Advantages of Life Pulse HFJV Compared to Other HFV

The Life Pulse High-Frequency Jet Ventilator (HFJV) offers important advantages compared to other high-frequency ventilators (HFV). The advantages can be grouped into four categories related to ventilatory efficiency, physiologic impacts, operational considerations, and therapeutic flexibility.

Greater Ventilatory Efficiency

The Life Pulse uses a jet nozzle incorporated into a special ET tube adapter to squirt gas into the endotracheal tube. This nozzle produces a very brief but helpful phenomenon called *transitional flow.*

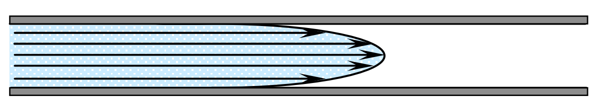
In 1915, Henderson demonstrated that a transitional flow pattern could be used to explain how panting animals can breathe effectively using very small tidal volumes (V_Ts).[1] Transitional flow allowed fresh (O_2 rich) gas to penetrate dead space gas in the airway making smaller tidal volumes as effective as larger tidal volumes because there is less "rebreathing" of dead space (CO_2 rich) gas.

The Life Pulse uses transitional flow, produced by very brief (~0.02 sec) high velocity, small tidal volume inspirations, to deliver fresh gas close to the alveoli without pushing all the dead space gas ahead of it. Thus, adequate ventilation and oxygenation occur using less pressure than is required by either conventional ventilation (CV) or high-frequency oscillatory ventilator (HFOV).

HFOV inspiratory flow begins slowly, accelerates rapidly, and then slows down again at the end of inspiration as the oscillator's piston reaches the end of its forward stroke. Therefore, the velocity profile of HFOV inspirations is similar but not as pointed as that of HFJV inspirations. This difference, in part, explains why HFJV has been shown to be more effective than HFOV at maintaining normal gas exchange.[2, 3]

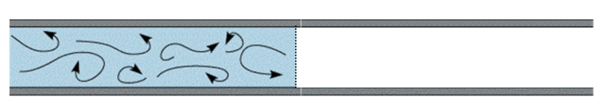
Laminar flow creates a velocity profile that looks like the head of a bullet, where the gas in the middle of the tube is flowing faster than the gas near the walls of the tube.

Laminar Flow:



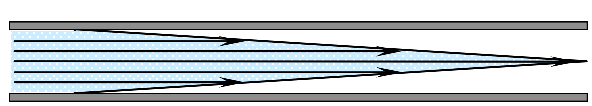
Turbulent flow produces a chaotic pattern with gas flowing in every direction at once, but overall, the gas flows down the tube with a flat velocity profile.

Turbulent Flow:



When gas accelerates very suddenly, it takes a certain amount of time and distance for turbulence to develop. During that time, a very distinctive, sharp velocity profile develops. Since this happens routinely when gas is accelerated from laminar to turbulent flow, it has been labeled "transitional." In transitional flow the gas in the middle of the tube goes much, much faster than the gas near the walls.

Transitional Flow:



Positive Physiologic Impacts

There are three primary physiologic advantages of HFJV over HFOV. The first advantage is HFJV's ability to ventilate effectively at lower mean airway pressure (MAP), which results from passive versus active exhalation. The second advantage is that HFJV enhances mucociliary clearance by combining very fast inspirations with relatively slow, passive exhalations. Finally, HFJV's high velocity, small tidal-volume jet breaths cannot penetrate injured areas of the lung with high resistance, allowing those areas to rest and heal.

1) Ventilates at Lower MAP: The passive exhalation used by the Life Pulse allows ventilation to occur at lower MAP compared to the active exhalation used by HFOV.

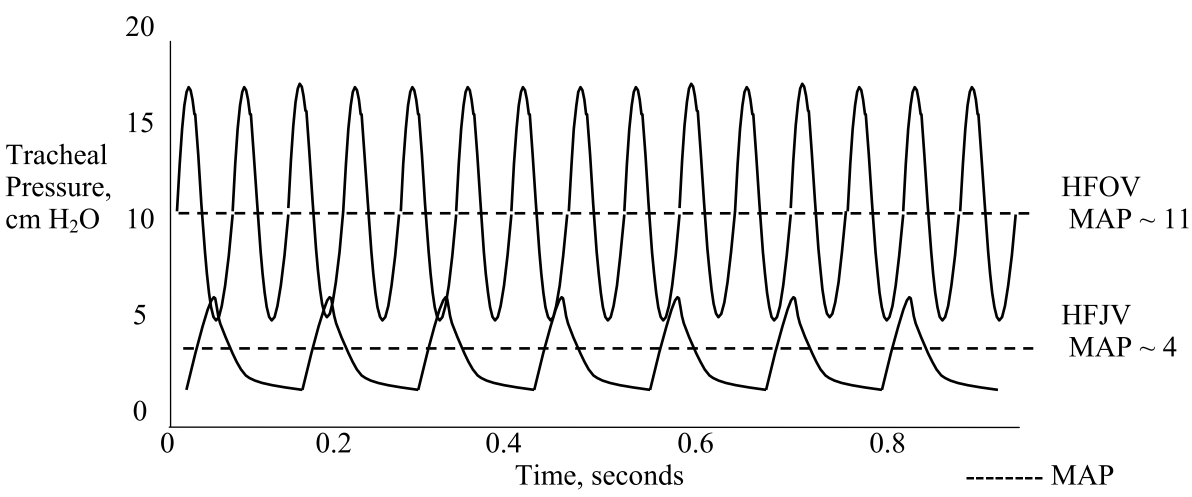
Whenever exhalation is assisted, whether by sucking on the lungs or squeezing on the chest, gas gets trapped in the alveoli by airways getting pinched off or "choked." This kind of gas trapping occurs because airways are flexible and surrounded by alveoli. If gas is sucked from the trachea, the pressure drops in the airways before it drops in the alveoli; the higher alveolar pressure creates "choke points" in the airway, trapping gas in the alveoli.

The best way to prevent choke points is to allow exhalation to occur naturally or passively. However, active exhalation can work if pressure in the airways is raised by increasing MAP. If a patient has no airleak or hemodynamic complications, and if the higher MAP also helps stabilize surfactant deficient alveoli, active exhalation can be used.

It is also possible to create gas trapping during passive exhalation. If the expiratory time is too short, exhalation will not be completed when the next inspiration starts. This type of gas trapping is dependent on tidal volumes, lung time-constants, and I:E settings.

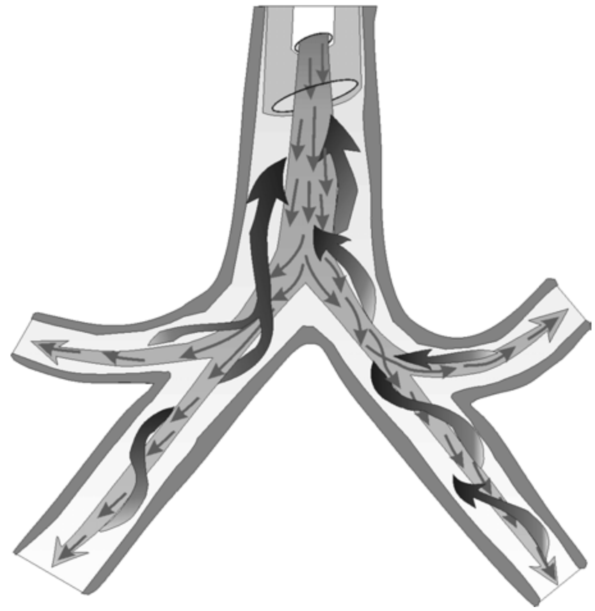
Since HFJV tidal volumes are very small, it doesn't take long for them to be exhaled, especially when the patient's lungs are stiff (i.e., they have short time-constants). If gas trapping does occur with HFJV, it can be easily corrected by lowering the rate, which lengthens expiratory time. (Inspiratory time is a control setting on the Life Pulse, rather than being a percentage of the breath cycle as with the SensorMedics 3100 HFOV.)

The following figure illustrates the effect active expiration had on the mean airway pressure required to achieve the same PaO_2 in a series of anesthetized, paralyzed, normal cats when they were switched back and forth between HFJV and HFOV.[3]



Pressure amplitudes and MAPs were independently adjusted in this experiment to produce the same arterial blood gases. Since it doesn't take much mean airway pressure to oxygenate or ventilate a cat with normal lungs, the Life Pulse was able to provide normal gas exchange at a very low MAP. The SensorMedics 3100A, on the other hand, required the MAP to be raised above the level where choke points occurred to get normal blood gases. While the pressure amplitudes in this experiment were also remarkably different, the difference in rates at which the Life Pulse and SensorMedics 3100A were run (7 Hz versus 15 Hz, respectively) makes any comparison of those parts of the waveforms difficult to interpret.

2) <u>Enhanced Mucociliary Clearance</u>: The Life Pulse squirts gas into the airways at high velocity and allows exhalation to occur slowly as noted above. Inspired gas shoots down the center of the airways so the path of least resistance for exhaled gas is against the airway walls as shown in the adjacent figure. This phenomenon helps facilitate mucociliary clearance, and can be demonstrated in the lab using a water droplet in a small diameter tube.



Blowing a very quick puff of gas into a capillary tube with a water droplet in it will not blow the droplet out of the tube. The puff of gas just drills a hole through the droplet, and the droplet reforms after the puff goes past. However, blowing gas slowly into the tube expels the water droplet very easily. Thus, the flow patterns generated by the Life Pulse allow gas to drill through secretions on inspiration and push them up and out during exhalation.

Inhalation and exhalation with HFOV are more complex: inspiratory flow starts out slowly, accelerates, and then slows down again at the end of inspiration. Gas going into the lungs slows down as it is repeatedly split in half at every bifurcation, and the resulting laminar flow may push secretions deeper into the lung. When exhalation is accelerated by the sucking action of HFOV, turbulence is promoted as two airways repeatedly empty into one. The consequences of these flow patterns are that secretions may be pushed into the lung during inspiration and pushed out again during exhalation. Therefore, the two patterns cancel each other out with respect to mucociliary clearance.

3) <u>Injured Lungs Can Rest and Heal</u>: The rapid inspiratory flow of HFJV inspirations is ideal for treating PIE. PIE increases airway resistance as the interstitial gas dissects its way along airway walls, compressing airways and restricting their internal lumens. Whatever tidal volumes get downstream past restricted portions of the airways, become trapped as they encounter airways with decreased diameters and increased airway resistance during exhalation. However, if HFJV is used to ventilate this lung, the small high velocity breaths will not penetrate those long time-constant areas with increased airway resistance.

The best way to ventilate lung areas with increased airway resistance is to slow down and give the gas adequate time to overcome the increased resistance of the narrow airways. Slow rates and long I-times are most successful at getting gas beyond such restrictions, if that is appropriate for the specific pathophysiology. The faster gas is pushed in, the less gas penetrates through such affected airways. Thus, injured areas of lungs (areas with PIE) have a much better chance of healing with HFJV.

The Life Pulse HFJV is the only HFV ever proven to be more effective in the treatment of PIE when compared to rapid rate, small tidal volume conventional ventilation.[4]

<u>Ease of Operation</u>

The Life Pulse is easy to set up and connect to a patient using the LifePort jet ET tube adapter. Just replace the standard ET tube adapter with the LifePort, make your tubing connections, and you are ready to go. No circuit calibration is necessary, and any conventional ventilator can be used with the Life Pulse to provide PEEP and sigh breaths.

The patient can be turned in any direction without interference from the Life Pulse circuit, and the new *WhisperJet* Patient Box (inhalation valve) reduces the noise associated with HFJV by as much as 75%. This is in sharp contrast to the SensorMedics Oscillator (3100A), which gets louder when its power is increased, and its stiff large-bore circuit tubing makes patient positioning more difficult.

Managing the Life Pulse is as easy as conventional ventilation. Setting changes on HFJV and CV are analogous in their effect. Turn up rate for smaller patients and blow off more CO_2. Turn up PIP to increase V_T. Turn up PEEP for better oxygenation. The differences are the Life Pulse Rate is about ten times faster than the CV rate, HFJV I-time is about twenty times shorter, and V_Ts are about five times smaller. Those tiny tidal volumes can easily get in and out of a patient's lung when the I-time on the Life Pulse is at its lowest setting: 0.02 sec. Therefore, an infant that is comfortable at 50 bpm on CV should be comfortable at 500 bpm on the Life Pulse.

The only management parameters that are not analogous between CV and HFJV are I-time and the importance of rate versus V_T for eliminating CO_2. Unlike CV, the shortest I-time works best on almost all patients during HFJV, regardless of their size. Using the shortest I-time means you get a longer exhalation time as rate is turned down. Rate must be turned down to allow enough time for passive exhalation in larger patients.

Finally, V_T is more important than rate for eliminating CO_2, because in high-frequency ventilation CO_2 elimination is directly proportional to frequency times tidal volume <u>squared</u> (rate x V_T^2) . Therefore, making relatively small changes in tidal volume by increasing ΔP (delta pressure is the difference between PIP and PEEP) has a much bigger effect on $PaCO_2$ compared to making comparable percentage changes in HFJV rate.

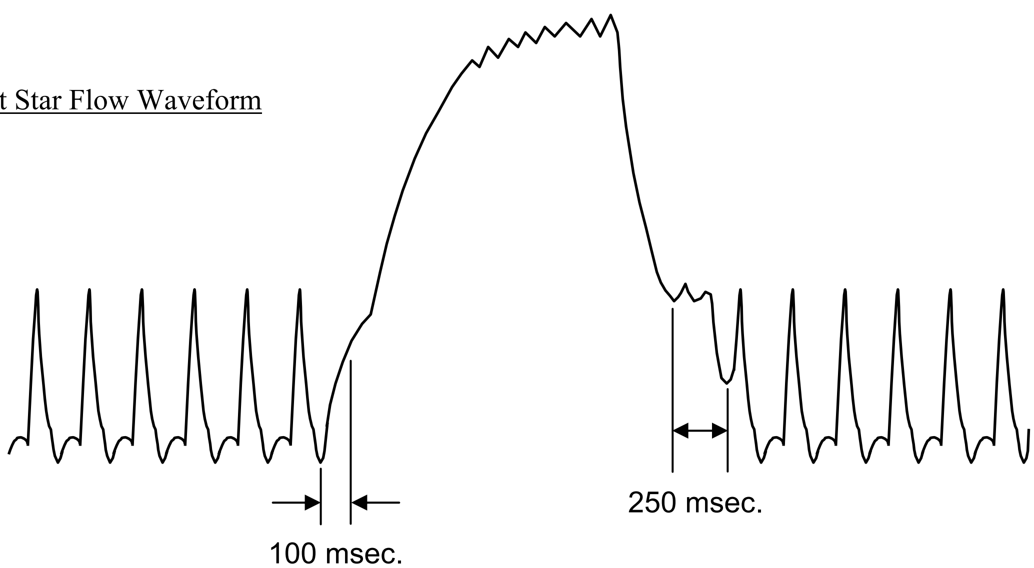
Changing HFJV rate has no effect on tidal volume since the I-time is held constant; whereas, changing rate on the SensorMedics 3100 changes tidal volume because I-time cannot be held constant (I:E ratio is held constant: 1:1 or 1:2). The effect of changing the 3100's rate on $PaCO_2$ is counterintuitive because of its inverse effect on tidal volume. Turning the 3100's rate up decreases tidal volume, so less CO_2 is blown off at higher rates when I:E and pressure amplitude are held constant. This relationship is contrary to every other ventilator, including the Infant Star in its HFV mode. The I-time on the Infant Star is held constant and is independent of rate changes, just like the Life Pulse

More Therapeutic Flexibility

In addition to having direct control of I-time, another similarity between the Infant Star with HFV and the Life Pulse HFJV is the ability to use a combination of HFV and intermittent mandatory ventilation (IMV). Larger tidal volume IMV breaths can open collapsed alveoli that small HFV tidal volumes cannot, and that combination of HFV and IMV capability is important for some patients.

IMV breaths with the Infant Star HFV are always delivered separately from HFV breaths, as shown in the following flow-wave figure taken from the Infant Star Operator's Manual. There is a 100 msec delay before the IMV breath and a 250 msec delay after the breath to avoid stacking HFV breaths on top of IMV breaths.

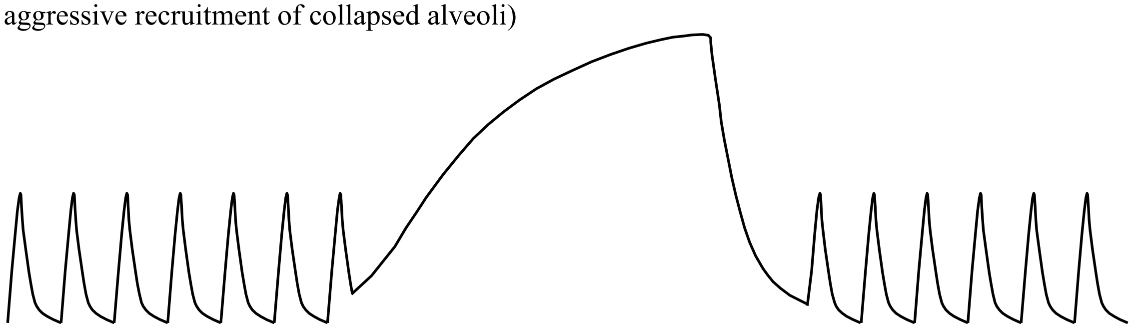
Infant Star Flow Waveform



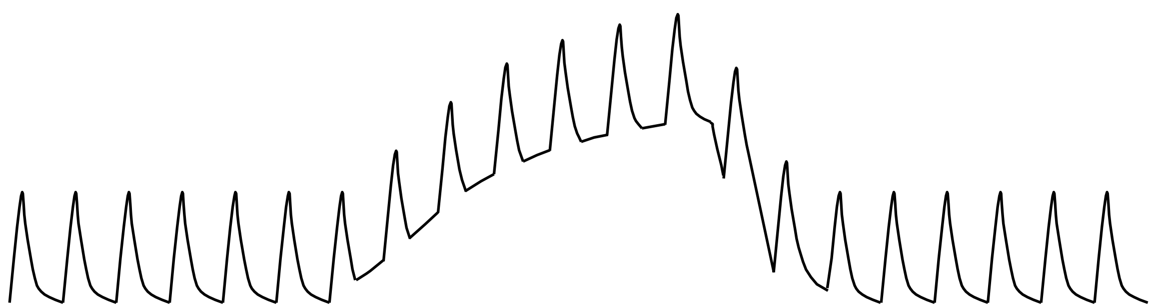
With the Life Pulse HFJV, IMV breaths can be kept separate, or they can be combined (stacking small HFV tidal volumes on top of individual IMV breaths) by adjusting their relative peak inspiratory pressures (PIP). If IMV PIP is set above HFJV PIP, the Life Pulse will pause as soon it detects a pressure above the set HFJV PIP. If IMV PIP is set below HFJV PIP, the Life Pulse breaths will ride up and over the IMV breath. This flexibility allows users the option of using IMV breaths as a tool to expand airways during the delivery of HFJV breaths, so that the latter may penetrate into areas of the lungs that are otherwise unreachable.

A variety of HFJV/IMV pressure waveforms can be delivered with the Life Pulse as illustrated below. (Pressure waveforms are used here because the Life Pulse is a pressure-limited ventilator.)

<u>HFJV interrupted by a relatively large IMV breath:</u>
(for aggressive recruitment of collapsed alveoli)

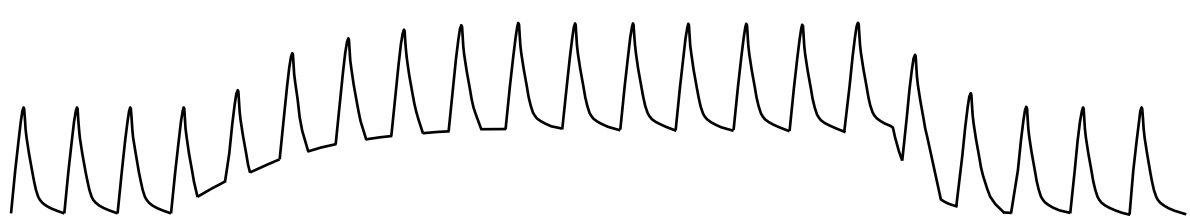


<u>HFJV uninterrupted by a moderately sized IMV breath:</u>
(for less aggressive alveolar recruitment and non-homogeneous lung disorders)

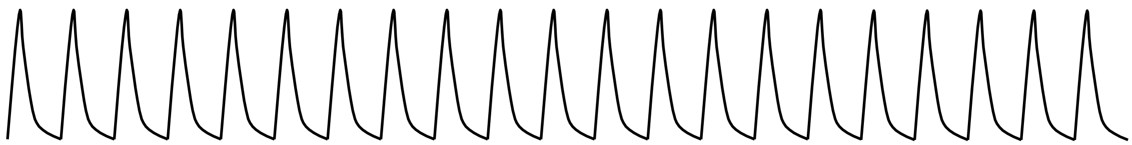


<u>HFJV uninterrupted by a modest size IMV breath</u>:
(for modest alveolar recruitment and more gentle ventilation of non-homogeneous lung disorders)

<u>HFJV uninterrupted by a modest size, long I-time IMV breath</u>:
(for periodic airway expansion during HFJV for non-homogeneous lung disorders)



HFJV uninterrupted with CV in CPAP mode:
(for optimal HFJV treatment of homogeneous lung disorders)



Clinical strategies using various combinations of HFJV and IMV provide users with added versatility as they try to determine what works best in patients with more complicated, non-homogeneous lung disorders.

Summary

The following table summarizes the advantages of HFJV discussed above.

Gas Delivery	Jet inspirations penetrate further into tracheal-bronchial tree.	Minimizes effective dead space and increases ventilation efficiency
Physiology	Passive exhalation	Effective ventilation at lower mean airway pressures
	Fast inspirations and slow expirations	Enhances mucociliary clearance
	High velocity breaths avoid airways with high resistance (e.g., PIE).	Injured areas of the lungs can rest and heal
Ease of Use	Easy to set up	No calibrations required
	Easy to run	Similar to conventional ventilation
	Easy on the patient	No stiff tubing to manipulate
Versatility	HFJV + IMV possibilities are numerous.	Ventilation can be tailored to treat complicated, non-homogeneous lung disorders

REFERENCES

1. Henderson Y, Chillingworth FP, Whitney JL. The respiratory dead space. *Am J Physiol;* 1915;38:1-19

2. Zobel G, Dacar D, Rödl S, Proximal and tracheal airway pressures during different modes of mechanical ventilation: an animal model study. *Ped Pulmonol.* 1994; 18:239-243

3. Boros SJ, Mammel MC, Coleman JM, et al. A comparison of HFOV and HFJV in cats with normal lungs. *Ped Pulmonol.* 1989; 7:35-41.

4. Keszler M, Donn SM, Bucciarelli RL, *et al*: Multicenter controlled trial comparing high-frequency jet ventilation and conventional mechanical ventilation in newborn infants with pulmonary interstitial emphysema. *J Peds.* 1991; 119: 85-93.