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High frequency oscillatory ventilation in children: an overview

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A B S T R A C T

The last 30 years, high frequency ventilation (HFV) has found its way from the neonatal to the paediatric and adult ICU. With its small tidal volumes, strict intrathoracic pressure variations and disengagement of ventilation from oxygenation, HFV fits in our insights nowadays in lung protective ventilation. This review provides you with an understanding of the different modes of HFV, gas exchange mechanisms during HFV which uses tidal volumes below dead space volume, and some information on nursing and weaning a child on HFV. Focus will be on the clinical use of high frequency oscillatory ventilation with a practical overview of the strategies used: the high-volume strategy designed to rapidly recruit and maintain optimal lung volume in diffuse alveolar disease and lung haemorrhage, the low volume strategy in airleak, and the open airway strategy in small airway disease where the continuous distending pressure is used to recruit and stent the airways.

Educational aims

- To discuss the use of high frequency oscillatory ventilation (HFOV) in the PICU
- To illustrate the different modes of high-frequency ventilation
- To understand the basic principles of gas exchange mechanisms during HFOV
- To discuss the HFOV strategies most commonly used as a (rescue) therapy in paediatric respiratory failure.
- To provide the reader with an algorithm of the open lung approach during HFOV in diffuse alveolar disease.
- To emphasise the importance of lung protective ventilation in children with acute respiratory failure and how HFOV fits in these insights.

1. Introduction

Mechanical ventilation has come a long way since its first reference in 175 AD from Galen who used a bellows to inflate the lungs of a deceased animal.[1] While the exchange of oxygen and carbon dioxide between blood and the alveolus works by diffusion and requires no external work, air must be moved in and out to make it available to the gas exchange process. With the introduction of the iron lung during the polio pandemic, the age of practical ventilation was started.[2] Ventilators have evolved from simple machines into microprocessor-controlled devices that allow synchronization of a patient's ventilatory demands.

Although often life-saving, mechanical ventilation has complications.[3] Perhaps not surprisingly, the use of bellows in the early days could easily rupture the lungs. Barotrauma refers to alveolar and small airway destruction when high inspiratory pressures are applied.[4] Recently, the paradigm has shifted: volutrauma recognizes that alveolar overdistension is more likely to occur as a result of excessive volume and not pressure per se.[5] In addition, there is a large body of evidence indicating that ventilation at low lung volume levels may contribute to injury. In diffuse alveolar disease (DAD), the more dependent alveoli often reach a critical closing volume at end-expiration, resulting in collapse followed by re-opening during inspiration. The cyclic repetition of collapse and re-opening generates shearing forces capable of causing damage, hence the term atelectrauma.[6] The injuries described here are largely thought to be mechanical. Nevertheless, there is evidence that mechanical factors can lead to injury that is cell and inflammatory mediator based. This biotrauma contributing to the genesis of organ failure is related to exacerbation of inflammation and locally produced cytokines.[7]

Mechanical ventilation can no longer be seen as a treatment modality that simply supports the patient until the primary disease resolves. Taken into account the above mentioned observations, it seems logical to avoid both overstretching and cyclic closing and

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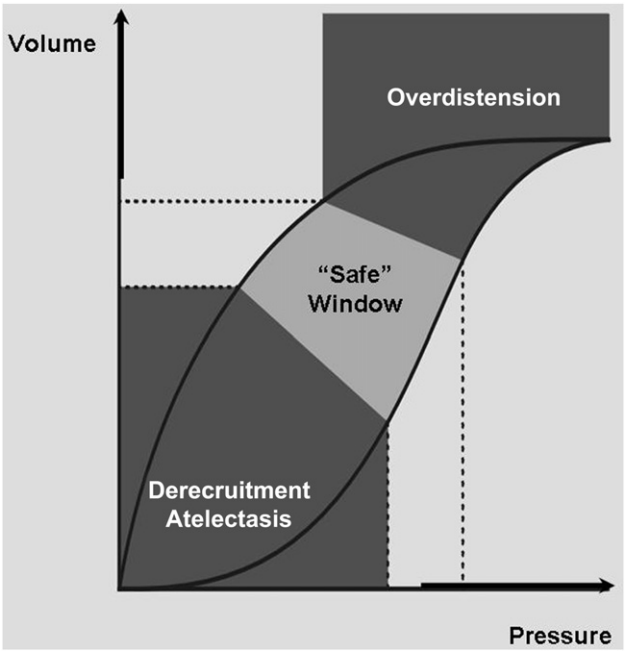

Fig. 1. Volume–pressure relationship of the respiratory system indicating the zones of ventilator reduced lung injury and the theoretical "safety zone".

opening of terminal units. Froese assumes in the pressure–volume relation of the respiratory system a safe window, an area between a lower zone of atelectasis and an upper zone of overdistension (Fig. 1).[8] Ideally, tidal volumes (V_T) should fit within this area by setting the PEEP level above the lower inflection point and reducing plateau pressures to avoid overinflation.[9,10] In the disordered lung the safe window may be too small to harbour the conventional tidal volumes. High frequency ventilation (HFV) with its small V_T, strict intrathoracic pressure variations and disengagement of ventilation from oxygenation, appears to be an ideal candidate for ventilation within the safety zone.[8,11]

2. High frequency ventilation

There are different modes of HFV and each type has its own unique advantages and disadvantages, but they are all characterized by a breathing frequency $\geq$1 Hz (60 breaths/min) and V_T lower than dead-space volume.[12] They can be classified in four types:

- high-frequency positive pressure ventilation (HFPPV)
- high-frequency jet ventilation (HFJV)
- high frequency flow interrupter (HFFI)
- high-frequency oscillatory ventilation (HFOV).

HFV was introduced in the early 1970s, following the experiences by Oberg and Sjöstrand. They used higher frequencies and smaller V_T to eliminate the effect of respiratory variations on carotid sinus reflexes. The increase in dead-space volume was overcome by insufflating the gas directly into the trachea. They ended with V_Ts of 3–4 mL/kg, high flow rates and frequencies of 60–100 breaths/min. Expiration was passive, depending on lung and chest wall elastic recoil. They called their method HFPPV.[13] With newer specifically designed devices becoming popular, HFPPV is rarely used nowadays.

HFJV was introduced by Sanders in 1967 to facilitate gas exchange during bronchoscopy.[14] Combining these and Sjöstrands observations, Klain and Smith introduced in 1977 high-frequency transtracheal jet ventilation.[15] Gas under high pressure or "jets" were introduced through a small catheter placed in the tube. A V_T of 2–5 ml/kg was delivered at high frequency (100–200 breaths/min). The use of an associated continuous high flow system permitted entrainment of additional gas via the Venturi principle. A complex interaction between jet velocity, inspiratory time, nozzle type and system characteristics determined the volume of entrained gas. Because this is not operator-controlled, it is difficult to manipulate with precision the V_T delivered. Conventional breaths are sometimes used to aid in reinflating the lung. During HFJV, high flow rates prevent optimal humidification, increasing the risk of necrotising tracheobronchitis. As with HFPPV, expiration is passive. Nowadays, HFJV is used primarily in situations requiring minimal upper airway movement, such as laryngeal surgery.

HFFI is similar to HFJV but the gas control mechanism is different. A rotating bar or ball with a small opening is placed in the path of a high-pressure gas. As the bar or ball rotates, a small pulse of gas is allowed to enter the airway. Expiration, again, is passive.

In 1980 Bohn et al. and Butler et al. demonstrated that adequate gas exchange was possible by generating oscillations in the airways at a frequency of 15 Hz.[16,17] The oscillations could be generated either by a loudspeaker or an electronically driven piston pump. Earlier Lunkenheimer et al had found adequate ventilation in dogs using frequencies of 20–40 Hz.[18] This method was referred to as HFOV since oscillations generated the required pressure swings. The pressure oscillates around a constant distending pressure (CDP) delivered via a continuous flow which passes through a variable restriction valve on the expiratory limb. This keeps the lung volume stable and controllable. CDP in HFOV functions similarly to CPAP in CMV in that it provides the pressure for alveolar recruitment and thus regulates oxygenation. Ventilation in HFOV is mainly dependent on frequency and V_T^2. As frequency decreases the delivered V_T increases because the longer respiratory cycle allows a larger swing of the oscillating membrane. Therefore, at a given power more CO_2 is removed at lower frequencies. Gas is pushed into the lung during inspiration, and actively pulled out during expiration. Thus, both expiration and inspiration are active processes.

3. Gas exchange mechanisms during HFV

One of the basic concepts taught in physiology is that for adequate gas exchange V_T should exceed the volume of the conducting airways, known as dead space. Nevertheless, adequate ventilation can be achieved during HFOV which generates V_Ts smaller than dead space. Gas transport mechanisms other than conventional bulk flow must thus be involved.[19] There are seven potential mechanisms:

- direct ventilation of proximal alveoli
- turbulent flow with lateral convective mixing
- Pendelluft flow between adjacent areas of lung with varying time constants for alveolar emptying
- Cardiogenic mixing due to distortion of lung units adjacent to the contracting heart
- Asymmetric velocity profiles with air in the centre moving fastest, entraining gas closer to the airway walls. This leads to the streaming of "fresh" gas toward the alveoli and "alveolar" gas away from the alveoli along the outer wall.
- laminar flow with lateral transport by diffusion (Taylor dispersion)
- collateral ventilation through non-airway connections between neighbouring alveoli.

Major gas transport mechanisms that work under physiologic conditions in each region are shown in Fig. 2.[20] Although all these

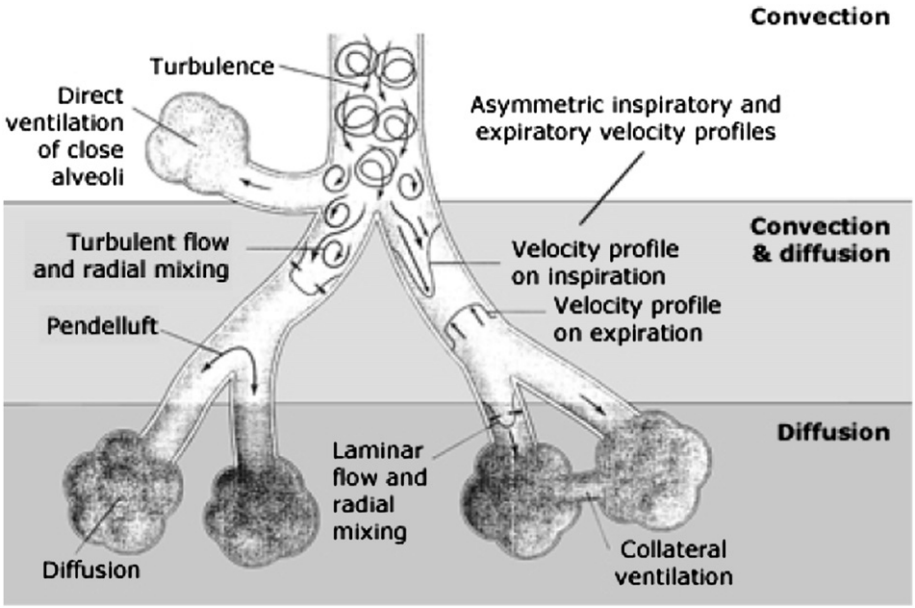

Fig. 2. Gas transport mechanisms during high-frequency ventilation. Reproduced with permission from: Slutsky, AS, Drazen, JM. Ventilation with small tidal volumes. N Engl J Med 2002; 347:631.

mechanisms collectively account for ventilation during HFOV, the precise quantitative contribution of each is unknown.

4. Clinical application

HFOV was used primarily and still most frequently in neonates.[21–25] In some of them HFOV is used as the first-line ventilator due to the high susceptibility of the premature lung to injury. In 1994 Arnold published his results on the use of HFOV in paediatrics.[26] The following years much of the data on the application of HFOV outside the NICU, came from case series.[27–34] These suggest that HFOV can be safely used and that its use is associated with improvements in oxygenation and ventilation without worsening air leaks. Despite high expectations, HFOV is still primarily used as a rescue therapy in children with DAD and, to a lesser extent, in children with air leak or small airway disease (SAD). DAD patients primarily have oxygenation disturbances and a chest X-ray with bilateral opacities (ARDS, lung contusion, pneumonia). SAD patients usually have ventilatory problems with an increased airway resistance and hyperinflation on chest X-ray.

HFOV as a *rescue* therapy is usually started when the following criteria are met: ventilatory failure with plateau pressures of 30 cm H_2O despite the use of permissive hypercapnia for at least two hrs (ventilatory failure) or an oxygenation index $\geq$13 demonstrated by two blood gas measurements over a six-hr period (oxygenatory failure). However, at times the decision to start HFOV is earlier, based on clinical judgement. Taken into account that a small number of RCTs in paediatric or adult HFOV support the suggestion that HFOV may be more successful if applied earlier in the course of the disease, this approach might be justified.[26,35,36]

Depending on the underlying condition, three different strategies can be used:

- *the high-volume or open lung strategy* designed to rapidly recruit and maintain optimal lung volume in DAD and lung haemorrhage (Fig. 3). The initial CDP is set 3–5 cm H_20 above the mean airway pressure (MAP) during CMV with a FiO_2 of 1.0. The aims are a $SaO_2 \geq 90\%$ at an $FiO_2 \leq 0.4$, a pH above 7.25 irrespective of $PaCO_2$, and stable hemodynamics. To optimally recruit the lung, CDP is increased in steps of 2 cm H_20 with subsequent decreases of FiO_2 until the oxygenation target is reached. Usually a frequency of 10 Hz is used in children $<$10 kg, 8 Hz in children $>$10 kg. The amplitude (dP) is initially set to achieve adequate chest wall vibration and sequentially adjusted to achieve the ventilatory target. If respiratory acidosis persists with maximal dP, frequency is decreased. A more appropriate approach would be to set power at maximum and adjust frequency downward until adequate chest wall vibration is achieved. This would achieve ventilatory support at the smallest V_T possible,[37,38] but this practice has not yet gained widespread acceptance. It has also been known for years that recruitment manoeuvres are needed to reverse atelectasis. Although recent studies have demonstrated the safety and efficacy of such manoeuvres in adults, they are not routinely used in the PICU yet. Fig. 3 points out at which steps recruitment manoeuvres might be considered.
- *the low volume strategy* in air leak where, after an initial identical approach as in the open lung strategy, CDP is reduced until the air leak ceases. Lower SaO_2 and higher oxygen supply is accepted (permissive hypoxemia)
- *the open airway strategy* in SAD where CDP is used to recruit and stent the airways. One starts with an FiO_2 of 1.0 and CDP set 2 cm higher than MAP on CMV. If necessary, CDP is increased according to SaO_2 and, in contrast to the "open-lung" strategy, also in regard to $PaCO_2$. Since the CDP is applied throughout the entire respiratory cycle, airways open, their diameter stabilises and resistance during expiration decreases. The limiting flow is dependent on small airway diameter, which is dependent on lung volume, thus at higher lung volume flow limitation can be minimised. In addition, open small airways enable a better propagation of the oscillations down to the alveolus. CDP thus has an influence on ventilation. The active expiratory phase assists further with moving gas from the alveoli.[28,29] Once the airways are opened, careful attention must be paid to overinflation since the normal compliant alveoli are faced with relatively high CDP. For the same reason, additional recruitment manoeuvres are not performed. Every incremental change in CDP should be followed by PaCO2 determination to see at which CDP the airways open and PaCO2 decreases. Overdistention is suspected if the circulation becomes

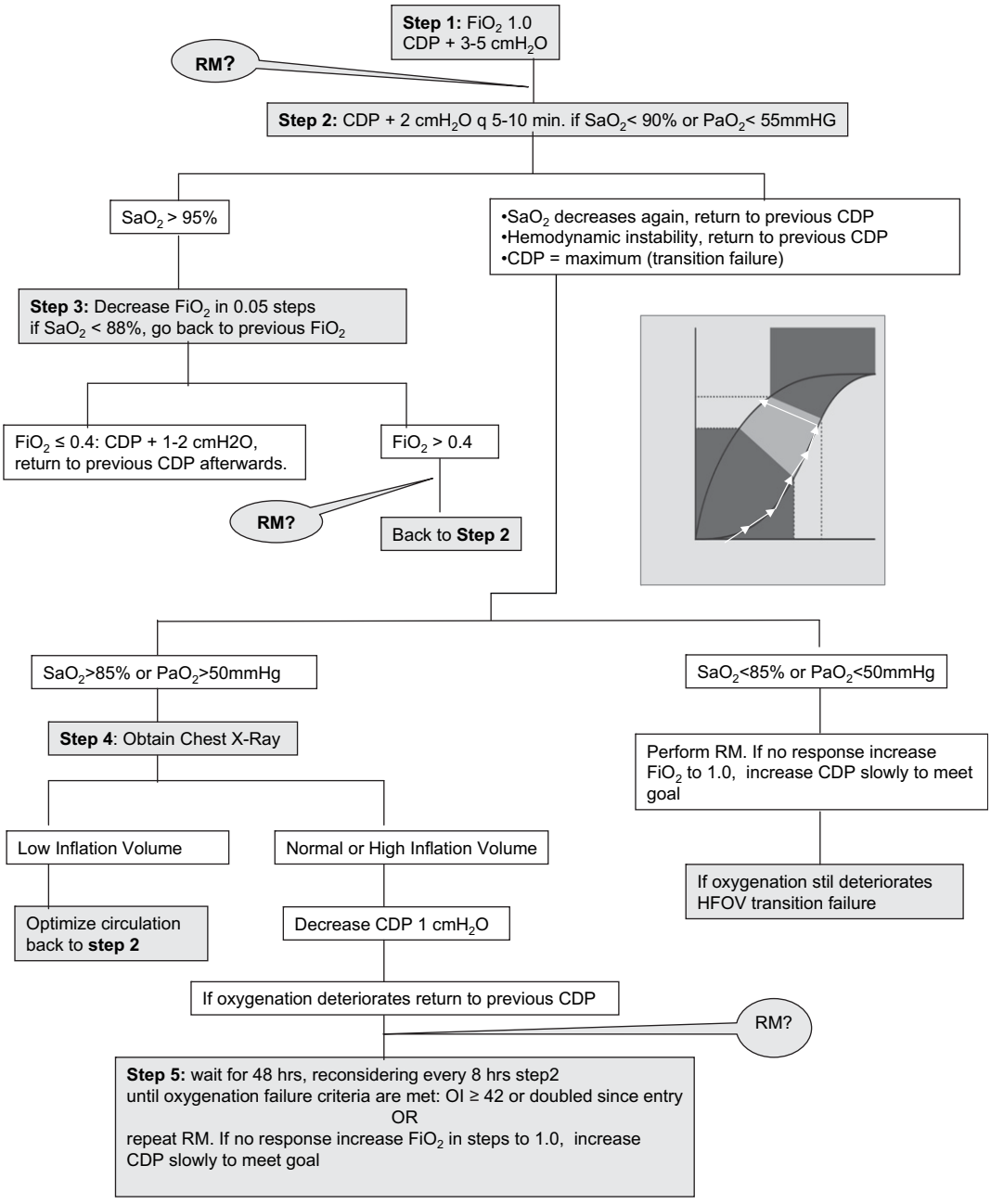

Fig. 3. Algorithm of the open lung approach in diffuse alveolar disease. RM = recruitment manoeuvre; CDP = continuous distending pressure.

compromised, this can be restored by lowering CDP or fluid administration. The degree of lung hyperinflation on chest X-ray is not used to modify CDP.

Based on the positive experiences in paediatrics and with evolving technology, HFOV has now found its way into adult intensive care as well.[35,39–41]

5. Nursing a child on HFOV

There are a number of aspects that should be highlighted. The sight of someone being 'oscillated' can be disturbing for the family, it is therefore essential to provide adequate information. After a patient has been attached to an oscillator, careful observation for the vibration pattern (the chest wiggle factor) constitutes the most reliable clinical measure which may reveal early evidence of changing lung disease or adverse effects. If chest wiggle diminishes, the ET tube might have slipped down or became obstructed. One sided chest wiggling may indicate a pneumothorax. Auscultation during HFOV may be difficult, but not useless. Reduced breath sounds can indicate one-sided ventilation by either a tube too low, or a pneumothorax.[42] One can also listen to the intensity or sound the piston makes. However, what sounds one is supposed to hear is debated and any accurate interpretation requires appropriate training. Suctioning for the first 24 h is usually not necessary. When using a closed system, it is important to draw back the catheter all the way on completion. Alarm limits must be set within safe boundaries (usually 3–5 above and below the desired CDP). When positioning a patient, at least two nurses should assist

with ET tube protection. Finally, it is important to humidify gases to prevent necrotizing tracheobronchitis.

6. Weaning

Weaning should not be delayed unnecessarily, nor should it be done prematurely. Unfortunately, there is no specific criteria that generalizes to all children. The level of CDP might be more likely a range than just one value. Generally, weaning may be considered when CDP is at least reduced to $\leq$17 cm H_20, FiO_2 to $\leq$0.4, and the patient tolerates suctioning. Often the child demonstrates satisfactory gas exchange on CMV on a MAP several cm below the last CDP on HFOV. It is possible to successfully extubate a child directly from HFOV. However, older children often don't tolerate tapering of sedation that allows spontaneous breathing on an oscillator, and their spontaneous breathing may significantly depressurize the circuit, leading to alarms or even ventilator shutdown.

7. About smart ventilators, and the people who use them

Rest is undoubtedly, the best way to heal an injury and this is also true for the lungs.[43] The less the lungs are forced to expand-collapse, the less likely a lung injury is. The question nowadays is: should we move towards tidal volumes as small as possible without permitting the lung to deflate at all? This can be achieved using HFOV. Although the oscillations may cause significant pressure swings in the tube, the pressure fluctuations are significantly attenuated at the alveolar level.[44] This helps protect the alveoli from volutrauma.[8] By optimizing recruitment and ventilation perfusion matching, the use of HFV also allows reductions in oxygen to less toxic levels. Theoretically HFOV provides the ultimate open lung strategy, preserving end expiratory lung volume, minimizing cyclic stretch, and avoiding parenchymal overdistention by limiting V_T and transpulmonary pressure.[45]

Such is the promise of HFOV, but like many other promises, it has been hard to fulfil. Although animal studies clearly demonstrated less pulmonary damage using HFOV compared to CMV, clinical trials are less unequivocal. This may be due to the wide range of aetiologies of acute respiratory failure in the PICU, together with a gradual trend toward the use of more protective conventional ventilation strategies. Although none of the paediatric RCTs demonstrated any survival benefit, they were all underpowered to do so. Nevertheless, children treated with HFOV demonstrated improvements in oxygenation, were exposed to less oxygen and had less chronic lung disease.[22–26,36,46–48] All trials that demonstrated an oxygenation benefit with HFOV have emphasized lung volume recruitment.[23,24,26,36]

In a cumulative meta-analysis it was shown that, over time, CMV treatment improved, diminishing the relative benefit of HFOV.[49] It turned out that the way how the ventilator was used had more impact on pulmonary outcome, than the type of ventilator. For patients with lung injury, the ventilation strategy should be based on low V_Ts, with a relatively fast rate, with or without more generous PEEP has heretofore been given. Nevertheless, Rubenfeld et al showed that despite the widely accepted data on lung protective ventilation (LPV), most patients with ARDS are currently not managed with LPV during CMV.[50] HFOV not only perfectly fits in our insights nowadays in LPV, but it has the potential to remove most barriers to its use in critically ill patients. HFOV is easy to work with, oxygenation and ventilation are independently regulated, and it is at least as safe and efficient as CMV in children of all ages and with different diseases, provided certain strategies are followed. An important lesson learned along the years of development of HFOV is that it is much easier to introduce a laboratory technology in clinical practice than it is to reach consensus on how to use it. The next step in the story will be to evaluate a better HFOV protocol (i.e. with volume recruitment manoeuvres and higher frequencies) against whatever is the best conventional alternative at the time.

Practice points

- High frequency ventilation with its small V_T, strict intrathoracic pressure variations and disengagement of ventilation from oxygenation, appears to be an ideal candidate for ventilation within the safety zone
- In contrast to most other modes of HFV, expiration during HFOV is an active process.
- The earlier use of HFOV seems to be more beneficial
- RCTs in children and adults have emphasized ''aggressive'' lung volume recruitment during HFOV
- A more appropriate approach with the power set at maximum and frequency adjusted downward until adequate chest wall vibration is achieved, would support ventilation at the smallest V_T possible.

Conflict of interest statement

The authors have no conflict of interest.

CME section

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Educational questions

Answer the following questions: true/false

1. With regard to ventilator induced injury
   a. Barotrauma refers to great airway destruction
   b. Ventilation at low lung volume may contribute to lung injury
   c. Atelectrauma occurs most often in the non-dependent alveoli
   d. Ventilator induced injury may lead to multi-organ failure
   e. High-frequency ventilation has strict intrathoracic pressure variations
2. Different modes of high-frequency ventilation
   a. In HFPPV, expiration depends on lung and chest wall elastic recoil
   b. In HFJV, the volume of entrained gas (which determines the V_T delivered) is operator controlled
   c. In HFOV oscillations are generated at a frequency of 50 breaths/min

   d. In HFOV, the delivered V_T decreases with increasing frequency
   e. In HFFI both inspiration and expiration are active processes
3. Gas exchange mechanism during HFOV
   a. conventional bulk flow ventilation does not take place
   b. pendelluft takes place due to heterogeneity in the diseased lung areas
   c. V_T is $<$ VD
   d. The contracting heart augments gas exchange during HFOV
   e. Taylor dispersion relates to collateral ventilation
4. Clinical use of HFOV
   a. paediatric case series suggest that HFOV can be safely and effectively used in acute respiratory failure
   b. The use of HFOV in children can only be propagated as a rescue therapy after failure of conventional ventilation due to the high risk of air leak
   c. Permissive hypoxemia might be justified in the low volume strategy for SAD
   d. The open lung strategy aggressively recruits the lung in which the FiO_2 need functions as a hallmark
   e. Maximum power with the highest frequency to achieve good chest wall vibration, will result in ventilation at the smallest V_T
5. Nursing and weaning
   a. unilateral wiggling of the chest can indicate a pneumothorax
   b. cardiac auscultation is not possible during HFOV
   c. when CDP is $\leq$17 cm H_20 with a $FiO_2 \leq 0.4$, the child *must* be transitioned back to CMV
   d. suctioning is usually not necessary the first 24 h
   e. in transitioning the child back to CMV, the MAP on CMV should be at the same level of the last CDP on HFOV
6. Smart ventilators
   a. There is an attenuation of pressure swings down the endotracheal tube, which fits in the insights of LPV nowadays.
   b. HFOV has the advantage of disengagement of ventilation from oxygenation
   c. The paediatric RCTs showed a small survival benefit in the HFOV group compared to the conventionally ventilated group
   d. Children treated with HFOV showed less chronic lung disease
   e. A cumulative meta-analysis showed that the way how the ventilator was used had more impact on pulmonary outcome, than the type of ventilator

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