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Clinical applications of high-frequency jet ventilation

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Abstract. Six patients with acute respiratory failure were treated with high-frequency jet ventilation (HFJV): 3 because they developed barotrauma while on conventional mechanical ventilation (CMV), 2 because of sedative- or PEEP-induced hypotension on CMV, and 1 because of bronchopleural fistula. In all patients, except the one with bronchopleural fistula, who was treated from the start with HFJV, gas exchange before (while on CMV) and after institution of HFJV could be compared. In these five patients, including the two with acute respiratory failure *not* complicated by barotrauma, gas exchange was better during HFJV than during CMV for the same levels of F_IO_2 and PEEP. HFJV therefore seems the method of choice for ventilatory support, not only in patients with bronchopulmonary disruption, but also in patients with hemodynamic embarrassment during CMV.

Key words: High-frequency jet ventilation – Acute respiratory failure – Gas exchange – Bronchopulmonary disruption – Hemodynamics

Since the introduction and refinement of mechanical ventilation, the outcome of patients unable to self-maintain adequate gas exchange has greatly improved. Conventional (positive pressure) mechanical ventilation (CMV) delivers relatively large tidal volumes (V_T: 10 – 15 ml/kg) at relatively low frequencies (f_b: 10 – 20/min). Depending on the mechanical properties of the patient's respiratory system, airway pressure (AWP) can rise to substantial levels, especially when positive end-expiratory pressure (PEEP) is applied. This elevated AWP is essentially responsible for the complications of CMV, the most common of which are barotrauma [14] (alveolar disruption, leading to pneumothorax, pneumomediastinum, pneumopericardium and subcutaneous emphysema) and interference with cardiac pump function. These complications develop most frequently in those patients who are the least likely to tolerate them. Therefore, equally effective ventilatory techniques, capable of delivering frequent (1 – 20 Hz) small tidal volumes (1 – 5 ml/kg) at lower AWP, such as high-frequency ventilation (HFV) were investigated. Today, three different, not interchangeable techniques of HFV are in clinical use: (1) The original technique, high-frequency positive pressure ventilation (HFPPV) has recently been reviewed by its designers [26, 27]; (2) high-frequency oscillation (HFO) [1]; and (3) high-frequency jet ventilation (HFJV) [17], which forms the subject of this review.

Jet ventilation at normal f_b was first used by Sanders [23] in 1967 to ventilate anesthetized patients through the rigid bronchoscope during laryngobronchoscopy. Percutaneous transtracheal jet ventilation has been successfully applied in anesthesia [30], cardiopulmonary resuscitation (CPR) and upper-airway emergencies. Combining these and Sjöstrand's observations [26, 27], Klain and Smith [17] introduced in 1977 *high-frequency* transtracheal jet ventilation in dogs. Subsequently, the clinical applicability of HFJV by both the transtracheal and translaryngeal approaches has been well established.

Technique and mechanism of action

At the Royal Victoria Hospital, Montreal, HFJV is delivered by the commercially available IDC Model VS 600 (Instrument Development Corporation, Pittsburgh, Pa, USA), connected to the central air/oxygen distribution system of the hospital. This high-pressure source (50 pounds/square inch, psi[1]) provides via an

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[1] The unit psi is used since it is this unit that appears on the HFJ Ventilator front panel; 1 bar ≃ 14.5 psi

air-oxygen blender a gas mixture of preset oxygen concentration (F_IO_2) to the ventilator, whose internal compressible volume is minimal. The ventilator allows adjustment of the final driving pressure (P_d: 5 – 45 psi) and, by means of an electronic timer, of the duty cycle (inspiration/expiration or I/E ratio) and opening frequency of its solenoid valve (corresponds to f_b). Non-compliant Teflon tubing connects the ventilator output to a small bore injector cannula (18 – 14 g; 1.06 – 1.6 mm internal diameter), which is placed through a T-connector inside the endotracheal or tracheotomy tube. An endotracheal tube with jet-channel incorporated in its wall has recently been developed [16], facilitating suctioning through the lumen of the endotracheal tube. In non-intubated patients, the injector cannula can be inserted transcutaneously by tracheal or cricothyroid membrane puncture (the preferred way in upper-airway emergencies). Humidification of the pulsed gases is obtained by dripping heated saline (15 – 30 ml/h) via a unidirectional Y-connector in the Teflon-tubing between ventilator and injector cannula.

During their passage through the injector cannula, the pulsed gases are accelerated and their pressure drops. The jet stream exciting the injector cannula develops an area of relative negative pressure at right angles to the direction of the jet, thus causing a drag effect that moves the surrounding gases forward (Venturi principle).

Additional humidified and heated gases (with the same F_IO_2 as the jet stream), delivered to the inspiratory side port of the T-connector will be entrained to replace those that have been advanced forward. The turbulent gas stream moves down the airways as a progressively broader wave front of decreasing velocity, the central jet stream transferring some of its kinetic energy to the surrounding gases. Alveolar pressure changes will be minimal because by the time the jet stream has reached the alveoli, its pressure has fallen to the level of the prevailing AWP. PEEP can be applied by connecting an adjustable expiratory threshold resistor to the expiratory side port of the T-connector, where expired gas flow, i.e., minute ventilation ($\dot{V}_E$) and entrained bias flow, can also be measured. By dividing this expired gas flow (typically 20 – 30 l/min) by f_b (typically 100 – 200 min), delivered V_T (consisting of jetted and entrained gas) can be calculated to be much lower than with CMV. Indeed, V_T (100 – 300 ml; 2.5 – 6 ml/kg) may even be lower than the anatomical dead space (V_D) and yet alveolar ventilation ($\dot{V}_A$) and oxygenation are adequate in most instances of HFJV. At present, there is no clear understanding as to how HFJV accomplishes this, but theoretical considerations suggest the intervention of both diffusion-augmented convection in larger airways (bulk transport of the elongated central cone) and convection-facilitated diffusion in smaller airways [9]. CO_2 elimination along the fluid-layer lining the airways has also been proposed [32].

The initial ventilator settings for a patient connected to our HFJV-system will typically consist of a P_d of 30 – 40 psi; a f_b of 100 – 150 min; an I/E ratio of 1/2; an F_IO_2 of 0.8 – 1, and zero PEEP (HFJV per se creates a small PEEP-effect of 2 – 3 cm H_2O, increasing with f_b) [17]. After 30 min, the settings are adjusted according to the results of an arterial blood gas (ABG) sample. The P_d is adjusted to achieve a P_aCO_2 of 35 – 45 mmHg and/or a pH of 7.35 – 7.45: increasing the P_d enhances gas entrainment rather than elevating AWP, and thus is a means to increase V_T, hence $\dot{V}_A$ and CO_2 elimination at a given f_b. CO_2-elimination can also be enhanced by reducing the I/E ratio, thus providing more time for expiration. The initially high F_IO_2 is employed to avoid the temporary and reversible increase in intrapulmonary shunt and subsequent drop in P_aO_2, sometimes observed following the start of HFJV. After 30 min, the F_IO_2 is decreased by 0.1 decrements, paralleled, if necessary, by 2 – 4 cm H_2O PEEP-increments, in order to maintain a P_aO_2 above 70 mmHg with a F_IO_2 of 0.4 or less. The f_b can be independently prescribed, or can be electronically coupled to the cardiac cycle, utilizing the electrocardiogram. Synchronization of inspiration with ventricular systole or opening of the aortic valve has been shown to increase ventricular ejection fraction and cardiac output in some instances [3, 15]. When higher f_b or PEEP are used to achieve satisfactory gas exchange, or to minimize peak inspiratory AWP, the cannula size is reduced from 14 to 18 g.

Patient results

To date, we have used HFJV in 6 patients requiring mechanical ventilation for acute respiratory failure (ARF), of various etiologies (Table 1, which also summarizes indications for and outcome of HFJV).

In 3 of the 6 patients (patients 1, 3 and 4), HFJV was instituted because of barotrauma developing while on CMV. In patients 1 and 4 this caused air leaks large enough to result in alveolar hypoventilation and hypercapnia (Table 2). In the third patient, alveolar ventilation could be maintained on CMV but only at the expense of high cycling volumes. She was switched to HFJV which allowed the institution of PEEP and subsequent reduction of F_IO_2. A fourth patient (patient 6), who was admitted because of spontaneous bronchopulmonary disruption with resulting acute respiratory failure, was treated from the outset with HFJV. In all these four patients the bronchopleural leak was successfully minimized dur-

Table 1. Patient characteristics and indications for HFJV

Patient no.	Age	Sex	Underlying condition	Cause of ARF	Indication for HFJV	Days on HFJV	Final outcome
1	75	F	COPD	Pneumonia	Barotrauma on CMV (weaning)	9	Died (pulmonary embolism)
2	73	M	COPD	Pneumonia	CMV-patient discoordination ("fighting"), sedative-induced hypotension, (weaning)	5	Successfully weaned
3	31	F	Amniotic fluid embolism	ARDS	Barotrauma on CMV	12	Successfully weaned
4	27	M	CML Chemotherapy-induced pancytopenia	ARDS due to Pneumocystis carinii Pneumonia	Barotrauma on CMV, ("fighting")	17	Died (pulmonary hemorrhage)
5	22	F	AML Chemotheraphy-induced pancytopenia	ARDS due to pneumonia (organism unidentified)	Hypotension on CMV, ("fighting")	10	Successfully weaned
6	43	F	COPD, bronchiectasis (old TBC) with recurrent pneumothorax	Pneumonia	Spontaneous pneumothorax and subcutaneous emphysema	6	Successfully weaned

F = female; M = male; COPD = chronic obstructive lung disease; AML = acute promyelocytic leukemia; CML = chronic myelocytic leukemia; ARDS = adult respiratory distress syndrome; ARF = acute respiratory failure; HFJV = high-frequency jet ventilation; CMV = conventional mechanical ventilation

ing HFJV as indicated by adequate alveolar ventilation (P_aCO_2).

In the remaining two patients, the indication for HFJV was cardiodepression occurring under CMV in spite of adequate intravascular volume: in patient 2, high-dose sedatives, necessary to suppress patient-CMV incoordination induced vasoplegia and hypotension (mean arterial blood pressure consistently below 70 mmHg). In patient 5, cardiac output (cardiac index 1.9 $l/min/m^2$ body surface area) and mean arterial blood pressure (consistently below 70 mmHg) were severely compromized during CMV and PEEP, precluding the use of PEEP and necessitating toxic F_IO_2 levels. In both patients, hemodynamic status improved following institution of HFJV, so that mean arterial blood pressure could be restored above 70 mmHg, even after inotropic support was discontinued.

Table 2. Comparison of CMV and HFJV at same PEEP and F_IO_2

Pat. no.	PEEP (cm H_2O)	F_IO_2	CMV		HFJV	
			P_aO_2 mmHg	P_aCO_2 mmHg	P_aO_2 mmHg	P_aCO_2 mmHg
1	0	0.40	60	67	72	42
2	0	0.35	64	49	76	41
	5	0.35	74	51	86	46
3	0	0.70	70	36	66	32
	5	0.50			80	36
4	10	0.65	66	64	63	49
5	0	1.00	52	38	206	42
6	0	0.45			86	58

PEEP = positive end-expiratory pressure; F_IO_2 = fractional oxygen concentration in inspired gas; CMV = conventional mechanical ventilation; HFJV = high-frequency jet ventilation; P_aO_2 and P_aCO_2 = partial pressure of oxygen, resp. carbon dioxide, in arterial blood

In all but one patient (patient 6), HFJV and CMV were compared at the same levels of F_IO_2 and PEEP during the switch-over from CMV to HFJV (Table 2). Oxygenation improved in 3/5 patients, and was unchanged in patients 3 and 4; however, in patient 3, a small PEEP of 5 cm H_2O improved P_aO_2 to such a degree as to allow a reduction of the F_IO_2 from 0.7 to 0.5. CO_2 elimination improved markedly in the three patients (1, 2 and 4) with hypercapnia on CMV; in patients 3 and 5, who were normocapnic on CMV, CO_2 elimination was equally efficient on HFJV.

Patient 6 was treated from the outset with HFJV, since she was admitted with pneumothorax and subcutaneous emphysema. In this patient with COPD, extensive pulmonary fibrosis, scarring from previous tuberculosis and recurrent brochopleural fistulae, oxygenation was satisfactory while P_aCO_2 was kept at levels similar to her usual P_aCO_2 (Table 2). Of note is that HFJV achieved superior gas exchange as compared to CMV in the two patients (2 and 5) with ARF without barotrauma; the improved oxygenation resulted mainly from improved cardiac output, but also from better alveolar ventilation (in patient 2, as evidenced by reduced P_aCO_2).

The mean (±SD) duration of HFJV therapy was 9.8 (±4.3) days for all six patients, and 8.25 (±3.3) days for the four survivors: these were successfully and smoothly weaned from HFJV. Two patients (1 and 4) died after 9 and 17 days respectively due to causes unrelated to HFJV (Table 1). In both these patients, adequate gas exchange was maintained until the terminal events.

No major complications occurred during the 59 days of HFJV in the six patients.

Discussion

HFJV has been employed or recommended in a number of conditions where CMV is either impossible or complicated (Table 3). The advantages and clinical applications of HFJV evolve from consideration of its physiological effects. The main advantage is that, by delivering small V_Ts, peak inspiratory AWP is at any given level of PEEP substantially lower with HFJV (7–10 cmH_2O) as compared to CMV (30–50 cmH_2O) [24]. Once barotrauma has developed in patients on CMV, substantial amounts of the V_T, directly proportional to the size of the leak and to (the elevated) peak inspiratory AWP and inversely proportional to the compliance of their respiratory system (C_{RS}), will be lost through the leaks into the pleural space, mediastinum or subcutaneous tissues, and CMV fails to provide adequate gas exchange in most instances. This also applies to patients with preexisting tracheo-oesophageal or bronchopleural fistulae, requiring mechanical ventilation for treatment of complicating ARF. In the two patient-subsets (to which four our six patients belonged), HFJV is the preferred mode of mechanical ventilation [3, 6, 32]. Lower peak inspiratory AWP with HFJV has the theoretical, but unproven, advantage of reduced risk of ventilator-induced barotrauma, and could be considered in patients at high risk of developing barotrauma on CMV (e.g., patients with emphysematous bullae, recently repaired bronchial stumps and very stiff lungs). However, since peak inspiratory AWP depends not only on V_T but also on inspiratory flow rate, and the mechanical properties of the patient's respiratory system, the beneficial effect of HFJV on peak inspiratory AWP may be lost in patients with increased airway resistance (R_{aw}), particularly when high gas velocities (high f_b and reduced I/E ratio) are utilized [24].

Table 3. Possible clinical applications and indications for HFJV

1. *Anesthesia*
   Rigid laryngoscopy or bronchoscopy
   Laryngotracheal surgery
   Thoracic surgery
   Microneurosurgery
2. *Weaning* from mechanical ventilation
3. *Cardiopulmonary resuscitation* (transcutaneous HFJV)
   Difficult or impossible endotracheal intubation
   Heimlich-like maneuver
4. *Respiratory failure "complicated"* during or as a result of CMV
   Barotrauma
   Tracheoesophageal or bronchopleural fistulae
   Following pulmonary resection
   During endotracheal tube replacement
   During tracheobronchial suctioning
   Intolerance to CMV ("fighting")
   Hypotension (low cardiac output) due to
   - excessive sedation
   - high airway pressures
5. *"Uncomplicated" respiratory failure* necessitating mechanical ventilation

In view of the small tidal volumes inherent to HFJV, the technique seems well suited for mechanical ventilation during thoracic surgery (reduced pulmonary excursions) and microneurosurgery (reduced respiratory brain "pulsations"). Anesthesiologists can also employ HFJV through rigid laryngobronchoscopes and/or during laryngo-tracheal surgery.

In two of our patients, HFJV was instituted because of cardiodepression and hypotension directly or indirectly related to CMV. The cardiac effects of mechanical ventilation are primarily related to mean AWP, which depends on the same factors as peak inspiratory AWP in addition to expiratory duration and the expiratory resistance of the respiratory system (including PEEP). In patient 5, PEEP could be discontinued on HFJV, resulting in lower mean AWP. Subsequently, cardiac output improved and inotropic drugs could be discontinued. Others have shown cardiac output not to deteriorate [24, 31] and often to improve [2, 17, 32] during HFJV, even though mean AWP is in general only slightly lower during HFJV than during CMV. In patient 2, "fighting" necessitated high-dose sedatives, which resulted in hypotension. After institution of HFJV, the patient settled, sedatives could be discontinued and blood pressure remained stable. In general, the patient tolerates and accepts HFJV better than CMV. Since the injector cannula can be introduced through a smaller-sized endotracheal tube, whose cuff does not necessarily have to be inflated for airway protection, the patient experiences less local airway trauma and general discomfort. HFJV also does not interfere with spontaneous breathing and can be superimposed on it [17]. Probably by stimulation of pulmonary stretch receptors and chest wall receptors, HFJV often leads to vagally induced suppression of spontaneous breathing in normocapnia, without causing the sensation of dyspnea. For these reasons, patient-ventilator discoordination is much less of a problem during HFJV, reducing the need for sedatives, narcotics and neuromuscular blockade. Accordingly, drug-related side effects are reduced, proper assessment of neurologic status becomes possible [5], and stress-induced antidiuretic hormone production and water retention are minimized [29].

In our six patients, including the two without airway leaks, HFJV provided adequate alveolar ventilation and oxygenation with nontoxic levels of F_IO_2. As a matter of fact, gas exchange was at the same F_IO_2 and PEEP better with HFJV than with CMV (Table 2), in spite of the small V_T (often not exceeding V_D) and lower peak inspiratory AWP. For our four patients with airway leaks, this is not surprising and is in agreement with the literature, but whether our findings for the two patients with ARF uncomplicated by airway disruption can be generalized is debatable. In some of such patients with "uncomplicated" ARF, substitution of CMV by HFJV has been shown to maintain or even improve – at least temporarily – gas exchange [2, 5, 25], but generally, exact comparisons at the same levels of F_IO_2 and PEEP were not made. The only currently available studies comparing HFJV to CMV in patients with "uncomplicated" ARF do not reveal HFJV to be superior to CMV when all other variables (F_IO_2, PEEP) are held constant [4, 24]. Since mean AWP, an important determinant of oxygenation, is usually quite similar in HFJV and CMV, one would not expect HFJV per se to improve P_aO_2 by this mechanism. However, our experience with patients 2 and 5 indicates that in the individual patient, HFJV improves gas exchange, presumably by alleviating the direct or indirect depressant effects of CMV on cardiac output. Improved cardiac outputs were indeed measured (by thermodilution technique) in these two patients following institution of HFJV.

HFJV offers smooth, accelerated weaning from short-term mechanical ventilation (e.g. post-anesthesia [18]), and could become the preferred method for weaning of ventilator-dependent patients, when other methods have failed [12]. Weaning from HFJV is started when, during stepwise reduction of PEEP the P_aO_2 remains above 80 mmHg on a F_IO_2 of less than 0.4. It is accomplished by stepwise reduction of the P_d, which allows resumption of spontaneous breathing (as mentioned before, at higher P_d, HFJV produces apnea) while still assisted by superimposed HFJV. The weaning process can be continued as long as the pH and P_aCO_2 remain normal at a spontaneous f_b of less than 30/min. Unassisted spontaneous breathing is allowed as soon as P_d is less than 15 psi and PEEP less than 5 cmH_2O.

In patients on CMV, HFJV can temporarily be instituted during tube replacement [10] and suctioning [11], thus avoiding interruption of ventilatory support and subsequent hypercapnia, hypoxemia, cardiac arrhythmias, atelectasis (from suctioning) and aspiration (during tube replacement). HFJV has been proposed for CPR [15]. When intubation is difficult or impossible emergency use of transcutaneous HFJV by cricothyroid membrane puncture offers a fast and less traumatic alternative to emergency tracheotomy. In dog experiments, transtracheal HFJV can dislodge aspirated foreign material from the airway above the puncture site [15, 22] (Heimlich-like maneuver), especially by initially directing the cannula-tip cephalad. During CPR, there is no need to interpose ventilations between external cardiac compressions, so that both maneuvers can be continuously applied. It has been shown in these dog experiments that, in spite of its Venturi-effect, HFJV (administered either transtracheally or via uncuffed translaryngeal catheters) is not complicated by aspiration and can prevent it, provided f_b is 100/min or more and expiration is not prolonged [15, 22]. Even in between external cardiac compressions, when sharp dips in intratracheal pressure occurred, aspiration was not observed [15].

Provided the injector cannula is well centered in the airway (and this becomes more important the nearer the distal tip of the cannula is to the carina), HFJV results in uniform intrapulmonary gas distribution [7]. By transporting drugs, nebulized into the jet stream, to the peripheral airways, it provides a route for intrapulmonary drug administration [15].

Even though HFJV appears an effective and safe method of mechanical ventilation, a number of drawbacks and potential complications exist. It is not a cost-effective way of moving gases, since large amounts of gases (O_2) are needed to provide the high $\dot{V}_E$. Theoretically, high $\dot{V}_E$ could result in mucosal damage, by increasing the shearforces on the tracheobronchial walls, and in interrupting mucociliary transport (MCT) from drying-out of the mucus layer. Proper humidification of inspired (jetted *and* entrained) gases is of critical importance in preventing these complications: with adequate humidification, neither tracheobronchial mucosal [22] nor lung-parenchymal [8, 13, 29] damage are observed even by electronmicroscopy [21], and MCT is preserved [20]. By contrast, HFO techniques, which operate at higher frequencies, comparable to the frequency of ciliary beating (approximately 20 Hz), reduce MCT reversibly (and thus not as a result of major structural damage to the mucosa) and result in increased amounts of tracheal mucus, presumably due to increased local production [19]. Under the influence of the high gas velocities, this mucus moves rapidly toward smaller airways, without however affecting gas exchange (underscoring the efficiency of HFV techniques) [19]. In our experience with HFJV, at least part of the tracheobronchial secretions are pushed back up, since we not uncommonly see abundant secretions in the external tubing. Bronchospasm [2, 24] has been described in patients with chronic obstructive lung disease. As mentioned before, immediately following institution of HFJV, hypoxemia probably due to an increase in intrapulmonary shunt [28], may occur. This justifies the administration of high F_IO_2 (0.8 – 1) during the first 30 min.

In conclusion, HFJV appears to be an efficient mode of mechanical ventilation without adverse cardiopulmonary effects, even when applied for prolonged periods of time. In patients with barotrauma and airway disruption (fistulae), it is our first-choice mode of mechanical ventilatory support. Accordingly, HFJV seems to be the preferred way of ventilating patients during pulmonary resection (decreasing lung movement and improving surgical access) and whilst recovering from it (when recently repaired bronchial stumps are unlikely to tolerate high peak inspiratory AWP). HFJV can be considered as an alternative to CMV when the latter produces excessive hemodynamic embarrassment or patient-ventilator discoordination. In patients with uncomplicated ARF, there is, as yet, no evidence that HFJV is superior to CMV. Two comparative studies [4, 24] have shown it to be a safe and reliable method of mechanical ventilation but it did not offer obvious benefits over CMV. Therefore, HFJV can not at present be recommended as the first choice in these patients. With HFJV, a number of new concepts, which are usually not considered during CMV, have been introduced into the domain of mechanical ventilatory support. Refinement and elucidation of these concepts might further improve our understanding of HFJV and its applicability in clinical practice.

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