The use of jet ventilation in today's anesthesia: a narrative review

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Abstract

Objective: **This narrative review seeks to examine the fundamental mechanisms, optimal settings, current applications, and emerging indications of jet ventilation. This review is focused on jet ventilation in interventional procedures both within and outside the operating theatre, through a critical analysis of existing literature.**
Background: **Jet ventilation is primarily utilized in otolaryngology (ENT) surgical procedures, particularly those involving the larynx or trachea. It allows for an unobstructed operating field by eliminating the need of a conventional endotracheal tube. Because of the minimal thoracic expansion it generates, jet ventilation is now used in other fields such as interventional radiology and electrophysiology. Despite its benefits, this technique carries risks such as barotrauma, hypoventilation, hypercapnia, and catheter misplacement. Expertise and a thorough understanding of its principles are therefore essential for its use.**
Methods: **A literature search was conducted in October 2024 using the PubMed Database. Additional search es were carried out in Google Scholar. Main keywords were combine using the Boolean equations. This narrative study does not aim to be as methodologically comprehensive as a systematic review. The selection of articles is influenced by clinical relevance. However, it offers a critical overview of current practices and future prospects for jet ventilation. This article respect the Scale for the quality Assessment of Narrative Review Articles (SANRA).**
Results: **Fifty-five publications from 1956 to 2024 were selected for the review. Only three of these articles were published before the year 2000. A thematic analysis was used to structure the results. The use of high-frequency jet ventilation is validated in ear, nose and throat (ENT) surgery, interventional pulmonology, and has its place in emergency situations. It can be used in both adults and children. More recently, its use in interventional radiology, electrophysiology, and lithotripsy has been studied and appears to show certain advantages. The complications related to the use of jet ventilation are generally associated with a lack of experience from the teams.**
Conclusions: **Jet ventilation is a critical modality in certain clinical settings, particularly within anesthesia for upper airway procedures, laryngeal surgery, bronchoscopy, or when surgical access necessitates an unobstructed operating field. The principal benefits of jet ventilation include preserving excellent operative visibility, minimizing thoracic movement, and frequently ensuring adequate oxygenation despite low tidal volumes. This technique necessitates specialized expertise and diligent monitoring due to its limitations, such as the risk of barotrauma or CO2 accumulation. Further research, including comprehensive comparative studies, is necessary to more precisely delineate its indications, contraindications, and long-term effects, particularly in emerging fields such as interventional radiology, electrophysiology, and lithotripsy.**

Meetings where the work has been presented None.
Conflict of interest None.
All listed authors significantly contribute to and approved the content of the manuscrit.

Introduction

Airway control is an important consideration in anaesthesia, especially in cases where conventionnal ventilation presents challenge.

Jet ventilation was developed in the 1970s following the work of Klein and Smith[1]. Jet ventilation is a mode of controlled ventilation based on the pulsed injection of high frequency, low amplitude gas through a high pressure system, via a fine probe or catheter. The pressure variations in the airway are on the order of a few centimeters of water (cmH_2O). This specific ventilatory technique helps to provide sufficient oxygenation and ventilation when anatomical or surgical conditions are restrictive.

Jet ventilation is primarily utilized in otolaryngology (ENT) surgical procedures, particularly those involving the larynx or trachea. It allows for an unobstructed operating field by eliminating the need of a conventional endotracheal tube. Additionally, jet ventilation is employed outside the operating theatre, including in intensive care units, during endoscopic procedures, and in the management of difficult airways and acute respiratory emergencies. Because of the minimal thoracic expansion it generates, jet ventilation is now used in other fields such as interventional radiology and electrophysiology.

Despite its benefits, this technique carries risks such as barotrauma, hypoventilation, hypercapnia, and catheter misplacement. Expertise and a thorough understanding of its principles are therefore essential for its use.

This narrative review seeks to examine the fundamental mechanisms, optimal settings, current applications and emerging indications of jet ventilation. This review is focused on jet ventilation in interventional procedures both within and outside the operating theatre, through a critical analysis of existing literature.

Methods

A literature search was conducted in October 2024 using the PubMed Database. Additional search were carried out in Google Scholar. The main keywords used are listed in Annex 1 (read QR). Boolean equations were used to combine terms. Inclusion and exclusion criteria were as follows

Inclusion

- Articles published until october 2024.
- Languages English or French.
- Clinical studies, literature reviews, guidelines from learned societies, documented clinical cases.
- Articles about jet ventilation mechanisms or in anaesthesia for interventional procedures.

Exclusion

- Intensive care or pre-hospital articles.
- Letters to the editor without clinical data

An initial selection was made on the basis of title and abstract. Articles deemed potentially relevant were then analyzed in full text. Reference lists of selected papers were also reviewed to identify additional pertinent studies. Main articles reviewed are listed in the annex 2 (read QR)

A thematic analysis was used to structure the results according to the following mains areas

- High Frequency Jet Ventilation Basics
- Anaesthetic considerations for Jet Ventilation
- Current applications for High Frequency Jet Ventilation
- Emerging applications for High Frequency Jet Ventilation

Limitations

This narrative study does not aim to be as methodologically comprehensive as a systematic review. The selection of articles is influenced by clinical relevance. However, it offers a critical overview of current practices and future prospects for jet ventilation. This article adheres to the Scale for the Quality Assessment of Narrative Review Articles (SANRA)[2].

Review

High Frequency Jet Ventilation: basics

Operating principles

Jet ventilation is based on the pulsed injection of high-frequency, low-amplitude gas through a high-pressure system, via a fine probe or catheter. Gas is injected at high pressure into the catheter, which is also called an injector. At the exit of the injector, the pressure is converted into kinetic energy[3]. So high frequency jet ventilation is a mode of controlled ventilation performed at high frequency, high velocity, and low pressure within

Annexes - qrco.de/beNP4S

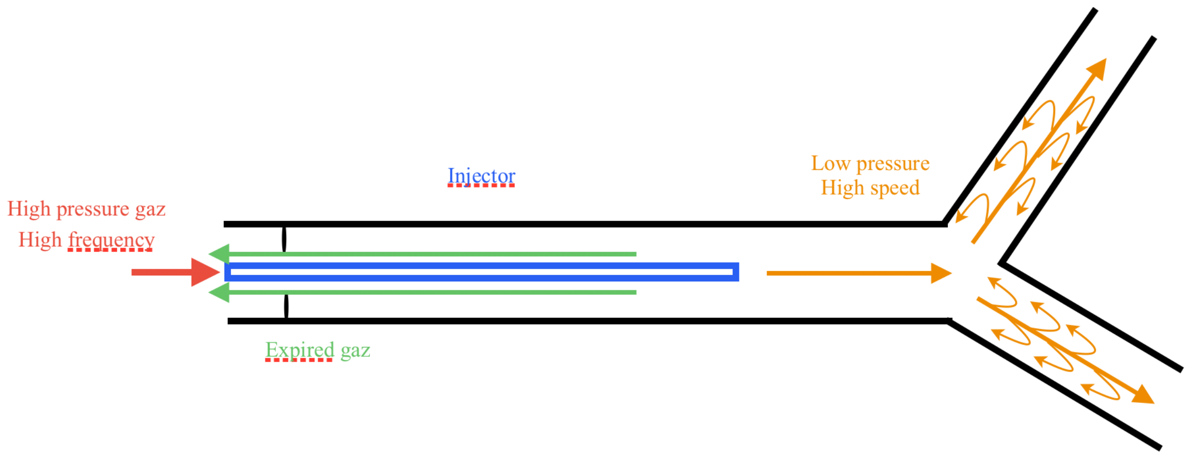

Fig. 1 —Jet ventilation mecanism.
Inspired by Chollet-RivierM., Bourgain JL. La jet-ventilation pour les nuls. Anesthésie & Réanimation. 2015. Dec;1(6):522-7.

the airways. The decompression of gas at the injector outlet results in the surrounding air being drawn in, due to the Venturi effect, during the inspiration phase. Expiration of air occurs passively.

Delivery techniques

Jet ventilation can be administred through three approches depending on the indication and the patient's anatomy[4]

- Supraglottic approach via the lateral channel of the microlaryngoscope. If the injector is improperly positionned, there is a risk of alveolar hypoventilation and esophageal insufflation.
- Transglottic approach uses a cannula introduced into the trachea or through the channel of the bronchoscope. This is the approach that generates the least complications[5]. However, there is a risk of esophageal insufflation and gastric rupture if the cannula migrates into the esophagus. This mode of ventilation can also be performed by placing the catheter in the endotracheal tube.
- Subglottic approach via a trans-tracheal catheter is also described. This technique is only applicable for patients aged 8 and older and is generally used in ENT oncology and in emergency situations, with specific precautions to avoid barotrauma.

Alveolar gas delivery

When using jet ventilation, the patient oxygenation will depend on alveolar ventilation and the fraction of oxygen inspired (FiO_2). Alveolar ventilation (VA) is calculated as the respiratory rate (RR) multiplied by the tidal volume (TV). This same tidal volume equals the volume delivered by the device (Vd) plus the entrained volume (Ve) minus the reflux volume (Vr)[6]. The formula for TV is shown in Figure 2.

Depending on the airway opening and the position of the injector, the entrained volume can represent from 15% to 74% of the tidal volume7. The tidal volume is therefore highly variable and will depend on different parameters cited in the annex 3.

In addition, alveolar gas delivery differs from conventional ventilation. No data were found for HFJV, but it can be assume that the physical phenomena involved in the exchanges observed in High-frequency oscillatory ventilation (HFVO)8 are applicable. High-frequency oscillatory ventilation (HFOV) is a mode of high-frequency ventilation, where the tidal volume is less than the anatomical dead space, and both inspiration and expiration are active processes9. The involved physical mechanisms are listed in Table I and illustred in Figure 3. They explain how alveolar gas delivery can be achieved despite a tidal volume

Formula
TV = Vd + (Ve-Vr) TV = Tidal Volume Vd = volume delivered by the device Ve = entrained volume Vr = reflux volume

Fig. 2

close to anatomical dead space (around 2ml/kg in a healthy adult).

Other phenomena are involved, such as collateral ventilation and cardiogenic mixing[8].

To address hypoxemia, we can increase the FiO_2 or increase the O_2 supply in the ambient air, raise the work pressure and/or increase the inspiratory time[1]. In some refractory cases, it remains necessary to switch to conventional ventilation.

Carbon dioxyde removal

During jet ventilation, expiration occurs passively due to the elastic force of the thoraco-pulmonary complex. Expired gas escape through the airways, around the injector. Therefore, It is essential to keep the upper airways and glottis open. Inefficient expiration can lead to air trapping, which may result in barotrauma[4]. The closer the injector tip is to the carina, the more efficient the removal of CO_2[3]. This is likely due to improved coaxial flow.

Measurement of the end-tidal partial pressure of CO_2 ($ETCO_2$) is not a good indicator of the arterial partial pressure of CO_2 ($PaCO_2$). As the system is open, the tracheal measurement will take a mixture of inspired gas, expired gas and atmospheric gas[11]. For $ETCO_2$ measurement to accurately reflect alveolar concentration, it is necessary either to perform a large insufflation before measurement or to stop ventilation and analyze a gas sample after ten seconds. Some devices allow these inspiratory pauses, and are equipped with a double-lumen injector with a sampling line. This line may be obstructed by secretions[3]. It is possible to perform arterial blood gas analysis, but this is invasive and provides only an intermittent value. Since the early 2000s, measurement of transcutaneous CO_2 pressure ($PtCO_2$) has been accepted as a reliable estimate of $PaCO_2$, particularly in pediatric intensive care[12]. Its use in surgery has also been studied and accepted for laparoscopic surgery[13] and for one-lung ventilation[14]. A 2017 prospective study shows that the relationship between $PtCO_2$ and $PaCO_2$ in jet ventilation is also reliable and enables ventilation to be adjusted[15]. Continuous, reliable CO_2 measurement enables the physician to adopt a more proactive rather than reactive ventilatory approach. However, there is a limit to transcutaneous CO_2 measurement ; it seems less reliable, with a tendency to underestimate $PaCO_2$ for a $PaCO_2$ greater than 60 mmHg[16]. This monitoring is an aid to patient management and should not replace clinical judgment, observation of symmetrical chest rise and correct expiration[6].

In the case of hypercapnia, efforts should be made to increase tidal volume and promote the expiratory phase by increasing driving pressure, decreasing frequency, and reducing the inspiratory time[1].

Use of helium

The use of an oxygen-helium mixture, also known as heliox, tends to decrease the resistance to the flow of the gas mixture. This is due to two factors. First, the lower density of helium compared to nitrogen. A helium-oxygen mixture (78%-21%) has a density three times lower than that of air (78-21% nitrogen-oxygen)[17]. Second, the properties of helium reduce the Reynolds number, which promotes laminar flow in areas where the flow would be turbulent with an air-oxygen mixture, thus making it more efficient[18]. Heliox also improves elimination CO_2 removal due to its better diffusion coefficient for carbon dioxide than air or oxygen[18]. In addition, at equal driving pressure and frequency in the same patient, the tidal volume will be greater with a heliox mixture than with air[19]. Although its effects have been known since the 1930s, the use of heliox in jet ventilation is limited due to its cost, storage in in fixed-concentration cylinders, the need for machines approved for the use of heliox, and the lack of studies defining its indications for use[6,17].

Table I. — Physical mechanisms involved in alveolar gas delivery.

- Taylor Dispersion : This is a concept from fluid mechanics explains how fresh oxygenated gas, propelled at high speed, can penetrate deeply into the bronchial tree[8]. This mechanism is considered to be the main one in high-frequency jet ventilation[10].
- Bulk Convection : The pressure decrease in the alveolus, caused by the absorption of oxygen by the bloodstream, leads to the movement of gas towards the alveolus[8].
- Pendelluft Effect : This describes the movement of air from one pulmonary unit to another when their compliances are significantly different[8].
- Increased Molecular Diffusion : The high velocity given to the gas will enhance the Brownian motion of the molecules[7].
- Coaxial Flow : There is a bidirectional flow within the respiratory tree, with a central inspiratory column and a peripheral expiratory flow. This expiratory flow is at a lower speed and is pushed out of the lung by the force of the inspiratory flow[8].

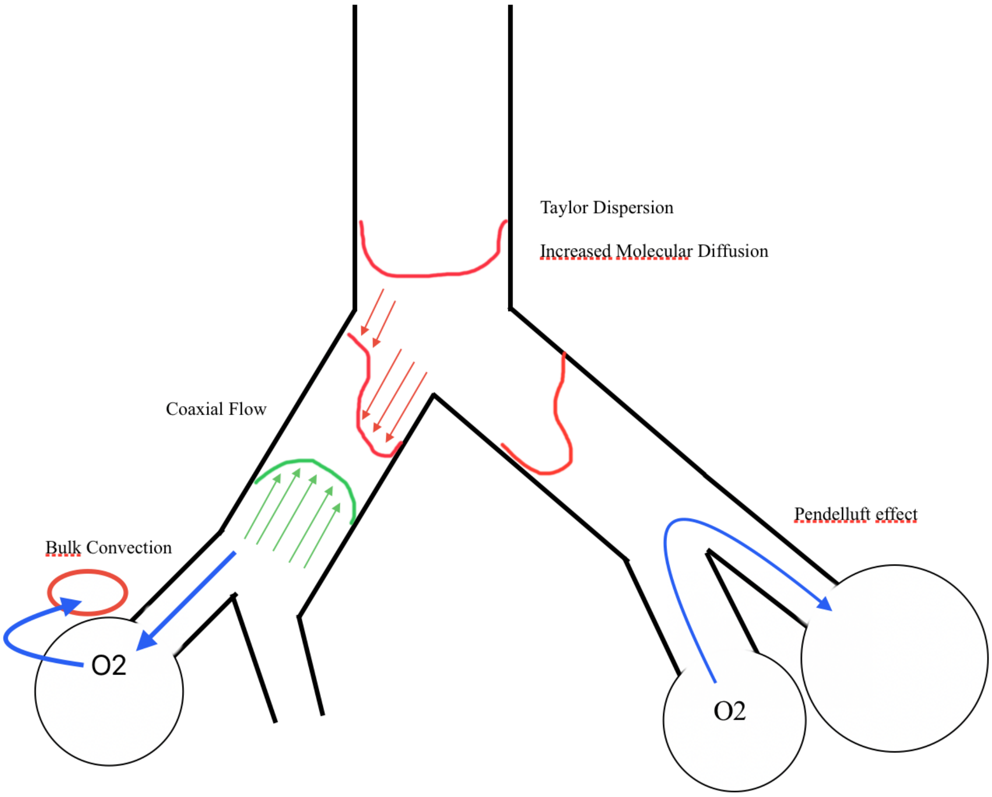

Fig. 3 —Inspired by Pillow JJ. High-frequency oscillatory vantilation: Mechanisms of gas exchange and lung mechanics. Vol. 33, Critical Care Mdicine. 2005

Settings for High Frequency Jet Ventilation device

The main settings to be made on the device are frequency, driving pressure, end-expiratory pressure (EEP), I:E ratio, and FiO_2[4]. It is advisable to start with the lowest possible driving pressure, and gradually increase it according to the quality of expiration3. Expiratory lung emptying is equal to 3 times the time constant (τ), where τ is the product of compliance and resistance[6]. The goal is to tailor ventilation to the patient and his or her time constant τ in order to achieve minimum effective pressure. The initial driving pressure will depend on the frequency and the patient's weight. End-expiratory pressure (EEP) is the pressure measured in the trachea 10 ms before the next insufflation. If the EEP exceeds a predifined threshold, the device does not perform the next insufflation and waits until the pressure in the upper airway is below this threshold before delivering the next insufflation[1]. The device will increase its expiratory time. The EEP measured corresponds to the tracheal pressure plus the residual pressure in the system. This expiration indicator does not replace the anaesthetist's clinical judgment. It is therefore important to observe and manually perceive the return of the thorax to the expiratory position.

Suggested initial settings to be adapted according to the patient's clinical condition are shown in Table II[4]. All these parameters should be adjusted based on the machine used, the anaesthetist's experience, and the patient's ventilatory mechanics.

Table II. — Initial HFJV settings.

Frequency : Between 120 and 180/min (2 and 3 Hz) is generally used.*
Driving pressure : For a frequency of 100/minute or less, a driving pressure of 0.03 bar/kg will be used. For a respiratory frequency greater than 100/minute, a working pressure of 0.02 bar/kg will be used.
End-expiratory pressure threshold : Generally between 5 and 10 mmHg (6.8 – 13.6 cmH2O). It allows automatic cut-off of inspiratory flow in case of overpressure[1]
I:E ratio: Between 30 and 35%. This allows lung exsufflation and prevents air trapping.
FiO2 :** Adjusted on the basis of pulse oximetry
* Jet ventilation between 6 and 100/min (0.1 – 1.5 Hz) will be considered low-frequency jet ventilation. Jet ventilation between 100 and 600/min (1.6 – 10 Hz) will be considered high-frequency jet ventilation. ** For information, the FiO_2 set on the machine is generally slightly higher than the FiO_2 at tracheal level due to the volume entrained, particularly during pre-glottic ventilation[3].

Before the age of 8 years, jet ventilation settings differ from those used in adults. Children, especially infants, have a high time constant (τ) due to greater thoracopulmonary compliance and greater bronchial resistance[6]. To ensure alveolar ventilation, higher pressures should be used and expiratory time should be increased to ensure exsufflation[4]:

- The initial driving pressure should be set between 0.1 and 0.3 bar and then gradually increased to 0.03 bar/kg, depending on chest expansion and SpO_2.
- The jet ventilation frequency should be initially set low (< 100 per minute), and then increased to 200 per minute if expiration is easy.
- The end expiratory pressure should be less than 4 cm H_2O, or 2-3 mmHg.
- The Inspiratory Time (Ti) should be less than < 30% of the total time, generally around 20%.

In summary, in children under 8 years of age, jet ventilation involves higher driving pressures, a lower respiratory frequency, and a lower inspiratory-to-total time ratio than in adults. From the age of 5, airway resistance becomes similar to that of adults, but it is not until the age of 8 that compliance also becomes comparable. From the age of 8, jet ventilation settings are identical to those for adults[6].

Superimposed high frequency jet ventilation

Superimposed high-frequency jet ventilation (SHFV) is a combination of two forms of jet ventilation. It is performed using two catheters located in the laryngoscope. The first provides high-frequency ventilation, between 100 and 600 breaths per minute, while the second provides low-frequency ventilation, between 12 and 20 breaths per minute. Both ventilation modes are simultaneous. The driving pressures are identical to those of conventional jet ventilation for both cannulas. Its use and safety have been proven[20]. This ventilation mode has the advantage of increasing ventilation and threfore eliminating CO_2[21]. An improvement in residual functional capacity and recruitment is also observed, without however improving oxygenation[21].

Anaesthetic considerations for Jet Ventilation

Anaesthesia procedures, devices and accessories for Jet Ventilation

With jet ventilation, the goal is to achieve deep anaesthesia with inhibition of cough ans swallow reflexes[6]. As this is an open circuit and jet ventilation circuits are not equipped with vaporizers, total intravenous anaesthesia (TIVA) is used. Deep neuromuscular bockade and monitoring, can also be useful in keeping the vocal cordes open to facilitate complete expiration[22] and reduce opiode-induced thoracic rigidity induced. This will improve thoraco-pulmonary compliance and thus decrease reflux volume[3].

As mentioned above, transcutaneous monitoring of CO_2 measurement will provide a indicator of the patient's minute ventilation, but will not replace clinical judgment.

Jet ventilation can be delivered either by a manual system, or by a specific ventilator dedicated to jet ventilation. French experts do not recommend the use of manual systems outside emergency situations[3].

The characteristics of the injector are important in jet ventilation. In order to maintain pressure at the tip of the injector and thus ensure conversion of pressure into kinetic energy, the injector should be low-compliant, have a small radius - typically 2mm in adults - and be resistant to the CO_2 laser. Rigidity at the tip of the injector can injure the tracheal mucosa. The larger the diameter, the lower the resistance, the slower the pressure increases[3]. The length of the injector can also influence ventilation. Measuring end-expiratory pressure has been shown to reduce complications[4]. For end-expiratory pressure measurement to accurately reflect tracheal pressure, the system must have had time to decompress. Decompression time depends on the volume contained in the dead space of the ventilatory system: the larger the diameter and lenght of the injector, the longer the pressure reduction[23]. According to the frequency of jet ventilation and characteristics of the injector, the end-expiratory pressure measurement at the injector tip may be higher than the tracheal pressure, as it reflects the sum of the tracheal pressure and the residual pressure in the system[23]. Knowledge of the different types of injectors and the frequencies at which they can be used is essential to prevent the ventilator from entering safety mode too quickly.

The prevention of hypothermia through temperature monitoring and active warming is recommended. The temperature of the gas decreases during decompression, helping to cool the patient. This is particularly true in paediatrics, where active rewarming should be systematic[3]. Some machines are equipped with gas heating and humidification systems. Humidification helps protect the bronchial mucosa by preserving ciliary function, but can increase flow resistance. Humidification should be with distilled water, not 0.9% saline, to avoid chloride and sodium aggregation in the circuit[24].

Regarding the equipment used and monitoring devices, attention should be paid to the cannula used for jet ventilation in children, since the cannula occupies more than 50% of the tracheal diameter, there is a risk of significant obstruction to exsufflation[4]. Regarding exsufflation, in addition to monitoring end expiratory pressure and the alarm threshold previously defined according to age, clinical observation of respiratory movements will be important since end expiratory pressure does not correlated with alveolar pressure or functional residual capacity[25]. It will also be crucial to closely monitor the child's temperature to prevent hypothermia, especially in infants[6].

Complications of jet ventilation

In 2012, a retrospective study of 839 patients between 1995 and 2010 for whom subglottic high-frequency jet ventilation (HFJV) was used, reported a complication rate of 5.8%[1]. By comparison, a study of protective conventional ventilation published in 2013 reported a rate of grade 3 or 4 pulmonary complications at 7 days after major abdominal surgery of 5%[26].

Respectively in 2006 and 1990, an UK national survey of complications related to high-pressure ventilation[27] and an US survey[28] show that the majority of complications are pneumothorax, pneumomediastinum, subcutaneous emphysema or ventilation defects (hypercapnia or hypoxia). No deaths related to these complications have been reported whit HFJV. In the UK survey, of the 5 patients admitted to intensive care over 5 years, 3 benefited from jet ventilation with a manual system. It also shows that in centers where more than 100 cases of trans-tracheal jet ventilation are performed each year, the survey reports only 4 complications, none of which had any impact on morbidity or mortality[27].

Barotrauma is caused by overpressure in the tracheobronchial tree. This overpressure is often due to air trapping. The main identified cause is vocal cord closure if anaesthesia or muscle relaxation is not sufficiently deep[5]. It is also important to maintain an open upper airway, with the option of performing a jaw thrust maneuver or inserting an oropharyngeal canula[3]. Surgical instruments can also obstruct the airway during expiration. Therefore, communication with surgical teams and careful attention to the surgical field are essential. Device adjustement is also important. Indeed, if the expiratory time is too short to allow for complete expiration, lung distension and auto-PEEP will occur. Measuring end-expiratory pressure and installing a safety feature on the jet ventilation machine help reduce the risk of barotrauma4. In a prospective study published in 2018, including 222 patients who underwent subglottic HFJV with end-expiratory pressure monitoring, no barotrauma, pneumothorax, pneumomediastinum, or subcutaneous emphysema were observed[29]. When using preglottic HFJV, the tele-expiratory pressure measurement does not reflect the pressure in the tracheobronchial tree, and the generated volume tends to be larger[7], therefore, the use of HFJV should be even more cautious.

Chronic obstructive pulmonary disease (COPD) or asthma are not risk factors for pneumothorax[30], but these conditions can represent a challenge to alveolar ventilation due to their increase resistance and reduced compliance[31]. This is confirmed in a prospective study published in 2000, where restrictive and/or obstructive pulmonary syndrome is a good predictor of poor CO_2 elimination. In contrast, normal pulmonary function does not prevent poor gas exchange[30]. Risk factors for poor gas exchange (hypercapnia or hypoxia) during HFJV also include duration of ventilation, a history of laryngeal surgery[29] and a Body Mass Index (BMI) greater than 25[26]. Therefore, morbid obesity could be considered a relative contraindication for HFJV[3].

In many studies, the experience of the anaesthetic team with jet ventilation is cited as a factor reducing the occurrence of complications[5,28,33].

Contraindications of jet ventilation

There are some contraindications to jet ventilation. A full stomach or a surgical procedure with a high risk of bleeding are contraindications to high-frequency jet ventilation, as the airway is not protected.

Tracheal stenosis is a relative contraindication. The use of high-frequency jet ventilation in the presence of tracheal stenosis should be approched with caution. The risk of air trapping, and therefore of barotrauma, is greater. Following in vitro measurements conducted on a model of laryngotracheal stenosis, Buczkowski[7] demonstrated that in cases of severe tracheal stenosis, the use of jet ventilation downstream of the stenosis provides the best oxygenation and the lowest pressures in the trachea, making it the safest method. This assertion is confirmed in vivo by a retrospective study in 2017[34] and by Ross-Anderson J. and al. on a series of 50 patients in 2011[33] with stenosis greater than 75%. The last study shows that the use of jet ventilation via a trans-tracheal catheter, distal to the stenosis, results in only 20% minor complications (kinked catheter, minimal bleeding, or subcutaneous emphysema)[33]. It should be noted that in both studies, they were familiar with the use of jet ventilation and monitord end-expiratory pressure. Caution should be exercised when using jet ventilation by passing the cannula beyond the stenosis in severe stenoses, as the cannula can cause excessive obstruction during expiration[7]. No studies were found regarding the use of jet ventilation proximal to the stenosis ; therefore, it cannot be recommended at this time.

Laryngeal papillomatosis, the most common benign laryngeal tumor in paediatrics, results from a papillomavirus infection. These children frequently undergo surgery to burn the lesions with CO_2 laser. Due to its viral origin, supraglottic jet ventilation is contraindicated in this case to prevent broncho-pulmonary dissemination[35].

The use of jet ventilation in cases of obesity or obstructive airway syndrome has already been discussed above.

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Contraindications of jet ventilation

There are some contraindications to jet ventilation. A full stomach or a surgical procedure with a high risk of bleeding are contraindications to high-frequency jet ventilation, as the airway is not protected.

Tracheal stenosis is a relative contraindication. The use of high-frequency jet ventilation in the presence of tracheal stenosis should be approched with caution. The risk of air trapping, and therefore of barotrauma, is greater. Following in vitro measurements conducted on a model of laryngotracheal stenosis, Buczkowski[7] demonstrated that in cases of severe tracheal stenosis, the use of jet ventilation downstream of the stenosis provides the best oxygenation and the lowest pressures in the trachea, making it the safest method. This assertion is confirmed in vivo by a retrospective study in 2017[34] and by Ross-Anderson J. and al. on a series of 50 patients in 2011[33] with stenosis greater than 75%. The last study shows that the use of jet ventilation via a trans-tracheal catheter, distal to the stenosis, results in only 20% minor complications (kinked catheter, minimal bleeding, or subcutaneous emphysema)[33]. It should be noted that in both studies, they were familiar with the use of jet ventilation and monitord end-expiratory pressure. Caution should be exercised when using jet ventilation by passing the cannula beyond the stenosis in severe stenoses, as the cannula can cause excessive obstruction during expiration[7]. No studies were found regarding the use of jet ventilation proximal to the stenosis ; therefore, it cannot be recommended at this time.

Laryngeal papillomatosis, the most common benign laryngeal tumor in paediatrics, results from a papillomavirus infection. These children frequently undergo surgery to burn the lesions with CO_2 laser. Due to its viral origin, supraglottic jet ventilation is contraindicated in this case to prevent broncho-pulmonary dissemination[35].

The use of jet ventilation in cases of obesity or obstructive airway syndrome has already been discussed above.

Current applications for High Frequency Jet Ventilation

Jet ventilation in ENT surgery

Jet ventilation finds its main application in maxillofacial and ENT surgery, particularly in laryngology. Its main indication remains suspension laryngoscopy, as it frees the surgical field for the surgeon, immobilizes the glottic structures, unlike spontaneous ventilation[5], and facilitates smoke evacuation when using CO_2 laser[4]. The use of high-frequency jet ventilation could decrease with the introduction of high-flow nasal cannulas in the operating room. Apneic oxygenation by high-flow nasal cannulas is not yet recommended in this type of surgery[36]. However, in surgery where spontaneous ventilation can be preserved, the STRIVE Hi study[37] showed that the use of high-flow nasal cannulas in spontaneous ventilation allowed good oxygenation and efficient CO_2 elimination without the complications associated with jet ventilation. A comparative study would be necessary to determine the most effective method. Panendoscopy for the diagnosis and evaluation of head and neck cancers can be performed under orotracheal intubation, high-frequency jet ventilation, or spontaneous ventilation. Orotracheal intubation offers the advantage of protecting the airway, but it can be difficult and reduces the quality of tumor assessment due to trauma or bleeding caused by laryngoscopy. Trans-tracheal jet ventilation allows for a clear surgical field and had fewer episodes of desaturation[38]. This technique requires the experience of the anaesthesia team. In France, according to a national survey, panendoscopy is performed under general anaesthesia with spontaneous ventilation in 37% of cases[39]. No studies comparing spontaneous ventilation and jet ventilation in panendoscopy were found.

In laser surgery, the risk of ignition of the intubation tube, even if flame-resistant, is not negligible[5]. This is why it is important to clear the surgical site. Regardless of the type of ventilation used, an FiO_2 lower than 30% must be administered during laser surgery to avoid any risk of airway fire. The use of nitrous oxide is also prohibited during laser procedures due to the same risk of combustion[6].

Jet ventilation in bronchoscopy

Rigid bronchoscopy, which allows for diagnostic and therapeutic procedures, is the main indication for jet ventilation in interventional pulmonology. Indeed, other procedures such as flexible bronchoscopy, endobronchial valves insertion, or pleuroscopy are generally performed under spontaneous ventilation[40]. .

As in ENT surgery, rigid bronchoscopy requires the pulmonologist and anesthesiologist to share the airway. Ventilation is generally provided through a side channel in the bronchoscope, making it transtracheal jet ventilation. In addition to maintening an open airway, it is important to ensure that the position of the rigid bronchoscope does not result in single-lung ventilation[24].

In all these indications, the disadvantage of jet ventilation is that it does not protect the airway from aspiration and bleeding.

In cases of foreign body aspiration, jet ventilation has been considered, but Zhang 's prospective study shows that there is a higher risk of pneumothorax with jet ventilation compared to pressure-controlled ventilation[41]. This is because, as mentioned earlier, insufflation in this setting occurs upstream of the obstruction. High-frequency jet ventilation also carries the risk of pushing the foreign body further into the tracheobronchial tree.

Rescue Jet Ventilation

Currently, opinions regarding its use in rescue techniques are divided. In 2015, the Difficult Airway Society (DAS) removed jet ventilation from its 'can't intubate, can't ventilate' (CICO) algorithm and replaced it with cricothyroidotomy[42,43]. However, transtracheal jet ventilation is still mentioned in the new DAS recommendations for teams familiar with this technique in their daily practice. In contrast, rescue transtracheal jet ventilation is still included in the CICO algorithms of both the French Society of Anesthesia and Intensive Care and the American Society of Anesthesiologists[44,45]. This reflects the different conclusions found in the literature. A 2016 systematic review shows that the complication rate when using transtracheal jet ventilation in CICO situations reaches 51%[46]. In contrast, a more recent retrospective study showed no complications in a series of 26 patients requiring emergency jet ventilation during difficult intubation[34]. The authors of this study explain this by the use of a rigid catheter, preventing flexion, a jet ventilator equipped with an end-expiratory pressure monitoring system (unlike the Manujet®), which reduces the risk of barotrauma, and the teams' experience using this method.

The use of jet ventilation during an anticipated difficult intubation is safe and effective. Only 20% of minor complications were observed (catheter flexion in 14%, bleeding in 2%, and emphysema in 2%) in this series of 50 patients with upper aerodigestive tract cancer[33]. Transtracheal jet ventilation improves intubation conditions and ensures oxygenation during intubation[34]. Some centers place the transtracheal catheter under local anesthesia in situations where identification of the cricothyroid membrane may be complicated[33]. There are few contraindications to percutaneous tracheal puncture: cutaneous or subcutaneous infection, recent endotracheal intubation (granulomas are generally present in this area), and cancer near the puncture site. These contraindications are considered relative and are waived in case of livesavings measures[3]. If the only device available is the Manujet®, here are some usage recommendations for use[4]. The manometeris set at 0.5 bar, and gradually increased if expiration is easy (do not exceed 1 bar in children). The inspiratory time is

1 second. The respiratory frequency is between 1 and 10 per minute, while monitoring the quality of exsufflation.

Other methods of rescue oxygenation via a transtracheal catheter include bag-valve mask ventilation, Ventrain®, which allows active inspiration and expiration, and Rapid-O2[47].

Emerging applications of High-Frequency Jet Ventilation

Jet Ventilation in interventional radiology

Jet ventilation reduces the movement of subdiaphragmatic organs, such as the liver, by 66% compared to conventional ventilation[48]. Its use in radiology for percutaneous ablation of lung, liver, or kidney tumors is accepted and considered safe[49,50]. The expected advantage of jet ventilation over other approaches (local anesthesia, sedation, or general anesthesia with conventional ventilation) is to increase probe accuracy and reduce damage to adjacent tissues. It should be noted that its use sometimes renders the lesion inaccessible or invisible due to the intermediate position of the diaphragm or alveolar atelectasis[50]. .

In the management of percutaneous cryoablation of lung tumors, jet ventilation allows the treatment of of lesions that are more complex in terms of their location or number, without increasing the risk of complications or the duration of irradiation compared to sedation in cases initially considered simpler[49]. .

Its use should be discussed based on the patient, the location of the tumor, and the operator's preferences. Indeed, the use of jet ventilation requires the presence of an anaesthesiologist trained in its use and prolongs the duration of room occupancy.

Jet Ventilation in electrophysiology

The use of jet ventilation under general anaesthesia for pulmonary vein isolation is increasingly common. Its implementation, thanks to the reduction of thoracic movements and the stability of left atrial volume, improves catheter stability, which is tought to reduce operative time[51], improve the quality of induced lesions, and decrease the risk of pulmonary venous reconnection[52]. However, its use should remain cautious because, in a retrospective study of 1,822 patients, jet ventilation prolonged the recovery room stay, due to intraoperative hypocapnia and hypotension[53]. In this study, $PaCO_2$ was monitored using recurrent arterial pH measurements. As mentioned previously, transcutaneous $PaCO_2$ monitoring could improve gas exchange management by allowing more rapid adjustment of minute ventilation.

For the same reason of thoracic stability, jet ventilation could also prove useful in other types of interventional cardiology procedures[54].

Jet Ventilation in lithotripsy

In extracorporeal lithotripsy performed under general anaesthesia, the use of jet ventilation reduces the number of shocks delivered and, consequently, the duration of the procedure, without compromising its effectiveness[55]. Its benefits in terms of postoperative pain, nausea, vomiting or postoperative complications have not yet been thoroughly studied.

Conclusion

Jet ventilation is a critical modality in certain clinical settings, particularly within anesthesia for upper airway procedures, laryngeal surgery, bronchoscopy, or when surgical access necessitates an unobstructed operating field. The principal benefits of jet ventilation include preserving excellent operative visibility, minimizing thoracic movement, and frequently ensuring adequate oxygenation despite low tidal volumes.

This technique necessitates specialized expertise and diligent monitoring due to its limitations, such as the risk of barotrauma or CO_2 accumulation. Therefore, its application must be judiciously indicated, considering the patient's condition, the operative environment, and the resources available.

In conclusion, although jet ventilation is not routinely employed, it remains an indispensable technique in certain clinical scenarios. Studies on high-frequency jet ventilation in the operating room are generally retrospective or involve small sample sizes. Further research, including comprehensive comparative studies, is necessary to more precisely delineate its indications, contraindications, and long-term effects, particularly in emerging fields such as interventional radiology, electrophysiology, and lithotripsy. Practitioner training and the standardization of usage protocols will be crucial to ensuring its safe implementation and optimizing its benefits.

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