Ventilator Therapy in the Newborn

Some Mechanical Considerations

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Picton-Warlow, C. G. (1970). *Archives of Disease in Childhood*, **45**, 460. **Ventilator therapy in the newborn: some mechanical considerations.** Premature infants have been studied while receiving intermittent positive pressure ventilation for the management of respiratory failure which was due either to severe respiratory distress syndrome or to apnoea of prematurity. Simultaneous recordings were made of transpulmonary pressure change and volume change induced by a pressure-regulated intermittent positive pressure ventilator. This information has been of clinical value in selecting a ventilator setting for individual infants. Using an electrically-switched pressure-limited ventilator the following settings have been found to be the most appropriate in the various forms of neonatal respiratory failure: rate, 50–70/min., pressure blow-off, 20–35 cm. H₂O; inspiratory duration, 30–35% of the respiratory cycle; flow of gas in the circuit, 5–7 l./min.

Artificial ventilation is becoming more frequently used as an adjunct to therapy in newborn infants with respiratory failure (Adamson *et al.*, 1968). Generally accepted indications for its use are either prolonged apnoea or inadequate ventilation leading to persistently deranged blood gas levels in spite of other forms of therapy.

A widely used method for artificial ventilation is that of pressure-limited intermittent positive pressure ventilation (IPPV). A number of suitable machines are available, but the essential features are similar to that shown in Fig. 1. This is a diagrammatic representation of a simple IPP ventilator developed at the Hammersmith Hospital (Grausz, Watt, and Becket, 1967). A flow of gas under pressure is introduced into an open-ended circuit which has as a side limb the infant's respiratory tree, connected by an endotracheal tube. The open end of the circuit is occluded intermittently, by an electric solenoid valve. The number of occlusions per minute, and thus the respiratory rate, is controlled by the operator through an electronic switching system. The duration of occlusion as a percentage of the time between successive occlusions, i.e. the inspiratory duration, is also controlled electronically, and can be varied by the operator between 10% and 60% of the respiratory cycle.

Also in the circuit is an adjustable pressure blow-off valve which allows gas to escape when a preset pressure is exceeded, thus avoiding the obvious danger of overinflation of the lungs. The other important component of any ventilator system is the provision of humidification; in this system water is infused into the endotracheal tube through fine bore tubing at the rate of 2 ml./hr. using a constant infusion pump.

In setting up such a circuit to ventilate an infant the operator is confronted with four variable settings: respiratory rate, blow-off pressure, duration of the inspiratory phase, and flow rate of gas in the circuit. A method of studying the effect of varying these settings is reported and the effect of such variations on ventilation discussed.

Method and Materials

The 12 infants studied were receiving IPPV from the Hammersmith ventilator because of apnoea: either apnoea which failed to respond to peripheral stimulation, followed by intubation and IPPV by hand for a period of 2–3 minutes, or repeated apnoeic spells with shallow respiration and a persistently low P_aO₂ (<30 mm. Hg). The cause of the respiratory failure was either respiratory distress probably due to hyaline membrane disease, (HMD), or recurrent apnoea of prematurity without obvious respiratory disease (see Table I).

The pressure and volume changes occurring during IPPV were studied in the following manner. A wide-bore, air-filled manometer tube was connected into the

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FIG. 1.—Diagram of pressure limited, intermittent positive pressure ventilator. The infant is connected to the circuit by a Jackson-Reese tube which has been fitted into a stainless steel adaptor which is strapped to the infant's forehead and in turn fits into a nasotracheal tube.

TABLE I
Clinical Details of Infants Receiving IPPV on whom Pressure-Volume Studies were Performed.

Case No.	Birthweight (g.)	Gestation (wk.)	Clinical Diagnosis	Indications for IPPV	Time on IPPV (hr.)	Outcome and Necropsy Findings
1	2010	32	RD, ? HMD	Prolonged apnoeic attack	48	Survived
2	2000	32	RD, ? HMD	Prolonged apnoeic attack	96	Survived
3	1360	29	Apnoea of prematurity	Prolonged apnoeic attack	120	Died pneumonia
4	1500	28	RD, ? HMD	Prolonged apnoeic attack	96	Survived
5	2200	35	RD, ? HMD	Prolonged apnoeic attack	24	Died, HMD
6	3602	40	RD, ? HMD	Prolonged apnoeic attack	96	Survived
7	1460	33	RD, ? HMD	Recurrent apnoea $P_{aO_2} < 30$ mm. Hg	16	Died pneumonia
8	1360	29	Apnoea of prematurity	Prolonged apnoeic attack	20	Died pseudomonas septicaemia
9	1610	30	Apnoea of prematurity	Prolonged apnoeic attack	30	Died IVH
10	900	28	Apnoea of prematurity	Prolonged apnoeic attack	120	Died IVH, HMD
11	1100	28	Apnoea of prematurity and RD present	Prolonged apnoeic attack	72	Died IVH
12	2040	32	Apnoea, congenital heart disease	$P_{aO_2} < 30$ mm. Hg., recurrent apnoea	35	Died, pulmonary atresia

RD, respiratory distress; HMD, hyaline membrane disease; IVH, intraventricular haemorrhage; IPPV, intermittent positive pressure ventilation.

ventilator circuit at the nasal end of the endotracheal tube. At the other end of this manometer tube was a pressure transducer, from which a continuous recording of pressure change in the trachea was made during IPPV (Fig. 2). In Fig. 2 the ventilator switches on at

FIG. 2.—Pressure and volume changes during IPPV. The solenoid valve of the ventilator closes at A and opens at B. The corresponding volume of inflation of the lungs is indicated by the size of the deflection in the impedance pneumograph trace. Gas flow rate in circuit 7 l./min.

point A and off at point B. The change in pressure between those points is the pressure applied across the lungs and chest wall during an artificial inspiration. The corresponding volume change induced was recorded simultaneously by impedance pneumography (Pallett and Scopes, 1965; Walker, 1968). An apnoea monitor was used for this purpose.* In the impedance pneumograph a very high frequency, low voltage, alternating current signal is passed across the chest between two electrodes applied to the chest wall. The impedance of tissues between the electrodes to this current alters with respiration, and the fluctuation in voltage so produced is amplified in the instrument and may be displayed or recorded as desired. As the infants being studied were apnoeic it was possible to calibrate the system by inflating the lungs with known volumes of air. 5, 10, and 15 ml. air were injected into the endotracheal tube and the deflection obtained was recorded. Over this range the response was linear and the impedance pneumograph deflection obtained during IPPV could be measured in terms of volume of each inflation.

These measurements were made as soon as possible after ventilation therapy had been started and repeated where possible at daily intervals while an infant was being ventilated.

Two sets of observations were made. First, the effect on tidal volume and tracheal pressure of altering the ventilator settings one at a time over a wide range was recorded. Secondly, serial observations of 'total compliance' were made over the duration of ventilator therapy in some of the infants. The 'total compliance' of the lungs and chest wall was calculated by relating the inflated volume to the pressure change inducing it where

a plateau occurred on the pressure trace at end-inspiration.*

Results

Respiratory rate. It has been argued that, since infants with respiratory distress syndrome (RDS) who have a high respiratory rate have a better prognosis (Miller, Behrle, and Smull, 1958), a high rate should be used when such infants require ventilation treatment (Grausz *et al.*, 1967). However, increasing the rate in an electrically switched ventilator such as the type being considered is achieved by shortening both inspiratory and expiratory time, with the effect that can be seen in Fig. 3. The only change in the ventilator settings

FIG. 3.—Effect on volume and pressure changes of increasing rate of respiration by altering rate setting of ventilator is merely to decrease tidal volume. Gas flow rate in circuit 3.5 l./min.

across the trace is that the rate has been changed from 45 to 90; the machine switches off earlier in the pressure rise, and in consequence the volume of inflation is greatly reduced. This effect may be overcome only to a limited extent by increasing the gas flow rate through the circuit. Fig. 4 is

FIG. 4.—Effect on tidal volume, minute volume, and alveolar ventilation/min. of increasing respiring rate from 22/min. to 120/min. Flow rate in circuit 7 l./min. Alveolar ventilation fell sharply with rates above 80 l./min.

*The values obtained for 'total compliance' and their changes during the course of ventilator therapy in different infants were intended to be the subject of a later communication.—Ed.

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another example showing the effect on tidal volume (VT) and minute volume (MV) of increasing the rate by steps from 22 to 120 per minute. In this case, because a higher flow in the circuit was used, the pressure remained at 25 cm. H₂O for the first four points and only fell to 20 cm. H₂O on the last. At rates above 50/min. the tidal volume began to fall quite steeply, and above a rate of 80/min. the minute volume also fell. Alveolar ventilation (VA), calculated by assuming an anatomical dead-space of 5 ml., probably fell a little at rates between 50–80/min.; it certainly did not increase. At rates above 80/min. VA decreased quite rapidly, indicating that little more than dead-space ventilation was being achieved. This pattern of change was universal in the babies examined (Table II), but the respiratory rate at which tidal volume began to decrease varied from baby to baby between 40 and 60/min.

Blow-off pressure. It is commonly acknowledged that premature infants on ventilators require higher inflation pressures than older children and adults, and infants with presumed HMD are often subjected to very high inflation pressures (up to 40 cm. H₂O) (Adamson *et al.*, 1968). The relation of VT to inflating pressure was therefore examined. Increasing the inflating pressure initially increased tidal volume, but a pressure was reached above which further increase in inflating pressure did not cause any further increase in VT (Fig. 5). It can be seen that in the case illustrated in Fig. 5 maximum VT was achieved with an inflating pressure of 25 cm. H₂O, and increasing pressure to 35 cm. H₂O did not increase VT. This was a general finding in the infants examined (Table II) though the pressures

FIG. 5.—Relation of tidal volume achieved by ventilator to blow-off pressure. Rate 60/min., flow rate of gas in circuit 7 l./min., inspiratory duration 30% of respiratory cycle. Increasing pressure beyond 25 cm. H₂O did not increase tidal volume.

at which maximum inflation was achieved varied between 20 and 35 cm. H₂O in different cases. It is undesirable to use higher inflating pressures than necessary because of the risks of rupturing alveoli, and also the possible cardiovascular effects of interference with venous return and reduction of cardiac output. This method of VT monitoring is therefore of immediate practical value in deciding appropriate inflating pressures for a particular infant, and shows that increase in tidal volume will not necessarily be achieved by increasing inflating pressure.

Rate of gas flow in ventilator circuit. Increasing the rate of flow increases ventilation, up to a point, but thereafter further increments of flow do not increase ventilation (Fig. 6). The actual

FIG. 6.—Effect on tidal volume of increasing flow rate in ventilator circuit. Rate 45/min., blow-off pressure 25 cm. H₂O, inspiratory duration 35%. Flow rates above 6 l./min. did not increase tidal volume.

level depends upon the length and diameter of tubing used and the rate and blow-off pressure settings of the ventilator. As a general rule, however, rates of flow greater than 6 l./min. did not increase tidal volume (Table II). Flow rates below 4 l./min. resulted in a slower rise in pressure during inspiration and therefore, particularly at high respiratory rates, were associated with small tidal volume.

Duration of inspiration. The most appropriate inspiratory duration appeared to be between 30 and 35% (Fig. 7) of the respiratory cycle when the other settings were adjusted to produce maximum tidal volume. Under these circumstances, inspiratory duration greater than 35% produced a prolongation of the pressure plateau without increase in VT (Table II). In two cases (Table II) when successful VT measurement could be made at a

TABLE II

Effect on Tidal Volume (VT) of Altering Ventilator Rate (f), Pressure Blow-off (P), flow Rate of Gas in Ventilator Circuit (F), and Inspiratory Duration (I/(I+E)). Observations made shortly after start of ventilator treatment in each case.

Case No.	Change in f; Other Controls not Altered f VT (ml.)	Change in P; Other Controls not Altered P (cm. H ₂ O) VT	Change in F; Other Controls not Altered F (l./min.) VT	Change in I/(I+E); Other Controls not Altered I/(I+E)(%) VT
1	(P21, F7, I/(I+E)35) 40 11.7 70 9.4	(f40, F7 I/(I+E)35) 13 6.5 20 12.5 30 12.5	(f40, P21, I/(I+E)35) 4 10.8 7 12.5 9 13.0	(f40, P21 F4) 30 12.8 35 12.5 40 12.8
2	P25, F6 I/(I+E)35) 60 17.5 72 14.4 96 9.9	(f54, F6 I/(I+E)35) 14 12.5 22 16 26 17.3 38 17.3	(f54, P25 I/(I+E)35) 3 16 4 17 6 17	(f60, P23, F4) 35 17 50 17
3	P25, F4, I/(I+E)35) 30 15.2 45 15.2 60 13.0	(f40, F4, I/(I+E)35) 10 12 14 13.2 22 14.8 30 14.8	(f45, P25, I/(I+E)35) 3 12 4 15 6 16	(f45, P26 F5) 30 15.6 40 15.6
4	(P30, F4, I/(I+E)35) 45 16.8 90(P15) 9.6	(f70, F4, I/(I+E)30) 6 7.2 14 10 20 15 40 15	(f70, P20, I/(I+E)30) 3 15 4 15	(f70, P20, F4) 30 15 45 15
5	(P25, F7, I/(I+E)35) 22 15.6 50 15 66 12 86 10 120(P20) 5	(f54, F7, I/(I+E)35) 15 8.8 27 16 36 16	(f54, P27, I/(I+E)35) 5 13 6 16 7 16	(f60, P27, F7) 12 5 26 15.2 35 16 50 16
6	(P19, F10, I/(I+E)35) 45 18.3 60 18.4 100(P11) 10	(f60, F10, I/(I+E)35) 20 10.4 29 18.3 38 18.4		
7	(P30, F4 I/(I+E)30) 46 14 65 10 80 8	(f52, F4 I/(I+E)30) 20 10 25 12 34 14 45 14		
8	(P34, F6, I/(I+E)35) 48 13.0 60 11.5 72 10 100(P27) 7	(f54, F6 I/(I+E)35) 20 8.5 25 11.5 35 13 40 13	(f54P I/(I+E)35) 2(P20) 9 4(P25) 11.5 6(P34) 13 8(P38) 13	
9	(P27, F6, I/(I+E)35) 50 8 60 8 90 3	(f60, F6, I/(I+E)35) 14 5 20 6 28 8 40 8	(f60, P25, I/(I+E)35) 3 4 4 6 5 8 6 8	
10	(P14, F6.5, I/(I+E)30) 60 10 75 9 100 7	(f60, F6.5, I/(I+E)30) 10 8 14 10 20 10.6	(f60, P20, I/(I+E)30) 4.5 10 6.5 11.3 6.5	(f60, P20, F6.5) 20 8 30 10.6 50 10.7 70 10.7
11		(f, F, I/(I+E)) 14 6.5 20 7.6 26 9.1 30 9.1		
12		(f60, F6, I/(I+E)30) 16 8.3 23 10.8 33 11.6 40 11.6

FIG. 7.—Changes in inflating volume caused by altering the percentage of the respiratory cycle during which the solenoid valve was closed (inspiratory duration %). Rate 60/min., blow-off pressure 25 cm. H_2O , flow rate in circuit 6 l./min. Inspiratory duration greater than 35% did not increase tidal volume.

short inspiratory duration this was found to be reduced. In 3 other cases, inspiratory durations of less than 20% induced a Head's paradoxical reflex (Cross *et al.*, 1960) with each inspiratory phase and resulted in the infant gasping during the next expiratory phase.

Discussion

This method of monitoring tidal volume and tracheal pressure used in conjunction with blood gas estimation has been of value in selecting ventilator settings for individual babies. Blood gas estimation is the final arbiter of the efficiency of respiration, but the method allows changes to be made in ventilation on a rational basis, where a change is indicated by blood gas values. The observations show the interrelationship of the ventilator settings, and the fact that altering one

setting may not have the expected effect on ventilation and may indeed on occasion have the reverse effect.

Based on the observation of these 12 infants, the following guide-lines for the use of this type of ventilator were established. First, increasing the ventilatory rate initially increases ventilation, but rates over 70/min. quickly decrease ventilation and are probably inappropriate. Secondly, blow-off pressures of 20–35 cm. H_2O may be required, but continued, indiscriminate increase in inflating pressure does not increase tidal volume and is potentially dangerous. Thirdly, the gas flow rate in the circuit also has an optimal value, depending upon the tubing used, of from 5 to 7 litres/min. beyond which increases do not significantly increase ventilation. Finally, an inspiratory duration of 30–35% of the respiratory cycle appears the most efficient in this type of electrically switched ventilator, if the maximum VT with the maximum amount of intrathoracic positive pressure is required.

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