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NNF NeoVentURE

Neonatal Ventilation pLus Respiratory CarE

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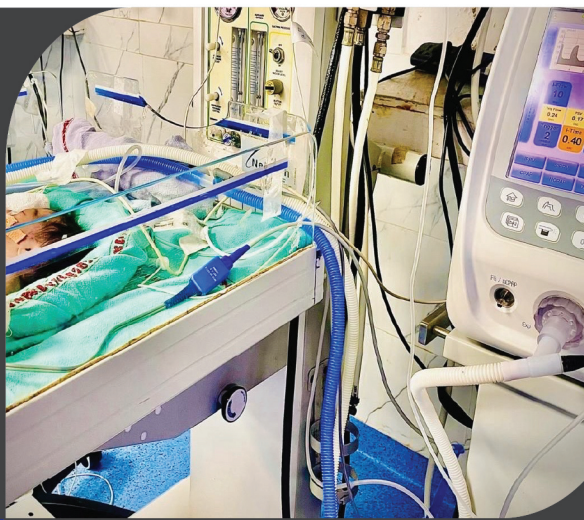

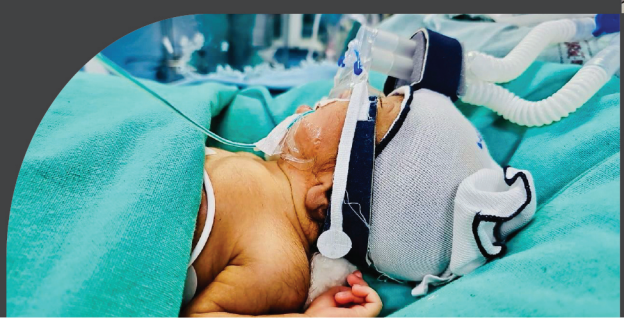

Foreword
VC Manoj

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7 High-frequency Ventilation

CHAPTER

7 High-frequency Ventilation

Tapas Bandyopadhyay

INTRODUCTION

Despite significant technological advancement in ventilation devices as well as neonatal respiratory care management, bronchopulmonary dysplasia (BPD) remains the most prevalent chronic respiratory morbidity among very preterm neonates. The main pathophysiological mechanism behind BPD is ventilator-induced lung injury (VILI).

High-frequency ventilation (HFV) is a form of assisted ventilation that uses small tidal volumes (less than anatomic dead space) and very rapid ventilator rates (2.5–25 Hz or 150–1,500 cycles per minute).

As compared to conventional mechanical ventilation (CMV), HFV uses lower peak airway pressures; oxygenation and ventilation are independently handled in the recruited lung, and the preservation of normal lung architecture even when using high mean airway pressures (MAPs).

PHYSIOLOGY

The physiology responsible for gas transport during involves several contributing mechanisms, which are briefly reviewed as shown in **Figure 1**.

- *Bulk convection:* Even with small tidal volumes, gas flow may reach proximal alveoli and participate in direct alveolar ventilation.
- *Pendelluft:* At high frequencies, gas distribution is influenced by inequalities in time-constant, and there is redistribution from units with lower to units with higher time constant.
- *Asymmetric velocity profiles:* Inspiratory gas tends to pass along the center of the airway, while expiratory gas escapes along the outer wall.
- *Taylor dispersion:* Superimposition of convective gas flow into diffusive process leads to an increased diffusion of the high-velocity central gases to the margins of the airway.
- *Molecular diffusion:* As in physiological mechanism, there is movement of molecules from higher concentration to lower concentration.

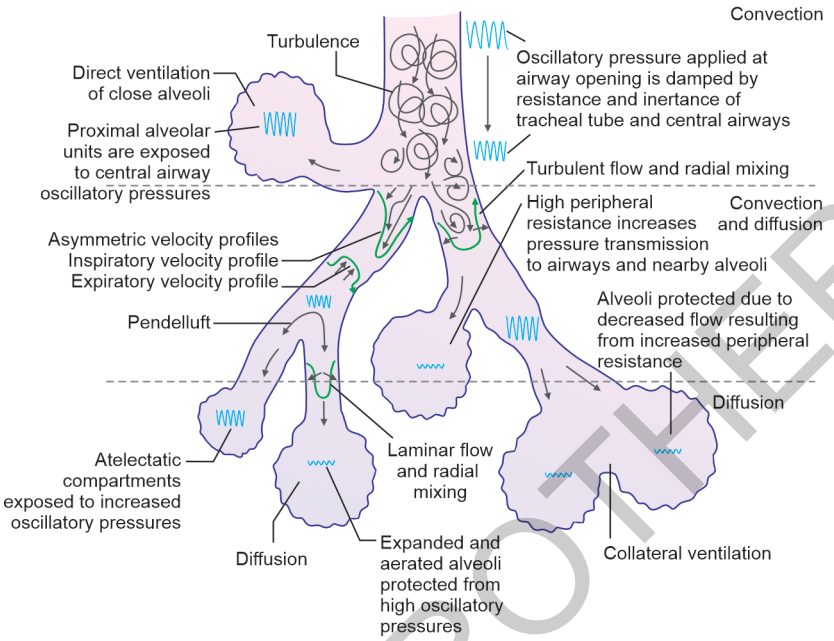


Fig. 1: Gas exchange mechanism in high-frequency ventilation.

Source: Adapted from Slutsky S, Drazen JM. Ventilation with small tidal volumes. N Engl J Med. 2002;347:630-1.

BASIC CONCEPTS

Factors Influencing Oxygenation and Ventilation

Oxygenation

The two most important players of oxygenation are MAP and fraction of inspired oxygen (FiO_2). Since, the lack of alveolar recruitment is the major pathophysiology behind neonatal lung disease. Hence, providing a higher MAP improves the recruitment and reduces ventilation-perfusion mismatching.

Achieving an optimal MAP is important as higher MAP can cause hyperinflation, which restricts venous return, and compromises cardiac output. Additionally, a higher airway pressures exert compressive forces against the capillaries within the alveolar wall and may also increase pulmonary vascular resistance and impede pulmonary blood flow and consequently impairs oxygenation. On the other hand, a low MAP leads to hypoventilation, worsening ventilation/perfusion mismatch and impairs oxygenation.

As compared to the CMV, in high-frequency oscillatory ventilation (HFOV) the pressure at the proximal airway opening is considerably higher

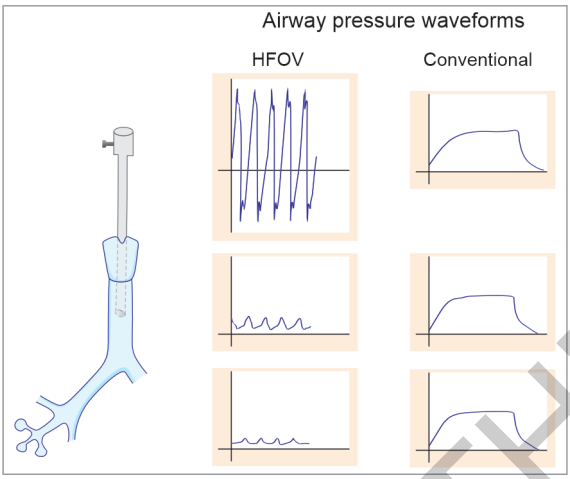


Fig. 2: Comparison of proximal airway pressure transmission to distal alveolar units in conventional mechanical ventilation (CMV) as compared to high-frequency oscillatory ventilation (HFOV).

but significantly decreases till it reaches the distal alveolar unit as shown in **Figure 2**. Additionally, the transmission or attenuation of proximal airway pressure is also not uniform across different areas of the lung and depends on their physical location in the respiratory system and the disease state. Due to the lack of transmission of uniform pressure or volume to the different segments of the lungs it becomes difficult to determine the pressure–volume curves as is the case in CMV, a crude way to assess adequate lung inflation is with the help of chest radiographs to look for lung expansion.

Ventilation

The two most important players of oxygenation are amplitude (most important) and frequency.

In CMV alveolar ventilation (CO_2 elimination) is a linear function of ventilator rate (f) and tidal volume (Vt). However, in HFOV, it is largely dependent on tidal volume (Vt) as compared to frequency (f) as given in the following formula:

$$\text{Alveolar ventilation in CMV} = f \times Vt$$
$$\text{Alveolar ventilation in HFOV} = f \times Vt^2$$

This said difference is due to the fact that during HFOV, Vt is determined by the stroke volume the ventilator applies to the system which is represented by the area under the volume-time curve as demonstrated in the **Figure 3**.

Amplitude: It is the most important parameter to control ventilation in HFV. It represents the "force" with which the piston moves and is measured in "cmH_2O". While setting the amplitude it is important to initially achieve

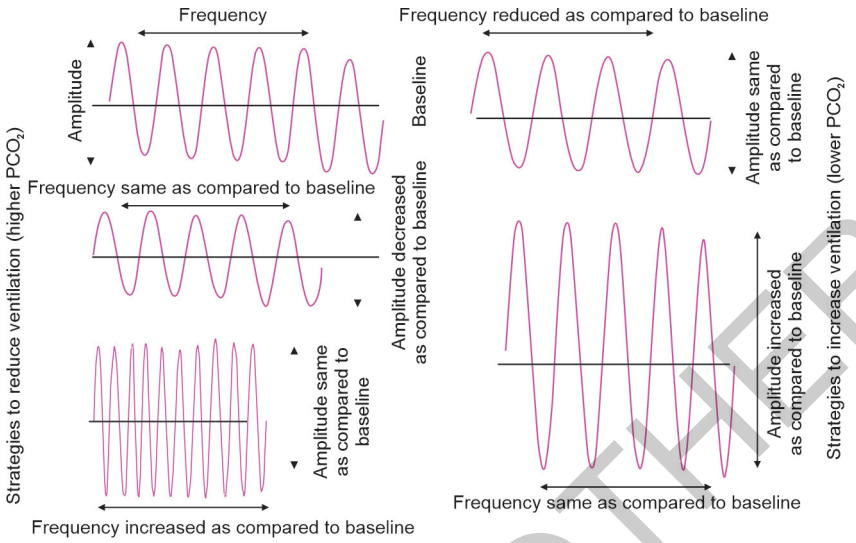


Fig. 3: Volume time curves in high-frequency ventilation (HFV) showing the effect on partial pressure of carbon dioxide (PCO_2) due to changes in the amplitude and frequency.

adequate lung recruitment by optimizing the MAP. The best way to assess adequacy of the amplitude is by visualizing the chest wiggle which should not cross the umbilicus. A rough estimate for setting the initial amplitude is twice the MAP. Any further changes in amplitude will, thereafter, depend on the extent of visualization of wiggles and partial pressure of arterial carbon dioxide ($PaCO_2$) values.

Frequency: The frequency controls the time allowed for the piston to move. The lower the frequency is set, the greater the volume displacement by piston is achieved, and hence, greater removal of CO_2 [low partial pressure of carbon dioxide (PCO_2)] and vice versa.

The most important aspect in setting the optimal frequency is the time constant (compliance X resistance). In general, patients with short time constants [e.g., respiratory distress syndrome (RDS)] can be ventilated effectively at higher frequencies than those with longer time constants [e.g., meconium aspiration syndrome (MAS) and BPD].

The control parameters of HFV, their typical range, target values, changes produced in blood gas values due to their manipulations, and side effects, are depicted in **Table 1**.

INDICATIONS OF HIGH-FREQUENCY VENTILATION

The various indications for using HFV in neonatal disease conditions are shown in **Table 2**.

TABLE 1: HFV control parameters, typical range, target values, changes in blood gas values due to their alteration, and side effects.

Control parameter	*Typical range*	*Target*	*Changes in blood gas values*	*Side effects*
Mean airway pressure (MAP)	10–25 cmH_2O	• Adequate lung recruitment as seen by the reduction in FiO_2 requirement • Adequate lung inflation on chest X-ray till 8–10 posterior ribs	• Increase: ↑PaO_2 • Decrease: ↓PaO_2	• Too high: Decreases cardiac output, barotrauma • Too low: De-recruitment
Fraction of inspired oxygen (FiO_2)	21–100%	SpO_2 between 90 and 95%	• Increase: ↑PaO_2 • Decrease: ↓PaO_2	FiO_2 > 0.6–0.7 increases the risk of oxytrauma
Amplitude	15–100%	$PaCO_2$ in target range of 45–55 mm Hg	• Increase: ↓$PaCO_2$ • Decrease: ↑$PaCO_2$	• High: Hypocarbia • Low: Hypercarbia
Frequency	5–15	Same as above	• Increase: ↑$PaCO_2$ • Decrease I:E: ↓$PaCO_2$	Changes have modest effect on gas exchange
Inspiratory time or I:E	1:1–1:3	Same as above	↑PaO_2	

(HFV: high-frequency ventilation; I:E: inspiratory to expiratory ratio; $PaCO_2$: partial pressure of arterial carbon dioxide; PaO_2: partial pressure of arterial oxygen; SpO_2: oxygen saturation)

TABLE 2: Indications of high-frequency ventilation in neonates.

Established	*Other*
• Air leak • Severe respiratory failure refractory to conventional ventilation [high PIP (22–24 in PT, 25–28 in term)] • Pulmonary hypoplasia • Adjunct to iNO	• Persistent pulmonary hypertension • Meconium aspiration syndrome • Congenital diaphragmatic hernia

(iNO: inhaled nitric oxide; PIP: peak inspiratory pressure)

MODES OF HIGH-FREQUENCY VENTILATION

Based on exhalation characteristics (active/passive/hybrid) and source of generation, high-frequency ventilation has been classified into three categories as shown in **Table 3**:

1. HFOV
2. High-frequency jet ventilation
3. High-frequency flow interrupter

TABLE 3: Types of high-frequency ventilation devices available and their characteristics.

Variables	*HFOV*	*HFJV*	*HFFI*
High-frequency pulses generated by	Piston or other means	Pinch valve, injector cannula	Solenoid valve
Tidal volume	< dead space	> or < dead space	> or < dead space
Frequency	5–15 Hz	5–10 Hz	8–12 Hz
Expiration	Active	Passive	Passive
I:E	1:1 or 1:2	1:4 to 1:8	1:3 to 1:6
Ability to superimpose a sigh	No (SensorMedics) Yes (Draeger)	Yes	Yes
Entrainment	None	Possible	None
Waveform	Sine	Triangular	Triangular

(HFFI: high-frequency flow interrupter; HFJV: high-frequency jet ventilation; HFOV: high-frequency oscillatory ventilation; I:E: inspiratory to expiratory ratio)

OPTIMIZING MEAN AIRWAY PRESSURE IN HIGH-FREQUENCY VENTILATION IN DIFFERENT PULMONARY CONDITIONS

Setting Mean Airway Pressure

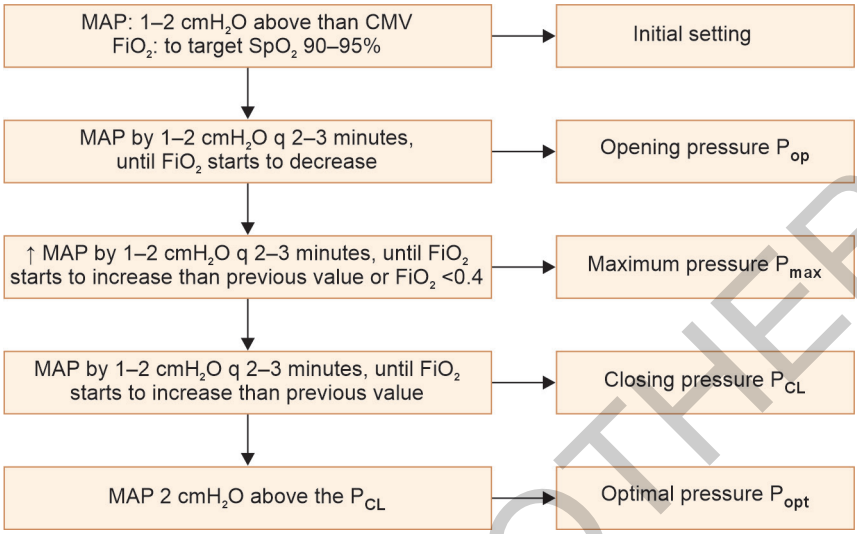
High-volume Open Lung Strategy

This strategy is used during ventilation of lungs with low compliance (e.g., RDS and atelectatic form of MAS). This is based on the principle of open lung strategy which encompasses lung volume recruitment and avoidance of volutrauma. In this method, lung volume optimization is done by inflating the lung to near-maximum volume with stepwise increases in MAP. The lung is considered fully inflated when FiO_2 can be weaned to under 0.40 or when FiO_2 starts to increase to maintain target SpO_2. It is then deflated to the closing volume that is manifested by again an increase in FiO_2. The lung is then reinflated to a point just above closing volume as depicted in **Flowchart 1**. This technique allows ventilation to move from the inspiratory limb of the P-V curve to the expiratory limb, allowing effective ventilation and oxygenation at lower airway pressures.

Low-volume Lung Strategy

This strategy is used during ventilation of lungs with air leaks, pulmonary hypoplasia, and nonhomogenous lung disease to minimize the risk of further lung injury whereas maintaining optimum lung ventilation. In this strategy, the set MAP should be same as that on conventional ventilation. Other principle used in this strategy includes a lower frequency, permissive hypercapnia, and higher FiO_2.

Flowchart 1: Recruitment maneuver in HFV in low compliance disease states.



(CMV: conventional mechanical ventilation; FiO_2: fraction of inspired oxygen; HFV: high-frequency ventilation; MAP: mean airway pressure; SpO_2: oxygen saturation)
Source: De Jaegere A, van Veenendaal MB, Michiels A, van Kaam AH. Lung recruitment using oxygenation during open lung high-frequency ventilation in preterm infants. Am J Respir Crit Care Med. 2006;174(6):639-45.

DISEASE SPECIFIC VENTILATION SETTINGS

The pathophysiology, initial ventilation setting, and titration is as shown in **Table 4**.

OPTIMIZATION OF INITIAL VENTILATION SETTINGS

The target for optimal ventilation is decided based on the clinical and radiological assessment coupled with the blood gas parameters as shown in **Tables 5 and 6**.

Subsequent monitoring should be done based on clinical assessment, any change in ventilatory parameters

GUIDE FOR ADJUSTMENT OF VENTILATOR SETTINGS TARGETING BLOOD GAS PARAMETER

Adjustment of HFV settings based on blood gas values is given in **Table 6**.

SUPPORTIVE CARE

The supportive care of neonate on HFV is summarized in **Box 1**.

TABLE 4: High-frequency ventilation settings for different disease conditions.

Disease condition	*Respiratory distress syndrome*	*Air leak*	*Meconium aspiration syndrome*	*Pulmonary hypoplasia (e.g., CDH)*
Pathophysiology				
Compliance	↓	↓	↓	↓
Resistance	N/↑	N/↑	↑↑	N
Functional residual capacity	↓	N	↑	↓
Time constant	↓	N/↓	↑	↓
Initial settings and titration				
MAP	2 cmH_2O above MAP on CMV and titrated based on high volume open lung strategy	Same as that of MAP on CMV. Stay at lower MAP, accept higher FiO_2. May consider volume targeting with target tidal volume of 1.5–2 mL/kg.	2 cmH_2O above MAP on CMV and titrated based on high volume open lung strategy (atelectatic form) For hyperinflation type low volume lung strategy may be employed	2 cmH_2O above MAP on CMV and titrated to use the lowest MAP that will achieve adequate lung inflation by the appearance of the lung fields, heart size, and diaphragms, not just the rib count to avoid MAP that worsens pulmonary hypertension
FiO_2	Titrated to achieve target saturation	Titrated to achieve target saturation	Titrated to achieve target saturation	Titrated to achieve target saturation
Frequency	10–15 Hz	5–8 Hz	6–8 Hz	8–10 Hz
Amplitude	Set at twice the set MAP (or 20–25 cmH_2O). Adjust in increment of 2–5 to achieve adequate chest wall movement or "wiggle"	Set at twice the set MAP (or 20–25 cmH_2O). Adjust to achieve adequate chest wall movement or "wiggle". However, permissive hypercapnia is desired	Set at twice the set MAP (or 20–25 cmH_2O). Adjust in increment of 2–5 to achieve adequate chest wall movement or "wiggle"	Set at twice the set MAP (or 20–25 cmH_2O). Adjust to achieve adequate chest wall movement or "wiggle". However, permissive hypercapnia is desired

Contd…

Contd…

Disease condition	*Respiratory distress syndrome*	*Air leak*	*Meconium aspiration syndrome*	*Pulmonary hypoplasia (e.g., CDH)*
I:E	1:2	1:2 or 1:3	1:2	1:2
Chest X-ray	8–9 posterior rib inflation above diaphragm	6–8 posterior rib inflation above diaphragm	Atelectatic form: 8–9 posterior rib inflation above diaphragm Hyperinflation form: 6–8 posterior rib inflation above diaphragm	8–9 posterior rib inflation above diaphragm of the contralateral lung

(CDH: congenital diaphragmatic hernia; CMV: conventional mechanical ventilation; FiO_2: fraction of inspired oxygen; I:E: inspiratory to expiratory ratio; MAP: mean airway pressure)

TABLE 5: Target for initial HFV settings based on clinical assessment, radiological evaluation, and blood gas parameters.

Clinical (most important)		*Blood gas*	*Radiological*
• Baby should be breathing comfortably • Chest wall wiggle or movement should not cross the umbilicus • Absent or minimal retractions	• *Color:* Pink, capillary filling time: <3 seconds, normal blood pressure, adequate urine output • *Saturation:* 90–95%	• pH: 7.35–7.45 • PCO_2: 45–55 mm Hg • PO_2: 50–80 mm Hg • BE: ±5 • Bicarb: 20–24 mEq/L	• ET tube should be at the level of T2–T4 vertebrae • *Lung inflation:* – High volume open lung strategy: 8–9 posterior rib inflation above diaphragm – Low volume lung strategy: 6–8 posterior rib inflation above diaphragm • May require serial chest radiograph for optimization of setting

(ET: endotracheal; HFV: high-frequency ventilation; PCO_2: partial pressure of carbon dioxide)

TABLE 6: Adjustment of HFV settings based on blood gas values.

High $PaCO_2$	• Review patient and assess chest "wiggle", DCO_2, clinical events and last CXR (lung inflation) • Is the ET tube patent and correctly positioned? • Consider in-line ET suction • Consider increasing VThf • Consider adding volume target if not already in use • Reassess in 20–30 minutes with repeat blood gas and consider a repeat CXR • If not improving, despite open lung and ET tube patency, consider a change in frequency
Low $PaCO_2$	• Review patient and assess "wiggle" • Consider reducing VThf • Consider addition of volume target if not already being used • Review overall ventilation strategy and readiness for weaning based on PaO_2 and clinical status
Low PaO_2	• Increase FiO_2 • Review lung inflation and circulatory status • Consider increasing MAP by 1–2 cmH_2O • Consider a recruitment maneuver if loss of volume is likely, e.g., postsuction • Consider CXR to review lung inflation; if over expanded reducing MAP may improve PaO_2 • Consider factors associated with pulmonary hypertension as well as need for adjuncts such as surfactant and nitric oxide • Consider the possibility that the MAP is excessive, leading to impairment of pulmonary blood flow
High PaO_2	• Decrease FiO_2 till <0.4 for high volume lung strategy followed by MAP by 1–2 • For low volume lung strategy reduce MAP by 1–2 cmH_2O followed by FiO_2

(CXR: chest X-ray; DCO_2: diffusion coefficient of carbon dioxide; ET: endotracheal; HFV: high-frequency ventilation; MAP: mean airway pressure; $PaCO_2$: partial pressure of arterial carbon dioxide; PaO_2: partial pressure of arterial oxygen; VThf: high-frequency expired tidal volume)

WEANING AND EXTUBATION

Weaning can be considered once the FiO_2 is <0.4 and baby remains stable for at least 6–8 hours on same settings. Each change should be made gradual with careful attention to the clinical parameters, i.e., heart rate, SpO_2, and blood pressure (BP). Routine blood gas may be avoided but can be considered if there is clinical deterioration.

MAP: It may be weaned in steps of 1 cmH_2O every 4–6 hours decided based on SpO_2.

BOX 1: Supportive care in neonates on high-frequency ventilation (HFV).

Humidification of inspiratory gases: Warmed to 37°C and fully saturated [100% relative humidity (RH) or 44 mg/L of vapor] when they reach the airway

Endotracheal suctioning:
- Strict asepsis with stepwise protocol
- Suctioning should be done only if there are visible secretions/desaturations and/or decreased breath sounds
- Routine normal saline irrigation prior to the suctioning should not be done

Prevention of ventilator associated pneumonia:
- Elevation of head end of bed to 30°
- Strict asepsis during handling and performing procedure
- Avoid breaking into respiratory circuit
- Oral suction must follow and not precede endotracheal (ET) suction or else separate ET and oral suctioning tubing
- Sterile water in humidification systems
- Periodic drainage of condensate from breathing circuits
- The tubing should remain in dependent position as compared to the ET adapter
- Daily assessment for extubation readiness

Positioning and physiotherapy:
- Change position every 6–8 hours
- Physiotherapy has a therapeutic role in presence of chest X-ray consistent with collapse
- Should not be done in very preterm infants during the first week of life

Follow-up:
- Neuroimaging
- Retinopathy of prematurity (ROP) screening as indicated
- Hearing assessment
- Neurodevelopmental assessment

Amplitude: If volume targeting is being used, the amplitude will "autowean". However, in the absence of volume targeting amplitude may be weaned in steps of 1–2 cmH_2O every 4–6 hours guided by DCO_2.

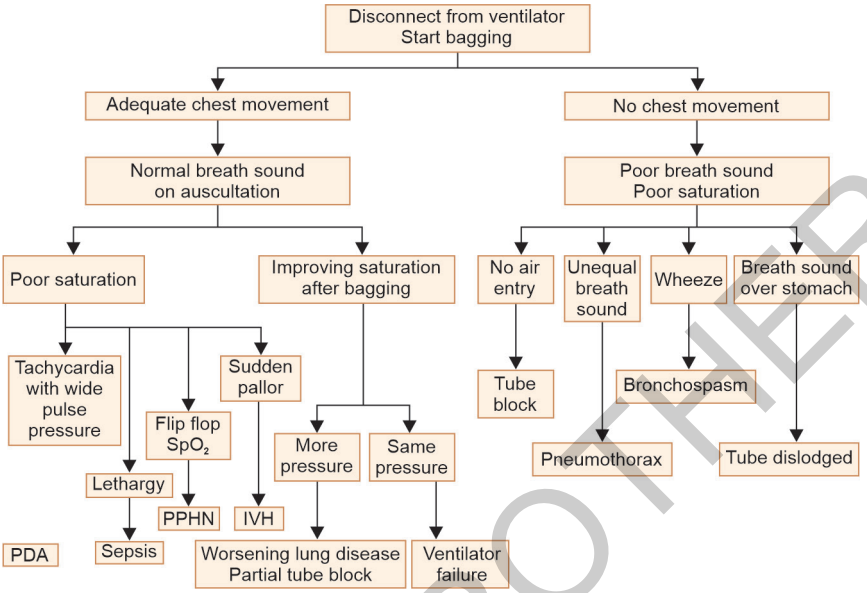
Frequency: Kept same

Babies can be successfully weaned to conventional ventilation or extubated from HFOV.

Typical settings for extubation are:
- MAP: 9–10 cmH_2O
- FiO_2: <0.4
- Amplitude: 15–20 cmH_2O

Periextubation care:
- Feeding is stopped 3–4 hours prior to the extubation
- In babies <1.5 kg, loading dose of caffeine is used to improve the respiratory drive

Flowchart 2: Algorithm for acute deterioration of a baby on high-frequency ventilator.



(IVH: intraventricular hemorrhage; PDA: patent ductus arteriosus; PPHN: pulmonary hypertension of the newborn; SpO_2: oxygen saturation)

Postextubation care:

- Humidification, nebulization, and frequent position change should be done.
- Meticulous monitoring for respiratory distress and vitals should be done

PRINCIPLES OF SUPPORTIVE CARE AND BEDSIDE BEST PRACTICES FOR VENTILATED BABY

Principles of supportive care are presented in **Box 1**.

ACUTE DETERIORATION OF A BABY ON VENTILATOR

Acute deterioration of a baby on high-frequency ventilator is depicted in **Flowchart 2**.

CONCLUSION

High-frequency ventilation (HFV) represents an important advancement in neonatal respiratory support, offering an effective alternative to conventional mechanical ventilation (CMV) in selected conditions. By delivering very small tidal volumes at rapid frequencies, HFV reduces ventilator-induced lung injury while maintaining optimal gas exchange. Its utility lies in the ability to independently control oxygenation through mean airway pressure (MAP) and FiO_2, and ventilation primarily through amplitude and frequency

adjustments. The open lung and low-volume strategies allow tailoring of ventilation according to disease pathophysiology, thereby optimizing lung recruitment while minimizing barotrauma and volutrauma.

Clinical application of HFV is especially beneficial in severe respiratory failure, air-leak syndromes, pulmonary hypoplasia, and conditions refractory to CMV. Successful use requires meticulous attention to ventilator settings, radiographic and blood gas monitoring, and integration of supportive care measures to reduce complications. With careful weaning protocols and structured peri extubation care, HFV can facilitate better outcomes and reduce long-term morbidity such as bronchopulmonary dysplasia. Overall, HFV is a powerful modality in neonatal intensive care that, when judiciously applied, significantly enhances the safety and efficacy of respiratory management in critically ill neonates.

SUGGESTED READING

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NNF NeoVentURE

Neonatal Ventilation pLus Respiratory CarE

Salient Features

- Contribution by more than 50 national experts in "Neonatology" as authors
- Reviewed by seven members of the editorial board
- Practical approach-based description of the relevant respiratory physiology and practice of neonatal ventilation
- Algorithmic evidence-based practice tips for noninvasive and invasive ventilation
- Holistic care of neonatal on noninvasive and invasive ventilation
- Figures and pictures to describe the nuances of neonatal ventilation

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