Jet ventilation

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Key points

Jet ventilation is highly versatile; gas delivery is possible at various points along the airway.

High driving pressures of gas are used and barotrauma will occur if there is inadequate egress of air during expiration.

High-frequency jet ventilation is relatively inefficient, requiring large minute volumes to ensure adequate CO_2 removal.

Modern high-frequency jet ventilators monitor airway pressures and can warm and humidify the inspired gas.

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Ventilating bronchoscopes have been in use since the mid-1950s; these instruments permitted ventilation through a side arm through occlusion of the proximal end of the bronchoscope by the surgeon's thumb or a glass window. Both manoeuvres required withdrawal of instruments and temporary cessation of surgery. Jet ventilation was developed in the late 1960s in an attempt to reconcile the practical problems of maintaining adequate ventilation and good surgical access during rigid bronchoscopy.

In 1967, Douglas Sanders[1] described a technique that allowed uninterrupted patient ventilation concurrent with unhindered surgical access through an open, rigid bronchoscope. His adapter attached to the proximal end of the bronchoscope and was connected to the oxygen supply pipeline by means of a pressure regulator and hand-held on/off valve that allowed control of ventilation frequency. Oxygen was thereby delivered at the supply pressure of 50 lb in^{-2} in a jet through a 0.035-in diameter nozzle inside the lumen of the bronchoscope and parallel to its long axis. Each jet of oxygen entrained air into the bronchoscope, contributing to the tidal volume; this allowed ventilation without the use of valves. The pause between each jet delivery allowed passive expiration. Adequacy of ventilation was assessed by direct observation of chest wall movement and confirmed using blood gas evaluation. A further adaptation of a wide-bore side-arm allowed entrainment of anaesthetic vapours in addition to air. During subsequent years, modifications included the development of narrow, non-distensible catheters that could be used alone, in conjunction with rigid bronchoscopes or laryngoscopes or passed through tracheal tubes.

High-frequency jet ventilation developed as a ventilation modality in the 1970s. In 1977, Klain and Smith[2] developed a fluidic logic-controlled ventilator capable of delivering jets at rates of 60–100 min^{-1}. They described its use during fibreoptic bronchoscopy and in conjunction with Babinski and colleagues[3] used high-frequency jet ventilation (HFJV) via a narrow-bore, rigid, tracheal catheter in patients undergoing laryngoscopy under general anaesthesia. As with conventional jet ventilation, good exposure of the larynx was achieved, but the use of high-frequency breaths and small tidal volumes produced less vocal cord movement and allowed superimposed resumption of spontaneous respiration during emergence.

High-frequency oscillatory ventilation (HFOV) is a type of HFV and is mentioned briefly in this article. Both modes of HFV use a rapid respiratory rate and small tidal volumes. In HFOV, both inspiration and expiration are active—the oscillatory flow generated by a piston pump or similar device at the airway opening via tracheal tube or mouthpiece. Alternatively, HFO can be generated by rapid thoracic or whole body surface compression. It has been most extensively employed in the neonatal intensive care setting, but can be used in all age groups. Ventilator frequencies of 10–15 Hz are used. This type of ventilation can be superimposed on top of conventional ventilation to improve oxygenation and attempt to reduce ventilator-associated lung injury.

Physiology

Much of the gas exchange in low-frequency jet ventilation (LFJV) is achieved by means of *convective ventilation or bulk flow* (i.e. the mass flow of gases into and out of the lung) in a similar manner to spontaneous respiration. The alveolar ventilation V_A generated is calculated by the formula:

$$V_A = f \times (V_T - V_D)$$

where V_T and V_D are tidal volume and dead space, respectively; f is the ventilatory rate.

HFJV utilizes tidal volumes that may be smaller than series (anatomical plus equipment) dead space. Consequently, normal physiological principles do not hold and the above equation cannot apply. A few alveoli are close enough to the conducting airways that some gas may enter during HFJV by bulk flow even at volumes below conventional V_D, but this is not enough to support effective gas exchange.[4] Successful gas exchange is achieved in HFJV because of the relatively greater contribution of other mechanisms of gas transport.

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Laminar flow occurs in small airways where Reynolds number is low. The velocity profile of airflow in these regions is parabolic: air closest to the wall has lower velocity than air in the centre of the airway. The difference in flow rates becomes more exaggerated with each breath such that HFJV produces a spike of rapidly moving gas travelling down the axis of the airway, while gas in the margins moves out of the lung.

Further mixing occurs in the smaller airways as a result of *Taylor-type dispersion*[4] (enhanced molecular diffusion); this is the result of the interaction of the axial parabolic velocity profile seen in laminar flow and the radial concentration gradient producing further mixing of gases. In larger airways, where flow is turbulent, eddies produced by the turbulence precede the bulk flow and produce a similar radial-mixing effect.

Pendelluft, or collateral ventilation,[4] occurs as a result of regional variation in airway resistance and compliance causing some areas of the lung to fill or empty more rapidly than others. Such variation in time constants (resistance $\times$ compliance) leads to a phase lag between neighbouring lung units and causes gas to flow from one alveolus to another. This type of ventilation leads to rebreathing of CO_2 and an increase in effective dead space. This effect is exaggerated by high-frequency breaths and facilitated by the higher mean airway pressures seen in HFJV leading to extensive Pendelluft with recirculation of gas between regions. Smaller gas volumes effectively reach more respiratory units than similar volumes generated during conventional ventilation.

Other mechanisms that may contribute to gas exchange during HFJV are *molecular diffusion* and *cardiogenic mixing*. The latter occurs as a result of mechanical agitation of lung units in close proximity to the heart.

Types of jet ventilation

Jet ventilation may be high- or low-frequency. The general principles of both methods are the same: jet-streams originating from high-pressure sources are cut by pneumatic or electronically controlled flow interruption devices; this generates a tidal volume that is supplemented by entrainment of gases at the jet nozzle. Expiration is dependent on passive lung and chest-wall recoil.

Low-frequency jet ventilation

LFJV is usually applied via hand-triggered devices such as the Sanders injector or Manujet III (VBM, Germany). Its application is usually limited to short investigative procedures such as laryngoscopy or bronchoscopy, but also has an important role as part of the management of a difficult airway or the 'can't intubate, can't ventilate' scenario via a cricothyroidotomy cannula.

In practice, cannulae or jet-tubes should be short, narrow-bore and non-compliant and are often already integral to devices such as the rigid bronchoscope or laryngoscope. The oxygen source (primary gas source) is the high-pressure wall-piped oxygen at 4 bar. This is passed through pressure-reducing valves and can be further adjusted via a regulator sited near the handset to a pressure that produces the desired chest-wall excursion and maintains oxygenation and adequate gas exchange. Short, rigid piping extends from the handset and must fasten securely to the cannula, usually via a Luer-Lock connection. The cannula must be secure to prevent dislodgement when the high-pressure jet is in use. The nozzle or cannula should also be aligned along the axis of the airway to be effective and prevent gastric distension if positioned above the glottis. The tidal volume is the sum of the injected and entrained volumes. A jet frequency of 8–10 min^{-1} allows adequate time for exhalation via passive recoil of the lung and chest wall and prevents air-trapping and build up of pressure in small airways.

When used during surgical procedures, total i.v. anaesthesia is employed. If 100% oxygen is used as the jet gas, the effective $F_{I_{O_2}}$ in the trachea is 0.8–0.9 because of dilution by entrainment of ambient air. A side-arm attachment to a bronchoscope or laryngoscope may allow oxygen entrainment instead of ambient air if the decrease of oxygen concentration due to entrainment is undesirable.

High-frequency jet ventilation

HFJV requires special equipment and familiarity with the technique.[5]

Ventilators

Commercial jet ventilators are available that deliver heated, humidified jets at 1–10 Hz. Continuous flow is chopped into square wave pressures by a high-frequency flow interrupter which is usually an electrical solenoid valve, but can be a fluidic or rotating cylinder valve. Driving-pressure, frequency, inspiratory time, and the composition of the jet gas can be adjusted. All ventilators are equipped with alarms and automatic shutdown devices to discontinue gas flow in the presence of inadvertent high airway pressures.

Most also have a manual setting to allow delivery of large volume breaths at a slow rate to provide opportunity for more accurate, though intermittent, end-tidal CO_2 monitoring. Humidification is important in view of the drying effects of high gas flows and also helps prevent significant heat loss.

Catheters and delivery routes

Jet catheters can be inserted through tracheal tubes or can be used alone. The catheter tip position can be either above or below the vocal cords. Trans-tracheal jet cannulae may also be used. Catheter design varies considerably. The catheters are usually made from metal or plastic and may have more than one lumen. The extra lumen is used for continuous intra-tracheal pressure or intermittent CO_2 sampling. There are specially modified tracheal tubes available that are equipped with two small lumens opening distally for delivery of the jet gas and airway pressure monitoring, respectively.

Carbon dioxide measurement

Carbon dioxide measurement is difficult in such an open breathing system utilizing high gas flow; it requires temporary cessation of respiration for side-stream sampling following standard, tidal volume inflation. Alternative techniques include trans-cutaneous continuous CO_2 monitoring,[6] intermittent blood gas sampling from an arterial line or a continuous intra-arterial blood-gas measurement device.

Oxygen delivery

$F_{I_{O_2}}$ can be selected on modern jet ventilators (e.g. the Monsoon, Acutronic Medical Systems AG, Baar, Switzerland), but the delivered $F_{I_{O_2}}$ will depend on the degree of air entrainment.

Pressure

HFJV is a form of time-cycled, pressure-limited ventilation such that if ventilator parameters are held constant, a decrease in chest wall or lung compliance will result in a reduction in minute ventilation. The driving pressure, rather than the respiratory frequency, is most influential for CO_2 elimination. End-expiratory pressure is measured through the injector at the end of insufflation but may not reflect true intra-thoracic pressures in view of the regional variations that are exaggerated at high frequencies. Modern jet ventilators are equipped with a second airway measurement line, which monitors the airway pressure continuously and independently of the jet insufflation line.

During HFJV ventilation, a frequency-dependent positive end-expiratory pressure is usually present, but the resulting mean and peak airway pressures are far lower than during conventional ventilation. This property can be used to reduce gas leak through a broncho-pleural fistula or airway pressures in intensive care patients. HFJV causes rapid build up of pressure if there is inadequate egress of air during expiration. A ventilator high-pressure alarm and an automatic shut down facility is a necessity for safe utilization of this ventilation modality. Additional monitoring of oesophageal or intra-pleural pressure may give more accurate information about peripheral airway pressures and the occurrence of gas trapping in those undergoing prolonged HFJV.

Parameters and settings

The important and inter-related variables in clinical practice are rate/frequency, f; driving pressure, DP; inspiratory time, I-time (% ventilatory cycle); and inspired oxygen fraction, $F_{I_{O_2}}$.

The tidal volume is not set; it is a function of driving pressure, cannula resistance, inspiratory time, entrainment volume, and the impedance of the respiratory system. Responses to adjustments may seem counterintuitive; for example, increasing the frequency can induce hypercapnia by reducing the tidal volume if DP and I-time are kept constant.[7] Intrinsic PEEP is an important component of HFJV; it is inversely related to expiratory time and so increases with the frequency. It is most likely to exceed desirable values in lung units with long time-constants. Increasing DP leads to increased V_T and airway pressure and a reduced P_{CO_2}. However, large increases in DP may lead to CO_2 retention if the set frequency is too high to allow time for adequate expiration in the shortened respiratory cycle. Oxygenation can be improved by increasing DP, $F_{I_{O_2}}$ or I-time, but CO_2 retention may occur if I-time is set too high to allow adequate expiration.

A typical parameter-set for HFJV via a subglottic catheter is DP, 2 atm; f, 150 min^{-1}; $F_{I_{O_2}}$, 1.0; I-time, 50%.

Indications for jet ventilation

Emergency

LFJV via a trans-tracheal cannula as an interim life saving measure in the 'can't ventilate, can't intubate' scenario (with an assured gas egress pathway).

Elective

Elective use of jet ventilation includes management of the anticipated difficult airway using pre-emptive placement of a trans-tracheal jet cannula, direct laryngoscopy, and vocal cord surgery. A major application for jet ventilation is in airway and thoracic surgery (e.g. major conducting airway surgery such as carinal resections, resection of tracheal stenosis, and tracheal reconstruction).

HFJV employs an open breathing system, so there is no need for an airtight connection between the airway and the breathing system. Thus, the trachea can be open and ventilation still maintained. HFJV also minimizes the degree of bronchial and mediastinal excursion compared with conventional ventilation. The fine jet catheter can be passed through the surgical field, bridging the defect or pathology and manipulated by the surgeon during the operation. Airway resection and end-to-end anastomosis can be accomplished around the fine catheter.

During one-lung ventilation, HFJV applied to the non-dependent lung during surgery, instead of PEEP alone, can aid CO_2 elimination and improve oxygenation, reducing the ventilatory stresses on the dependent lung. In the management of broncho-pleural fistula and

Table 1 Complications of jet ventilation

Barotrauma
Pneumothorax
Pneumomediastinum
Pneumopericardium
Pneumoperitoneum
Subcutaneous emphysema
Malposition of catheters
Gastric distension
Gastric rupture
Miscellaneous
Dysrhythmias
Necrotizing tracheo-bronchitis
Increased incidence necrotizing enterocolitis in neonates
Inadequate gas exchange (hypoxaemia, hypercapnia) in patients with severe lung pathology, predominantly restrictive pulmopathy

Table 2 Advantages and disadvantages of HFJV

	Advantages	Disadvantages
Physiological	Reduced peak airway pressure. Haemodynamic compromise less than conventional IPPV. Cardiac output may be augmented using ECG synchronization. Reduced ADH production and fluid retention.	Potential risk of barotrauma. Cooling and drying of conditioned inspiratory gases by expansion at nozzle. Efficacy of gas exchange less predictable, e.g. obesity, COPD. Delivered FI_{O_2} is multifactorial. Pendelluft increases effective deadspace.
Surgical	Minimal vocal cord/surgical field movement. Improved visibility and surgical access. Avoidance ETT ignition during LASER surgery.	Potential for lower airway soiling in ENT surgery. Contamination of expired gas flow by surgical debris
Anaesthetic	Good in low resistance large volume airway leak. Emergency trans-tracheal jet ventilation. Versatility: good in airway surgery.	Inhalational anaesthesia often impractical. Contamination of operating room air if anaesthetic gases are used. Intermittent end-tidal CO_2 monitoring. Pressure measurements may be unrepresentative. High gas flow required. Need for humidification.

tracheo-bronchial tree disruption, HFJV results in a smaller gas leak through pathological low-resistance pathways, because peak and mean airway pressures are smaller than with IPPV. Arterial CO_2 tension can be restored to normality in the acute surgical setting and in chronically-ventilated intensive-care patients.

Intensive care

The physiology of HFJV would seem to make it an ideal modality for patients with acute lung injury or adult respiratory distress syndrome (ARDS). It is accepted that ventilator-associated lung injury (VALI) is a significant factor in the morbidity of intensive care patients. High pressures and volumes cause damage through over-distension and collapse-reopening of lung units; small tidal volumes at small mean pressures can cause deterioration through shear stresses associated with repeated opening and closing of terminal airways. The current lung protective strategies employed using conventional ventilation include PEEP at a level above the (static) lower inflection point to maintain recruitment of alveoli and low tidal volumes to reduce peak airway pressures. The trade-off is hypercapnia with consequent respiratory acidosis and associated dyspnoea, circulatory depression, increased cerebral blood flow, increased intracranial pressure, and increased requirements for sedation and neuromuscular blockade. High-frequency ventilation uses very small tidal volumes allowing the use of higher end-expiratory lung volumes to achieve greater levels of lung recruitment, while avoiding injury from excessive end-inspiratory lung volumes. The high respiratory rates allow preservation of near normal Pa_{CO_2}.

These seem to be compelling reasons to employ HFV in ARDS, but advantages over conventional ventilation have not been borne out by clinical trials conducted to date. Some authors believe that these trials have less validity today in view of our increased understanding of the pathogenesis of VALI.[8,9] Most trials were conducted during the 1980s when VALI was poorly understood. Their drawbacks include: the use of HFJV as a salvage strategy; the use of much lower ventilation rates than those employed in HFJV today; the use of low lung volumes so that ventilation occurred below the lower inflection point for alveolar recruitment; and statistical under-powering for chosen end points. The final problem with these studies is that they are too heterogeneous a group to allow application of any meaningful meta-analysis.

Unfortunately, until large, multi-centre clinical trials are conducted, which show benefit of one ventilation modality over another, then the cost of equipment acquisition and manpower-training is difficult to justify on the basis of anecdotal reports of the success of HFJV in this setting.

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Please see multiple choice questions 1–3