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Assessment of high-frequency neonatal ventilator performances

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Abstract *Objective*: To assess the efficacy and reliability of neonatal high-frequency ventilators.
Design: Bench evaluation of neonatal high-frequency ventilators.
Setting: Physiology department and university hospital neonatal intensive care unit.
Interventions: HFV-Babylog 8000 (Dräger Medical), OHF 1 (Dufour), and SensorMedics 3100A (SensorMedics) ventilators were connected to a neonatal test-lung. Tidal volume, peak-to-peak pressure amplitude, and mean airway pressure were measured for several ventilator settings, endotracheal tube sizes, and lung compliances.
Measurements and results: Increasing peak-to-peak pressure resulted in a linear increase in tidal volume delivery in the 0–30% range of maximum amplitude. No significant increase in tidal volume was observed with the HFV-Babylog 8000 when pressure amplitude was above 50%. The maximum tidal volume delivered was substantially smaller with the HFV-Babylog 8000 than with the OHF 1 or SensorMedics 3100A. Tidal volume increased with endotracheal tube size with all three ventilators. Increasing test-lung compliance resulted in lower tidal volumes only with OHF 1. Decreasing mean airway pressure was responsible for a decrease in tidal volume delivery with HFV-Babylog 8000.
Conclusion: We found that under our test conditions two of the three ventilators delivered adequate tidal volumes at the usual frequency of 15 Hz, regardless of the size of the endotracheal tube and of the mechanical properties of the respiratory system. When lung compliance increased or mean airway pressure decreased, both of which are common events during the recovery phase of hyaline membrane disease, we found that the intrinsic properties of two of the ventilators tested were responsible for a decrease in tidal volume. This decrease may account for some cases of heretofore unexplained hypercapnia.

Key words High-frequency ventilation · Pediatric intensive care

Introduction

High-frequency ventilation (HFV) uses frequency rates above 300/min (5 Hz), which have been shown to provide adequate ventilation and oxygenation in neonates with respiratory failure at tidal volumes smaller than the respiratory dead space [1–3]. Although the ability of HFV to improve outcomes remains unproven, the use of HFV has expanded noticeably over the last 5 years in neonatal intensive care units [4].

Several techniques are collectively referred to as HFV, namely high-frequency oscillation, high-frequency flow interruption, and high-frequency jet ventilation [1, 5]. In 1987, Fredberg et al. [6] performed a bench evaluation of the high-frequency ventilators available at the time, and found that the tidal volumes delivered were highly dependent on the frequency used and on the load produced by the endotracheal tubes. No such evaluation has been performed for the high-frequency ventilators used at present. In Europe, the most widely used devices include two high-frequency oscillators, the OHF 1 and the SensorMedics 3100A, and one ventilator which provides high-frequency oscillation of the exhalation valve membrane, the HFV-Babylog 8000. Furthermore, the parameter settings of these ventilators include frequency, peak-to-peak pressure amplitude, and mean airway pressure, and the relationships between these settings have not been evaluated.

In this study, we evaluated the main factors that may influence the mechanical performances of commercially available neonatal high-frequency ventilators, with the goal of analyzing their efficiency and reliability in simulated clinical conditions. Indeed, the incomplete characterization of these devices and of their mechanical interaction with the respiratory system often complicates the interpretation of published work on HFV.

Materials and methods

Ventilators

Three neonatal high-frequency ventilators were studied. Each ventilator was checked by the manufacturer before the study. The ventilators were the HFV-Babylog 8000 (Dräger Medical, Lübeck, Germany), the OHF 1 (Dufour, Villeneuve d'Asc, France), and the SensorMedics 3100A (SensorMedics, Bilthoven, The Netherlands). The three main parameters controlled by these ventilators were peak-to-peak pressure amplitude, mean airway pressure, and frequency rate.

The HFV-Babylog 8000 is based on "membrane oscillation," in which a continuous flow (from 10 to 30 $l \cdot min^{-1}$) is modulated by high-frequency oscillation of the exhalation valve membrane (5–20 Hz). Control of mean airway pressure (3–30 cmH_2O) is ensured by a number of systems that are automatically modulated by the ventilator: (a) active expiration, provided by a Venturi effect at the expiratory port; (b) modulation of the continuous flow; and (c) modification of the inspiratory/expiratory (I/E) ratio (1/5–1/1). Peak-to-peak pressure amplitude is determined on an arbitrary scale from 0 to 100%. Tidal volume is monitored by a flow sensor placed in the Y-piece. All these parameters are displayed in digits.

The OHF 1 provides high-frequency ventilation by transmitting the oscillation (10–20 Hz) of a piston directly to the Y-piece via a rigid tube. A steady transverse ("bias") flow of fresh gas (0–20 $l \cdot min^{-1}$) is delivered to the Y-piece to maintain proper gradients for oxygen and carbon dioxide transfer. An adjustable resistance is placed at the end of this bias flow circuit. Mean airway pressure can vary from 5 to 30 cmH_2O, according to the bias flow and expiratory resistance settings. Peak-to-peak pressure amplitude can be increased from 0 to 115 cmH_2O. I/E is set at 1/1. Pressure signals are displayed in digits. Tidal volume is not monitored.

The SensorMedics 3100A provides HFV which transmits the oscillations (3–15 Hz) of a loudspeaker directly to the Y-piece via a low-compliance tube. The bias flow (0–40 $l \cdot min^{-1}$) is delivered to the Y-piece. There is an adjustable resistance at the end of the bias flow circuit. Mean airway pressure can vary from 3 to 45 cmH_2O, according to bias flow and expiratory resistance settings. Peak-to-peak pressure amplitude can be increased from 0 to 90 cmH_2O. The I/E ratio can vary within the range 1/2 to 1/1. Pressures are displayed in digits. Tidal volume is not monitored.

In addition to high frequency oscillatory tidal volumes, large tidal volumes, called sighs, can be generated on demand by the HFV-Babylog 8000 and OHF 1.

Experimental set-up

The high-frequency ventilators were connected to a lung model composed of an endotracheal tube and a plexiglass sphere in series [7]. Six conditions were tested by combining three endotracheal tubes (i.d. 2.5, 3, and 3.5 mm) with two sphere volumes simulating either a normal neonatal lung (compliance = 5 ml/cmH_2O) or a lung with hyaline membrane disease (compliance = 1 ml/cmH_2O).

The ventilators were studied with the circuit tubings recommended by the manufacturers. These tubings were tested for leaks.

"Alveolar pressure" was measured using an 8510-2 Endevco pressure transducer (San Juan Capistrano, Calif., USA) placed in the test-lung. Pressure variations in the sphere were assumed to be instantaneous, since the sphere diameters were much smaller than the wavelength of the oscillations. Airway pressure was measured using an identical pressure transducer connected to a hole drilled in a standard endotracheal tube connector in such a way that the head of the transducer was flushed with the inner wall of the tube and did not interfere with the streamline of the flow. No tubings were used for these two pressure transducers, which have a flat frequency response up to 20 kHz. Signals were digitized at 512 Hz, using an MP 100 Biopac system (Goletta, USA) connected to a 6100 Macintosh computer. Tidal volume (V_T) was calculated from alveolar pressure amplitude using the equation $V_T = \Delta P \cdot C$, where ΔP is the amplitude of the alveolar pressure and C the compliance of the test-lung. C was determined from a calibration procedure during which 2 and 5 ml air were injected into the spheres (in less than 200 ms). Adiabatic conditions can be assumed for both the calibration procedure and the 5–20 Hz oscillation studies [6].

Tidal volume tests

In the first part of the study, mean airway pressure was set at 10 cmH_2O and peak-to-peak pressure amplitude at the maximum value for each ventilator. V_T delivery was measured for increasing rates of frequency (5, 10, 15, and 20 Hz, if possible). This test was performed for the three endotracheal tube sizes and the two volume compliances.

The relationship between the peak-to-peak pressure amplitude setting and V_T was evaluated by gradually increasing the peak-to-peak pressure amplitude from the minimum to the maximum value for each ventilator (5–100% for the HFV-Babylog 8000, 6–115 cmH_2O for the OHF 1, and 4–90 cmH_2O for the SensorMedics 3100A). This test was performed with an endotracheal tube size of 2.5 mm, a test-lung compliance of 5 ml/cmH_2O, a frequency of 15 Hz, and a mean airway pressure of 10 cmH_2O.

To evaluate the interdependence between V_T and mean airway pressure set on the ventilator, we measured V_T at five predetermined mean airway pressures (5, 10, 15, 20, 25 cmH_2O). This test was performed with an endotracheal tube size of 2.5 mm, a test-lung compliance of 5 ml/cmH_2O, a frequency of 15 Hz, and a peak-to-peak pressure amplitude providing a V_T of 2 ml.

Monitoring test

To evaluate the reliability of ventilator monitoring, the mean airway pressure and fractional inspired oxygen (FIO_2) settings displayed on the front panel of the ventilators were compared with the actual values measured simultaneously using an independent method. In addition, monitored V_T values were compared with measured values for the HFV-Babylog 8000 ventilator. Mean airway pressure, and V_T for the HFV-Babylog 8000 ventilator, were obtained from data gathered during evaluations of ventilator performance.

FIO_2 monitoring was assessed by setting the ventilator FIO_2 on 0.21, 0.25, 0.30, 0.50, and 0.75. Samples of inspiratory gas were taken with a 50-ml syringe and analyzed in duplicate using an ABL 30 blood gas analyzer (Radiometer, Copenhagen, Denmark).

Results

Frequency- and load-dependence of V_T

Changes in V_T in the frequency range 5–20 Hz, with a 2.5-mm endotracheal tube and a test-lung compliance of 1 ml/cmH_2O are shown in Fig. 1 for each of the three ventilators. There were striking differences in the performance of the three ventilators: at a given frequency rate, the maximum V_T delivered was noticeably smaller with HFV-Babylog 8000 than with the OHF 1. When peak-to-peak pressure amplitude was set at the maximum value, the SensorMedics 3100A ventilator delivered supraphysiologic V_T, especially at 5 and 10 Hz (Fig. 1).

When endotracheal tube size was increased, V_T increased substantially, as shown in Fig. 2. This effect was more marked with the OHF 1 and the SensorMedics 3100A ventilators than with HFV-Babylog 8000 (Fig. 2).

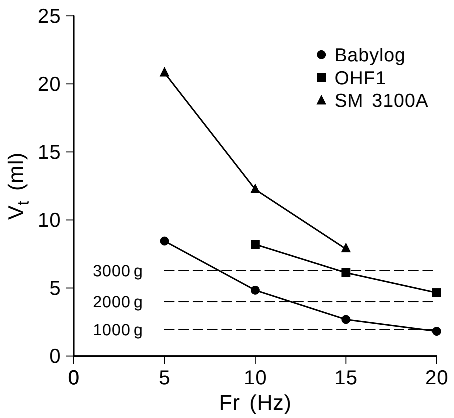

Fig. 1 Tidal volumes V_T obtained with the maximum pressure amplitude settings of the three high-frequency ventilators tested: HFV-Babylog 8000 *Babylog*, OHF 1, and SensorMedics 3100A *SM 3100A*. Measurements were made in the range 5–20 Hz at the frequencies available for each ventilator. Mean airway pressure was 10 cmH_2O, endotracheal tube size was 2.5 mm, and test-lung compliance was 1 ml/cmH_2O. *Horizontal broken lines* indicate tidal volumes of 2 ml/kg for neonates weighing 1000, 2000, and 3000 g. At a frequency *Fr* of 15 Hz, Babylog delivered adequate tidal volumes in this test condition only to neonates weighing less than 1500 g; at lower frequencies, heavier neonates could be ventilated. In contrast, the two other ventilators were powerful enough to deliver adequate volumes to neonates weighing 3000 g at frequencies of 15 Hz or less. SM 3100A generated very high volumes at this maximum amplitude pressure setting

Table 1 gives the overall results for changes in V_T according to frequency rate, endotracheal tube size, and test-lung compliance. When test-lung compliance increased, V_T was lower with the OHF 1, higher with the SensorMedics 3100A, and virtually unchanged with the HFV-Babylog 8000.

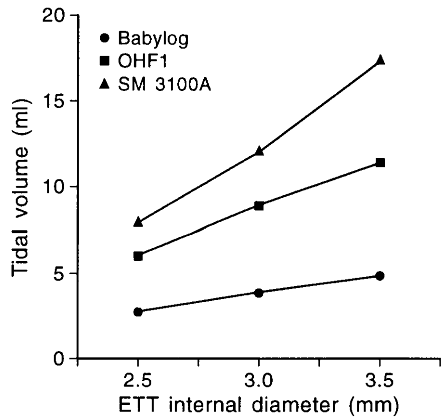

Fig. 2 Tidal volume variations resulting from an increase in endotracheal tube *ETT* size (2.5, 3, and 3.5 mm). Three ventilators were compared: HFV-Babylog 8000 *Babylog*, OHF 1, and SensorMedics 3100A *SM 3100A*, using the same mean airway pressure setting of 10 cmH_2O, maximum pressure amplitude, a frequency rate of 15 Hz, and a test-lung compliance of 1 ml/cmH_2O

Table 1 Tidal volumes delivered by the three high-frequency ventilators tested, which were connected to endotracheal tubes with i.d.'s of 2.5, 3, or 3.5 mm and to a test-lung compliance c of 1 or 5 ml/cmH_2O. Peak-to-peak pressure amplitude was set at the maximum value and mean airway pressure was 10 cmH_2O. Results are expressed in ml for the measurements performed with the test-lung compliance of 1 ml/cmH_2O and as the percent variation of this value when the test-lung compliance was changed to 5 ml/cmH_2O

	C = 1 ml/cmH_2O (ml)			C = 5 ml/cmH_2O (%)		
	2.5	3	3.5	2.5	3	3.5
HFV-Babylog 8000						
5 Hz	8.4	11.6	14.2	–2	0	0
10 Hz	4.7	6.5	7.7	–1	0	0
15 Hz	2.7	3.9	4.9	–6	0	–1
20 Hz	1.7	2.6	3.3	–2	2	–4
OHF 1						
10 Hz	8.0	11.4	14.8	–29	–4	–7
15 Hz	6.0	8.9	11.5	–26	–3	–6
20 Hz	4.6	6.6	8.7	–25	–5	–8
SensorMedics 3100 A						
5 Hz	21.0	32.0	48.0	23	18	0
10 Hz	12.3	29.0	26.1	26	25	0
15 Hz	8.0	10.0	17.5	58	35	14

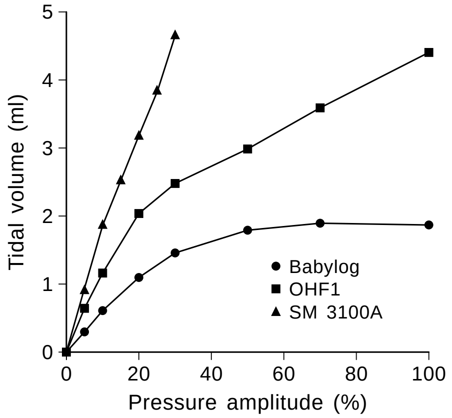

Fig. 3 Tidal volume variation resulting from an increase in pressure amplitude (expressed as a percentage of the maximum pressure amplitude). Three ventilators were compared: HFV-Babylog 8000 *Babylog*, OHF 1, and SensorMedics 3100A *SM 3100A*, using the same mean airway pressure setting of 10 cmH_2O, a frequency rate of 15 Hz, an endotracheal tube size of 2.5 mm, and a test-lung compliance of 5 ml/cmH_2O. Tidal volumes increased quasi-linearly in the 0–30% range of pressure amplitude, whereas the increase was considerably smaller above this range

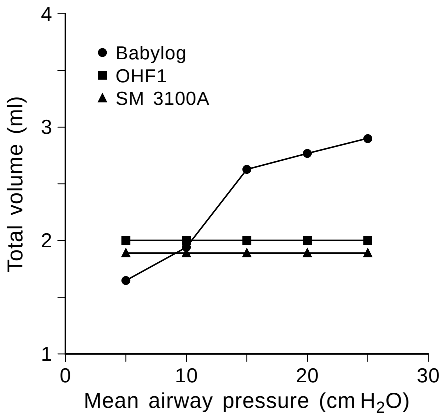

Fig. 4 Tidal volume variation resulting from an increase in mean airway pressure. Three ventilators were compared: HFV-Babylog 8000 *Babylog*, OHF 1, and SensorMedics 3100A *SM 3100A*. Pressure amplitude was set to obtain a tidal volume of 2 ml at a frequency rate of 15 Hz. Endotracheal tube size was 2.5 mm, and test-lung compliance was 5 ml/cmH_2O

Influence of peak-to-peak pressure amplitude on V_T

V_T increased when peak-to-peak pressure amplitude increased. The relationship between these two parameters was linear in the range 0–30% of maximum peak-to-peak pressure amplitude and clearly nonlinear at higher peak-to-peak pressure amplitudes (Fig. 3). In terms of V_T, there was little advantage in increasing the peak-to-peak pressure amplitude above 50% with the HFV-Babylog 8000 ventilator (increasing the pressure amplitude setting from 50 to 100% resulted in an increase in V_T of only 6%). By contrast, some advantage was seen with the OHF 1 (V_T increase was 32% for the same increase in pressure amplitude). The SensorMedics 3100A ventilator generated a considerably higher V_T than the other two ventilators, and the increase was 11% when the amplitude setting was changed from 50 to 100% (data not shown).

Interdependence between mean airway pressure and V_T

When mean airway pressure varied in the range 5–25 cmH_2O, V_T did not change with the OHF 1 or SensorMedics 3100A (Fig. 4). With the HFV-Babylog 8000, V_T decreased as mean airway pressure decreased: for instance, a decrease in mean airway pressure from 20 to 10 cmH_2O resulted in a 30% decrease in V_T.

Influence of I/E ratio on mean airway and alveolar pressures

With the SensorMedics 3100A ventilator the I/E ratio could vary between 1/1 and 1/2. When standard peak-to-peak pressure amplitude settings for neonates were used (up to 30 cmH_2O), a decrease in I/E ratio from 1/1 to 1/2 had no effect on mean airway or alveolar pressure. By contrast, with higher pressure amplitudes, the mean airway pressure rose above the alveolar pressure when the I/E ratio was 1/2 (data not shown).

Monitoring

The HFV-Babylog 8000 estimated the FIO_2 with an error of less than 3% when the FIO_2 was in the range 0.21–0.30 and less than 5% when the FIO_2 was 30% or more. Overestimation in the range 21–30% was more marked with the SensorMedics 3100A and the OHF 1 (6 and 10%, respectively).

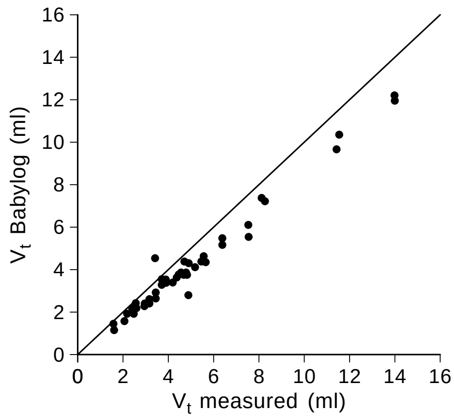

Fig. 5 Reliability of tidal volume monitoring of HFV-Babylog 8000 *V_T Babylog*. On the vertical axis, tidal volume is computed as the ratio of expiratory minute volume to the frequency rate. Measured tidal volume V_T is plotted on the horizontal axis

Mean airway pressure monitoring was adequate with the three ventilators (differences with measured values were –10%).

V_T was monitored only with the HFV-Babylog 8000 ventilator. We found that the flow sensor underestimated the V_T by approximately 20% (Fig. 5).

Discussion

The results of this study show that performance characteristics vary widely across high-frequency ventilators. We found that, under our test conditions, two of the ventilators provided adequate V_T (2 ml/kg) [8, 9] at the usual frequency of 15 Hz, irrespective of the size of the endotracheal tube and of the mechanical properties of the respiratory system. In addition, our results demonstrate that the intrinsic properties of two of the three ventilators studied may be responsible for a decrease in V_T when downstream compliance increases or when mean airway pressure decreases, two events that occur during the recovery phase of the respiratory distress syndrome (RDS). This decrease in V_T may contribute to the impairment of alveolar ventilation during this phase.

Our experimental set-up was identical to that used in the bench evaluation of high-frequency ventilators performed by Fredberg et al [6] – namely, an endotracheal tube connected to a gas compliance system (tube-bottle system). Although this model does not faithfully replicate the mechanical characteristics of the RDS lung, it is of value for identifying factors that influence the mechanical performance of ventilators. Despite wide differences in design among the ventilators tested, we consistently found an inverse relation between V_T and frequency oscillation and a positive relation between V_T and endotracheal tube size, in keeping with Fredberg's results. An ideal high-frequency ventilator should have a high "internal impedance" to ensure that its output remains relatively insensitive to moderate changes in respiratory system impedance [6, 10]. The load-dependence of V_T demonstrates that the ventilators tested in this study are far from ideal.

Removal of carbon dioxide is mainly dependent on V_T and, to a lesser extent, on oscillatory frequency (f): CO_2 removal $= a \cdot V_T^b \cdot f^c$, with $b > c$ [8, 9, 11, 12]. Although the data from our bench evaluation of ventilators cannot accurately predict the V_T that would be delivered by each ventilator in a specific clinical situation, they suggest that there are substantial differences in delivery of V_T among the three ventilators.

The SensorMedics 3100A was the most powerful ventilator in our study. When peak-to-peak pressure amplitude was set at the maximum value, this ventilator delivered supraphysiologic V_T, especially at 5 and 10 Hz. This characteristic has led the manufacturer to recommend a frequency rate of 15 Hz for premature babies with RDS and a peak-to-peak pressure amplitude of no more than 30 cmH_2O. It is important to bear in mind that with this ventilator a decrease in frequency induces a major increase in V_T associated with a risk of baro-/volotrauma, even when the pressure amplitude setting remains unchanged.

The OHF 1 appeared to be well suited to the delivery of 15 Hz high-frequency oscillations in neonates. With this ventilator, we recommend that the frequency rate be decreased to 10 Hz when the V_T is too small.

By contrast, the HFV-Babylog 8000 clearly failed to deliver adequate V_T at frequencies <15Hz, regardless of the size of the endotracheal tube and of the mechanical properties of the test-lung. If we assume that the data generated by our model predict the maximum V_T delivered to an infant with RDS, we can conclude from our study that the HFV-Babylog 8000, set at a frequency of 15 Hz, delivers adequate V_T only in small neonates (body weight <1500 g) under our test conditions. When the V_T is too small to achieve adequate CO_2 removal with maximum peak-to-peak pressure amplitude, the frequency rate should be decreased and/or the endotracheal tube changed if the latter is inappropriate. With the HFV-Babylog 8000 ventilator, a decrease in frequency to less than 8 Hz can result in a decrease in the I/E ratio to 1/5 with an asymmetric waveform, which is clearly not an oscillatory pattern.

Our study provides clues to the cause of the unexplained hypercapnia sometimes observed during the recovery phase of RDS treated by HFV with the OHF 1 or HFV-Babylog 8000 ventilators (this is a common, albeit underreported, event in neonatal intensive care units). Contrary to Fredberg et al. [6], we found that modifications in respiratory compliance and mean airway pressure induced unexpected changes in V_T delivery. These two modifications are common during the recovery phase of RDS, when the compliance of the diseased lungs improves and when the weaning strategy is based on a gradual decrease in mean airway pressure [3]. Our data suggest that hypercapnia may occur as a result of a decrease in V_T following a decrease in mean airway pressure (with the HFV-Babylog 8000) or an increase in lung compliance (with the OHF 1).

In contrast to the OHF 1 and SensorMedics 3100A, the HFV-Babylog 8000 showed a marked decrease in V_T when the mean airway pressure was lowered. This feature can be ascribed to the design of the ventilator, which cannot generate negative expiratory pressures of less than –4 cmH_2O, in contrast to the two other ventilators, which can produce much lower values. With the HFV-Babylog 8000, the only means of achieving a decrease in mean airway pressure are the modulation of the continuous flow and lowering of the I/E ratio. When these fail, the decrease in mean airway pressure is accompanied by a decrease in peak-to-peak pressure amplitude and, therefore, in V_T.

In addition to the decrease in mean airway pressure used to wean the patient, in the RDS recovery phase there is an increase in lung compliance. A surprising observation was made for the OHF 1 ventilator, which delivered lower V_T when test-lung compliance was increased from 1 to 5 ml/cmH_2O. This finding cannot be explained on the basis of the simple mechanical model used in our study to replicate the neonatal respiratory system. This model is essentially composed of a resistance (R, the small-diameter endotracheal tube) and of a compliance (C). It has been evaluated by Isabey et al. [13], who found that the pressure amplitude ratio between the alveolar pressure swing (ΔP_A) and the pressure swing at the inlet of the endotracheal tube (ΔP_T) was inversely related to the time constant of the system (R·C) and to the frequency (f), according to the following formula:

$$\frac{\Delta P_A}{\Delta P_T} = \frac{1}{\sqrt{1 + (2 \cdot \pi \cdot f \cdot R \cdot C)^2}}$$

Any increase in C results in an increase in the time constant, and consequently in a decrease in the ΔP_A swing for a given ΔP_T value. However, the tidal volume (ΔV) remains virtually unchanged, since $\Delta V = C \cdot \Delta P_A$, $\frac{\Delta V}{\Delta P_T} = \frac{1}{\sqrt{1+(2 \cdot \pi \cdot f \cdot R \cdot C)^2}}$ or $\approx \frac{1}{2 \cdot \pi \cdot f \cdot R}$ under our experimental conditions.

A model taking into account the inertance within the airways can also be used and may lead to different conclusions when endotracheal tube volume and/or frequency are higher than in the present study [13].

In fact, our finding that V_T was lower when test-lung compliance increased was mainly due to a decrease in peak-to-peak pressure amplitude. Indeed, with a 2.5-mm endotracheal tube, a 25% decrease in peak-to-peak pressure amplitude was noted when compliance was increased from 1 to 5 ml/cmH_2O (see Table 1). No such decrease occurred when the ventilator was connected to a 3-mm or 3.5-mm endotracheal tube. We have no explanation for this observation, and a detailed analysis of the balance between the internal impedance of the ventilator and the external impedance of the test-lung would be needed to further describe this phenomenon [10]. This paradoxical decrease in V_T when compliance increases may contribute to the occurrence of hypercapnia during recovery from RDS. Our data suggest that the pressure amplitude generated by the OHF 1 ventilator should be checked carefully, especially when respiratory mechanics vary.

The HFV-Babylog 8000 is the only high-frequency ventilator that monitors V_T, whereas all ventilators monitor peak-to-peak pressure amplitude. Because numerous parameters influence V_T delivery, mainly the frequency rate and mechanical properties of the respiratory system, monitoring the V_T delivered during HFV is very useful and should be provided by every high-frequency ventilator as a means of improving safety. For instance, partial obstruction of the endotracheal tube by secretions can result in a decrease in V_T responsible for a decrease in CO_2 removal in newborns that can be missed if V_T is not monitored.

In conclusion, this study was designed to investigate the performance of newly available high-frequency neonatal ventilators. Our findings suggest that efficiency in terms of V_T and interactions between parameters should be taken into account when adjusting ventilation to obtain adequate CO_2 removal in neonates. The design of high-frequency ventilators should be improved to meet two requirements: (a) delivery of a constant V_T in the range 5–20 Hz, regardless of the load required by the respiratory system, and (b) V_T monitoring.

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