Whitepaper

A comparison of High-Frequency Percussive Ventilation (HFPV), High-Frequency Oscillatory Ventilation (HFOV), and High-Frequency Jet Ventilation (HFJV)

Author: David Lockwood, RRT

Reviewers: Tom Russell, RRT, Crystal Sinclair, RRT, Shawn Goughnour, Giles Wilson

General Principles of high-frequency ventilation

For high-Frequency Ventilation, it is important to remember that, as with all ventilators, flow over time equals volume.

High-frequency ventilation has been associated with increased molecular diffusion, improving arterial oxygenation, but carbon dioxide elimination improves with an increase in ventilation or minute volume.

- High-frequency ventilators create sub-anatomical volumes (volumes that are smaller than the anatomical dead space of the tracheal-bronchial tree) with each pulse.
- Controlling delta P (ΔP) on high-frequency vents is similar to conventional pressure control ventilation—the wider the ΔP, the more volume (up to the limit of hyper expansion).
- Control of volume and ventilation with high frequency has similarities to conventional pressure control ventilation management with variations in how minute ventilation is controlled.
- Control of high-frequency minute ventilation is opposite to how it is controlled on slower rate conventional ventilators, in that lowering the high-frequency rate will increase minute ventilation. This rationale relates to this paper's first sentence: flow over time equals volume. The exception to this is how the Bunnell high-frequency jet ventilator works.
- High-frequency ventilators produce pulse volumes with an inspiration and an expiration phase which equals a total cycle time, the same as conventional ventilators.
- With high-frequency rate ventilators, the inspiratory time of the individual pulse can either be a percentage of the total cycle time or a set time in milliseconds. Lowering the rate of high-frequency ventilators that use an inspiratory percentage allows for more inspiratory time, equating to a larger pulse volume. For example, at a rate of 500 bpm, an increase of 0.50ml/pulse would increase minute volume by 250 ml. The exception is high-frequency jet ventilation on the Bunnell LifePulse® 204 ventilator, which uses a set I time and auto-adjusts the I:E ratio based on the frequency rate.

There are currently three types of high-frequency ventilatory modes available in the U.S. market: High-Frequency Oscillatory Ventilation (HFOV) (Vyaire™ Medical, Mettawa, IL); High-Frequency Jet Ventilation (HFJV), (Bunnell Inc., Salt Lake City, UT); and High-Frequency Percussive Ventilation (HFPV), (Percussionaire®, Sandpoint, ID). This paper intends to describe the similarities and differences in how each device functions and explain why each mode should be operated the way it is designed and not necessarily managed like the other high-frequency devices. While all three utilize a high-frequency rate (defined by the FDA as a ventilator rate greater than 150 breaths per minute) and generate sub-anatomical tidal volumes, they differ in several other ways. Therefore, it is essential to understand the differences between each ventilator to manage the patient properly. The Vyaire oscillator and the ventilators from Percussionaire have models for neonates, pediatrics, and adults. The Bunnell Jet ventilator is for neonates up to 3592 g.[1]

Both Vyaire, the oscillator ventilator (HFOV) manufacturer, and Bunnell, the manufacturer of the jet ventilator (HFJV), make only one model of their devices. Percussionaire, the manufacturer of high-frequency percussive ventilators (HFPV), has several models that utilize this technology. HFPV is also available in two forms and, therefore, will be discussed last, and how each form functions will be contrasted separately to HFOV and HFJV.

HFOV – Vyaire

Recommendations for use are drawn from the user manual (with footnotes referenced).

High-frequency oscillatory ventilation on the Vyaire 3100 A or B is accomplished by a push-pull force created by a permanent, hollow tube-shaped magnet. Suspended inside the magnet is a coil. A piston attached to the coil moves a plate forward or backward against the flexible diaphragm, which is part of the oscillator breathing circuit. This push-pull action is created by alternating polarity between positive (inspiration) and negative (expiration).[2] Expiration with HFOV is, therefore, an active process and creates a sub-ambient pressure or cavitation during the expiratory phase. Spontaneous respiration can be hampered because of the active expiration of HFOV. With HFOV, the oscillation stays the same with each pulse, i.e., the amplitude does not change from peak to peak. While this design is bi-phasic, for the purposes of high-frequency ventilation, this version may be called a mono-phase design in some literature, due to the fact that there are some types of high-frequency ventilation modes that will also alter the amplitude at regular intervals and have been deemed as a bi-phasic high frequency design.

Oxygenation on HFOV (excluding FiO_2 adjustment) is primarily achieved by manipulating the "Mean Pressure Adjust" knob to adjust the Paw. This is the same as mean airway pressure, (MAP). Changing the amplitude (Power) or frequency will also affect the Paw.[3]

The oscillator has several controls. The two main or most common controls used in patient management are Power (oscillatory amplitude) and Paw.

Power: Increases or decreases the amplitude. Increasing the amplitude increases ventilation by allowing greater piston displacement and ΔP swing, increasing the pulse volume.[4]

Frequency: Changing frequency will increase or decrease the delivered pulse volume. Going down in frequency will cause an increase in volume due to the inspiratory time of the pulse being a percentage of the total cycle time rather than a set time. A lower rate will result in a longer inspiratory time allowing for more flow delivery. Going up on the rate will raise the MAP, which improves diffusive oxygenation, but the smaller pulse volumes may allow a rise in $PaCO_2$.[5]

% Inspiratory Time: The range is 30% to 50% of the total inspiratory-expiratory cycle time. The standard setting per the Vyaire manual is 33%, creating a 1:2 I/E ratio. In cases where $PaCO_2$ is too high, increasing % Inspiratory time will increase the pulse inspiratory time, allowing flow for a longer time, which increases volume.[6] A % Inspiratory Time of 50% creates a 1:1 ratio.

Bias Flow: Bias flow setting will depend on patient size and should be at least 10 L/min (preemies). It needs to be adjusted higher as patient size increases. Increasing bias flow has negligible effect on ventilation unless a high amplitude is required, then bias flow should be increased to ensure that it exceeds oscillatory flow to avoid increasing circuit dead space.[7]

Paw (MAP): The oscillator does not directly read out PEEP, preferring to instead focus on MAP. MAP is adjusted on the oscillator by changing the inflation of a mushroom valve on the expiratory limb of the circuit, increasing or decreasing the blockage of the exiting bias flow. The knob for adjusting Paw is Mean Pressure > Adjust (bias flow-dependent). Increasing the inflation of the mushroom valve reduces exiting flow and will cause a rise in MAP. [8]

HFJV – Bunnell

Recommendations for use are drawn from the user manual (with footnotes referenced).

High-frequency jet ventilation is created using continuous flow through a circuit tube from the ventilator unit to a servo pinch valve (patient box) placed close to the patient. A flexible section of the jet circuit tubing passes through the pinch valve. Closure of the pinch valve creates the expiration phase. Changing the duration of the valve closure manipulates the expiratory time. Manipulation of how frequently the valve closes controls the frequency. A unique endotracheal adapter is used to allow the connection of a conventional ventilator, a proximal pressure line, and the jet tube itself. Expiration on the Bunnell jet is passive, relying on the elastic recoil of the diaphragm, lung tissue, and ribs. The jet ventilator must be interfaced with a conventional ventilator. The conventional ventilator is needed for several factors; it provides fresh gas for spontaneous respiration, produces positive end-expiratory pressure (PEEP), and provides intermittent mandatory ventilation for lung recruitment, all of which the Bunnell jet ventilator alone is not capable of doing itself. [9] This type of high-frequency ventilation has been classified as a flow interrupter by most researchers. As with the oscillator, peak-to-peak pressure does not change with the jet ventilator. This may also be called a single or mono-phase device in some literature.

According to the Bunnell 204 manual, oxygenation (excluding FiO_2 adjustment) is primarily controlled by manipulating the conventional ventilator PEEP, rate, PIP, or I time. Carbon dioxide removal, or ventilation, is achieved via the LifePulse high-frequency ventilator.[10]

Like HFOV, control of volume on the LifePulse 204 is also affected by several factors:

PIP: Increasing PIP will allow more flow, which will increase each pulse volume.

I TIME: Increasing I time will allow more flow over time, resulting in an increase in minute volume.[11]

PEEP: Adjusting PEEP on the jet is much like using PEEP on conventional pressure control ventilation. Delta P (ΔP) is affected by both PIP and PEEP and affects volume. PEEP on the jet is non-oscillatory, meaning that PEEP is created, depending on the conventional ventilator used, by increasing or decreasing the exiting of expiratory gas flow. **Rate:** Increasing the rate on the jet, because of the set I time, will increase the minute ventilation, much like conventional ventilation, but it usually is less effective on CO_2 evacuation compared to adjusting PIP.[12] Decreasing the HFJV rate will lower the minute ventilation, again because of the set I time. The starting I:E ratio on the jet is 1:6 based on the default I time of 0.02 and frequency of 420 bpm. The closest it can get to a 1:1 ratio is at maximum I time of 34 milliseconds (0.034) and maximum rate of 660. The I:E ratio at those settings will be 1:1.6.[13] This is opposite of both the Vyaire oscillator and Percussionaire HFPV, which set I time as a percentage (%) of total inspiratory/expiratory cycle time, and both can have an I:E ratio of 1:1. With those vents, based on percentage, decreasing the rate will give a longer I time, allowing more flow, increasing the volume per pulse, and increasing minute ventilation. **This difference between the function of**

rate and I time on the Bunnell jet ventilator must be well understood if switching between the Bunnell jet ventilator and either the Vyaire Oscillator or Percussionaire HFPV ventilators.

HFPV- Percussionaire

Percussionaire makes two types of high-frequency devices. One design is based on either a single- or mono-phase design, similar to HFOV or HFJV. The other design uses a dual or Bi-phase design, similar to BiPAP or Bi-level. Percussionaire ventilators use passive exhalation, the same as the Bunnell jet.

A differentiating factor of Percussionaire ventilators is the use of a sliding venturi injector module known as the Phasitron®. The Phasitron works on Bernoulli's principle and Newton's Third Law of Motion. By utilizing the physics of Bernoulli's principle, the Phasitron reacts to changes in resistance and compliance in the lung. Increasing resistance will automatically slow down or stop the entrainment of flow that is delivered to the lung. Because of this feature, the appropriate volume is delivered to fill the lung in its present resistive state. Because of how the Phasitron works with physics, peak-to-peak amplitude can change over time. If resistance decreases, the venturi will entrain more flow, but amplitude (pressure) will decrease. If resistance increases, the opposite is true with amplitude increasing but flow (volume) decreasing. The Phasitron is an "open system" much like airway pressure release ventilation (APRV). With an open system, the patient can spontaneously breathe at any point in the inspiratory/expiratory cycle.

Another feature of Percussionaire ventilators is that they are completely pneumatic and do not need an electrical power source to operate.

Mono-phase devices:

The TXP®-2D (OEM-International Bio Med) and TXP® 5 are transport ventilators. Both ventilators have an I:E ratio that auto-adjusts from 1:1 (extreme high rate and maximum amplitude) to 1:4 (extreme low rate and low amplitude). With rates and amplitudes in the usual operating ranges, I:E ratio will vary between 1:1 to 1:2.5. Controls on these ventilator are for frequency and amplitude, and function similarly to HFJV and HFOV.

Amplitude: Increasing or decreasing the amplitude will allow more or less flow by altering the pressurization. Allowing a higher pressure affects flow, increasing the pulse volume.

Frequency: Increasing or decreasing frequency will also affect the pulse volume and MAP with negligible effect on the amplitude. Lowering the rate will give more inspiratory time for flow to be delivered and raising the rate will have the opposite effect. Raising the rate, thus increasing MAP, will help with diffusive oxygenation, but the resultant smaller volumes caused by reducing the ΔP may allow a rise in $PaCO_2$.

PEEP: PEEP is created using a spring valve on the expiratory port combined with a one-way valve on the inspiratory entrainment port. PEEP on these devices is non-oscillatory.. Increasing PEEP will increase the MAP without affecting the amplitude.

Bi-phase devices:

The Percussionaire Bronchotron® Transport ventilator and the Volumetric Diffusive Respirator (VDR®-4) ventilators use the same basic Phasitron® as the mono-phase TXP® ventilators but, in addition to the high-frequency rate, utilize a distinct higher pressure inspiratory phase, also called T High and a distinct lower pressure expiratory phase, also called T Low.

The primary controls on the Bronchotron are:

Pulsatile Flow rate (Amplitude): Pulsatile flow rate or amplitude is the same as on the TXP ventilators and is the same as on HFOV and HFJV. The name “pulsatile flowrate” is an accurate description of how amplitude adjusts on any of these devices.

Pulse Frequency: Frequency is the same as the TXP ventilators and works the same as frequency on HFOV. Pulse I:E ratio is self-adjusting and is between 1:1 to 1:1.5.

Inspiratory Time & Expiratory time: The Bronchotron is bi-phasic. Setting inspiratory and expiratory time creates a convective (conventional) rate. This is comparable to how Bi-level, APRV, or BiPAP works. The set amplitude is applied during the inspiratory phase or T High. During the expiratory phase, the amplitude is adjusted down to the set oscillatory CPAP. In effect, the Bronchotron is a time-cycled pressure ventilator that uses high-frequency sub-anatomical pulse volumes over time (inspiratory phase) to create an inspiratory volume similar to what a conventional ventilator would deliver. Research shows that evacuation of CO_2 works better with ventilation or minute volume rather than molecular diffusion. This is related to carbon dioxide having a diffusion capacity approximately 20 times better than oxygen. Being able to move a larger volume of CO_2 allows for a larger gradient to exist. The larger the gradient, the faster the diffusion.[14]

Oscillatory CPAP: Unlike the oscillator, the Jet, and the TXP transport ventilators, PEEP (CPAP) is dynamic on the Bronchotron. What this means is that during the expiratory phase, T Low, there is still a pulsing action, but amplitude (or pressure) is decreased to what would be considered a PEEP level. (Although seldom used, a non-oscillatory PEEP can be used along with the oscillatory PEEP via a spring valve on the expiratory port on the Phasitron. The resultant total PEEP would be additive from both sources.) Thus, a continuous flow is created at a lower pressurization than during the inspiratory phase. This dynamic PEEP state continues the “rinsing effect” of HFV. Alternating between a high pressurization phase and a low pressurization phase helps to evacuate more CO_2.

Volumetric Diffusive Respirator (VDR)

The VDR ventilator is the hospital-based version of the Bronchotron.

In addition to the controls mentioned on the Bronchotron, the VDR has the following controls:

Demand CPAP: Demand CPAP is a non-oscillation CPAP that can be used in combination with oscillatory CPAP. The two are additive for the total PEEP. Demand CPAP is used to increase the bias flow in the circuit for patients that have a high minute volume demand. Demand CPAP can be used as a classical CPAP with the ventilator turned off.

Pulse i:e ratio: Pulse i:e ratio refers to the ratio of the high-frequency rate. Whereas the pulse frequency ratio in the Bronchotron is fixed between 1:1 to 1:1.5, the high-frequency ratio on the VDR can be manually adjusted between 1:1 to 1:3 to allow for more expiratory time within each pulse. This works like the % Inspiratory time on the oscillator. The lower case i:e ratio designation is used to avoid confusion with the uppercase I:E knobs used to set a conventional lower rate.

Convective pressure rise: Convective pressure rise allows the clinician to add a secondary pressurization phase during the conventional inspiratory time. This second pressurization is initiated after eight-tenths of a second of the I time has passed for the initial pressurization phase. For example, with a convective inspiratory time of 1.5 seconds, after the initial pressurization set by the pulsatile flowrate knob (amplitude) occurred for 0.8 seconds, pressure would increase to the set convective pressure rise level and be maintained for the last 0.7 seconds, equaling the I time of 1.5 seconds.

This feature is available for all patient populations, but due to typical I time settings of 1 second or less, this feature is seldom used in the neonatal environment.

Convective pressure rise can be used as a recruitment maneuver or to give a slower increase to maximum amplitude when tissue damage might be a concern. The concept is to use less initial flow in situations where prolonged inspiratory time constants may occur, to avoid overdistension of healthy areas with shorter inspiratory time constants. The flow, and thus the pressure created, is “stepped.”

Conclusion:

These three variations of high-frequency ventilation have similar characteristics, but all three also have significant differences in how they use flow and time to create volume.

All three methods of HFV should be studied and understood to correctly manage oxygenation and ventilation when using a particular ventilator rather than trying to make one ventilator mimic another. Care should be used when switching from one brand of HFV ventilator to another.

References

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