Resonance frequency in respiratory distress syndrome

S Lee, A D Milner

Abstract

Aim—To observe how the resonance frequency changes with the course of respiratory distress syndrome (RDS), by examining the effect of changing static compliance on the resonance frequency in premature infants.

Methods—In 12 ventilated premature infants with RDS (mean gestational age 26.6 weeks, mean birth weight 0.84 kg), resonance frequency and static compliance were determined serially using phase analysis and single breath mechanics technique respectively in the first seven days of life.

Results—The minimum number of measurements done in any one baby was three and maximum was five in this seven day study period. The first measurement in each baby was done within the first 72 hours of life. The increase in compliance in this period varied from 27% to 179%. The variation in the corresponding resonance frequency was within 2 Hz in eight babies and within 6 Hz in all recruited babies.

Conclusions—The resonance frequency of the respiratory system in preterm infants with RDS remains remarkably constant in the early stages of the illness, despite relatively large changes in static compliance. (Arch Dis Child Fetal Neonatal Ed 2000;83:F203–F206)

Keywords: resonance frequency; respiratory distress syndrome; high frequency oscillation; compliance

Newborn Respiratory Unit, Department of Paediatrics, 4th floor, North Wing, St Thomas' Hospital, London SE1 7EH, UK
S Lee
A D Milner

Correspondence to:
Prof. Milner
email:
anthony.milner@kcl.ac.uk

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Figure 1 Phase relationship of the driving signal, resistance, elastance, and inertance.

In 1972, Lunkenheimer introduced the technique of high frequency oscillatory ventilation (HFOV).¹ Since then, the technique has been increasingly applied in neonatal practice. The main advantage of HFOV over conventional ventilation is the reduction in pressure swing in the airways, which is believed to be contributing to both short and long term respiratory morbidity in these babies, in the forms of pulmonary airleaks and chronic lung disease. Previous studies have shown that this technique could improve pulmonary outcome in premature neonates with respiratory distress syndrome, especially when used early in the course of illness.^{2,3} The traditional frequency used for oscillation is 10 Hz. In theory, carbon dioxide elimination is dependent on oscillating frequency.⁴ However, the reduction in P_{aCO_2} at 10 Hz compared to 15 Hz, although significant, was small. This can be explained by the interaction between two opposing factors: at 15 Hz, the frequency is obviously higher but at 10 Hz the performance of the oscillator is better. A further factor is that 15 Hz is closer to the resonance frequency of the respiratory system at which ventilation is expected to be most efficient.⁵ The resonance frequency of the respiratory system is the frequency at which elastance (the reciprocal of compliance or a measure of the resultant pressure per unit volume changed) and inertance (force necessary to cause acceleration or deceleration of a mass) cancel out. Inertance is normally of negligible magnitude; but in the setting of high frequency ventilation, the force necessary to cause acceleration and deceleration of the lung mass becomes significant. This is an exciting prospect as elastance, which is a major contributor to difficulty in ventilation in the surfactant deficient lung, is eliminated simply through the mechanics of oscillation.

In order to ascertain the feasibility of ventilating infants with the resonance frequency of their respiratory system, we examined the variation of this frequency with the course of respiratory distress syndrome. If this frequency is highly variable from hour to hour, it would not be practical in a clinical setting. We felt that the most representative clinical variable of the illness is static compliance. Static compliance reflects the elastic properties of the lungs and is defined as the amount of pressure necessary to stretch the system. Therefore, we designed our study to examine the effect of changing static compliance on the resonance frequency in premature infants with respiratory distress syndrome.

Table 1 Patient characteristics

Subject	Gestation (wk)	Sex	Birth wt (kg)
1	25+1	M	0.74
2	26+3	M	0.54
3	25+4	F	0.86
4	26	M	0.8
5	25+4	M	0.85
6	27	M	0.995
7	29	F	1.11
8	28+4	M	0.89
9	24+5	F	0.72
10	26+2	M	0.93
11	26+1	M	0.7
12	28+6	F	0.97

Methods

MEASUREMENT OF RESONANCE FREQUENCY OF THE RESPIRATORY SYSTEM

The resonance frequency was determined using phase analysis. This technique employs the principle of the forced oscillatory method for measuring respiratory impedance and has been described previously in detail.^{6,7} In an oscillating system driven by a sine wave pump, airflow or ventilation is only possible after impedance has been overcome. Impedance is made up of resistance, elastance, and inertance. Figure 1 shows the phase relationship of these forces.⁸ At resonance frequency, elastance and inertance become equal in magnitude, and as they are 180° out of phase, they cancel out. Flow then becomes in phase with resistance, as this is the only opposing force.

The oscillating system was set up by incorporating a custom built, piston based oscillator with a sine-cosine electrical generator into a conventional ventilator circuit, using either a Sechrist Infant Ventilator, model IV-100B or SLE2000 Infant Ventilator. The conventional ventilator provided the continuous distension pressure, while the oscillator provided the oscillations via a sine wave pump. Pressure at airway opening, which is a representation of resistance, was measured using a Validyne DP 103 pressure transducer through

a side port of the endotracheal tube connector by a 15 cm long, 0.2 cm diameter tubing. Previous studies on dummy lung had shown that this produced critical damping so that there was neither significant augmentation or damping of the signals up to 30 Hz.^{9,10} Pressure changes at airway opening and the driving signal were recorded simultaneously onto magnetic tape via a frequency modulated tape recorder. The data acquired were then fed into a custom built program on a desktop computer, which identifies the frequency at which phase difference between these two signals is zero degrees—that is, when the two traces are in phase. The digital data acquisition system used has an anti-alias filtering device and the signals from the magnetic tape were sampled at 2000 Hz. The reproducibility of the phase analysis program had been checked by repeating each measurement four times, and was found to be within 1 Hz.^{6,7}

MEASUREMENT OF STATIC COMPLIANCE

This is determined using the single breath occlusion technique.¹¹ Pressure changes at airway opening were measured using the same pressure transducer as mentioned above at the same site. A Gould pneumotachograph was added into the ventilator circuit next to the endotracheal tube connector to measure flow. Monitoring was done with the infant on a conventional ventilator circuit. Occlusion at the top of a ventilator breath was achieved using a shutter system with an added dead space of 1.6 ml. The pressure and flow traces were directly acquired onto a custom built program on a desktop computer. This program integrated the flow trace to give a volume trace. With each occluded breath, a pressure-volume curve was plotted during the passive expiratory phase, the gradient of which was calculated as the time constant (τ_{rs}). Extrapolation of the slope of the flow-volume profile to zero flow allows the estimation of the total volume that would be exhaled if the baby emptied his lungs, with no influence from the ventilator or the effect of the Hering-Breuer deflationary reflex. Ratio of this volume to the corresponding pressure change was calculated as the static compliance (C). Resistance (R) could then be derived from the formula: $\tau_{rs} = R \times C$. At least 10 occluded breaths were sampled and the mean of all 10 measurements was used.

PATIENT RECRUITMENT AND STUDY

Twelve ventilated premature infants with respiratory distress syndrome were recruited within the first 72 hours from birth. Respiratory distress syndrome was diagnosed on a clinical basis and/or x ray appearance at four hours. Gestational age according to scan dates ranged from 24.7 to 29 weeks (mean 26.6 weeks). Birth weight ranged from 0.54 to 1.11 kg (mean 0.84 kg) (table 1). Infants with severe intraventricular haemorrhage, on inotropic support, or were otherwise clinically unstable at the time of recruitment were excluded from the study. Informed written consent was obtained from at least one parent and the study was approved by the Ethics Committee of West

Table 2 Serial measurements of static compliance (ml/cm H₂O/kg) in subjects 1–12

Subject	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1		0.77	0.45	0.5	0.73		
2	0.26					0.69	0.37
3	0.35	0.27		0.28	0.37		0.55
4	0.94	0.9	1.28	1.58	0.98		
5		0.37	0.58	0.67			0.56
6		0.39	0.48		0.43	0.41	0.65
7			0.117	0.32	0.19	0.3	
8	0.62	0.52			1.05		0.71
9	0.22	0.44	0.36	0.42	0.47		
10			0.4	0.44	0.37	0.4	0.47
11		0.3	0.29	0.39	0.36	0.64	
12			0.69	0.44			0.63

Table 3 Serial measurements of resonance frequency (Hz) in subjects 1–12

Subject	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Span (Hz)
1		21	20	20	22			2
2	20					21	19	3
3	18	18		18	18		18	0
4	18	20	20	20	19			2
5		13	18	17			17	5
6		20	25		19	21	20	6
7			24	23	23	24		1
8	18	18			18		18	0
9	21	20	19	19	17			4
10			23	24	26	25	21	5
11		20	20	20	19	19		1
12			23	23			23	0

Figure 2 Comparison between changes in compliance and changes in resonance frequency in one subject.

Figure 3 Percentage variations in resonance frequency and corresponding change in static compliance.

Lambeth Health Authority. Resonance frequency was determined serially on a daily basis, using phase analysis as described previously, as far as clinical condition allowed in the first seven days of life. Static compliance was measured by single breath technique at the same time.

Results

All 12 babies completed the study with no ill effects. All babies received at least one dose of surfactant before 12 hours of age as per unit protocol for respiratory distress syndrome. The first measurements in all babies were performed within the first 72 hours after delivery, with five of 12 done within the first 24 hours. The minimum number of serial measurements collected in any one baby was three and the maximum was five in the seven day study period. The increase in static compliance varied from 27% to 179% (table 2). The variation in the corresponding resonance frequency

Key messages

- (1) HFOV decreases risk of barotrauma by reducing pressure swings in the airways during artificial ventilation
- (2) CO₂ elimination is dependent on the oscillating frequency
- (3) Resonance frequency is the frequency at which oscillatory ventilation is most efficient owing to the elimination of elastance through the mechanics of oscillation
- (4) Resonance frequency remains relatively stable despite significant changes in compliance in the early stages of respiratory distress syndrome
- (5) It is possible that resonance frequency can be incorporated as part of the management strategy to provide more efficient HFOV

measurements was within 2 Hz in eight babies and within 6 Hz in all 12 recruits (table 3). The resonance frequencies obtained during this time in our group of infants ranged from 13 to 25 Hz (median 20 Hz, mode 20 Hz; table 3). The highest resonance frequencies did not correspond to the lowest compliance measurements. We could find no direct relationship between gestational age or birth weight and resonance frequency of the respiratory system (figs 2 and 3).

Discussion

Respiratory distress syndrome remains the commonest cause for the requirement of ventilatory support in the neonatal period. The lack of compliance in the surfactant deficient lung poses a major challenge. Since the early 1950s, significant progress has been made in this field. Initially, mechanical ventilation was introduced.¹² This was followed by the introduction of the use of exogenous surfactant in the late 1960s.¹³ The main complication that neonatologists worldwide are attempting to prevent is barotrauma induced chronic lung disease by using high frequency oscillations generated by either a diaphragm or piston to produce gas movements in a lung held open by a continuous distension pressure.¹⁴ The swing of pressures during such ventilation is reduced and continues to dampen as it travels down the endotracheal tube and generations of airways.

By studying the intricacy of oscillatory mechanics,^{6,7} there are potentially ways of further improving the efficiency of this type of ventilation. Hoskyns *et al* suggested that the delivered volume during high frequency oscillations in a system driven by a sine wave pump is greatest at resonance frequency of the intubated respiratory system,¹⁵ while Dorkin *et al* found this frequency to lie between 13 and 23 Hz in premature neonates with respiratory disease.¹⁶

We studied premature neonates in the early stages of respiratory distress syndrome, and found that despite relatively large changes in

compliance (ranging from 27% to 179%) over the first seven days of life, the resonance frequency of their respiratory system stayed remarkably constant (tables 2 and 3). In theory, compliance can be related to resonance frequency through the formula: $I = 1/(4\pi^2 f^2 C)$ or rewritten as $f = (1/2\pi)\sqrt{1/IC}$, where I is the inertance, f is the resonance frequency, and C is the compliance.¹⁷ As compliance improves, resonance frequency should come down. This was certainly not the case in the 12 babies we have studied. The general trend as compliance improved was a reduction of the resonance frequency. However, the magnitude of change was minimal. This could possibly be because of changes of other physiological factors at the same time, for example the simultaneous clearing of lung water. Referring back to the equation mentioned above, if compliance increases and resonance frequency stays the same, there must be a significant decrease in inertance. This reduction would be consistent with the clearing of fetal lung fluid and better aeration of the pulmonary air sacs.

For whatever reasons, the resonance frequency of the respiratory system in premature infants with respiratory distress syndrome does stay remarkably constant in the early stages. This certainly makes it feasible to be incorporated as part of the management strategy. It is now necessary to test whether this frequency provides more effective ventilation with lower airway pressure swings clinically, as suggested by the theory. Of course, oscillator performance is also a significant factor, and the presently available machines would need to be modified to perform over the range of 10 to 30 Hz.⁵

We were unable to find a direct relationship between compliance and the resonance frequency. This frequency was not related to gestational age or birth weight.

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