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High-Frequency Ventilation

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High-frequency ventilators (HFV) use increased respiratory rates and decreased tidal volumes to achieve gas exchange similar to conventional mechanical ventilators (CMV). This reverses the relative importance of convection and diffusion to gas exchange. There are currently 3 major types of HFV. They differ from each other in how gas is delivered, how they work, and what physiological effects they have. Conclusions drawn using one type of HFV cannot necessarily be applied to the others. This review examines the different types of HFV as well as the studies that have been conducted using HFV. It stresses the role that HFV may play in the surgical intensive care unit. The one certain indication presently for HFV is in patients with a bronchopleural fistula. It may also be useful as an adjunct to endoscopy and in adult respiratory distress syndrome (ARDS). If the underlying lung disease cannot be reversed (i.e., end-stage fibrotic ARDS), HFV has little to offer.

High-frequency ventilators (HFV) have been in use clinically and experimentally for about 20 years. Much has been written about their potential uses, their supposed advantages, and their possible benefits. High-frequency ventilators have been reported to be helpful for intraoperative and intensive care unit (ICU) care, bronchopleural fistulas, adult respiratory distress syndrome (ARDS), and other problems by decreasing airway pressures and lung movement, increasing gas exchange, and decreasing the risk of barotrauma and cardiovascular dysfunction. Unfortunately, the literature is quite confusing for a number of reasons. First, there are at least 3 different forms of HFV which can be produced by many different techniques and circuits. These 3 forms work in different ways and have different effects. Second, much of what was initially published was based on case reports, uncontrolled studies, and speculation. Claims were made, and, in some cases, have been perpetuated without being proven in controlled, prospective studies. Finally, there has been little standardization in ventilators, terminology, or experimental design, so comparing one study with another has been difficult.

This article will discuss the 3 types of HFV and some of the ways they can be produced. It will look at how they are alike and how they differ. It will examine the claims that have been made for HFV and the data to support the claims. It will also examine how they have been used clinically, especially in the intensive care setting, and how they might be useful in the future.

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High-Frequency Ventilation

High-frequency ventilation, in its widest sense, refers to a range of ventilatory techniques with the common characteristics of using increased frequencies and decreased tidal volumes, as compared to either normal breathing or conventional mechanical ventilation (CMV). The minimum frequency for HFV is generally defined as 60 breaths/min. These ventilators have been used at rates as high as 3,000 breaths/min (often noted as 50 Hz). Tidal volumes (TV) also cover a wide range and are often difficult to measure, but are usually less than dead space volume.

The first category of HFV is high-frequency positive pressure ventilation (HFPPV), developed in 1967 by Sjostrand and colleagues, who were looking for ways to decrease respiratory effects on hemodynamic variables [1]. Of the 3 techniques, it is the most like CMV. In fact, some conventional ventilators can be configured to deliver HFPPV. To do so requires a ventilator and circuit with low internal compliance so that gas loss does not occur in the system. Gas is delivered to the upper airway through a pneumatic valve. Exhalation originally occurred around an uncuffed endotracheal tube; now, however, exhalation values have been developed that respond rapidly enough to use with the system. This allows the use of cuffed endotracheal tubes without the fear of high pressures developing within the lungs. Tidal volume is usually 3–6 ml/kg of body weight, and all of the volume is delivered by the machine. Rates used are generally 60–80/min, but may be up to 150/min. The ratio of inspiration to expiration (I:E) is usually 1:4. HFPPV has been used largely in Europe by Sjostrand's group.

The second type of HFV is high-frequency jet ventilation (HFJV). This system was developed by Sanders in 1967 [2] and modified by Klain and Smith in 1977 [3]; it is the type that has been used most commonly in the United States and clinically. Most reports on HFV in the recent past have used HFJV. With HFJV, gas under high pressure (500–3,000 mm Hg) is delivered through a narrow cannula or injector (the jet source) into a relatively stationary volume of gas in an endotracheal tube. The impact of the jet stream starts this gas moving (entrainment) to deliver the tidal volume. The jet stream is delivered in short bursts by valves (fluidic, pneumatic, or solenoid) at rates of 80–300/min—most commonly 100/min.

The jet ventilator itself is a relatively simple and compact machine with controls that can be used to vary the frequency, the driving pressure, and the I:E ratio of the jet. The FiO_2 is controlled by supplying the gas to the jet from a blenderized source as well as controlling the FiO_2 of the entrained gases. The entrained gas is usually supplied by a standard conventional ventilator connected to the main port of the endotracheal tube. Positive end-expiratory pressure (PEEP) can be supplied by the conventional ventilatory and/or can be developed with the HFJV (which will be discussed later). Tidal volume delivered to the patient is increased by increasing the driving pressure of the jet.

The third type of HFV is high-frequency oscillation (HFO). The concept of HFO has been around since 1959; however, most work with HFO has occurred recently [4]. This system involves the greatest departure from CMV. HFO operates on a column of air between the lungs and the oscillator source (usually a rotary piston or a diaphragm such as a loudspeaker). This air column is vibrated back and forth rapidly (600–3,000 oscillations/min) by the oscillator source. Actual tidal volume of air moved is very small, a total of 50–80 ml at most. As gas exchange occurs and oxygen in the system is used, oxygen is resupplied to the system as necessary through a bias flow of fresh gas. Carbon dioxide may be removed by a CO_2 scrubber, but is more commonly removed through the bypass bias flow circuit. This can be either via a low-pass filter (which allows the low-frequency bias flow out but does not allow the high-frequency oscillations to escape) or simply through a suction source which balances the bias inflow. The bias inflow and outflow can be adjusted to vary mean airway pressure in the system and deliver PEEP.

More recent variations of HFO have involved oscillating not the air column, but the subject itself. Oscillations have been applied to the thorax (high-frequency chest wall oscillations, HFCWO) [5], and to the whole body (high-frequency body surface oscillations, HFBSO) [6]. Application to the whole body prevents downward excursion of the diaphragm, which occurs with the HFCWO. These transthoracic forms of HFO have yielded experimental results equivalent to airway HFO.

The major difference between the systems is how gas is delivered and how gas exchange takes place. In normal tidal breathing, 2 factors are felt to be important for gas exchange—convection (the movement of air through the airways) and diffusion (movement through the terminal airways and alveoli) [3]. Conventional mechanical ventilation attempts to duplicate this, using positive pressure rather than negative intrathoracic pressure to move air. Convection and diffusion both still occur (with air moving into and out of the lungs and diffusion occurring at the alveolar level). HFPPV is similar. Positive pressure is used to deliver a tidal volume and convective flow (all of the tidal volume is delivered by the high-frequency machine). The only difference is that the tidal volume is smaller and rates are faster than with conventional ventilators. Convection and diffusion play roles similar to CMV. HFJV also delivers a tidal volume with positive pressure. It differs from HFPPV, however, in that the tidal volume is composed of both the jet stream from the HFJV, as well as the gas from the entrained source, which is pulled along by entrainment from the high-pressure jet source. Convection still plays a large role, but kinetic energy is added to the system and diffusion becomes more important. Finally, HFO is a system that simply vibrates, or adds energy, to a column of air with minimal convective flow. The bias flow moves across this vibrating column and adds O_2 and removes CO_2. Enhanced diffusion is very important in this system.

The low compliance system, alluded to earlier with respect to HFPPV, is essential to all HFV systems. In CMV, tidal volume delivered is generally greater than the volume a patient would breathe to achieve similar gas exchange. The excess volume is necessary, among other reasons, because of the compliance of the circuits within the ventilator and connecting the patient to the ventilator. When the conventional ventilator begins to deliver the breath, the circuitry initially expands and then tidal volume is delivered. Because of the slow rates and high volumes used with CMV, the system can accommodate this expansion and convection is adequate. With HFV, however, the tidal volume is small and the rates are rapid. With a normally compliant system, all of the volume is used expanding the system and there is not enough time to adapt and deliver any gas flow downstream to the patient. Similarly, in HFO, in which tidal volume is much less important, the oscillations would be damped out by the compliance of the system, making them much less effective. To minimize compliance, dead space is decreased as much as possible. The injector cannula in HFPPV and HFJV is placed into the endotrachial tube and tubing from the HFO to the patient is kept as short as practical. The circuitry used for the HFV systems (but not for the source of entrained gas for HFJV) is noncorrugated, noncompliant tubing, e.g., Tygon®.

With HFPPV, the burst of air is delivered directly into a standard endotracheal (ET) tube or the side port of an endoscope. With the other systems, a specially adapted ET tube, the Hi-Lo® Jet tube (National Catheter Corporation, Argyle, New York, U.S.A.) has proven useful. This tube has 3 lumina—the main lumen, like any ET tube, as well as 2 small-diameter side ports. One side port opens into the main lumen at the distal end of the ET tube, while the other opens 5 cm from the end. With HFJV, the conventional ventilator is connected to the main port, to supply gas for entrainment. The jet stream can be directed down the proximal side port. In our experience, however, this has been somewhat inefficient, since much of the drive pressure of the jet is used to overcome the resistance of the small-diameter side port. We direct the jet through an injector cannula placed at the top of the ET tube through an access port of a connector. The cannula is positioned in the center of the main lumen. This allows better entrainment with lower driving pressure and more efficient ventilation. The distal port on the Hi-Lo® Jet tube is connected to an airway pressure monitor.

The Hi-Lo® Jet tube is also useful with HFO. The oscillator source is connected to the main lumen. The proximal side port can be connected to the bias outflow or suction source. The bias inflow is connected through a side port adapter at the top of the ET tube. The distal side port of the ET tube is again used to measure airway pressure.

Measuring airway pressure is a problem with these systems for several reasons. First, the rates are very high, so a rapidly responding transducer and system are necessary. Also, the pressures vary greatly at different points in the system, and choosing the appropriate point in the system to measure true airway pressure is difficult. The pressure at the point at which the high pressure from HFPPV and HFJV enters will obviously be high. This pressure decreases rapidly down the ET tube and into the lungs as the high pressure source encounters resistance from the air in the system and from the ET tube and airways. This decrease in pressure continues down the airways to the alveolar level. Measuring the pressure at the alveolar level is obviously difficult. In general, we have monitored pressure at the distal end of the ET tube, through the side port, and focused on mean pressure as a rough approximation of distending pressure. With HFO, especially, we have used this pressure more as a trend monitor than as an exact measurement. This is important since HFO frequently involves a closed system and imbalances between the bias inflow and outflow can lead to rapid increases and decreases in pressure within the system.

All 3 systems use high volumes of gas—15–20 l/min or more. Humidification becomes very important to prevent drying and damage to the tracheal mucosa. Humidifying HFPPV systems has been somewhat difficult, with saline usually being dripped in front of the high-pressure source. HFVJ is easily humidified, by humidifying and warming the entrained gases in the standard fashion using the conventional ventilator. The jet stream can also be humidified by dripping saline in front of the high-pressure source. HFO is humidified relatively easily by running the bias inflow through a humidifier.

Uses of HFV

ICU Use

High-frequency ventilators have been supported for use in the ICU because of the alternatives they offer to CMV and their use of low tidal volumes and high frequencies to achieve similar gas exchange. The use of HFV in the ICU is an attempt to change the way gas exchange takes place. The respiratory diseases that are found in patients in the ICU interfere with normal respiration by changing resistance and compliance within the lungs, leading to maldistribution of convective flow and/or destroying the architecture of the terminal airway units, altering diffusion [3]. As has been discussed, conventional ventilators use positive pressure to increase convective flow, but do little for diffusion. Use of CMV with application of higher and higher pressures to achieve gas exchange in a lung with nonuniform time constants (resistance × compliance) can lead to several problems—barotrauma, change in hemodynamics, or worsening of V/Q mismatch with deterioration of blood gases. HFV offers an alternative to increased convective flow through the possible enhanced diffusion as a means of gas exchange. As has been seen, the role that diffusion plays in HFV varies with the type of ventilator, with HFO depending more on diffusion while HFJV and HFPPV use a combination of diffusion and convection.

Several groups of ICU patients have been suggested and examined (both clinically and experimentally) as possibly able to benefit from HFV—those with bronchopleural fistulas, those with chronic obstructive pulmonary disease (COPD), and those with ARDS. Only with bronchopleural fistulas does HFV seem to be clearly of benefit at the present time [7]. Conventional ventilation applied to lungs with a bronchial suture line after surgery, especially if infected, can lead to disruption of the suture line. Whenever lung tissue is infected, conventional ventilation can lead to barotrauma at lower pressure than normal lungs can withstand. A bronchopleural fistula can result in loss of tidal volume through the fistula because of decreased resistance with resultant deterioration of blood gases. Attempts to improve gas exchange with CMV involve increasing the tidal volume and adding PEEP—both of which increase the volume lost through the fistula as well as keeping the fistula open and preventing healing [8]. High-frequency ventilation does not depend as much on regional time constants as CMV and can improve blood gases in this situation with less volume loss. Just as the bias outflow line on the HFO system can act as a low-pass filter (impeding the loss of the high-frequency oscillations), the impedance of the bronchopleural leak is increased for HFV, allowing more of a volume to be distributed to the normal alveoli. This effect is not achieved only with HFO. In fact, most of the clinical and experimental reports have used either HFPPV or HFJV and have almost universally confirmed that blood gases can be normalized using HFV in bronchopleural fistulas [9].

A second group of patients that an ICU deals with frequently are those with COPD. Very little work has dealt with the use of HFV in COPD. This is due to the finding that both HFJV and HFO tend to increase functional residual capacity (FRC). Patients with COPD already have problems with increased FRC (airtrapping, which leads to decreased PaO_2 and increased $PaCO_2$). As frequencies increase and tidal volumes decrease, the airway pressures tend to change: peak airway pressure (PAP) tends to decrease, while end-expiratory pressure tends to increase and approaches mean airway pressure (MAP). As diffusion becomes more important, PAP tends to become meaningless in relation to effects on the lung, while MAP tends to become mean alveolar pressure and causes a continuous "PEEP effect" [10]. The effect of this on blood gases in most situations will be discussed later, but the effect on pulmonary volumes is that of an increase, leading to a new, higher FRC. Patients who already have increased lung compliance (those with COPD) would tend to magnify this, possibly leading to excess alveolar and intrathoracic pressures which could decrease cardiac output (CO) and/or cause barotrauma [11]. Because of this, most investigators have been reticent to use HFV in patients with COPD. Investigation should be carried out in these patients, however, because the effects of HFV to enhance diffusion may improve gas exchange, provided PEEP effects are carefully controlled. Until further investigation is carried out, HFV should be used with caution in patients with COPD.

Use in ARDS

The group of patients most frequently dealt with in a surgical ICU who might benefit from HFV are those with ARDS, and much research has centered on this area [10, 12–14]. ARDS results from many insults, which apparently act through a common injury mechanism to produce severe hypoxemia (unresponsive to increased FiO_2), pulmonary compliance, and decreased FRC. Many of these patients can be stabilized on CMV with PEEP; however a certain number, perhaps 20%, do not respond [14]. Initial reports examining HFV as a possible technique to use on patients with ARDS argued that it would be helpful since it might improve gas exchange at lower airway and transthoracic pressure, decreasing the risk of barotrauma and/or adverse hemodynamic changes.

Several studies examined the effect of HFJV versus CMV on blood gases, especially PaO_2, in patients with ARDS. A case report by Schuster et al. [12] reported that PaO_2 improved on 4 occasions in a patient with respiratory failure when he was placed on HFJV. They did not measure MAP; however, the amount of PEEP was higher when the patient was on HFJV. The same group, in a later report [13], looked at 8 patients with acute respiratory failure and found that HFJV could provide adequate gas exchange, but PaO_2 did not necessarily improve. Only 1 of the 8 showed improvement in PaO_2 at the same level of FiO_2 and PEEP. Rouby et al. [10] examined 24 patients with postoperative respiratory failure and found that HFJV increased arterial oxygenation via an increase in MAP—the "PEEP effect" of HFJV. This PEEP can be increased with a jet ventilator by an increase in tidal volume (done by increasing driving pressure) or by increasing the I:E ratio. In general, frequency increases with HFJV will decrease tidal volume. Finally, Carlon et al. [15] found (in 309 randomized patients) that CMV provided higher PaO_2 at equivalent levels of PEEP than HFJV.

It does not seem unusual that the same factors that improve oxygenation in CMV (MAP, FRC) should also play a role with HFJV, since convection is still quite important with HFJV. By using diffusion to a greater extent, HFO may be able to improve oxygenation at lower pressures than CMV. One problem with HFO may be the small excursion of air. Hurst and Dehtaven [16] studied 9 patients randomized to HFJV/CPAP and HFJV/CPAP + IMV. The purpose of the IMV was to expand the lungs occasionally (in effect, a sigh). Patients on HFJV/CPAP alone showed a consistent and progressive decrease in oxygenation over 36–48 hours, probably secondary to decreased FRC caused by failure to maintain adequate opening volumes. HFO, with its smaller respiratory excursions, would probably have the same effect and, although not directly studied, this appears to have been supported in long-term (48-hr) animal studies we conducted [17]. Animals on HFO required periodic sighing (3 every 1–2 hours) to prevent atelectatic collapse and severe deterioration of PaO_2.

HFJV has been found to remove CO_2 very well in most clinical situations of ARDS [10, 13]. This is likely due to the very high minute volumes generated by the technique (almost double those with CMV). HFO has not been found to be as efficient in removing CO_2.

As discussed previously, HFV does cause changes in airway pressures even if similar MAP is required for similar PaO_2. There tends to be much less pressure variation over the course of 1 respiratory cycle. Peak pressures decrease, end pressures increase. It has been demonstrated with equal MAP's (thus, presumably, equal or similar oxygenation) that PAP's are significantly decreased in patients on HFV versus CMV [8]. Possible benefits of this decrease in PAP include a decrease in adverse hemodynamic effects and a decrease in the risk of barotrauma.

CMV in patients with respiratory failure often requires the use of high PEEP and high PAP, which results in decreased cardiac output secondary to increased pulmonary vascular resistance, increased right ventricular afterload and/or decreased filling pressure (preload) from decreased venous return. These effects, however, seem to depend more on MAP than PAP [8]. If equal MAP is used to achieve similar PaO_2, the hemodynamic effects will probably be similar. This was demonstrated by Fusciardi et al. [18] in an animal study in which MAP was increased in HFJV by increasing the I:E ratio. This improved oxygenation, but impaired hemodynamics. Their conclusion was that HFJV does not lead to better hemodynamics since MAP with HFJV is similar to PEEP with CMV.

It is still felt that PAP may be the pressure that is important in barotrauma [8], but this has not been confirmed. One clinical study found no difference in the amount of barotrauma in patients randomly assigned to HFJV versus CMV [15]. More work is necessary to further define this issue.

Other Uses

One of the earliest clinical uses of HFV was to provide ventilation while bronchoscopy and/or laryngoscopy was being performed [19]. This is accomplished by directing HFPPV or HFJV through the side port of the scope. Several studies have revealed that blood gases are well-maintained during the procedure when HFV is used [19, 20]. This could be useful in the ICU with a critically ill patient who appears to have undergone atelectatic collapse and for whom bronchoscopy is indicated but is dangerous because of ventilatory insufficiency.

The use of HFJV has been examined while patients underwent tracheobronchial suctioning [2]. Suctioning has been associated with cardiac arrhythmias, cardiac arrest, apnea, and atelectasis. Many of these complications can be related to deterioration of blood gases while suctioning is performed—the patients are disconnected from the ventilator for suctioning or the suction catheter simply interferes with convective flow through the endotracheal tube. In 15 patients compared by Guntupalli et al. [21], the FiO_2 was increased to 1.0 before suctioning. They were then suctioned conventionally while HFJV was directed down the side port of a Hi-Lo® Jet tube. The HFJV caused significant improvement in postsuctioning blood gases with PaO_2 being 15 ± 9 using conventional techniques and 90 ± 16 with HFJV. it is not known whether all complications of suctioning will be decreased with HFJV, but deterioration of PaO_2 certainly seems to be prevented.

HFV has been used to prevent aspiration in patients who could not tolerate cuffed endotracheal tubes [22]. HFPPV or HFJV is directed into uncuffed endotracheal tubes or simply through a needle inserted through the trachea. The outflow then proceeds around the outside of the uncuffed tube or through the glottis. The pressure generated has been found to prevent aspiration.

HFJV has been used to wean patients who could not be weaned conventionally [23]. Weaning with HFJV is carried out by decreasing driving pressure gradually (in 5 PSI steps every 4 hours). This results in a gradual decrease in minute volume. This technique proved successful in 9 patients who had failed attempts to wean using CMV. This has not been examined in a controlled fashion.

Finally, HFV has been examined as a means to enhance mucus clearance. All 3 techniques have been tried, but HFO appears to be somewhat better with slight changes of bias flow and pressure allowing movement of mucus out of the airways. Transthoracic HFO has been found to be better than airway HFO for this purpose [5].

Conclusion

HFV is simply a ventilatory technique that uses much higher frequencies and lower tidal volumes than CMV. The 3 categories of HFV differ in technique, in the way gas exchange occurs, in the effects they create, and in their uses. Research on HFV initially was fairly confusing, as conclusions from one group were applied to another group with different findings. This is being approached more systematically now and more controlled studies are appearing.

HFV may eventually find its own niche in the critical care armamentarium. At the present time, it appears that the only solid indication for HJV is in the patient with a bronchopleural fistula who is losing large amounts of tidal volume and cannot be maintained with CMV. HFJV and/or HFPPV may also have a place as a ventilatory technique while bronchoscopy and/or suctioning are being carried out in unstable patients who cannot tolerate being disconnected from ventilators. Finally, HJV may be helpful in patients with ARDS who have developed extremely noncompliant lungs and can no longer be ventilated or oxygenated without generating extremely high PAP. HFJV may allow improvement in ventilation and maintenance of the same oxygenation at the same MAP with a decrease in PAP. This may decrease the risk of barotrauma. Currently, HFO is still an experimental technique with very little clinical experience. It should be kept in mind that HFV, like mechanical ventilation itself, is not a cure for any disease or problem. It is simply a support system, a means to maintain gas exchange, and allow time for therapeutic processes to work.

Résumé

L'emploi de ventilateurs à haute fréquence (HFV) repose sur l'augmentation de la fréquence respiratoire et la diminution des volumes du flux gazeux qui permettent d'obtenir des échanges gazeux similaires à ceux fournis par les ventilateurs mécaniques conventionnels (CMV). Ceci inverse l'importance relative de la convection et de la diffusion des échanges gazeux. Trois types de ventilateurs à haute fréquence sont actuellement disponibles. Ils sont différents les uns des autres en ce qui concerne la manière dont le gaz est distribué, la facon dont ils travaillent, les effets physiologiques qu'ils entrainent. Les conclusions tirées de l'emploi de l'un d'eux ne peuvent s'appliquer nécessairement aux autres. Cet article est consacré à l'étude des différents types de ventilateurs à haute fréquence ainsi qu'aux travaux dont ils ont été l'objet. Il souligne le rôle que peut jouer le ventilateur à haute fréquence dans une unité de soins intensifs. L'indication élective de l'emploi de ce type de ventilateur est la fistule broncho-pleurale. Il peut jouer un rôle complémentaire au cours de l'endoscopie et du syndrome de détresse respiratoire de l'adulte. En revanche si la maladie pulmonaire est irréversible (le stade terminal du syndrome précité: la fibrose) il est de peu d'efficacité.

Resumen

Los ventiladores de alta frecuencia (VAF) utilizan elevadas frecuencias respiratorias y bajos volúmenes corrientes para lograr un intercambio gaseoso similar al que producen los ventiladores mecánicos convencionales (VMC), lo cual revierte la importancia relativa de la convección y la difusión en el intercambio gaseoso. Actualmente existen 3 tipos principales de VAF. Estos se diferencian en cuanto a la manera como se administra el gas, a la manera como funcionan, y a los efectos fisiológicos que producen. Las conclusiones que puedan derivarse del uso de un tipo determinado de VAF no necesariamente pueden ser aplicadas a los otros. La presente revisión hace un examen de los diferentes tipos de VAF y de los estudios realizados con el uso de VAF, y hace énfasis en el papel que los VAF pueden jugar en la unidad de cuidado intensivo quirúrgico. La indicación más clara para VAF es la fístula broncopleural. También pueden ser útiles como adyuvantes en endoscopia y en el síndrome de dificultad respiratoria del adulto (SDRA). Si la condición del pulmón afectado es irreversible (por ejemplo en la fase terminal fibrótica del SDRA), los VAF tienen muy poco que ofrecer.

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