Use of external expiratory resistance in intubated neonates to increase lung volume

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SUMMARY Ten intubated neonates (weights 0.90 to 2.58 kg) recovering from respiratory disease had lung mechanics, respiratory patterns, and functional residual capacity measured at 0 cmH₂O continuous positive airways pressure and then after application of serially increasing levels of external expiratory resistance. At an external expiratory resistance greater than 40 cmH₂O/l per second, there was a significant increase in mean functional residual capacity compared with control levels. Immediately after the application of external expiratory resistance, there was a significant decrease in flow which returned to control values after a few breaths. Tidal volume and respiratory rate decreased for a few breaths after the application of the external expiratory resistance, but returned to control values after several seconds. Study age, gestational age, or study weight had no appreciable effect on the relationship between functional residual capacity and external expiratory resistance. Application of external expiratory resistance may be useful for stabilising lung volume in neonates recovering from respiratory disease.

The stabilisation of lung volume is a major problem in preterm infants with respiratory disease. If the lung volume is unstable such infants may experience atelectasis, have difficulty in oxygenating,¹ or have apnoea.² These three complications are particularly likely to occur immediately before intubation or after extubation. Studies in infants at about the time of extubation have shown that continuous positive airways pressure (CPAP), delivered via nasal prongs or via a nasopharyngeal tube, is an effective treatment. CPAP and its effects on functional residual capacity (FRC) and arterial blood gases at about the time of extubation have been studied previously.³⁻⁴

Other methods for stabilising neonatal lung volume may exist, but few studies have been conducted and data are limited. It has been shown that externally applied expiratory resistance increases lung volume in conscious and anaesthetised adults,⁵⁻⁷ which suggests that this technique may be effective for maintenance of lung volume in neonates. In fact, one preliminary study that used low levels of external expiratory resistance (EER) in extubated neonates recovering from respiratory disease showed that it increased lung volume appreciably.^{8,9}

The purpose of this study was to investigate alterations in lung volume when varying levels of EER were applied, and to evaluate the effects on lung mechanics in intubated neonates recovering from respiratory disease. Such data may be useful in developing criteria for the effective management of neonates recovering from respiratory disease.

Patients and methods

Ten infants were studied in the Infant Intensive Care Unit. Informed consent was obtained from the parents. All neonates were intubated at the time of the study for a mean of 10.4 (range 2-38) days and were recovering from respiratory distress syndrome. Mean weight was 1.53 (range 0.90 to 2.58) kg, mean age 10.8 (range 2-38) days, mean gestational age 32.1 (range 27-36) weeks. Treatment consisted of CPAP, mean 2.5 (range 2-4) cmH₂O, and oxygen, mean inspired concentration 30% (range 25-34). Mean time of intubation was 10.4 days.

Fig. 1 shows the apparatus used in the study. In one position the solenoid valve allowed the patient to breathe ambient oxygen while CPAP was being applied and pulmonary function was measured with

CPAP = continuous positive airways pressure.
SV = solenoid valve with NO = normally open,
NC = normally closed, and COM = common ports.

Fig. 1 Diagram of the apparatus.

the pneumotachograph. When the solenoid valve was switched to a second position, the patient breathed through the applied EER and pulmonary function measurements were redetermined. The patients were studied in the supine position, using a pneumotachograph (Hewlett-Packard 21069A), solenoid valve (Fluorocarbon Solenoid Co.), 4-channel recording system (Hewlett-Packard 47601A), and the EER. Each EER consisted of an endotracheal tube with an adjustable clamp in the middle and endotracheal tube adapters at each end. The EERs equalled 24, 30, 40, 60, 80, and 100 cmH₂O/l per second, respectively. The EERs were calibrated with a U-tube water manometer by measuring pressure generated by a known air flow, comparable in magnitude with those seen in infants. The EERs were linear up to flow rates of 5 litres/minute. The system resistance was 12 cmH₂O/l per second, and the dead space was about 4 ml.

Intraoesophageal pressure changes were measured with a soft 2.5 × 0.5 cm latex balloon attached to the end of a 5 French polyvinylchloride catheter placed in the lower one-third of the oesophagus, about 12 cm from the gum line. The distal end of the pressure transducer was open.

Flow was measured using the pneumotachograph and was electronically integrated into tidal volume. Dynamic lung compliance was determined graphically by the method of Neergaard and Wirz.¹⁰ Lung resistance during inspiration and expiration was graphically computed by dividing the difference in oesophageal pressure at points of equal volume during inspiration and expiration respectively, by the algebraic difference in air flow at these constants.

Net work of breathing was calculated by determining the total area within the pressure-volume breathing loops.^{11 12} Baseline FRC was measured with a closed-circuit helium dilution technique adapted for use in the neonate.^{13 14} Inspiratory to expiratory time ratio was computed by dividing the length of time of inspiration by that of expiration as determined by the zero flow points. As soon as the respiratory rate and breathing pattern of the patient was stable at 2–3 cmH₂O CPAP, FRC was determined. The CPAP was then decreased to 0 cmH₂O, FRC was repeated, and pulmonary function tests were performed including lung compliance, lung resistance during inspiration and expiration, work of breathing, and inspiratory to expiratory time ratio. Then in the second phase, serially increasing levels of EER were added. After application of each EER, the patient was studied until at least 10 uniform breaths had been obtained to determine the effect of the EER on pulmonary function. In this stage of the study, changes in FRC were determined by measuring changes in end expiratory volume from the continuous polygraph recording. These changes in FRC were evaluated and compared with FRC at 0 cmH₂O and 2–3 cmH₂O CPAP measured by helium dilution.

EER levels of 24, 30, 40, 60, 80, and 100 cmH₂O/l per second were used. The serial application of the EERs continued until 100 cmH₂O/l per second was reached, or until a 50% increase in FRC occurred. Work of breathing was calculated at 2–3 cmH₂O and 0 cmH₂O CPAP, and at a level of EER that produced a level of FRC equivalent to 2–3 cmH₂O CPAP (or the highest FRC if smaller). Before beginning each study the mask and pneumotachograph were checked to make sure there was no endotracheal leakage.

For all statistical analyses, the paired Student's *t* test was used, using each patient as his own control.

Results

FRC values at 2–3 cmH₂O CPAP ranged from 17.5 to 87.7 (mean of 40.2 ± 7.4) ml. At 0 cmH₂O CPAP, FRC ranged from 10.0 to 82.2 (mean of 33.4 ± 7.1) ml (Table). Baseline pulmonary function data for all patients at 0 cmH₂O CPAP (Table) were consistent with ones previously published for neonates of similar weights and gestational ages recovering from respiratory disease.¹⁵ As shown in a typical tracing (Fig. 2), immediately after the application of EER (60 cmH₂O/l per second), the flow greatly decreased. After several seconds, the FRC increased and the flow returned to control level. After initial decreases, both the respiratory

Table Pulmonary function at 0 cmH₂O continuous positive airways pressure

Case	Tidal volume (ml)	Compliance (ml/cmH ₂ O)	Resistance (cmH ₂ O/l per second)		Functional residual capacity (ml)
			Inspiratory	Expiratory	
1	10.1	0.94	52.0	264.1	82.2
2	6.7	1.79	24.1	73.3	19.6
3	7.2	1.24	64.6	180.3	10.0
4	12.6	6.64	15.8	23.3	66.1
5	7.9	1.12	89.3	168.8	23.5
6	5.0	1.10	37.6	86.1	26.5
7	7.0	2.74	33.7	29.6	28.8
8	7.7	3.29	60.9	69.7	22.4
9	7.8	3.41	20.9	29.7	31.8
10	7.4	3.70	26.3	27.2	23.2
Mean	7.9	2.59	42.5	95.2	33.4
±SEM	0.7	0.56	7.4	26.0	7.1

FRC = functional residual capacity.

Fig. 2 Typical tracing (Case 3) showing both volume and flow response to application of external expiratory resistance (60 cmH₂O/l per second).

frequency and the tidal volume returned to control levels after a few breaths.

The mean FRC continued to increase with successively applied levels of EER (Fig. 3). At EER levels greater than 40 cmH₂O/l per second, mean FRC was significantly greater than at 0 cmH₂O CPAP ($P < 0.02$). Although not shown, inspiratory to expiratory time ratio decreased significantly with the EER of 80 cmH₂O/l per second ($P < 0.02$), but did not change significantly at any other level of EER. As Fig. 4 shows, there was little change in inspiratory resistance at any stage of the study.

It is worth noting that there was no statistically significant change in the mean net work of breathing with the application of external expiratory resistance (286 kμN-cm at 3 cmH₂O CPAP, 210 kμN-cm at

0 CPAP = 0 cmH₂O continuous positive airways pressure.

Fig. 3 (a) Plot of mean $\pm$ SEM compliance as percentage of control level (0 cmH₂O CPAP) versus level of external expiratory resistance applied. (b) Plot of functional residual capacity (mean $\pm$ SEM) as percentage of control level (0 cmH₂O CPAP) versus external expiratory resistance.

Fig. 4 (a) Plot of mean $\pm$ SEM inspiratory resistance as percentage of control level (0 cmH₂O CPAP) versus level of external expiratory resistance applied. (b) Plot of measured expiratory resistance (mean $\pm$ SEM) as percentage of control level (0 cmH₂O CPAP) versus applied external expiratory resistance.

0 cmH₂O CPAP, 240.2 kN-cm at EER which caused the significant FRC change). In addition, study age, study weight, or gestational age did not affect the relationship between lung mechanics and EER. There was also no significant change in respiratory rate at any stage of the study. No clinical complications were associated with the application of the EER.

Discussion

This study showed that a serial increase in lung volume occurred when serially increasing levels of EER were applied to intubated neonates recovering from respiratory disease. The lung volume increase was rapid and there were no appreciable changes in dynamic lung compliance, inspiratory resistance, work of breathing, or respiratory rate. Lung volume

changes after applying at least 40 cmH₂O/l per second of EER were equivalent to volume changes produced by 2–3 cmH₂O CPAP. In addition, there were no clinical complications associated with the application of the EER.

This study is consistent with a previous one which showed that the application of EER increased lung volume in a group of neonates recovering from respiratory disease;^{8,9} however the previous study only evaluated patients using a single, fairly low level of EER (30 cmH₂O/l per second). In the present study, it generally required levels above 40 cmH₂O/l per second to produce a significant increase in FRC. Between levels of 24 and 60 cmH₂O/l per second, FRC increased linearly; above 60 cmH₂O/l per second there was little effect, probably because the lungs were overdistended. The previous study evaluated extubated patients using a face mask. In that evaluation, it was not clear what effect the vocal cords had on expiratory resistance. Therefore, it appears that the application of EER is effective for increasing lung volume in both intubated and extubated neonates, regardless of their weight provided it is in the range 900 to 3810 g. The previous group was heavier in weight with a mean of 2530 g. In the present study, the mean weight was about 1500 g, with one infant weighing 900 g. It is these smaller babies who are reported to have the greatest difficulty maintaining adequate lung volume who develop atelectasis after extubation.³ Finally, this study compares CPAP with expiratory resistance and demonstrates that FRC can be increased by applying EER to an equivalent lung volume produced by 2–3 cmH₂O CPAP.

In small preterm infants¹³ and in infants with respiratory distress syndrome¹⁵ or apnoea of prematurity,² FRC is typically less than normal. As expected, the infants in the present study had lower control values for FRC compared with normal infants of similar weights and gestational ages. After application of EER levels above 40 cmH₂O/l per second, the lung volume increased significantly in these patients. Assuming that expiratory time remains constant, it is possible that the increase in FRC with the application of EER is due to increased peak intra-alveolar pressure during the expiratory phase of respiration. However, if this peak positive alveolar pressure is followed by a prolonged expiratory time, the increased FRC may return to its previously low level. In this group of patients there was no increase in expiratory time, and therefore FRC remained at the higher levels while the EER was applied.

After the initial stabilisation period of several

seconds, our patients did not demonstrate changes in flow, tidal volume, or respiratory rate that had been noted by others when continuous negative pressure¹⁶ or CPAP¹⁷ was applied to healthy newborn infants or to infants with respiratory distress syndrome. Bancalari *et al.*¹⁶ and Milner *et al.*¹⁷ have reported decreases in respiratory rate and tidal volume after the application of continuous negative pressure or CPAP to healthy newborn infants and to infants with respiratory distress syndrome. Their measurements were made 5 and 30 minutes after the application of the continuous negative pressure or CPAP. In this study, measurements were made several seconds after the application of the EER and the flow, tidal volume, and respiratory rate had returned to control values by this time.

If the use of EER before extubation can stabilise lung volume, the amount of time a patient is intubated may be reduced. Unlike CPAP, increased alveolar pressures are only generated during the expiratory stage of the respiratory cycle. The data from this study suggest that it is now appropriate to perform long-term clinical trials to determine the duration and frequency of application of EER, particularly for smaller neonates.

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