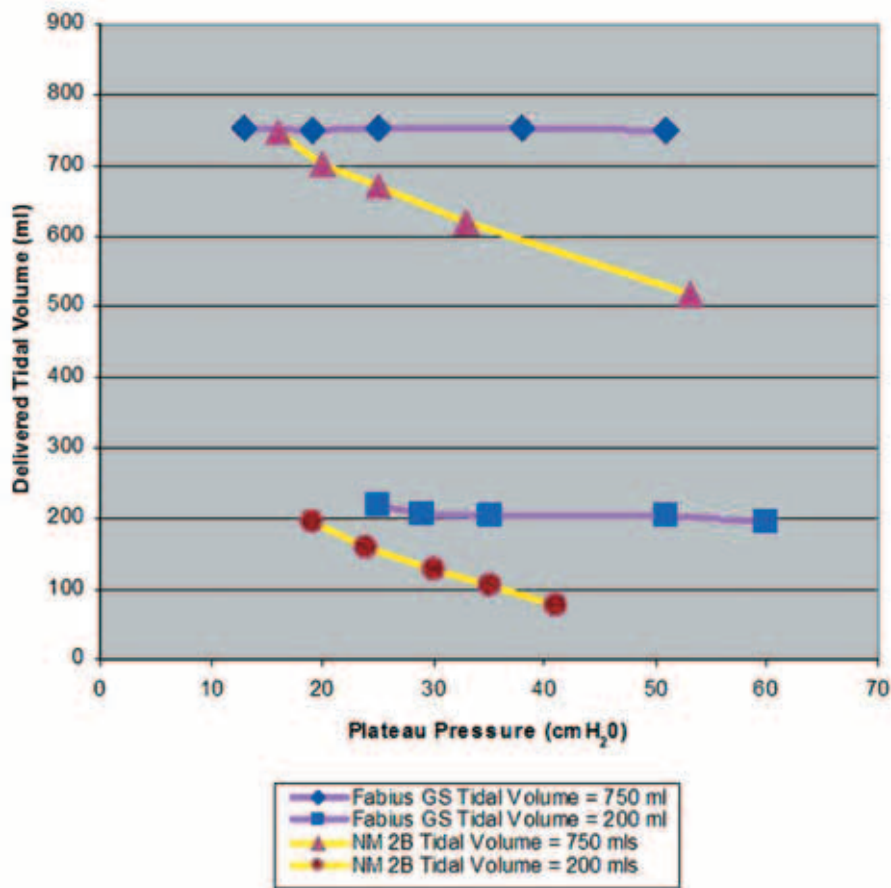


Fig. 5: Plot of tidal volume measured at the airway versus airway pressure. Data obtained using both adult and pediatric lung simulators and both a Draeger Medical Fabius GS equipped with a piston ventilator as well as a traditional Narkomed 2B. Airway pressure increases due to reduced lung compliance. Note constant volume delivery to the airway as airway pressure increases when using the Fabius GS. When using the NM 2B, the delivered tidal volume decreases as plateau pressure increases.

intensive care modes of ventilation in the operating room. The ability of the piston ventilator to deliver volume accurately enables the clinician to use volume controlled ventilation for all types of patients. From neonates requiring very small tidal volumes to adults with ARDS where accurate tidal volume is critical to ensuring oxygenation, Draeger piston ventilators are capable of meeting the clinical needs.

The demand for modes of ventilation in the operating room other than traditional volume controlled ventilation is also increasing. Pressure controlled ventilation (PCV) has found application in children and adults who require increased pressure to achieve adequate ventilation during anesthesia. PCV requires that the ventilator deliver sufficient gas to achieve the desired pressure

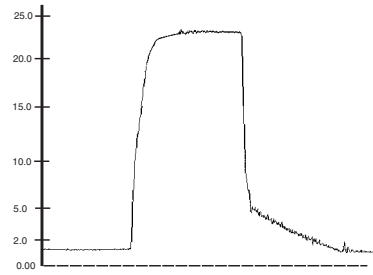
throughout the inspiratory cycle. The volume delivered to the patient will depend upon the lung compliance. (FIGURE 6)

Both piston and bellows ventilators can be designed to meet the needs of PCV. In both cases, the pressure in the circuit is measured and used to control the movement of the ventilator. As pressure builds in the breathing circuit, the flow delivered by the ventilator is progressively reduced generating the characteristic decelerating flow waveform. Since the goal of PCV is to develop the desired inspiratory pressure as rapidly as possible, bellows ventilators require a greater initial flow than a piston design to overcome compression of the drive gas. The flow required to achieve the desired inspiratory pressure in the breathing circuit will vary with lung compliance. When the lung compliance is low, relatively little

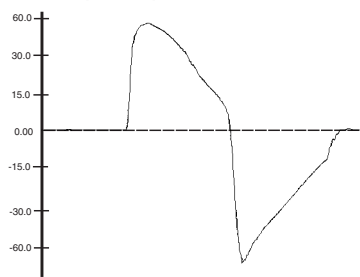
flow is required to achieve the desired pressure. Piston ventilators offer adjustable inspiratory flow settings. The default or initial flow setting is adequate for most patients. For patients with relatively large lung compliance, inspiratory flow can be increased to ensure that inspiratory pressure is rapidly attained. Limiting the maximum inspiratory flow is useful to avoid overshooting the target pressure especially when lung compliance is low.

SIMV has found application in the operating room to facilitate emergence from anesthesia as the patient transitions from controlled to spontaneous ventilation. Both piston and bellows ventilators can offer this mode of ventilation. As the procedure is concluding, SIMV can be used to ensure a minimal amount of ventilation until the patient begins spontaneous

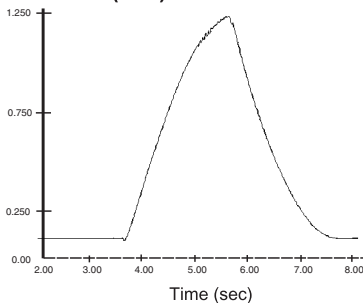
**Pressure (cmH<sub>2</sub>O)**



**Flow (L/min)**

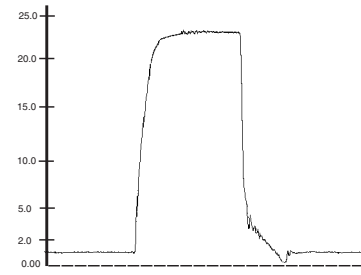


**Volume (ml)**

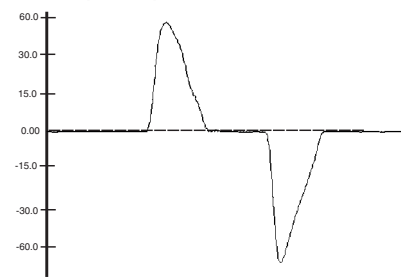


**CL = 50mls / cmH<sub>2</sub>O**

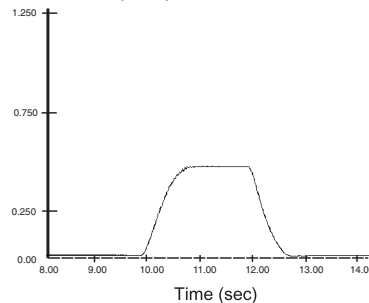
**Pressure (cmH<sub>2</sub>O)**



**Flow (L/min)**



**Volume (ml)**



**CL = 20mls / cmH<sub>2</sub>O**

Fig. 6: Plots of pressure, flow and volume obtained using a Draeger Medical Fabius GS to ventilate an adult test lung using Pressure mode at different lung compliance settings. Note constant pressure and less tidal volume as lung compliance is reduced. Also note decelerating flow pattern.

breathing efforts. As the patient begins to breathe, the ventilator will be triggered to begin inspiration in concert with the spontaneous breaths. The clinician is freed from the task of periodically ventilating the patient by hand. The ventilator will begin each breath from its maximum volume capability so that sufficient volume is available to the patient.

The use of laryngeal mask airways has led to a dramatic increase in spontaneous ventilation in the operating room. Pressure Support ventilation is used in the ICU to reduce the work of breathing associated with the breathing circuit and endotracheal tube and also to impose varying degrees of respiratory muscle exercise. Implementing this mode of

ventilation on an anesthesia ventilator requires a means to monitor for the onset of inspiration and exhalation and to maintain the desired pressures throughout each respiratory cycle. Both bellows and piston ventilators are limited by the volume of the ventilator chamber but maximum volume capabilities are adequate for virtually all patients.

Due to the accuracy with which the piston can be controlled, advanced ventilation modes are implemented through software enhancements to the piston ventilator. The basic piston design has proven itself to be a versatile platform for anesthesia ventilator design.

## FREQUENTLY ASKED QUESTIONS

### 1. What is fresh gas decoupling?

Fresh gas decoupling eliminates any interaction between fresh gas flow and the volume delivered to the patient. One can adjust fresh gas flow freely or even press the oxygen flush button during ventilation without concern for altering the volume delivered to the patient. Fresh gas decoupling is accomplished by the breathing circuit design and is not a feature of the piston ventilator per se. In the case of the Fabius GS, fresh gas decoupling is accomplished by placing a decoupling valve between the fresh gas inlet and the breathing circuit. When the circuit is pressurized during inspiration, the decoupling valve closes and fresh gas is directed towards the reservoir bag. (Figure 4)

### 2. Are all Draeger piston ventilators identical?

Although all of the newer Draeger anesthesia workstation designs utilize piston ventilators, these ventilators are not identical. Each ventilator is fully integrated with a specific workstation and designed to complement the functions available in that workstation.

### 3. How do I know the ventilator is working if I cannot see it?

Studies on safety in anesthesia have documented that human vigilance alone is inadequate to insure patient safety and have underscored the importance of monitoring devices. These studies have been reinforced by standards for equipment design, guidelines for patient monitoring and reduced malpractice premiums for the use of capnography and pulse oximetry during anesthesia. Draeger anesthesia workstations integrate ventilator technology with patient monitors and alarms to help prevent patient injury in the unlikely event of a ventilator failure. Furthermore, since the reservoir bag is part of the circuit during mechanical ventilation, the visible movement of the reservoir bag is confirmation that the ventilator is functioning.

### 4. If advanced ventilation is important, why not just use an intensive care ventilator?

Anesthesia ventilators are different from intensive care unit ventilators in that they must be able to deliver inhalation anesthesia in addition to provide mechanical ventilation. Whereas intensive care ventilators can function in an open circuit configuration, the need to deliver inhaled anesthetics efficiently requires that anesthesia ventilators contain patient gases within the breathing circuit. The purpose of the bellows is to separate the gases driving the ventilator from the gases being delivered to the patient. In a similar fashion, the piston chamber of a piston ventilator isolates the gases that the patient will receive. In both cases, the total volume that can be delivered per breath is limited by the maximum volume of the bellows and piston chambers. Standard designs offer sufficient volume capability to meet the needs of virtually all patients.

### 5. Why does the exhaled volume measurement differ from the set tidal volume?

The set tidal volume is the volume the clinician desires the patient to receive. In the case of a piston ventilator with compliance compensation, the volume delivered to the patient's airway will equal the volume set to be delivered. For a bellows ventilator with a flow sensor at the inspiratory valve, the set volume will equal the volume passing through that sensor. Exhaled volume measurement in a circle system is typically performed at the expiratory limb adjacent to the expiratory valve. This sensor measures exhaled gases plus the gas that is compressed in the breathing circuit during inspiration. When inspiratory pressure is high, the difference between measured exhaled volume and actual exhaled volume can be significant due to the compliance of the breathing circuit. Draeger anesthesia workstations can use the compliance factor of the breathing circuit to subtract the impact of compliance and obtain a better estimate of volume delivered

to the airway. Furthermore, most exhaled volume monitors have an inherent accuracy of only +/-15%.

### 6. What is the difference in compressed gas requirements between a piston and bellows ventilator?

The piston ventilator does not require compressed gas as a source of power whereas the bellows ventilator is completely dependent upon compressed gas to function. When using a cylinder source of compressed gas, the duration of time the anesthesia machine can be used will be significantly greater when using a piston ventilator since the only gas consumption by the piston ventilator is from the fresh gas flow. A full E cylinder contains 625 liters of gas. If fresh gas flow is set at 1 liter per minute, there will be a supply for more than 10 hours. The bellows ventilator will typically not function for more than one hour on an E cylinder due primarily to the compressed gas used to power the ventilator.

### 7. Can I still ventilate the patient when using a piston ventilator if the power fails?

All Draeger anesthesia workstations are equipped with battery supplies to provide at least 30 minutes of power in the case of AC power failure. If a total electrical power failure occurs, the piston ventilator will cease to function but manual or spontaneous ventilation and delivery of anesthetic gases will still be possible. Modern bellows ventilators are microprocessor driven and also require a source of electrical power to function.

### 8. How can I detect a leak in the circuit when using a piston ventilator?

In the case of a bellows ventilator, a leak is recognized when the bellows fail to return to their starting position and (instead) progressively fall in the bellows compartment. The leak may be observed but low pressure and volume alarms are required on all anesthesia machines to eliminate the need for vigilance

## Selected References

1. Stayer et. al. Comparison of NAD 6000 and Servo 900C Ventilators in an Infant Lung Model. *Anesth Analg* 2000;90:315-321.

In vitro study comparing delivery of small tidal volumes (30 and 100 mls) to a pediatric lung model by the NAD 6000 Divan ventilator and the Siemens Servo 900C ICU ventilator using a variety of settings for respiratory rate, lung compliance and PEEP. The NAD 6000 which uses the Draeger Divan piston ventilator was found to be equivalent to the Siemens 900C ICU ventilator for delivering small tidal volumes.

2. Stayer et.al., Pressure Control Ventilation: Three Anesthesia Ventilators Compared Using an Infant Lung Model. *Anesth Analg* 2000;91:1145-50.

In vitro study comparing the ability to deliver pressure controlled ventilation to an infant lung model by the Siemens Servo 900C ICU ventilator, the NAD 6000 Divan Ventilator and the Ohmeda Aestiva 3000 ventilator. Ventilator settings were selected to mimic near maximum conditions of ventilation for a neonate (30 cmH<sub>2</sub>O) and an adult (60 cmH<sub>2</sub>O). The tidal volumes delivered by the NAD 6000 and Aestiva ventilators were 5.8 mls and 18.9 mls less than the volume delivered by the 900 C respectively. The 900 C tended to overshoot the set inspiratory pressure during low lung compliance conditions underscoring the value of an inspiratory flow setting. The Aestiva did not achieve the set inspiratory pressure with shorter inspiratory times whereas the 6000 was not greatly affected by changes in inspiratory time.

3. Stayer et.al. Volume Ventilation of Infants with Congenital Heart Disease: A Comparison of Draeger, NAD 6000 and Siemens Servo 900C Ventilators. *Anesth Analg* 2001;92:76-79.

In vivo study of 20 patients undergoing complex repair of congenital heart defects were ventilated in a random fashion with the Draeger 6000 Divan ventilator and Siemens 900C ICU ventilator. Both machines provided adequate volume controlled ventilation.

4. Feldman JM, Smith J. Compliance Compensation of the Narkomed 6000 Explained. *Anesth.* 2001;543-544.

Technical explanation of the manner in which the Narkomed 6000 Divan ventilator accomplishes compliance compensation to deliver the set tidal volume to the patient's airway.

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and the potential for failing to recognize a leak or disconnect. With a piston ventilator, similar alarms alert the user to a potential leak. Furthermore, the reservoir bag will be observed to collapse and cause a low fresh gas alarm.

## 9. Do piston ventilators require more maintenance than bellows ventilators?

The piston ventilator technology in the Fabius GS and Narkomed 6000 series uses an innovative rolling seal that dramatically reduces the friction between the piston and the cylinder. The rolling seal is inexpensive, and is replaced as part of the preventative maintenance schedule every 2 years. The motor drive for the piston is a brushless system designed to operate for 10 years without maintenance. Unlike the servo valves in the bellows designs, the piston is not affected by dust or dirt in the compressed gas supplies and is more fault tolerant.

## 10. Are all bellows ventilators subject to the same limitations?

There are some differences in bellows ventilator designs that influence the accuracy of volume delivery. Draeger bellows ventilators fill only to the desired preset tidal volume and the user can set sufficient inspiratory flow to ensure that the bellows empties completely with each breath. Compression of drive gas does not influence the desired tidal volume in that case.

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