High-Frequency Ventilation

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Currently conventional modes of controlled mechanical ventilation, such as intermittent positive pressure ventilation (IPPV) and continuous positive pressure ventilation (CPPV), with high volumes and low rates are utilized for the rhythmic inflation of the lungs. Basically, the functional characteristics of these systems have not changed since Bjork and Engstrom first reviewed them in 1955 (Bjork and Engstrom 1955; Sjostrand 1983). Impairment of cardiovascular function and increasing the incidence of barotrauma with high airway pressure were problems which have needed to be solved. Thus respiratory support using high rates and low tidal volumes of ventilation was given. High-frequency ventilation (HFV) is not totally new idea, prototypes of it are found in nature in humming birds, insects and newborn babies. Moreover, HFV was reported in 1915 by Handerson who said that an adequate gas exchange could take place with a tidal volume less than the anatomical deadspace. But since the introduction of HFV in 1967, the basic concept of respiratory physiology has changed (Sjostrand and Smith 1983). HFV has received much attention in the last 20 years, resulting in a considerable accumulation of information. Many experimental and clinical studies have detailed the potential advantages of HFV but indicate that much work needs to be done to define and clarify the clinical role of these techniques and suggest that the standardized, reliable equipment with safety systems be developed. The purpose of this review is not to offer definite information for further investigation, but simply to provide background information for a better understanding of the experimental and clinical results recently achieved by many other researchers. Limited foci are as follows: 1) Definition and classification of HFV. 2) Technical developments and considerations. 3) Physiologic aspects of HFV. 4) Clinical applications. 5) Comparative studies between IPPV and HFV. 6) Problems and looking ahead.

Key Words: High-frequency ventilation, mechanical ventilation

DEFINITION AND CLASSIFICATION OF HFV

The many definitions and terms used for HFV may sometimes be confusing (Carlton and Klain 1984). This is due to the use of equipment and methods that are very different from the description of traditional modes.

Frequencies four times greater than normal or 1 Hz (60 cycles/min.) that can be applied by means of external or internal methods are usually defined as HFV (Slutsky et al. 1981).

Common characteristics of these modes include low tidal volumes the same or smaller than the deadspace volume, high-frequency rates, low airway pressure, good gas exchange, minimal interference with cardiovascular functions and better patient acceptance (Klain 1981). In spite of their general characteristics, techniques classified as HFV are differentiated from the original conception and the development of equipment.

At the present time, if HFV is categorized by frequency, there are three different ranges of HFV: High-frequency positive pressure ventilation (HFPPV) which refers to ventilatory rates between 60 and 110 breaths/min. (1 and 1.8 Hz), high-frequency jet ventilation (HFJV) which refers to rates between 110 and 400 breaths/min. (1.8 and 6.7 Hz), and high-frequency oscillation (HFO) which refers to rates above 400 and up to 2400 breaths/min. (6.7 and 40 Hz). There is some overlap in ranges to discriminate among them. High-frequency chest-wall compression (HFCWC) is still in
the experimental stages.

Another more appropriate way to classify HFV is based on the specific technology responsible for the ventilation. Ventilation takes place with fresh gas but without gas entrainment in HFPPV, while in HFV gas is forced into the airway in the form of a jet of gas from a high-pressure source, resulting in the simultaneous entrainment of a second gas. During HFO, gas in the airway is oscillated back and forth in a sinusoidal fashion, with a fresh gas flow-by located between the oscillator and the patient (Sjostrand 1983).

HFV is an all inclusive term encompassing HFPPV, HFJV, HFO and HF CW. Recently, the combination of conventional ventilation with superimposing HFV or HFO with intermittent mandatory ventilation, independent lung ventilation with or without synchronization of each lung and external chest wall oscillating techniques are under investigation in animal research for clinical application (Benjaminsson and Klein 1981; Harf et al. 1983; Zidulka et al. 1983; Boynton et al. 1984; Choi et al. 1986).

Froese (1985) subdivided HFV into HFV-P (HFV with passive expiration) and HFV-A (HFV with active expiratory phase). He used a “-P” to describe a ventilator with a passive expiratory phase and an “-A” to a ventilator which had been modified to make expiration active as by adding suction during expiration.

These arbitrary classifications based on technical and functional properties do not change the physiologic effects of HFV (Sjostrand et al. 1983).

TECHNICAL DEVELOPMENTS AND CONSIDERATIONS

a) HFPPV

In 1967, Oberg and Sjostrand introduced HFV during experimental animal studies on the carotid sinus reflex requiring minimal ventilation interference to blood pressure (Sjostrand 1983). They used a tracheal tube with an insufflation catheter inserted into its proximal end at frequencies of 60 to 100 breaths/min. and inspiratory times (insufflation time) of 14 to 35%.

After that, a pneumatic valve, based on the Coandă or wall effect, was developed and a controlled gas mixture could be delivered through the sidearm. These techniques were not capable of providing volume-controlled ventilation and were open systems without gas entrainment. For this reason system H an expiratory valve was added to the outlet of the main arm of the pneumatic. In 1981, a double-lumen endotracheal tube was introduced and adopted as an integral part of the patient circuit for volume-controlled ventilation (system J).

These systems have a decelerated inspiratory flow and a low compressible volume which is negligible in comparison to a conventional ventilator. To date, the technical problems associated with HFPPV have been no different from those related to conventional IPPV and CPPV.

b) HFJV

HFJV, proposed by Klain and Smith in 1977, is basically composed of a blender and a reducing valve which regulate the percentage of gas and driving gas pressure, directional devices such as fluidic, pneumatic or solenoid valve which control the passage of gas toward the injector, a timer for regulating the directional devices and for determining ventilatory frequency with an inspiratory: expiratory (I:E) ratio and an injector which functions as a small sized nozzle. Additionally, an entrainment circuit, a reserve balloon, a heated humidifier or nebulizer, a spirometer, a one-way passive valve and a positive end expiratory pressure valve can be adopted (Chiaranda and Giron 1985).

This system can utilize, in addition to the trans-tracheal technique, a tracheal insufflation catheter connected directly to a jet ventilator with expiration taking place throughout the natural airway (Kim et al. 1986). Another modification is the application of a jet nozzle adapter positioned on the tracheal tube utilizing a swivel adapter (Kim et al. 1984; Kim et al. 1986). Also, a double-lumen jet tube can be used. Due to its inspiratory cannula design, variable amount of air entrainment, position of the jet orifices and changing I:E ratio, driving gas pressure and frequencies, different results have been reported (Kim et al. 1985). Still technological research and development have continued without any standardization of equipment.

c) HFO

HFO, demonstrated by Lunkenheimer et al. in 1972, was first performed using a piston or rotating valve with sinusoidal flow waves up to a frequency of 50 Hz. An electromagnetic vibrator attached to the tracheal tube and a 12 inch loud speaker with a sine-wave generator and amplifier or similar devices were also used. In order to eliminate carbon dioxide, soda lime was initially used but was replaced by applying a bias flow device. A low pass filter tube was positioned at right angles to the oscillator and the tracheal tube and functioned a high-impedance filter or vacuum sink.

HFO appears to be a promising new method of
achieving gas exchange in newborn infants with respiratory failure (Bland and Sedin 1983) with minimal risk of pulmonary barotrauma and without the problems of pulmonary over-distension. But problems regarding the clinical application of HFO include the somewhat complicated ventilatory equipment, the open character of the system, and the relatively large amount of gas used (Kim et al. 1984; Babinski et al. 1984).

**PHYSIOLOGIC ASPECTS OF HFV**

a) Gas Exchange Mechanism

Although a great deal of investigative research has concentrated on gaseous exchange and specific HFV techniques, there is no clear agreement on the exact mechanism of HFV. As mentioned previously, depending on the specific techniques employed, gas transport may involve several methods from convection to diffusion.

Neither bulk flow of fresh gas or molecular diffusion alone can account for the effective gas mixing in the lung using a tidal volume less than the deadspace. The combined effects may suggest an explanation for the observed results of gas exchange. In HFPPV with relatively larger volumes, augmented dispersion and Pendelluft type flow (internal circulating currents) can occur. In HFO with a small volume, diffusion may predominate while the two effects of convection and diffusion can provide augmented gas transport in HFJV. Asynchronous alternation, longitudinal dispersion and Pendelluft flow at terminal alveoli may also play a part with the interaction but the has not been clarified at this time (Gallagher 1986).

Many different hypotheses have been suggested. Among them, Fredberg (1980) and Sludsky et al. (1981) proposed a quantitative model of gas transport during HFV based on the concept of augmented gas transport. However, there are a number of limitations to the model in spite of their results (Slutsky et al. 1980, 1981; Chang 1984).

At the time of this writing, this new mode of mechanical ventilation advances many important and unanswered questions. To determine the optimal means and clarify the exact mechanism of gas exchange, further experimental and theoretical studies on gas mixing by HFV are required.

b) Cardiovascular Effects

One finding characteristic of HFV is low airway pressure. There is some evidence to suggest that this reduced airway pressure may promote a reduction of pulmonary vascular resistance and contribute to an improved hemodynamic outcome. A recent study by Wetzel et al. (1985) suggested that HFV may attenuate hypoxic pulmonary vasoconstriction. It has been reported that there may be an increase in prostacyclin release during HFV (van der Zee et al. 1985) which would support these observed changes. These beneficial effects result in a decrease of pulmonary artery pressure and an improvement in hemodynamic function. This improvement is primarily related to a decrease in mean airway pressure during each respiratory cycle which may contribute to the more favorable venous return and ventricular function described in many studies (Gallagher 1986).

c) Pulmonary Effects

A reduced mean airway and peak airway pressure and a lower tidal volume of HFV than those of conventional ventilation has often been characterized. During HFPPV, Sjostrand (1983) observed that intrapleural pressure was negative and spontaneous breathing was absent. Intrapulmonary gas distribution was similar to that observed during spontaneous breathing. Lung compliance also remained unchanged.

The pulmonary effect of transtracheal HFV without humidification of gases in dogs revealed no adverse effects on the airway and pulmonary parenchyma in macroscopic and microscopic findings of 24 hours (Smith et al. 1981). But humidifying the gases had a favorable effect as in unhumidified HFV, mucociliary transport completely ceased within 10 minutes (Nordin et al. 1981).

The prolonged effect of HFJV and IPPV in dogs was studied by Frey et al. The average survival time of the HFJV group was longer, and atelectasis of the lungs were less often found (Frey et al. 1980).

d) Renal Effects

Although there are not many studies on renal function and HFV, the modification of renal function during HFV is a function of airway pressure rather than ventilatory frequency or mode of ventilation. Any alterations would appear to come from changes in plasma renin activity or cardiovascular hemodynamics (Marquez 1983; Gallagher 1986). The renal and cardiovascular effects of HFJV have been evaluated in swine by Marquez et al. (1981). No differences were found when compared to spontaneous ventilation and CPAP. Studies on diuresis, as an indirect measure of the production of an antidiuretic hormone, indicated a lower degree of stress during HFPPV than IPPV. This was evidenced by more active excretion during HFPPV (Sjostrand 1983).
e) Effects on ICP (intracranial pressure)

Studies have demonstrated a reduction in ICP with HFV when compared with conventional mechanical ventilation (Hurst et al. 1984; Fuke et al. 1984). Ventilator-synchronous fluctuations in intrathoracic pressure are believed to cause transient venous congestion and may be responsible for the pressure fluctuation in hemodynamic variables and ICP (Babinski and Smith 1986). The different results in ICP between HFV and conventional modes seem to relate to reduction of mean airway and peak inflation pressures which often decrease venous pressure less than IPPV does. Consequently, there is an overall improvement in cerebral perfusion pressure with reduction in ICP. Most observations from investigation of the effect of HFV on the cerebral blood flow and ICP have shown no change and no increase in ICP with HFV.

CLINICAL APPLICATIONS

Among the systems of artificial respiratory support used today, HFV undoubtedly holds the greatest interest. In particular, HFV and HPPVV may be considered integral procedures in the normal anesthetic routine of patients undergoing endoscopy and surgery of the upper airway at some medical centers. Results of the application of this ventilatory technique in intensive care patients suggest many potential advantages. Its use is beneficial in patients with altered gaseous exchange and cardiovascular failure, a time when the conventional ventilatory techniques are not able to support adequate oxygen delivery to the tissues. Better results can also be obtained in patients with high risk barotrauma or with bronchopleural fistula.

The first clinical application of HFV were during bronchoscopies and laryngoscopies (Sjostrand 1977; Eriksson and Sjostrand 1980). The pneumatic valve, together with a special ventilator has been used for HFPPV. Also jet ventilation techniques were widely accepted for bronchoscopies and laryngoscopies under general anesthesia. A special jet ventilator using fluidic technology was developed (Klain and Smith 1976). Both techniques proved to be clinically satisfactory, providing good oxygenation and ventilation with good airway control and excellent operative conditions. A definite benefit, particularly during laryngomicrosurgery, is an almost motionless operative field (vocal cords) due to the high rates and small tidal volume used (Kim et al. 1986). But HFPPV also uses an open system and as during HFV, volatile anesthetic agents cannot be used because of scavenging and the lack of a special vaporizer. Mandatory use of intravenous anesthesia carries the risk of patient consciousness during procedures. When HFV is used in these patients, it is essential that high airway pressure cutoff sensor be used to prevent barotrauma because of the possibility of airway obstruction.

HFV has been used successfully during surgery to the airway, such as resection and reconstruction of the trachea and carina, as well as a wider resection such as a sleeve pneumonectomy (Smith et al. 1981). The application of HFPPVV during transthoracic resection of tracheal stenosis was reported by Eriksson et al. in 1975. El-Baz et al. (1982) described the administration of HFV by endobronchial intubation of the dependent lung with one-lung ventilation.

According to the report of Seki et al. (1983), the most efficient mode of ventilation was HFV superimposed on IPPV with a rate of 3 Hz in 8 patients undergoing lung resections for malignancies. HFV during thoracotomy provides adequate ventilation similar to IPPV, good oxygenation, in many instances better than IPPV and superior operating conditions due to less ventilatory movement in the exposed lung (Kim et al. 1985). Because of its major advantages, it has become a useful method of ventilation during chest surgery.

HFV during abdominal surgery was first applied by Heijman et al. in 1972. A remarkable lack of diaphragmatic and visceral movement during upper abdominal surgery, combined with good oxygenation and ventilation of low airway pressure has been noted. This is especially valid during cannulation of the biliary tract and to permit easier access to the stomach during to stapling procedure, intra-abdominal vascular surgery and liver transplantation in an almost motionless operative field (Babinski and Smith 1986).

Massive trauma of the oro-facial region yield embarrassing problems during anesthetic management in regard to maintaining the airway. Using percutaneous transtracheal HFV with or without an endotracheal tube in place, adequate oxygenation and ventilation can be achieved (Miller et al. 1982).

The effects of HFV on ICP has been studied experimentally. Babinski et al. (1981) using HFV noted a marked decrease in ventilator synchronous fluctuation in ICP. But this did not affect mean ICP values. Similar results using HPPVV were reported (Bunegin et al. 1984). Todd et al. (1981) found that HFV markedly reduced cortical surface movement. Although application of HFV during neurosurgical procedures is limited, it was generally suggested that decreases in brain movement and ventilatory ICP fluctuation would provide better surgical conditions during microscopic neurosurgical operations. When HFV was first in-
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...roduced, there was a belief that HFV would improve the operative field for microsurgery such as cerebral aneurysms, arteriovenous malformation, and intracranial-extracranial vascular anastomosis. Despite the decreased brain movement during HFV, this has not proved to be a significant benefit to most neurosurgical procedures.

It was found that volume-controlled HFPPV and HFJV was as efficient and well accepted by patients with respiratory failure as conventional ventilation in terms of complication and survival, although it did not offer any obvious benefits over IPPV. HFO with 15 Hz was also given to patients as a treatment for respiratory failure following major vascular surgery. The shunt fraction decreased with no change in arterial carbon dioxide tension or cardiac output during mechanical ventilation with a promising new way of achieving gas exchange with minimal risk of pulmonary barotrauma (Butler et al. 1980).

There have been numerous case reports of successful management of bronchopleural fistula using HFV with the beneficial effect of decreasing the air leak (Carlon et al. 1980; Derderian et al. 1982). The main advantage in addition to adequate ventilation and oxygenation is simplified and comfortable weaning from mechanical ventilation in patients requiring respiratory support. Relatively low airway pressure may reduce the risk of barotrauma in the case of adult respiratory distress and hyaline membrane disease. This theoretical consideration, however, remains to be proven in clinical practice.

During extracorporeal shock-wave lithotripsy, HFJV has been demonstrated to be superior to conventional techniques. Reduction in mean airway pressure with HFV results in less kidney movement, which results in less parenchymal damage to the kidney as well as a reduction in the shock waves required for effective disintegration of stones (Carlon et al. 1985).

There is a lack of experience with HFV in intensive care for infants and children, but this is a field in which HFV should find many applications. It would appear among HFV, HFO might be the most appropriate for neonates with hyaline membrane disease.

The predicted advantages of the use of HFJV on patients with impaired hemodynamic status have not yet been widely confirmed on a clinical basis. More cummulative data must be obtained from HFJV applied in the post-operative period after open-heart surgery and on patients in shock. The results from six patients undergoing open-heart surgery indicated that adequate ventilation and oxygenation could be maintained with HFJV with minimal interference with the hemodynamics. Ventilation with low intrathoracic pressure was considered to be a major advantage (Dedhia 1981).

Clinically, HFPPV and HFJV have been used successfully in laryngoscopy, bronchoscopy, thoracic and abdominal surgery, oral surgery with complicated airway management, extracorporeal shockwave lithotripsy, to a certain extent in neurosurgery and in the treatment of bronchopleural fistula and hyaline membrane disease. Although, HFV has not replaced conventional low rate ventilation, it come to be an additional mode of effective ventilation. With advancement of future techniques, useful new clinical applications will be found. Perhaps a modified combination of HFV with or without IPPV might prove superior to the conservative approach to respiratory care support.

COMPARATIVE STUDIES BETWEEN IPPV AND HFV

A conventional volume-controlled ventilator and a prototype of a low-compression system (HFPPV) were compared in patients who were treated for respiratory failure. No differences were observed in the variables associated with circulation and oxygen transport. HFPPV showed same effect in regard to cardiac performance and oxygen transport with a lower mean airway pressure and tidal volume than during conventional ventilation. Moreover, patients acceptance was as satisfactory as conventional volume-controlled ventilation (Wattwill et al. 1983).

Based on studies by Slutsky et al. (1980, 1981), HFO using effective ventilation with a tidal volume smaller than the anatomical deadspace caused more favorable hemodynamic results and decreased barotrauma than conventional mechanical ventilation. Additionally, in certain models of lung injury, it can provide better oxygenation than conventional mechanical ventilation. Additionally, in certain models of lung injury, it can provide better oxygenation than conventional mechanical ventilation.

In dogs with hemorrhagic shock, data suggested that HFJV might cause less compromise of the ventricular function than IPPV. This effect could be based on the lower mean airway pressure during HFJV with less than 240 breaths/min. (Chiaranda et al. 1985).

Evaluation of regional organ blood flow during HFPPV and IPPV in animal models with normal and elevated ICP was made. In these experiments, cerebral, renal, lung and cardiac blood flow were measured. Statistical difference were not observed in regional or global flow by changing the mode of ven-
Problems and Looking Ahead

1. In the beginning, applied HFV had the problem of gas humidification. To provide humidification, Carlon (1981) devised the nebulization system which delivered small droplets of saline solution to the front of the nozzle, and he confirmed the efficacy by radionuclide studies (Carlon et al. 1985). Nordin et al. (1982) and Klain et al. (1984) demonstrated that optimal humidification could be maintained only by humidifying both of the gases, the one delivered by the jet with normal saline and the other from the entrainment circuit. Humidification might be of little importance when HFV is applied for a period of 2 or 3 hours, e.g., during anesthesia, but it is very important when used on neonates or in the intensive care unit, as well as during prolonged surgery. Humidification is definitely one of the unsolved problems in HFV.

2. Problems related to HFV include the absence of standardized equipment and the fact that presently employed devices utilize respiratory gases under very high pressures, frequently approaching 50 psi, which creates the potential hazard of barotrauma. Future high-frequency ventilators should have airflow pressure safety systems to prevent such complications. By utilizing modern technology, it is now possible to design a ventilator system that will precisely deliver preset tidal volumes at a preset I:E ratio and frequency and have alarm devices, a safety system and FiO₂, while simultaneously monitoring the fraction of expired gases. The addition of volatile anesthetic agents to such a system would make it ideal for intraoperative use.

3. Another problem comes from the difficulties involved in measuring tidal volume, gas flow, ventilation pressure, and compliance at very high frequencies. Thus we may have little information on what is actually happening within the inhomogenous aerodynamic conditions in the bronchial system or lung parenchyma. The future of these methods is not only linked to the improvement of techniques of application, but even more to the development of monitoring techniques for the prevention of barotrauma.

HFV should not be used in place of an inappropriate situation, without attention of known safety hazards, or with physiologically irrational settings. In a situation where the expiratory flow of gas from the lung is impeded and also with inadequate humidification, HFV is never used. As there is no known benefit of HFV in status asthmaticus, the use of HFV in that condition cannot be recommended at present.
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The impression that HFV will reduce or eliminate most of the deleterious effects of IPPV and other conventional therapeutic modalities has disappeared. Multidirectional approaches to experimental and clinical results are providing a basis for our knowledge. Both clinician and investigators are transforming these data into easily understood clinical applications. Until the final role of HFV is known, many questions remain unanswered or may be unanswerable. That it will provide an important addition to our advancement of respiratory care support seems clear, but that it will guide all that is currently inappropriate with conventional support is unlikely. ECMO (extracorporeal membranous oxygenator) was found to lack clinical efficacy, at least as it was originally proposed and was abandoned to the status of historical interest. We must be sure that the same mistakes are avoided with HFV (Kirby 1984).

Respiratory support has move to newer, more efficient types of artificial ventilation after iron lungs and IPPV. It is too early to forsee what role HFV will play in respiratory support, intraoperative applications and whether it will replace current methods. Besides providing a new type of respiratory support for certain conditions, it gives a fresh, new look at respiratory physiology and mechanical support. HFV is currently being studied by several groups, indicating interest in not only its potential for ventilatory support and intraoperative applications, but also a desire for a better understanding of pulmonary gas exchange.

It may be concluded that, when evaluated not only in terms of gaseous exchange, but also in terms of barotrauma, hemodynamic interference, patient acceptance, aid to physiotherapy and weaning from the ventilator, HFV can be considered, if not as an absolute alternative, at least an advantageous adjuvant in intensive care. It is predictable that technical progress, both in the design of HFV equipment and in monitoring systems, will permit it to obtain the flexibility and reliability necessary for safe, clinical application of HFV.

Instead of uncritical optimism or oppositional negativism, we must have enough optimism to accept the potential role of HFV through the accumulation of date being produced while maintaining reasonable restraint.

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