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High-Frequency Ventilation – Basics and Practical Applications

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High-Frequency Ventilation
Basics and Practical Application

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Foreword

High-frequency ventilation (HFV) as a ventilatory therapy has reached increasing clinical application over the past ten years. The term comprises several methods. High-frequency jet ventilation must be differentiated from high-frequency oscillatory ventilation (HFOV or HFO). In this booklet I concentrate on high-frequency oscillatory ventilation. Therefore, the difference in meaning notwithstanding, I use both acronyms, HFV and HFO, interchangeably.
Several devices are commercially available at present. They differ notably in technology, performance, versatility, user-friendliness, and last not least, in price. My recommendations and descriptions refer to the Babylog 8000 ventilator with software version 4.02 (Drägerwerk AG, Lübeck, Germany). Other oscillators may function quite differently [29, 41].

The goal of this booklet is to help less experienced clinicians become familiar with high-frequency oscillation and to outline its benefits, indications, control, ventilation strategies, and complications. I have placed special emphasis on practical application, whereas theoretical discussions recede somewhat into the background. To a team of neonatologists considering using HFV for the first time I would recommend that they seek advice and obtain comprehensive guidance from experienced users.

The strategies described to manage HFV are based on the results of numerous publications as well as my long-standing experience with this ventilation technique. I have described only such strategies that according to the current literature are generally accepted. However, controversial opinions are presented, too. Nevertheless, the rapid increase in medical knowledge may require that some of the descriptions and recommendations be revised in the future.

Hamburg, July 1995
Rainer Stachow

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1 High-frequency ventilation

1.1 Introduction

In the era of surfactant there are still some neonates who cannot be adequately ventilated with even sophisticated conventional ventilation. Therefore respiratory insufficiency remains one of the major causes of neonatal mortality. Intensification of conventional ventilation with higher rates and airway pressures leads to an increased incidence of barotrauma. Especially the high shearing forces resulting from large pressure amplitudes damage lung tissue. Either ECMO or high-frequency oscillatory ventilation might resolve such desperate situations.

Since HFOV was first described by Lunkenheimer in the early seventies this method of ventilation has been further developed and is now applied the world over.

1.2 Definition

There are three distinguishing characteristics of high-frequency oscillatory ventilation: the frequency range from 5 to 50 Hz (300 to 3000 bpm); active inspiration and active expiration; tidal volumes about the size of the deadspace volume (cf. figure 1.1).

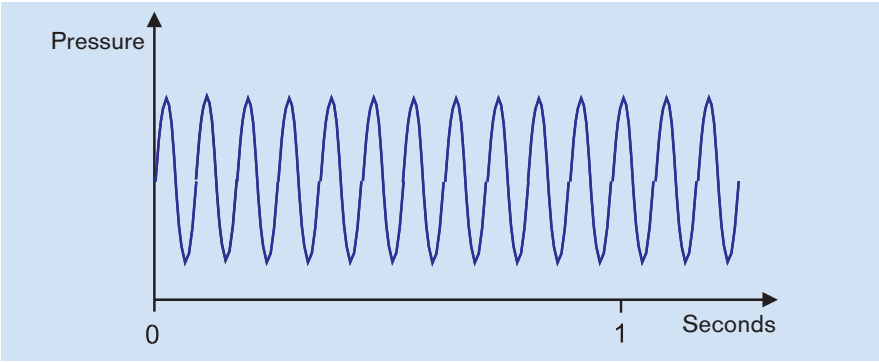


Figure 1.1: Pressure-time curve under HFO at a frequency of 12 Hz

1.3 Commercial ventilators

Various technical principles are used to generate oscillating ventilation patterns. The so-called "true" oscillators provide active inspiration and active expiration with sinusoidal waveforms:

– piston oscillators (e.g. Stefan SHF 3000, Hummingbird V, Dufour OHF1) move a column of gas rapidly back and forth in the breathing circuit with a piston pump. Its size determines the stroke volume, which is therefore fairly constant. A bias flow system supplies fresh gas (figure 1.2).
– Other devices (e.g. Sensormedics 3100A) generate oscillations with a large loudspeaker membrane and are suitable also beyond the neonatal period. As with the piston oscillators, a bias flow system supplies fresh gas. However, this device cannot combine conventional and HFO ventilation.

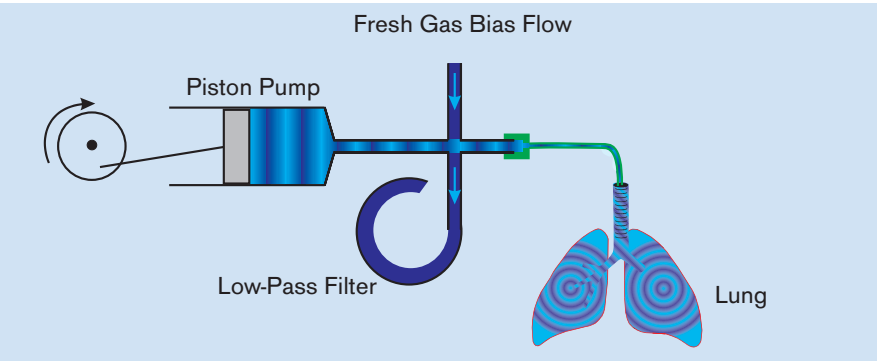


Figure 1.2: Operating principle of piston oscillators

The "flow-interrupters" chop up the gas flow into the patient circuit at a high rate, thus causing pressure oscillations. Their power, however, depends also on the respiratory mechanics of the patient [67].

– The InfantStar interrupts the inspiratory gas flow with a valve bank.

Some authors regard this device as a jet ventilator because of its principle of operation [83, 41].

– The Babylog 8000 delivers a high inspiratory continuous flow (max 30 l/min) and generates oscillations by rapidly switching the expiratory valve. Active expiration is provided with a jet Venturi system.

1) The Stefan SHF 3000 is the registered trademark of F. Stefan GmbH, Gackenbach, Germany; The Hummingbird V is registered trademark of Metran Medical Instr. MfG Co., Ltd., Japan; The Dufour the registered trademark of S.A Dufour, Villeneuve, d'Asco, France; The SensorMedics 3100 is the registered trademark of SensorMedics Corporation, USA; The Infant Star is the registered trademark of Infrasonics, Inc., San Diego, CA, USA.

OHF 1

2 Effects of high-frequent oscillations

The efficacy of HFV is primarily due to improvement in pulmonary gas exchange. Yet it can also have favourable influence on respiratory mechanics and haemodynamics.
During conventional ventilation direct alveolar ventilation accomplishes pulmonary gas exchange. According to the classic concept of pulmonary ventilation the amount of gas reaching the alveoli equals the applied tidal volume minus the deadspace volume.
At tidal volumes below the size of the anatomical deadspace this model fails to explain gas exchange. Instead, considerable mixing of fresh and exhaled gas in the airways and lungs is believed to be the key to the success of HFV in ventilating the lung at such very low tidal volumes.
The details of this augmented gas exchange are still not fully understood. Researchers still discover and study new and important mechanisms. However, they sometimes use idealised models to explain them. Probably various processes simultaneously come into play. Their individual contributions to the overall gas exchange may vary due to the lung unit involved, the respiratory mechanics (compliance, resistance), the ventilator type and settings (frequency, MAP, oscillation amplitude) [17, 35, 87, 90].

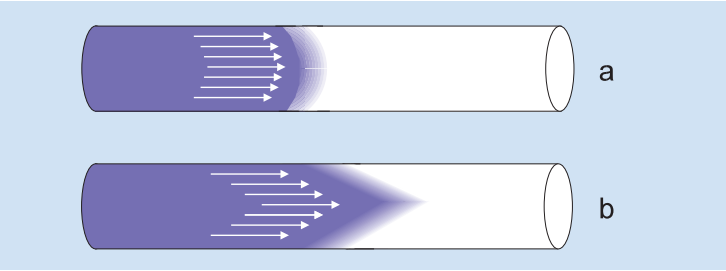


Figure 2.1: Taylor dispersion. Boundary surface between two gases with different flow velocities: a) low flow, b) high flow with tapering, pike-shaped flow profile. Gas exchange occurs at the boundary surface through lateral diffusion.

2.1. Augmented longitudinal gas transport and enhanced dispersion

A number of those mechanisms are derived from the fundamental dispersion process discovered by Taylor in 1953. In this process an initially plane boundary surface between two gases develops into a pike-shaped profile as the velocity of one of the gases increases (figure 2.1).

The resulting longitudinal gas transport is much higher than through molecular diffusion alone. In addition, the gases mix by lateral diffusion. The higher the molecular diffusivity the less the boundary surface between the two gases will taper off and the lower the effective longitudinal transport will be. In the ideal case of a constant flow in a straight tube the amount of gas transport depends on the effective longitudinal diffusivity, and is inversely proportional to molecular diffusivity. At airway bends or bifurcations secondary gas movements occur (figure 2.2), which increase lateral gas mixing but impede longitudinal gas transport.

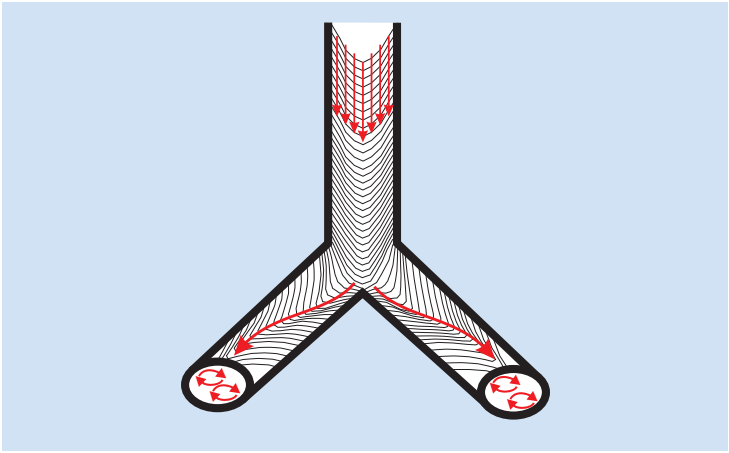


Figure 2.2: Deformation of gas flow profiles and boundary surfaces at bifurcations and generation of secondary eddying gas movements

Pulsation of bronchial walls can reverse gas flow and thereby increase the concentration gradient between the two gases. This causes additional longitudinal gas movement.

2.2 Direct alveolar ventilation

A small part of proximal alveoli is still ventilated directly. Here, gas exchange takes place as in conventional ventilation.

2.3 Intraalveolar pendelluft

Not all regions of the lung have the same compliance and resistance. Therefore, neighbouring units with different time constants are ventilated out of phase, filling and emptying at different rates. Due to this asynchrony these units can mutually exchange gas, an effect known as pendelluft. By way of this mechanism even very small fresh-gas volumes can reach a large number of alveoli and regions (figure 2.3).

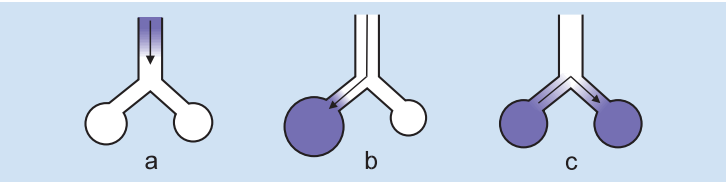


Figure 2.3: Pendelluft. a) before the beginning of a ventilation cycle. Initially, only a part of the alveoli is ventilated (b). During the next step (c) the alveoli mutually exchange gas. Of course, the individual phases last only a fraction of the entire ventilation cycle.

2.4. Effect on respiratory mechanics and haemodynamics

The application of a high mean airway pressure (cf. 3.1) will recruit additional lung volume by opening regions of the lung with poor inflation. An increase in compliance will result. At the same time a better ventilation – perfusion – ratio with reduced intrapulmonary right-to-left shunting is observed. In pulmonary hypertension caused by hypercapnia the rapid decrease in pCO_2 during HFV can reduce pulmonary vascular resistance.

3 Characteristic parameters and control variables of HFV

Three parameters determine oscillatory ventilation (figure 3.1): Firstly, there is the mean airway pressure (MAP) around which the pressure oscillates; Secondly, the oscillatory volume, which results from the pressure swings and essentially determines the effectiveness of this type of mechanical ventilation; Thirdly, the oscillatory frequency denotes the number of cycles per unit of time.

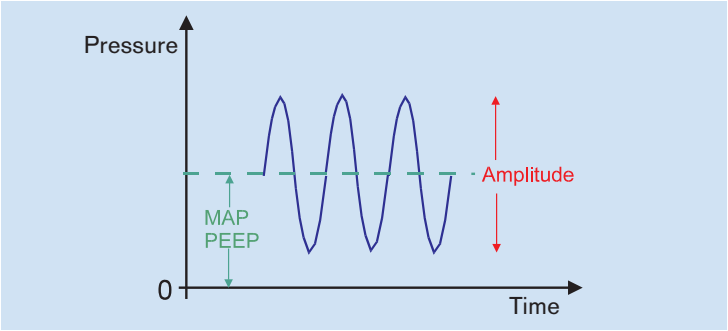


Figure 3.1: Characteristic variables MAP, amplitude, and frequency in pressure waveform during HFO

3.1 Mean Airway Pressure (MAP)

The Babylog 8000 uses a PEEP/CPAP-servo-control system to adjust mean airway pressure. In the CPAP ventilation mode, mean airway pressure equals the set PEEP/CPAP level. When conventional IMV ventilation cycles are superimposed, MAP also depends on both the peak inspiratory pressure (PIP) and the frequency.
Mean airway pressure in HFV should be about the same as in the preceding conventional ventilation, depending on the underlying disease, and should be higher than pulmonary opening pressure. In prematures with RDS this opening threshold is approximately 12 mbar (cf. chapter 8). The crucial physiologic effect of such continuously applied (inflation) pressure is the opening of atelectatic lung areas, resulting in marked recruitment of lung volume. Intermittent application of additional sigh manoeuvres (sustained inflation, cf. chapter 5) can further enhance this effect.
Moreover, opening of atelectases reduces ventilation-perfusion mismatch and thus intrapulmonary right-to-left shunting.

Therefore MAP is the crucial parameter to control oxygenation (cf. chapters 6.1 and 6.2). By way of the PEEP/CPAP-servo-control system the mean airway pressure with the Babylog 8000 can be set in the range from 3 to 25 mbar.

HFV: control 1

PEEP
y
mean airway pressure
y
oxygenation

3.2 Amplitude – oscillatory volume

So far the term amplitude has stood for pressure amplitude. In the end, however, ventilation does not depend on the pressure amplitude but on the oscillatory volume. Nevertheless, as a setting parameter the amplitude is one of the determinants of oscillatory volume.
The oscillatory volume exponentially influences CO_2 elimination (see chapter 3.4). During HFV volumes similar to the deadspace volume (about 2 to 2.5 ml/kg) should be the target.
In any HF ventilator, the oscillatory volume depends characteristically on the oscillatory frequency. Normally, lower frequencies permit higher volumes [18, 35].
Even small changes in resistance and/or compliance of the respiratory system, e.g. by secretion in the airways, or through the use of a different breathing circuit or ET tube, can change the oscillatory volume and thus the effectiveness of HFV [36, 41].

At high amplitude settings the ventilator measures considerable peak pressures. Yet these occur only at the proximal end of the ET tube whereas at the distal end they appear attenuated to 1/3 or 1/6 of their initial value due to the tube resistance [47].
In flow interrupters amplitudes and oscillatory volumes are additionally influenced by the flow.

The Babylog 8000 selects the flow rates automatically depending on frequency and MAP. The user cannot influence the setting. The oscillatory volume strongly depends on the set frequency, as illustrated in figures 3.2 and 12.2. Thus at low frequencies large volumes are obtained whereas above 10 Hz volumes become very small (cf. 12.1.2).
For safety reasons the expiratory pressure excursion is limited to – 4 mbar. Therefore amplitudes and oscillatory volumes vary also with MAP. Especially at MAP below 8 mbar oscillatory volumes are markedly reduced (see figures 3.2 and 12.2).
The oscillation amplitude is adjustable as a percentage from 0 to 100%, where 100% means the highest possible amplitude under the given circumstances of MAP and frequency settings as well as the characteristics of the respiratory system (breathing circuit, connectors, ET tube and airways) (cf. 12.1.3).

HFV: control parameter 2

MAP frequency
y y
oscillatory amplitude
y
oscillatory volume
y
pCO_2

for Babylog 8000

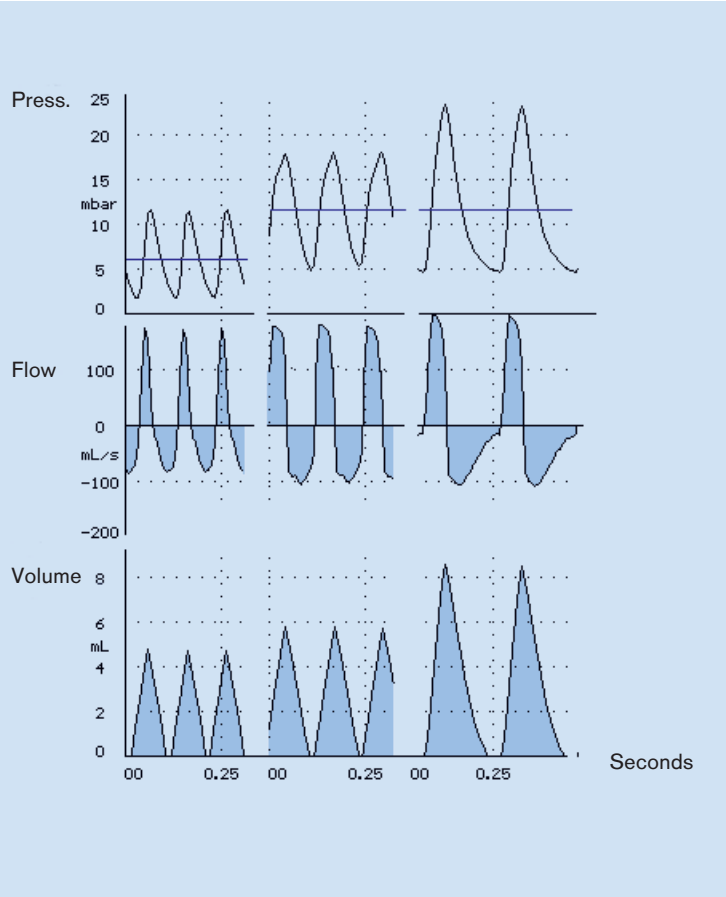


Figure 3.2: Oscillation amplitude and flow as functions of MAP and frequency with the Babylog 8000:
a) Start: F_{HFO} = 10 Hz, MAP 6 mbar, V_{THFO} = 4,6 ml
b) Increase in MAP: F_{HFO} = 10 Hz, MAP 12 mbar, V_{THFO} = 5,8 ml
c) Decrease in frequency: F_{HFO} = 7 Hz, MAP 12 mbar, V_{THFO} = 8,5 ml
The tracings were recorded via the serial interface of the Babylog 8000 ventilating a test lung (C=0.65 ml/mbar) connected to a Fisher-Paykel patient circuit. They represent pressure, flow, and volume, respectively, at the Y-piece connector. However, since the pressure transducer is located inside the ventilator, the pressure measurement should be assessed only qualitatively.

3.3 Oscillatory frequency

The oscillatory frequency, measured in units of Hertz (Hz = 1/s), influences the oscillatory volume and the amplitude depending on the ventilator type used [35].
Intraalveolar pressure can depend on the oscillatory frequency, too. At frequencies close to the resonance frequency of the intubated respiratory system higher alveolar than mouth pressures have been observed [5, 31, 50].

The choice of an optimal oscillatory frequency is currently subject of controversial discussion. In most studies of HFV in newborns frequencies below 16 Hz were used. On the other hand, it was demonstrated recently with powerful piston pumps that at constant oscillatory volumes frequencies around 25 Hz were required to ventilate and oxygenate large animals (65 to 99 kg) sufficiently. The frequencies necessary in these experiments rose with the animal size [2, 13, 18, 35, 36, 66].

With the Babylog 8000 frequencies of 10 Hz and below have been found to be favourable because then the internal programming permits high flow rates and in consequence high oscillatory volumes.

HFV: control 3

oscillatory frequency (↓)
y
oscillatory amplitude (↑)
oscillatory volume (↑)
y
pCO_2 (↓)

for Babylog 8000

3.4 The gas transport coefficient DCO_2

In conventional ventilation the product of tidal volume and frequency, known as minute volume or minute ventilation, aptly describes pulmonary gas exchange.
Different study groups have found that CO_2 elimination in HFO however correlates well with

$$\mathbf{VT^2 \times f}$$

Here, VT and f stand for oscillatory volume and frequency, respectively. This parameter is called 'gas transport coefficient', DCO_2, and is measured and displayed by the Babylog 8000. An increase in DCO_2 will decrease pCO_2 [34, 51, 57, 91, 95].

oscillatory volume frequency
y y
gas transport coefficient
DCO_2
y
pCO_2 (↓)

For a demonstration of the clinical relevance of the gas transport coefficient see appendix: chapter 12.2, 12.3, 12.4.

4 Indications for HFV

Since the early eighties results on oscillatory ventilation have been published in numerous case reports and studies. Yet there are only few controlled studies based on large numbers of patients [22, 25, 45, 46, 78, 83, 119]. In newborns HFV has first been employed as a rescue treatment. The goal of this type of ventilation is to improve gas exchange and at the same time reduce pulmonary barotrauma.

Oscillatory ventilation can be tried when conventional ventilation fails, or when barotrauma has already occurred or is imminent. In the first place this applies to pulmonary diseases with reduced compliance. The efficacy of HFV for these indications has been proven in the majority of clinical studies. In severe lung failure, HFV was a feasible alternative to ECMO [2, 4, 12, 16, 22, 25, 27, 28, 37, 39, 45, 46, 48, 69, 74, 78, 83, 94, 104].
When to switch from conventional ventilation to HFV must certainly be decided by the clinician in charge, according to their experience. Some centres meanwhile apply HFV as a primary treatment for RDS in the scope of studies [37, 42, 78, 83]. Likewise, in cases of congenital hernia and during surgical correction, HFV has been successfully used as a primary treatment [23, 38, 51, 75, 88, 96, 98].

HFV: Indications 1

When conventional ventilation fails

– reduced compliance
– RDS/ARDS
– airleak
– meconium aspiration
– BPD
– pneumonia
– atelectases
– lung hypoplasia

Other:
– PPHN

Also in different kinds of surgery, especially in the region of the larynx and the trachea, HFV has proven its worth [3].
Moreover, in primary pulmonary hypertension of the newborn (PPHN) HFV can improve oxygenation and ventilation (literature 8.5).
Always observing the contraindications (cf. chapters 10.1 and 10.2), in our NICU we follow this proven procedure: If conventional ventilation* fails, we will switch over to HFV. We will assume failure of conventional ventilation, if maintaining adequate blood gas tensions (pO_2 > 50mmHg, SaO_2 > 90%; pCO_2 < 55 to 65 mmHg) requires peak inspiratory pressures (PIP) in excess of certain limits. Those depend on gestational age and bodyweight: In small prematures we consider using HFV at PIP higher than 22 mbar. With PIP going beyond 25 mbar we regard HFV even as a necessity.
In more mature infants the pressure limits are somewhat higher (cf. indications 2).

HFV: Indications 2

When conventional ventilation fails

Prematures
relative: PIP > 22 mbar
absolute: PIP > 25 mbar

Newborns
relative: PIP > 25 mbar
absolute: PIP > 28 mbar

* Conventional ventilation strategy for prematures at Allgemeines Krankenhaus Heidberg: initial setting: ventilator rate 60 bpm; Ti 0.4 s; Te 0.6 s; PIP 16 to 20 mbar; PEEP 2 to 4 mbar
further management: rate up to 100 bpm; I:E > 1.5; PEEP 2 to 5 mbar; PIP up to 22 (25) mbar max; possibly increased expiratory flow (VIVE).

5 Combining HFV and IMV, and ‘sustained inflation’

Oscillatory ventilation on its own can be used in the CPAP mode, or with superimposed IMV strokes, usually at a rate of 3 to 5 strokes per minute (cf. appendix 12.1). The benefit of the IMV breaths is probably due to the opening of uninflated lung units to achieve further ‘volume recruitment’.

Sometimes very long inspiratory times (15 to 30 s) are suggested for these sustained inflations (SI). By applying them about every 20 minutes compliance and oxygenation have been improved and atelectases prevented (cf. figure 5.1), [10, 11, 37, 41, 65, 70, 113]. Especially after volume loss by deflation during suctioning the lung soon can be reopened with a sustained inflation. However, whether these inflation manoeuvres should be employed routinely is subject of controversial discussions. In most of the clinical studies no sustained inflations were applied. In animal trials no increased incidence of barotrauma was found [10].

Prevention of atelectases, which might occur under HFV with insufficient MAP (cf. 9.1 complications), is the primary benefit of combining HFV and IMV. HFV superimposed to a normal IMV can markedly improve CO_2 washout (‘flushing the deadspace’ by HFV) at lower peak pressures than in conventional ventilation [7, 8, 9, 12, 44, 50, 109].

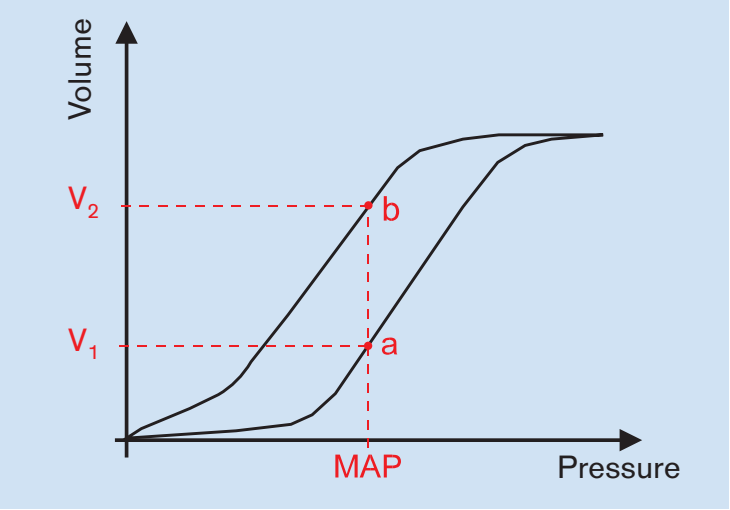


Figure 5.1: Effect of a sigh manoeuvres through sustained inflation (SI): prior to the SI the intrapulmonary volume equals V1 at the MAP level (point a); the SI manoeuvres temporarily increases pressure and lung volume according to the pressure-volume curve; when the pressure has returned to the previous MAP level, pulmonary volume remains on a higher level, V2 (point b), because the decrease in pressure occurred on the expiratory limb of the PV loop.

6 Management of HFV

6.1 Transition from conventional ventilation

Before you begin with high-frequency ventilation remember to read the mean airway pressure. Then switch over to oscillatory ventilation, which requires only the push of a button in case of the Babylog 8000.

Having reduced the IMV rate to about 3 bpm, or having switched to CPAP, immediately readjust MAP to optimally open up the lung. The Babylog 8000 PEEP/CPAP rotary knob controls mean airway pressure under HFV. Three different strategies have been described and found suitable for clinical application:

1. Set MAP 2 to 5 mbar above the MAP of the preceding conventional ventilation. Then increase MAP step by step until oxygenation improves and the lung is optimally inflated.
2. Within the initial 3 to 5 minutes of HFV set MAP 6 to 8 mbar higher than the MAP of the conventional ventilation. Then reduce MAP again to a level of 0 to 2 mbar above the MAP of the conventional ventilation. Thereafter vary MAP so as to maintain oxygenation.
3. Keep the MAP on the level of the conventional ventilation. Maintain lung expansion through initial and intermittent sustained inflations. (cf. chapter 5).

In our hospital we prefer the first strategy. Experienced users may also combine them.
Keep the IMV pressure 2 to 5 mbar below the PIP of the conventional ventilation. An oscillatory frequency of < 10 Hz is a good value to start with. Set the amplitude as high as possible to have the patient's thorax visibly vibrating. Strive to obtain oscillatory volumes of at least 2 ml/kg. After 30 to 60 minutes the inflation of the lung should be assessed with a chest x-ray. Optimal lung inflation correlates with obtaining an 8 – 9 posterior rib level expansion and decreased lung opacification. [4, 11, 22, 23, 29, 67, 95, 97, 103, 109].

HFV: Start

MAP(PEEP):	2-5-(8) mbar above MAP of conventional ventilation;
	if necessary, increase MAP until pO_2 (↑)
	after 30 min: X-ray: 8-9 rib level
IMV rate:	3bpm
pressure:	2 to 5 mbar below conventional ventilation
HFV frequency:	10 Hz
HFV amplitude:	100%
	watch thorax vibrations
HFV volume:	about 2 to 2.5 ml/kg

6.2 Continuation of HFV

The effect of a change in ventilation settings should be judged only after some 15 minutes. If hypoxia persists increase airway pressure gradually until oxygenation improves; up to 25 mbar is possible with the Babylog 8000. However, make sure this neither impairs systemic blood pressure nor significantly increases CVP (central venous pressure). Alternatively, volume recruitment can be obtained with sustained inflations. With a volume-constant oscillator, oxygenation may be improved by higher frequencies.
If oxygenation is satisfactory, reduce FiO_2 to about 0.6 – 0.3. Only then and very carefully and gradually lower the mean airway pressure (1 to 2 mbar in 1 to 4 hours).
In case of hypercapnia try to increase specifically the parameter DCO_2 or the oscillatory volume; to this end set the amplitude to 100%. By decreasing frequency and/or increasing MAP you can try to further push up the amplitude and thus the oscillatory volume (see also 12.1.2 for support). In hypercapnia you always have to rule out airway obstruction by secretion, because it impedes effectiveness of ventilation much more in HFO than it does in the conventional modes. During suctioning the lung often deflates, resulting in subsequent respiratory deterioration. As a precaution one can temporarily increase MAP a little (2 – 4 mbar) after the suctioning, or apply a sustained inflation.

HFV: Continuation

Hypoxia:	increase MAP up to 25 mbar max (if CVP does not increase) alternatively: apply sustained inflation at low lung volume apply sigh manoeuvre every 20 minutes for 10 to 20 seconds at 10 to 15 mbar above MAP
Hyperoxia:	reduce FiO_2 down to about 0.6 – 0.3 very carefully decrease MAP
Hypercapnia:	increase DCO_2 – amplitude 100% – decrease HF-frequency – increase MAP (above 10 mbar)
Hypocapnia:	decrease DCO_2 – decrease amplitude – increase frequency – reduce MAP (below 8 mbar)
Overinflation:	reduce MAP – decrease frequency – discontinue HFO
Hypotension/increase in CVP:	– volume expansion in hypotension – Dopamine/Dobutamine – reduce MAP – discontinue HFO

If ventilation deteriorates even at 5 Hz, maximum amplitude and optimal MAP, switch back to conventional ventilation. If ventilation and/or oxygenation does not improve within 2 to 6 hours you should consider the patient a non-responder to HFV.

Within a short time period (minutes to 2-6 hours) after the onset of HFV the compliance of the lung may improve rapidly. This will be accompanied by a rise in oscillatory volume and DCO_2 resulting in hyperventilation. At low pCO_2 values the DCO_2 should be reduced: reduce amplitude setting, increase frequency, or, with the Babylog 8000, decrease mean airway pressure (below 8 mbar). In general, CO_2 is eliminated effectively at oscillatory volumes above 2 ml/kg. This often corresponds to DCO_2 values higher than 40 to 50 $ml^2/s/kg$. However sometimes it is necessary to apply

much higher oscillatory volumes (3-4 mL/kg) to achieve adequate ventilation (cf. appendix 12.2, 12.3, 12.4).
In case of overinflation, first reduce MAP. If overinflation persists, decrease the oscillatory frequency to allow for better deflation in the expiration cycles.
In hypotension you first have to rule out hypovolemia. If there is an increase in CVP, or a prolonged capillary filling time, dopamine/ doputamine can be given. If there are still signs of heart insufficiency, MAP must be reduced. Less PEEP and at the same time a higher IMV rate at constant MAP can perhaps improve cardiac output [23].

6.3 Humidification

It is essential to adequately humidify (90% RH) the breathing gas. Otherwise severe irreversible damage to the trachea may result. Viscous secretion could obstruct bronchi and deteriorate the pulmonary situation. Excessive humidification on the other hand can lead to condensation in the patient circuit, the ET tube and the airways, completely undoing the effect of HFV [101, 104].
Experience has shown that the humidifiers available for the Babylog 8000, the Dräger Aquamod and the Fisher Paykel, yield satisfactory results.

6.4 Weaning from oscillatory ventilation

Weaning the patient from HFV mostly turns out to be easier than anticipated. At first, turn down oxygen to 30% to 50%. Reaching the threshold of 30% means that the lung is probably optimally inflated and there will no longer be compromised ventilation and perfusion [116]. Then reduce mean airway pressure in small steps to about 8 to 9 mbar. With an overinflated lung, however, reduction of MAP has priority. At the same time the IMV rate can be increased and oscillation amplitude decreased (see also 12.1.3). Note that a change in MAP does not instantaneously change oxygenation. In a stable clinical situation one should wait 30 to 60 minutes before assessing the effect of the new setting.

Then switch back to conventional ventilation and continue weaning with IMV. Nevertheless it is also possible to extubate directly from oscillatory ventilation.
The time necessary for weaning may vary significantly with the underlying pulmonary disease. In acute illnesses such as RDS or PPHN the weaning process may last only a few up to several hours. In diseases like BPD the reduction of HFV may require days to weeks depending on the individual circumstances; e.g. permissive hypercapnia, airleaks etc.

HFV: Weaning

1. Reduce FiO_2 to 0.3 – 0.5
2. Reduce MAP by 1 to 2 mbar per hour until (8) to 9 mbar; then increase IMV rate
3. Reduce amplitude
4. Continue ventilation with IMV/SIMV and weaning
5. Extubation from HFV is also possible if respiratory activity is sufficient

7 Monitoring during HFV

As in any assisted ventilation the vital parameters must be closely monitored. In addition to the standard ventilation parameters, mean airway pressure and tidal volumes for both the oscillatory and the IMV cycles must be observed [77]. Monitoring of DCO_2 has turned out to be useful for us (see appendix: 12.2, 12.3, 12.4, 12.5). Particularly in severely ill infants it is wise to measure the central venous pressure regularly or continuously. A notable increase can herald cardiorespiratory decompensation at too high mean airway pressure. Also prolonged capillary filling time and reduced urine output may indicate compromised cardiac function.
With the help of echocardiography contractility and cardiac output can be assessed as well as the right-ventricular pressure through quantitative evaluation of tricuspid insufficieny. The state of lung expansion has to be assesed by periodic chest radiographs. It is optimal on the 8th to 9th posterior rib level. When IMV is superimposed on HFV it is important to take the radiographs in the expiratory phases of the mandatory cycles.
In this mixed mode the Babylog 8000 measures and displays the tidal volume of the IMV strokes separately. If the inspiratory plateau is long enough, the pressure measured at the Y-piece will approximately equal the intrapulmonary pressure, given there is no significant tube leakage. Then dynamic compliance is easy to calculate:

$$C_{dyn} = \frac{V_{TIMV}}{PEAK_{IMV} - PEEP}$$

From dynamic compliance one can indirectly conclude to the inflation state of the lung. Oscillatory ventilation of an initially low-compliant lung (e.g. with RDS) can rapidly and markedly improve compliance through the opening of underinflated regions (cf. 2. and 12.4). With better compliance higher inflation at the same pressure will come along. However, it must be taken into account that dynamic compliance may considerably depend on the PEEP.
With high PEEP the pressure-volume loop of the respective cycle might already be located in the upper flat part of the static pressure-volume characteristic (figure 7.1). If a device for static lung function tests by way of the occlusion method is available, the state of lung inflation can be assessed also on the level of mean airway pressure. That enables one to rule out obstructive lung diseases before beginning oscillatory ventilation. In the end however, safe judgment of pul-

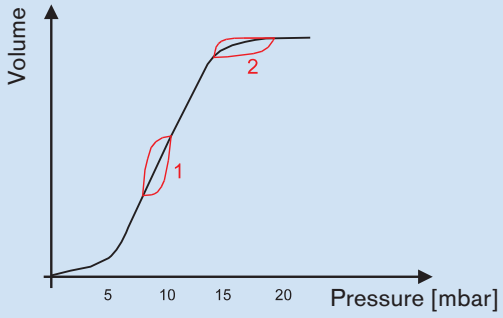


Figure 7.1: Static pressure-volume characteristic with dynamic PV loops at low (1) and high PEEP (2). The compliance is reflected by the mean gradient of the respective loop.

monary inflation with lung function measurement is possible only by determining residual volume [2, 23, 95, 96].

Monitoring during HFV

- ventilation parameters
- blood gases
- blood pressure, heart rate
- CVP if possible
- micro circulation
- urine output
- chest radiograph (expiratory)
- lung function if possible

8 Strategies for various lung diseases

For different pulmonary diseases dedicated strategies exist to be applied in oscillatory ventilation. The aims of therapy always determine the practical procedure.

8.1 HFV for diffuse homogeneous lung diseases

The respiratory distress syndrome, diffuse pneumonia, but also bilateral lung hypoplasia belong to this group. The primary goal with such patients is recruiting lung volume to improve oxygenation and ventilation at minimal barotrauma. When you have switched over to HFV adjust mean airway pressure 2 to 5 (8) mbar above the MAP of the preceding conventional ventilation. If necessary, increase MAP – but do not overinflate the lung! – in steps of 1 to 2 mbar every 10 minutes until oxygenation improves. Also, with signs of right-heart failure, reduce the MAP. Bevor reducing MAP in the further course of the treatment, turn down FiO_2 to about 0.3 – 0.5. The settings of frequency and amplitude depend on the necessity of CO_2 removal (cf. chapter 3) [22, 23, 29, 45, 63, 72, 73, 106].

HFV for diffuse homogeneous lung diseases

Goals: lung expansion
less barotrauma

- begin with MAP 2 to 5(8) mbar above that of conventional ventilation
- then increase MAP until pO_2 rises by 20 to 30 mmHg, or CVP increases, or signs of overinflation appear
- reduce FiO_2 to 0.3 – 0.5 then continue weaning

8.2 HFV for inhomogeneous lung diseases

Focal pneumonia, pulmonary haemorrhage, meconium aspiration, unilateral lung hypoplasia and possibly BPD fall into this disease category.
The aim is to oxygenate and ventilate at minimum mean airway pressure. Due to regionally different compliances and/or resistances, there is always the danger of overinflating the more compliant lung units. In fresh meconium aspiration, for example, airways are often plugged with meconium. Then, under HFV, airtrapping can easily occur and cause a pneumothorax.
Begin with a MAP lower or equal than that of the conventional ventilation. The oscillatory frequency should be low. If necessary, turn up MAP in small increments until pO_2 slightly increases. Then keep MAP constant. Mostly the situation will continue to improve. If not, return to conventional ventilation.

HFV for inhomogeneous lung diseases
Goals: improved oxygenation and ventilation at minimum MAP
Risk: partial overexpansion

- begin with MAP like or below that of conventional ventilation
- HFV frequency low, e.g. 7 Hz
- then increase MAP until pO_2 slightly rises; keep MAP constant; if respiratory situation fails to improve return to conventional ventilation

8.3 HFV for air leaks

The interstitial emphysema in particular but also big bubble emphysema and pneumothoraces belong to this category. The treatment aims at improving oxygenation and ventilation at minimum mean airway pressure.

To this end, lower pO_2 values and higher pCO_2 values often have to be accepted. Do not superimpose IMV for the risk of barotrauma. Place the infant on the side of the air leak. Adjust MAP below that of the conventional ventilation if possible. Choose a low HFV frequency. The further strategy heads above all for a reduction in pressure. If successful, continue HFO another 24 to 48 hours until the radiologic signs of the airleak have clearly subsided [2, 24, 29].

8.4 HFV for atelectases

HFV with air leaks
Goal: improved oxygenation and ventilation at minimum MAP;
(accept lower pO_2 and higher pCO_2)

– Do not superimpose IMV!
– Begin with MAP like or below that of conventional ventilation
– HFV frequency low, for example, 7 Hz
– Reduce pressure prior to FiO_2
– Continue HFV for 24 to 48 hours after improvement

Even under conventional ventilation, especially in the presence of pneumonia, meconium aspiration, or BPD, stubborn atelectases often develop. According to our experience intermittent oscillatory ventilation can resolve such atelectases. About six times a day before suctioning we apply HFV for some 15 to 30 minutes. With slightly raised PEEP, the IMV can continue, however, the rate should not exceed 20 bpm to ensure enough time for oscillations. After the suctioning we switch HFO off again. The effect on opening the atelectases is possibly based on ‘inner vibration’, elevated inflation through raised MAP, and increased mucociliar clearance [62, 71, 93].

8.5 HFV for Pulmonary Hypertension of the Newborn (PPHN)

Numerous authors have reported on effective therapy of pulmonary hypertension of the newborn with HFV. Continuous application of high mean airway pressure uniformly opens up the lung, diminishes pulmonary vascular resistance, improving ventilation-perfusion match and thereby reducing intrapulmonary right-to-left shunting. The favourable oxygenation along with improved CO_2 reduction additionally counteracts pulmonary vasoconstriction.

Of newborns with PPHN of different origin 39 to 67% have been effectively treated with HFV alone as well as with a combination of HFV and IMV. The prognoses of these patients were correlated directly with the APGAR score and inversely with the birth weight and oxygenation index.

The HFV strategy should consider the condition of the patient's lung as well as the cardiocirculatory status (cf. strategies 8.1, 8.2, 8.3). Before switching to HFV hypovolemia and hypotension have to be ruled out or treated if neccessary. Strive for normoventilation or slight hyperventilation by specifically influencing DCO_2. Start HFV with a MAP on the level of the preceding conventional ventilation. Optimise lung volume and oxygenation by way of adjusting MAP (PEEP, PIP, IMV rate). Just in these patients however overinflation as well as decreased lung volume can influence the pulmonary vascular resistance, pulmonary flow and can therefore reduce cardiac output and dramatically deteriorate the patient's condition. The central venous pressure should be monitored closely and serial chest x-rays are mandatory. Higher IMV rates and lower PEEP than those under CPAP-HFV will possibly improve cardiac function.

Since these patients respond delicately to manipulations, changes in ventilation should be carried out with great care [8, 43, 49, 64, 92, 97, 109, 110, 117, 118].

HFV in pulmonary hypertension of the newborn (PPHN)
Goals: to optimize lung volume and perfusion; to improve hypoxia and hypercapnia while minimising barotrauma

– HFV frequency:	<10 Hz
– HFV amplitude:	100%
– MAP:	on the level of conventional ventilation; increase as needed for oxygenation in 1 mbar in the presence of airleaks, MAP as low as possible; reduce MAP very carefully! observe cardiac function!
– IMV:	rate 0 to 15 (30) bpm;

– reduce O_2 prior to MAP
– Maintain HFV for 24 to 48 hours after recovery

Always: minimal handling, perhaps sedation or relaxation

9 Complications, contraindications and limits

9.1 Complications and side effects

Irritation: Primarily, children are often irritated by HFV at first and require deeper sedation. However, they often become quiet according to improved hypercapnia.

Secretion: With sufficient humidification secretion does not plug the airways but rather gets better resolved. However, even small amounts of secretion or foam after surfactant administration can considerably affect the efficacy of HFV. This shows in a decrease in oscillatory volume (VTHFO) or DCO_2 [8, 48, 62, 72, 93].

Haemodynamics: Often a slight reduction in heart rate is observed. This phenomenon as well as the frequently seen reflectory apnoea is attributed to an increased vagal activity during HFV. High MAP can compromise both venous return to the heart and cardiac output as well as lead to an increase in pulmonary vascular resistance. Optimising blood volume and myocardial function before the HFV treatment may help minimise these problems. Sometimes peripheral edema can be observed [29, 32, 102].

Intracranial haemorrhages: Whether HFV promotes IVH has been discussed for a long time. The almost always very critical condition of the patients is probably connected with this presumed effect. More recent studies, during which HFO was applied early, do not report a higher incidence of such complications in comparison with conventional ventilation. A rise in intracranial pressure could not be observed [22, 23, 16, 45, 46, 59, 78, 81, 89, 105, 108, 111].

Overinflation: Pulmonary overinflation in obstructive lung diseases (e.g. in MAS) is the most frequent complication and cause for failure of oscillatory ventilation. Here, especially with higher frequencies and inappropriate I:E ratios, massive airtrapping may occur. Therefore some studies have named airleaks as complications of HFV [96, 108, 109]. On the other hand, newer studies describe HFV as a form of ventilation reducing both barotrauma and the incidence of air leaks [22, 41, 59, 82].

BPD: With respect to the development of BPD and chronic lung

disease the published studies show contradictory results. Yet in some studies, particulary in animal studies, a preventive effect concerning the development of chronic lung injury has been clearly demonstrated. However, some of the clinical investigaters failed to show a beneficial effect of HFV in comparison with CMV in the treatment of RDS. But serious criticism rose concerning the design and the inconsistant strategies of those studies. Recently the Provo multicenter trial demonstrated that the incidence of chronic lung disease and mortality was 50% less in the early HFV- surfactant treated group than in the CMV-surfactant group [14, 23, 42, 54, 55, 83, 116, 119].

Necrotising tracheobronchitis: Local irritations up to necroses of the tracheo-bronchial system are known mainly as complications of HFJV but also of HFOV and conventional ventilation. Inadequate humidification and excessive MAP are named as pathophysiologic causes. In the studies published recently no significant difference between HFV and conventional ventilation was found [2, 29, 89, 109, 115].

Other: In three cases embolism of air has been reported [76, 52, 80]. This complication can also occur during conventional ventilation with high peak pressures [6].

9.2 Contraindications

Pulmonary obstruction is the only relative contraindication known to date. It can be present in fresh meconium aspiration, but also in bronchopulmonary dysplasia or in RSV bronchiolitis. In our unit, when there was doubt, lung function testing proved useful [94, 98] (see appendix 12.2). If you plan to apply HFV despite obstruction you should be aware of the risk of serious overinflation with all its consequences. There is no publication that presents intracranial haemorrhage or coagulopathy as contraindications of HFV.

9.3 Limitations of HFV

The success of HFV largely depends on the power of the HF ventilator, which is characterised by the size of the oscillatory volumes at sufficiently high frequencies. Compliance and deadspace of the patient circuit have crucial impact. With a low-compliant circuit the oscillatory volumes can be considerably increased (cf. 12.1.2). In flow interrupters lung mechanics and thus possibly the disease state of the patient additionally influence the power.
The Babylog 8000 allows high-frequency ventilation with infants weighing up to 4 kg. Depending on weight and lung mechanics one should however expect occasional failures due to insufficient oscillatory volumes in the upper frequency range (cf. 12.4).

10 Failure of HFV

If the bodyweight is suitable, and indications and contraindications are observed, HFV will at least temporarily improve the critical respiratory condition in the majority of patients. With appropriate ventilators even adults can be effectively ventilated [66]. The own experience has shown that clinicians who are not yet familiar with HFV feel reluctant to abandon some ideas and rules of conventional ventilation. Their most frequent mistake is to apply inadequate MAP for volume recruitment. Then again, excessive MAP can of course lead to failure of HFV, lung overexpansion, barotrauma, and severe impairment of the patient.

Moreover, clinicians often do not fully exploit the amplitude for fear of barotrauma and irritation. Only in course of time do they realise that the high pressure amplitudes are in fact attenuated by the ET tube. Also, for lack of confidence, they first dare not drastically turn down the IMV rate to 0 to 5 bpm. Hence they neither reduce the risk of barotrauma nor sufficiently open up underinflated lung units through continuous application of high mean airway pressure. Studying the literature one obtains the impression that some authors were not experienced enough and thus wrongly attributed iatrogenic complications or failures to the ventilation mode [14, 29, 74].

It is very important to recognize patients who are likely to fail on HFV as early as possible. These patients should be treated with ECMO in time. HFV-responders differ significantly from non-responders. Already at the initiation of HFV the non-responders were more critically ill and showed higher oxygenation index (OI) or lower arterial to alveolar oxygen ratio (A/a DO_2). Two to six hours after the beginning of HFV the non-responders are still characterised by significant higher FiO_2, OI, pCO_2, MAP or lower A/a DO_2. With the Sensormedics 3100, an A/aDO_2 < 0,08 after 6 hours of HFV showed the best correlazion in predicting failure of HFV and the need for ECMO in neonates. Those values are likely to vary with the ventilator in use. However, an increase in pCO_2 and/or OI after 2 to 6 hours should be considered a sign of failure of HFV.

If HFV fails with one oscillator a more powerful machine might be successful in certain patients and clinical situations.

Additionally the success rate of HFV varies with the diagnostic category. Patients with homogeneous lung diseases are more likely (70-87%) to respond to HFV than inhomogeneous diseases (50-79%), airleaks (63-80%), PPHN (39-69%), or CDH (22-27%). [24, 97, 118, 120]

11 Summary

High-frequency (oscillation) ventilation is a new form of treatment whose physiologic effect has not been fully clarified. Nonetheless in some centres it has left the experimental stage establishing itself in neonatology as an alternative treatment when conventional ventilation fails [58]. Severe pulmonary diseases like RDS, ARDS, pneumonia, MAS, airleaks, and lung hypoplasia as well as PPHN can often be treated more successfully and gentler with HFV than with conventional ventilation strategies.

Better oxygenation and ventilation and at the same time less risk of barotrauma are the biggest assets in comparison with conventional ventilation. Oxygenation and CO_2 elimination are controlled by mean airway pressure, oscillatory volume, and frequency.

Applying specific strategies, the clinician can adequately address the particular pathophysiology of the underlying disease. More controlled studies are necessary to work out the advantages and drawbacks of this ventilation technique in comparison with conventional ventilation before the scope of indications can be extended.

The commercially availabe high-frequency ventilators considerably differ in technology and power. Any device however can supply only limited oscillatory volumes, which is reflected in the strategies described. They are a compromise between the device capabilities and the patient requirements [66].

In the hands of an experienced team who observe all the indications, adverse effects, and contraindications, HFV is a safe technique of assisted ventilation [86, 78, 59, 25].

12 Appendix

12.1 The high-frequency mode of the Babylog 8000 – Software version 4.n –

In the Babylog 8000 the membrane of the exhalation valve controls the high-frequency pulses largely as it controls the breaths in conventional ventilation. This servo membrane lets pass just as much gas into the ambient that the desired pressure is maintained in the patient circuit. In a mandatory stroke this pressure corresponds to the set inspiratory pressure limit, whereas in the expiration phase, or in CPAP mode, it equals the PEEP/CPAP setting.
Each HF cycle consists of an inspiratory phase during which the pressure is above MAP level and an expiratory phase during which it is below MAP level. Switching rapidly to and from between two pressure levels the exhalation valve generates the high-frequent pressure swings oscillating around mean airway pressure. In HF inspiration the valve closes, and in HF-expiration it opens so the breathing gas can escape. A jet Venturi valve in the exhalation valve builds up negative pressure with respect to ambient, ensuring active expiration. The expiratory phase is always longer than or at least as long as the inspiratory phase. Thus the negative-going pressure excursion is normally smaller than the positive-going one. The I:E ratio is automatically regulated in the range from 0.2 to 0.83 depending on PEEP setting (=MAP) and oscillatory frequency. Only at MAP settings above 15 mbar and oscillation frequencies higher than 12 Hz the I:E ratio can reach 1.0.

Due to the short inspiratory and expiratory phases during HFV, adequate oscillatory volumes then require much higher continuous flow than during conventional ventilation. Therefore the Babylog 8000 adjusts the flow (range 1 to 30 l/min) automatically to meet the demand at the respective setting of frequency and amplitude. Flow and I:E ratio settings are taken from a look-up table stored in the microcomputer memory of the device. Consequently the VIVE function, which otherwise enables the user to select a separate continuous flow in the expiratory phases of mandatory cycles, is not available in HFO. Moreover, the minimum permissible PEEP/CPAP setting is 3 mbar. At high HF amplitudes and at the same time low MAP considerable negative expiratory pressure would be required to maintain mean airway pressure. To avoid the collapse of lung units a safety valve and an internal control mechanism ensure that the pressure swings do not go below about – 4mbar.

The pressure amplitudes obtained at the Y-piece depend on the continuous flow, the set HF amplitude and frequency, the respiratory system, and also the patient circuit compliance. The greater the system compliance, the smaller the pressure swings and consequently the oscillation amplitudes. Since different types of tubing systems are commonly used in clinical practice, it is impossible to predict pressure and volume amplitudes in a particular situation (12.1.2). The HF oscillation amplitude is adjustable on a relative scale ranging from 0 to 100%. Observing the resulting tidal volumes the clinician varies the amplitude until the HF oscillatory volume, or DCO_2 is adequate (cf. chapter 3).
The pressure amplitude setting in the Babylog 8000 defines a percentage of the pressure difference 60 mbar – MAP, which is the highest possible amplitude. By way of the exhalation valve, the device always strives to regulate airway pressure in inspiration such that it corresponds to the internal control pressure, $P_{control}$:

$$P_{control} = MAP + \frac{(60\ mbar - MAP)}{100\ \%} * x\ \%$$

This means: at 0% amplitude setting, the control pressure will equal MAP, that is, there will be no oscillations; at 100% the control pressure will equal 60mbar.
At the $P_{control}$ level the exhalation valve limits the amplitude during HFO in a similar way as in conventional ventilation, where the P_{insp} setting is the limit. Only during a plateau phase is the exhalation valve able to limit, or regulate, the airway pressure by letting escape more or less gas. However, with insufficient flow, or too short inspiratory times, or a very compliant patient circuit, the pressure might not reach the plateau. Then the pressure amplitude at the mouth will be lower than the control pressure of the exhalation valve. Thus, turning down the amplitude will influence the actual pressure at the Y-piece only if the control pressure is lower than the pressure actually obtained by the end of T_{insp} (see chapter 12.2).
With low MAP the amplitude is additionally limited by internal programming so as not to obtain expiratory pressures below – 4 mbar.

During inspiration the flow builds up pressure (Paw) in the system consisting of patient circuit, lung, airways, and ET tube. Disregarding the airflow through the ET tube for the moment, the pressure in the circuit at the end of inspiration approximately equals

$$P_{aw} = \frac{\text{Cont. Flow.} * \text{Ti}}{\text{System Compliance}}$$

This means that long inspiratory phases (low HF frequency), high flow, and low system compliances yield high amplitudes. Of course, due to the flow passing through the ET tube the actual mouth pressure amplitude is smaller. The basic relationship given above however still holds true.

Thus in any clinical situation the setting of 100% amplitude will generate the maximum pressure swings possible under the given circumstances. Pressure waveforms as well as peak pressures can be read from the ventilator screen. Using this feedback the clinician can adjust the settings to meet the requirements of the therapy.

Combining HFV with conventional ventilation modes
High-frequency oscillations can be superimposed whenever the patient could otherwise breathe spontaneously from the continuous flow. This results in the following possible combinations:

CPAP and HF
HF cycles are continuously applied, superimposed on the CPAP level. In this situation the MAP equals the CPAP.

IPPV/IMV and HF
HF cycles are applied during the expiratory phases between the mandatory strokes. About 100 ms before a mandatory stroke the oscillations stop, and about 250 ms after the stroke they continue. Two precautions against airtrapping are built in: Firstly, the short pause after each stroke is to give the patient sufficient time to exhale; Secondly, the oscillations always start with an expiratory phase (see figure 12.1). Due to the mandatory ventilation strokes the actual mean airway pressure now results from conventional cycles and the set PEEP.

SIMV and HF
This mode basically functions like the combination of IPPV and HF, but now the oscillations stop about 300 ms before the time window in which the ventilator looks for a spontaneous breathing effort for triggering. This is necessary to detect spontaneous breathing without disturbance from the HF oscillations. Of course this reduces the time available for oscillations. With poor ventilatory drive no oscillations occur until the next mandatory cycle, resulting in long episodes of apnea.
Applying SIPPV and HFV simultaneously is not possible.

Monitoring during HFV
As in conventional ventilation the Babylog 8000 monitors pressure and flow, but displays the real-time waveforms alternatively. Some monitoring capabilities have been specially adapted to high-frequency ventilation:
– $DCO_2 = VT_{HF}^2 * f$: gas transport coefficient (cf. 3.4)

– VT_{HF}: inspired tidal volume, averaged over several cycles
– MV_{IM}: nspired minute volume of IMV breaths
– V_{TIM}: inspired tidal volume of IMV breaths

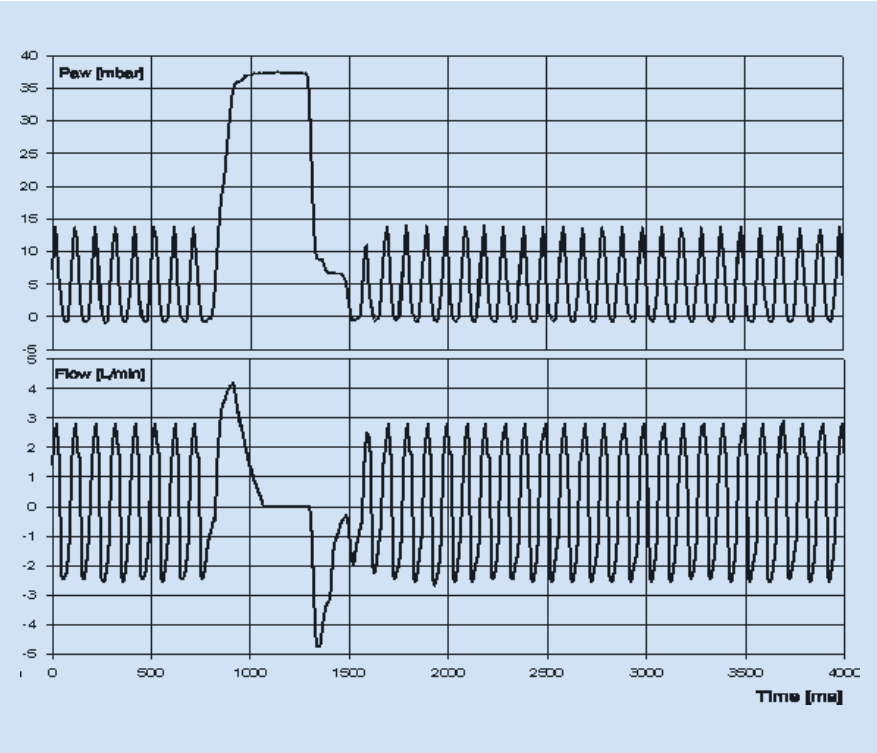
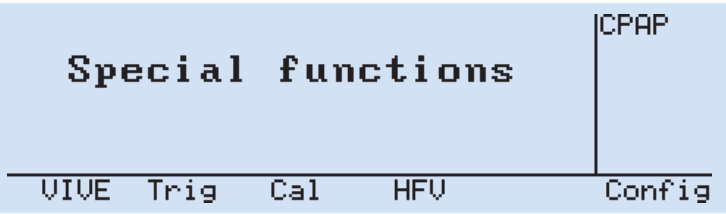


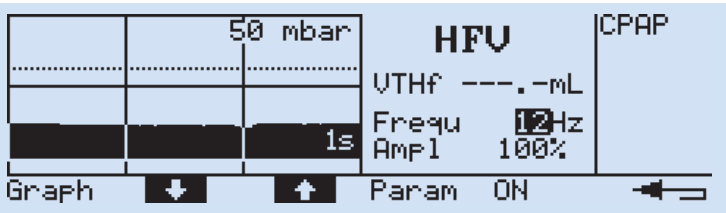
Figure 12.1: Pressure and flow waveforms: The first oscillation after the IMV breath starts with an expiratory phase.

12.1.1 Adjusting HFO with the Babylog 8000

To invoke the HFV submenu push the HFV button in the 'Mode Menu'.

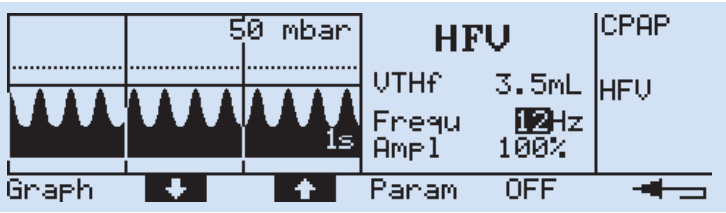


Here, you set oscillatory frequency and amplitude.

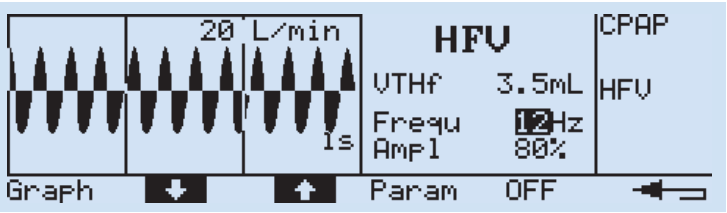


Push the 'Graph' button to change over between pressure (a) and flow waveform (b).

a)

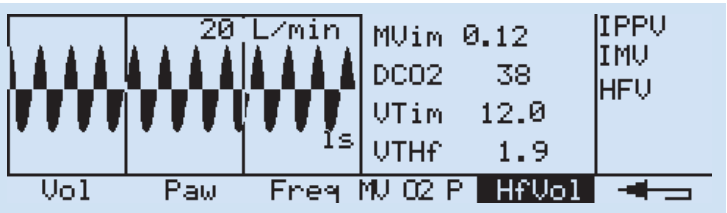


b)

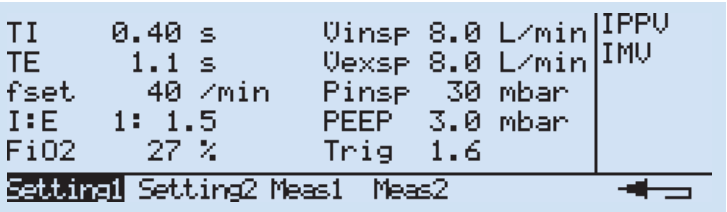


Monitoring and displaying the HFV parameters

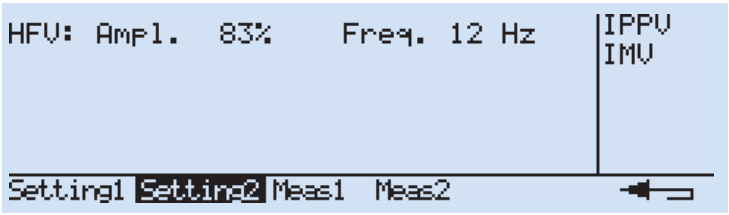
When HFV and IMV are combined both the IMV minute volume and the IMV tidal volume are displayed.
During HFV alone these values are blanked out.



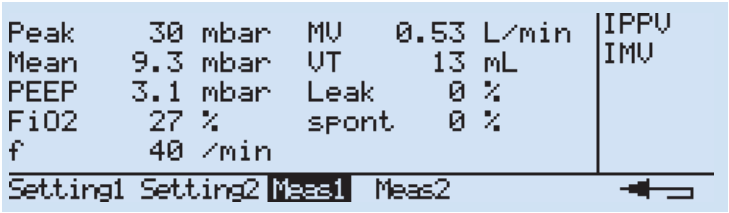
To look at the settings and measured values change to the submenu ‘List’. Under ‘Settings1’ all settings for conventional ventilation are displayed.



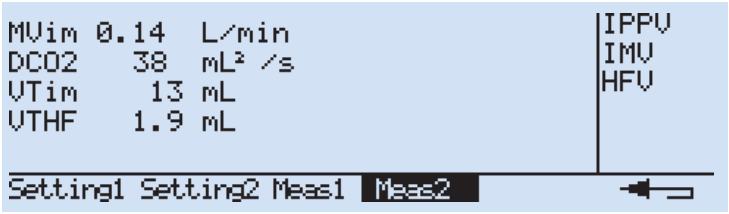
Under ‘Settings2’ you will find the HF amplitude and frequency.



To see all measured values of conventional ventilation push ‘Meas1’. Under ‘Meas2’ you will get the special HFV monitoring parameter.



12.1.2 Oscillatory volume, frequency and MAP with the Babylog



8000

The following table and illustration show the dependency of oscillatory volume on frequency and on mean airway pressure. Those data were measured using a setup with the Dräger Aquamod HF tubing system (compliance: 0.25 ml/mbar) and a Dräger test lung (compliance: 0.66 ml/mbar, resistance: 0.07 mbar/ml/s).

Frequency	MAP 5mbar	MAP 10mbar	MAP 15mbar	MAP 20mbar	MAP 25mbar
Hz	Vt-hf	Vt-hf	Vt-hf	Vt-hf	Vt-hf
5	9.7	12	14	12	10
6	9.7	11	14	12	11
7	9	10	13	12	11
8	8.5	8.2	13	11	11
9	8.2	8	10	11	11
10	6	6.6	8.3	8.7	8.3
11	5.3	5.9	6.6	7.7	8.3
12	4.9	4.6	6.1	6	7
13	4.4	4.3	6.2	4.9	5.6
14	4.4	4.3	5.1	4.9	5.7
15	2.8	3.9	4.9	4.8	4.8
16	2.9	3.9	4.9	4.8	4.7
17	2.8	2.7	3.6	3.6	3.5
18	2.8	2.7	3.6	3.5	3.5
19	2.8	2.7	3.7	3.5	3.5+
20	2.8	2.7	2.4	2.8	3.1

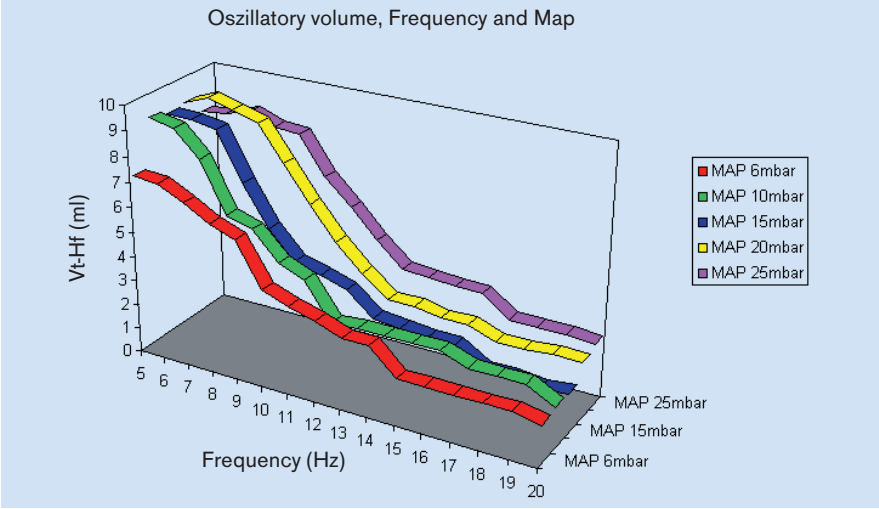


Figure 12.2 Graphical representation of the above table

With a test lung of higher compliance the oscillatory volumes may be higher.

A patient circuit with higher compliance, for example 0.77 ml/mbar, reduces the oscillatory volumes by 50%! (cf. figure 12.2 and 12.3).

Five different tubing systems are available for the Babylog 8000:

	Compliance ml/mbar
Patient circuit P Aquamod	0,50
Patient circuit P Aquamod light	0,45
Patient HF Aquamod	0,25
Patient circuit Fisher-Paykel[1)]	0,95-1,1
Patient circuit HF Fisher-Paykell[1)]	0,75-0,9

1) with MR340 chamber, max filling, the compliance of the system varies greatly with the level of water in the chamber!

12.1.3 Amplitude setting and oscillatory volumes

The relationship between the relative oscillation amplitude and the resulting volume is non-linear. The following illustration shows that only below 65% the oscillatory volume goes down. This was measured at 25 mbar MAP (patient circuit and humidifier: Fisher-Paykel; circuit compliance: 0.77 ml/mbar; test lung compliance: 0.66 ml/mbar).

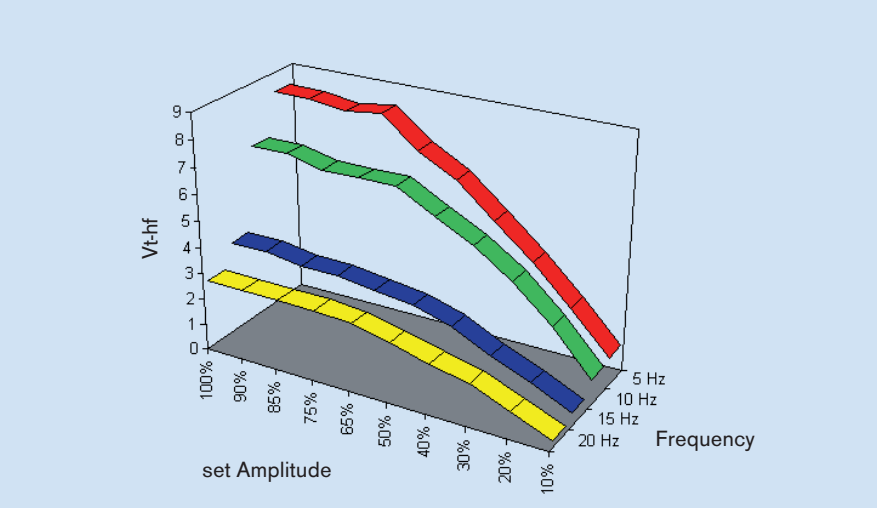


Figure 12.3: Oscillatory volume as a function of amplitude and frequency setting

12.2 Case reports

Case1

Female premature, 26th gestational week, birthweight 895 g. Cesarean section at premature rupture of membranes and pathologic cardiotocogram. APGAR 5/7/9, Ns-pH 7.19. Radiograph showed RDS stage 3 to 4. Natural surfactant was administered three times, 150 mg/kg in total. Despite relatively low peak pressures an interstitial emphysema develops on the third day of life. Around 7.45 the infant requires more and more oxygen, and is markedly hypercapnic. We decide to put her on HFV.

7.50: Upon switching over to oscillatory ventilation we choose to combine HFV and IMV first. We set the MAP by 2 mbar above that of the preceding conventional ventilation. Within few minutes oxygen demand decreases. Hypercapnia however persists. Oscillatory volumes are still too low (less than 2 ml/kg). Our aim is now to lower pCO_2 by specifically increasing DCO_2. Therefore, at

8.00: we turn the HFV frequency down from 10 to 7 Hz. The increased oscillatory volume results in continuously better CO_2 washout. Because of the interstitial emphysema we do without IMV now, trying to reduce barotrauma as much as possible. At FiO_2 of 0.5 we slightly lower mean airway pressure.

8.40: To counteract the rapid decrease in pCO_2 we increase frequency to 8 Hz again. Immediately VTHF and DCO_2 go down while pCO_2 rises again. Therefore we turn the frequency down to 7 Hz again. A radiograph shows lung expansion up to 8 rib level. We keep MAP constant..

9.00: With pCO_2 rapidly decreasing again, we reduce the amplitude to 80%; Then at

11.00: further down to 60%. With already improved lung compliance, however, there is no reduction in oscillatory volume.

11.15: Suddenly DCO_2 drops and pCO_2 rises. Secretion partially blocking the lumen of the ET tube turns out to be the cause.

11.25: After suctioning the situation soon normalises.

Mode Hour 11.25	IMV 7.45	IMV+HFO 7.50	HFO 8.00	HFO 8.30	HFO 8.40	HFO 9.00	HFO 11.00	HFO 11.15	HFO
IMV-Freq.	75	3	0	0	0	0	0	0	0
IMV-Peak	24	20	0	0	0	0	0	0	0
PEEP	4	12	14	12	12	12	12	12	12
MAP	10	12	14	12	12	12	12	12	12
FiO_2	0.70	0.55	0.50	0.50	0.50	0.50	0.40	0.50	0.50
HFO-Freq.		10	7	7	8	7	7	7	7
HFO-Ampl.%		100	100	100	100	80	60	60	70
V_{THF}		1.20	2.40	2.40	1.50	2.10	2.60	1.50	2.50
DCO_2		12	32	33	18	33	39	17	38
tc pO_2	60	70	63	65	65	71	49	61	58
tc pCO_2	80	78	55	52	65	44	36	60	39
pH	7.21			7.30		7.33			
Pulse	150	145	140	142	143	148			165
RR	55/32		52/28	55/30		58/35			46/29

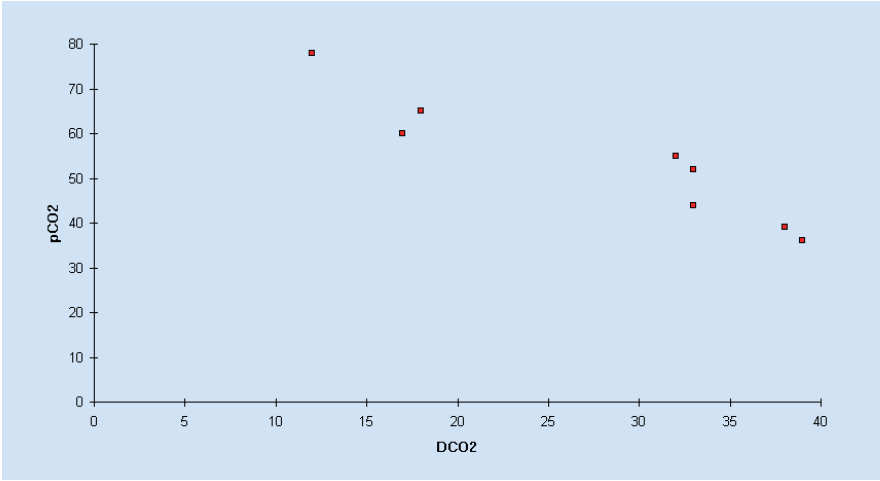


Figure 12.4: Relationship between pCO_2 and DCO_2 from case 1

Figure 12.4 depicts the relationship of DCO_2 and pCO_2 from this case. During this short time span a marked dependency shows.

Having received HFV for four days in total this patient is weaned off. The clinical situation has stabilised; the radiologic picture of PIE has improved. The final hours of the weaning process are outlined in the following table.

9.30: The patient is on oscillation alone, requiring low FiO_2 now; the amplitude setting is 60%. Due to the low oxygen demand and the improved interstitial emphysema we decide to wean her from HFV.
11.00: We combine HFV and IMV again but with reduced oscillation amplitude (40%). Still the reduction was too quick: DCO_2 goes down and pCO_2 goes up. With slightly reduced MAP we also observe a little decrease in pO_2.
11.30: An increase in IMV peak pressure to 20 mbar, and higher amplitudes and thereby higher VTHF and DCO_2 improve hypercapnia.
15.00: The CO_2 values have normalised, and at
16.00: we switch over to IMV alone at a rate of 25 bpm.

Two days later we finally extubate the infant.

Mode Hour 18.00	HFO 9.30	IMV+HFO 11.00	IMV+HFO 11.30	IMV+HFO 15.00	IMV
IMV-Freq.	0	8	8	12	25
IMV-Peak	0	18	20	20	20
PEEP	10	9	9	8	4
MAP	10	9.3	9.5	8.6	9.2
FiO_2	0.30	0.35	0.40	0.38	0.30
HFO-Freq.	7	7	7	7	0
HFO-Ampl.%	60	40	50	50	0
V_{THF}	2	1.70	2.10	2.20	0.00
DCO_2	27	15	25	27	0
tc pO_2	52	44	50	60	65
tc pCO_2	43	64	51	40	30
pH	7.36				7.46
Pulse	146	168	169	165	160
RR	38/19				

Case 2

Former premature of 25 weeks gestational age, birthweight 720 g. Surfactant administered twice. Condition after six weeks of assisted ventilation: BPD. Discharged after 17 weeks of in-patient treatment. Now 5 months old, 3300 g, receives assisted ventilation again because of respiratory insufficiency due to RSV bronchiolitis. Ribavirin treatment was initiated.

A radiograph of the lung shows both atelectasis and regions with large bubbles and overexpansion. Due to progressive deterioration we decide to apply oscillatory ventilation, even though a lung function test (occlusion method) has shown a considerable, largely peripheral obstruction (see figure 12.5).

0.00: Decision for HFV at peak pressures of 30 mbar and FiO_2 of 0.9..

0.15: Combining HFV and IMV, we set the MAP 5 mbar higher than during conventional ventilation. Soon oxygen requirement goes up. Despite 100% amplitude insufficient oscillatory volume VTHF of about 1.2 ml/kg causes progressive hypercapnia. Slight decrease in heart rate. Administration of Dopamin and Dobutrex as continuous infusion.

0.30: In spite of the reduced blood pressure we turn up MAP to 19 mbar, trying to improve oxygenation. Reducing the oscillatory frequency to 8 Hz yields higher VTHF and DCO_2 at this elevated MAP level. Within few minutes we observe a slight reduction in hypercapnia. Since blood pressure has gone up a little, we continue HFV.

1.00: Further reduction of oscillatory frequency to 6 Hz again increases VTHF and DCO_2. As a consequence, pCO_2 values normalise.

1.30-2.00: Oxygenation is deteriorating again. Not even a longer inspiratory time in IMV helps. We take another radiograph, which shows an increase in local overdistention. Once more we test lung function and find that static compliance has deteriorated, indicating increased FRC. Resistance has further increased. Since HFV has apparently led to a deterioration of the clinical situation, we return to conventional ventilation.

The flow-volume curve of case 2 shows a concave deformation. Such patients should not receive HFV because their condition is likely to deteriorate due to airtrapping.

Mode Hour	IMV 0.00	IMV+HFO 0.15	IMV+HFO 0.30	IMV+HFO 1.00	IMV+HFO 1.30	IMV+HFO 2.00
IMV-Freq.	30	3	3	3	3	3
Ti	0.6	0.6	0.6	0.6	0.6	1.2
IMV-Peak	30	30	30	28	27	27
PEEP	4	14	19	19	19	19
MAP	9	14	19	19	19	20
FiO_2	0.90	1.00	0.95	0.93	0.93	1
HFO-Freq.		10	8	6	6	6
HFO-Ampl.%		100	100	100	100	100
V_{THF}		4.00	5.30	6.80	6.30	6
DCO_2		162	202	264	220	218
tc pO_2	40	38	60	57	46	48
tc pCO_2	51	67	60	54	49	49
pH	7.32				7.35	
Pulse	158	142	144	146	160	
RR	101/64	74/43	87/43		89/51	

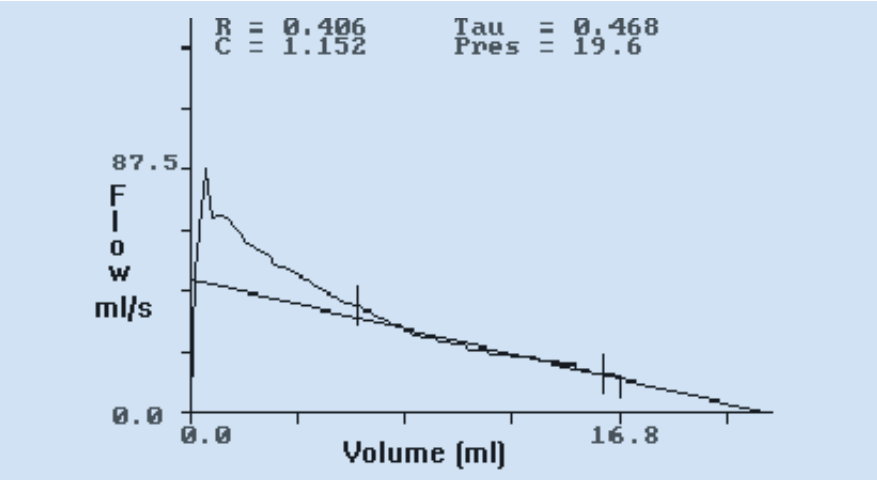


Figure 12.5: Example of a flow-volume loop of case 2

12.3 DCO_2 in 11 patients

We studied the relationship between pCO_2 and DCO_2 or VTHF, respectively in 11 neonates and infants receiving high-frequency ventilation. Considering short time intervals (1 to 6 hours), in 5 out of 11 patients we found the correlation of the regression line (pCO_2 as a function of DCO_2/kg and VTHF/kg) was relatively good (r=0.79 and r=0.72, respectively; see example in figure 12.4). In these and 3 more out of 11 patients an increase in DCO_2 or VTHF led to a marked decay in pCO_2. Taking into account the pCO_2 and DCO_2 (and VTHF) measurements in all of the 11 patients, however, we found correlation coefficients of only r=0.255 and r=0.288, respectively. With respect to ventilation control, the two parameters DCO_2/kg and VTHF/kg appear equivalent in this patient collective. The following table shows thresholds of DCO_2 above which pCO_2 was less than 50 mmHg. Accordingly, at VTHF above 2.5 ml/kg, 81% of the pCO_2 data points were less than 50 mmHg.

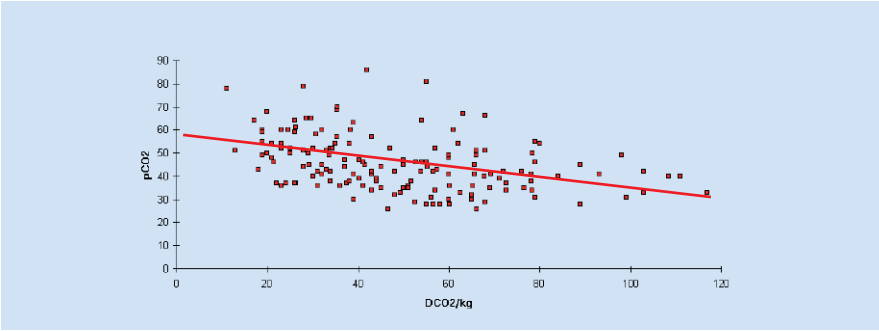


Figure 12.6: Measured data points of and correlation line between pCO_2 and specific DCO_2

DCO_2/kg	pCO_2 values below 50 mmHg
≤ 40	49%
40 to 60	85%
60 to 80	79%
> 80	100%

12.4 Results of HFV in a collective of neonates

From September 1993 until May 1995 61 patients received high-frequency ventilation with the Babylog 8000 at the pediatric intensive care unit of the A.K. Heidberg (Hamburg, Germany) and at the neonatologic intensive care unit of the Hopital Purpan, respectively (Toulouse, France) [96, 97].
In both clinics the indication for HFV was conventional ventilation failing (PIP > 24 mbar for pO_2 > 50 mmHg and pCO_2 < 65 mmHg). Moreover, the occurrence of barotrauma (pneumothorax, pneumopericardium, pulmonary interstitial emphysema) was regarded as an indication for HFV, too.

Main diagnoses	**up to 2 kg**	**above2 kg**
RDS	28	1
Pneumonia	3	
Barotrauma (pneumothorax, PIE))	5	3
BPD, MAS, ARDS, blood aspiration	1	9
CDH, lung hypoplasia, deformations	3	5
RSV-bronchiolitis		2
NEC	1	

Table 12.4.1

Lund diagnoses	up to 2 kg	above 2 kg
Homogeneous diffuse lung diseases	28	2
Inhomogeneous lung diseases	6	10
Airleak	7	5
PPHN (as main diagnosis)		3
additional PPHN (as second diagnosis)	9	9

Table 12.4.2

The main diagnoses as well as the findings with respect to the lung are summarized in tables 12.4.1 and 12.4.2, respectively, separated in two bodyweight categories.
All patients with RDS had received surfactant before HFV. In Hamburg HFV was combined with IMV in most cases whereas in Toulouse HFV was always used on its own.

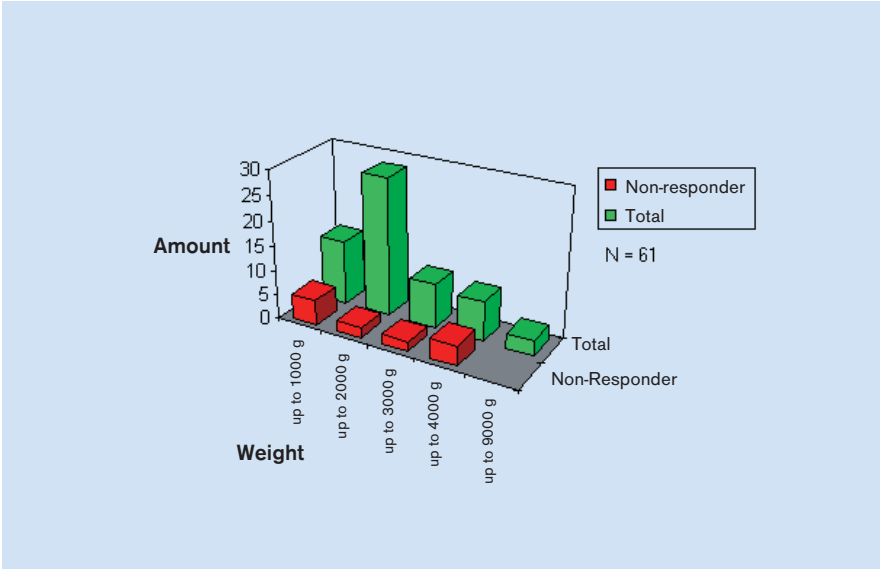


Figure 12.7: Bodyweight distribution of 61 patients at the beginning of oscillation. The red bars represent the numbers of non-responders.

The high-frequency treatment soon relaxed the critical ventilatory situation in 48 out of 61 patients HFV, but failed in 13 patients (figure 12.7).

After the onset of HFV the responders in all weight categories showed rapid improvement in blood gases, lung mechanics and ventilation parameters (figures 12.8 to 12.11). The elimination of the initial hypercapnia was most distinct with the small patients (figure 12.9). These partly dramatic changes require quick adaptation of ventilatory settings. Especially the increase in compliance (figure 12.11) can promote overinflation.
Failure of HFV was assumed when neither pCO_2 nor oxygenation index improved by at least 20% within 24 hours. With 2 out of 13 non-responders a contraindication (obstruction) was present.

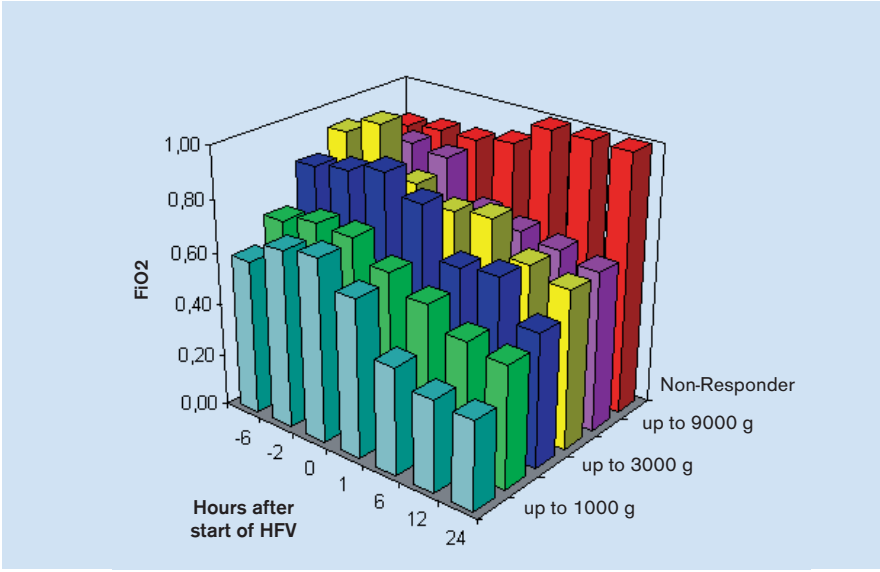


Figure 12.8: Development of oxygen requirement before and during HFV in different weight categories of responders and non-responders

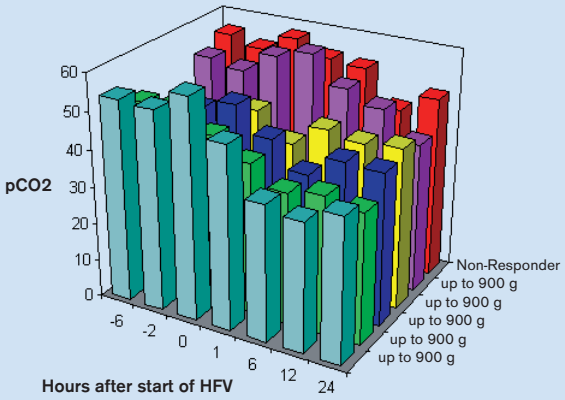


Figure 12.9: Development of CO_2 elimination before and during HFV in different weight categories of responders and non-responders

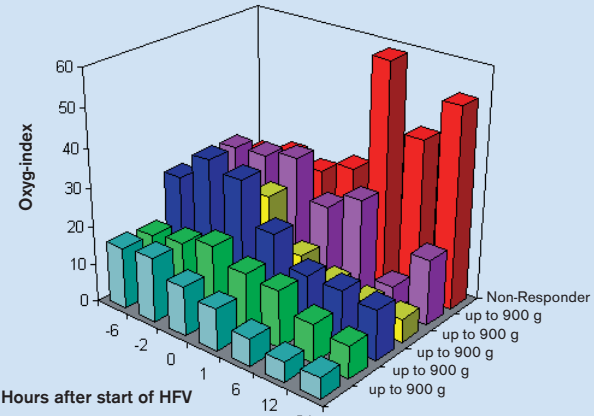


Figure 12.10: Oxygenation index (OI = MAP*FiO_2*100/pO_2) before and during HFV in different weight categories of responders and non-responders

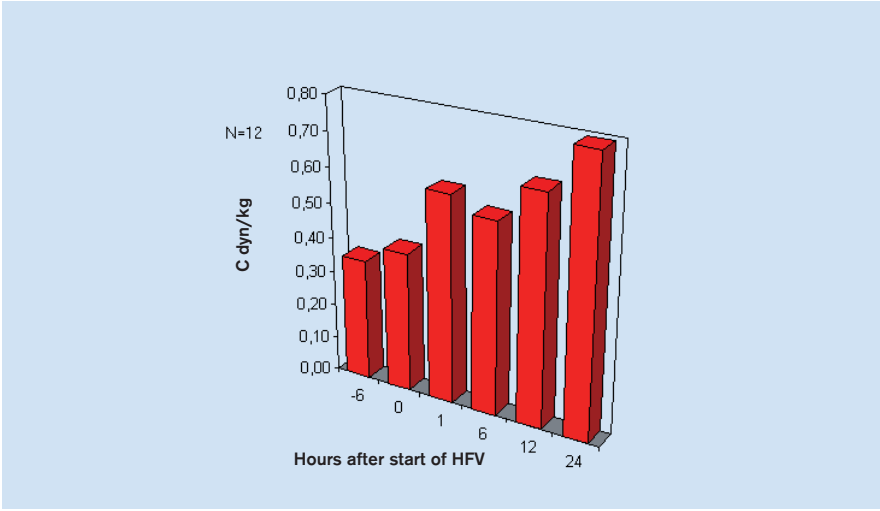


Figure 12.11: Dynamic compliance/kg with 12 HF-ventilated patients from Hamburg

The non-responders (mean body weight 2042 g) required significantly more oxygen and MAP at the beginning and in the further course of HFV than the responders (mean body weight 1982 g) and showed no improvement in oxygenation index. In addition CO_2 elimination was significantly worse in the non-responder group after 2 to 6 hours. (see figure 12.8.10).

The average age at the beginning of HFV was 8.5 days with the exception of one infant who was 1.2 years old, weighed 9 kg, and showed ARDS after aspiration. Duration of oscillation was between 6 hours and 15 days, 83 hours on average.
The mean oscillatory frequency was 8.9 Hz at the beginning of HFV and was lowered to 8.2 Hz in the further course. Mean airway pressure was 15 mbar on average at the onset and went down to 12.6 mbar within the first 24 hours.
The specific gas transport coefficient, DCO_2/kg, varied between average values of 47 and 63 ml^2/s with the patients from Hamburg. In Toulouse considerably higher values were found (139 to 154 ml^2/s). In some of these infants an ET tube leakage may explain the high values. No significant difference in CO_2 elimination was found between the patients in Hamburg and Toulouse.

The succes rate of HFV varied with the underlying diagnosis and is demonstrated in the following table. For better comparability the numbers are given in percent:

Results of HFV

lung disease	success	mortality
homogenous	83%	44%
inhomogenous	79%	28%
airleaks	80%	20%
PPHN	69%	47%
		N = 61

Airleaks occurred in four patients, probably as a complication of HFV. One of these children however had had an interstitial emphysema before HFV. In two patients showing imminent obstruction, progressive overexpansion was found. Therefore HFV was stopped before a barotrauma could develop. During the treatment severe intracranial haemorrhages occurred in four patients: two very small prematures (820 g and 750 g) with severe RDS and hypercapnia, two patients (1200 g and 1650 g) with marked PPHN and sepsis. Ten out of 28 RDS patients and one infant with lunghypoplasia in connection with diaphragmatic hernia later developed bronchopulmonary dysplasia. With most of the patients a slight drop in heart rate was observed. Necrotising tracheobronchitis did not occur.
In total 19 patients died (see table 12.4.3).

Causes of death:

Hamburg:	2 twins, 650 g severe asphyxia, hypothermia
	1 Potter sequence
	1 lung hypoplasia with multiple defects
	1 NEC/sepsis
Toulouse:	4 ICH grade 4
	4 PVL
	1 cardiac arrest with airleak and resuscitation
	1 lung hypoplasia
	2 sepsis (nosocomial infection), meningitis
	2 sepsis (nosocomial infection), meningitis
	1 asphyxia with MAS

12.5 Ventilation protocol

Name: Date of birth: Weight: Diagnoses

Date:

	Time								
Settings 1	Ti								
	Te								
	f-set (IMV)								
	FiO_2								
Sett. 2	HFO frequency								
	HFO amplitude								
Measurem.1	IMV peak								
	MAP								
	PEEP								
Measurem. 2	MV im								
	DCO_2								
	Vt-im								
	V_{THF}								
Patient data	pO_2								
	pCO_2								
	SaO_2								
	BGA								
	pulse								
	blood pressure								
	urine								

12.6 Abbreviations

BPD	Bronchopulmonary Dysplasia
C	Compliance
CDH	Congenital Diaphramatic Hernia
CLD	Chronic Lung Disease
CPAP	Continuous Positive Airway Pressure
DCO_2	Gas Transport Coefficient = $V_{THF}^2 * f$
f	Ventilation Frequency
FiO_2	Fraction of Inspiratory O_2 Concentration
FRC	Functional Residual Capacity
HFV	High Frequency Ventilation
HFJV	High Frequency Jet Ventilation
HFO	High Frequency Oscillation
HFOV	High Frequency Oscillatory Ventilation
ICH	Intracranial Haemorrhage
I:E	Inspiratory-to-Exspiratory Ratio
IMV	Intermittent Mandatory Ventilation
IPPV	Intermittent Positive Pressure Ventilation
kg	Kilogram bodyweight
MAP	Mean Airway Pressure
MV	Minute Volume
MVim	Inspiratory Minute Volume in IMV Ventilation Cycles
Paw	Airway Pressure
PEEP	Positive End-Exspiratory Pressure
PIE	Pulmonary Interstitial Emphysema
PIP	Peak Inspiratory Pressure
PPHN	Persistent Pulmonary Hypertension of the Newborn
PVL	Periventricular Leucomalacia
R	Resistance
RDS	Respiratory Distress Syndrome
RSV	Respiratory Syncitial Virus
SIMV	Synchronised Intermittent Mandatory Ventilation
SIPPV	Synchronised Intermittent Positive Pressure Ventilation
Ti	Inspiratory Time
Te	Expiratory Time

VIVE	Variable Inspiratory Flow, Variable Expiratory Flow
V_{THF}	Tidal Volume, mean over several inspiratory oscillation cycles
V_{Tim}	Tidal Volume of IMV ventilation breaths, measured in inspiration

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