1 Applied Physiology

A reasonable understanding of pulmonary physiology is elementary in the understanding the approach and bedside management of respiratory disorders. An attempt has been made to synchronize physiological or pathological deviations with ventilatory management.

PHYSIOLOGICAL PRINCIPLES

The physiological basis of treating any critical newborn lies in the optimization of ventilation and perfusion.

Under ideal conditions, ventilation and perfusion are evenly matched and the V/Q ratio = 1.

Ventilation (V)

Ventilation applies to a physiological tidal volume, which reaches the alveoli and distends it optimally. If the minute ventilation (tidal volume X rate) is optimal, the ideal CO_2 will be 35 to 45 mm of Hg. Normal tidal volume in neonate is 4 to 6 ml/kg.

Perfusion (Q)

This is maintained by the state of dilatation of the pulmonary arterioles and capillaries supplying the air sac. It is controlled to a large extent by systemic blood pressure (mean arterial blood pressure). Myocardial pump function determines the systemic blood pressure directly. In addition, certain physiological variables have to be taken into consideration (Fig. 1.1).

- Hb content of the blood
- State of dilation of the air sac (FRC)
- Nitric oxide metabolism (maintains pulmonary arteriolar dilatation).

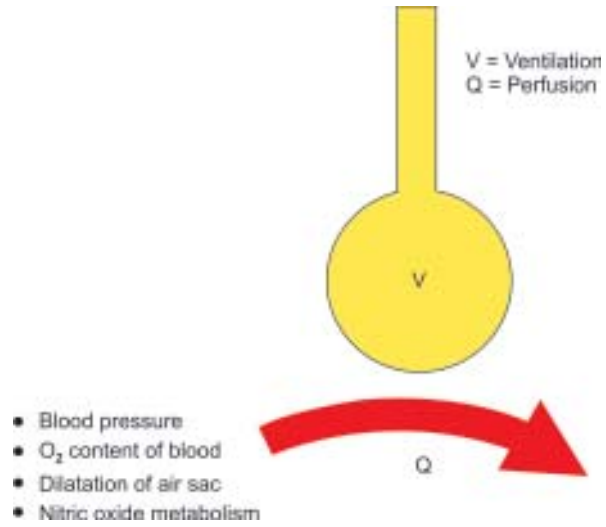


Fig. 1.1: Basis of gas exchange in alveolar— Capillary unit

Basic Understanding of Various Lung Units in Disease States

Three-lobe, three-compartment model of the lung with V/Q equal to 1 in A, V/Q equal to infinity in B, and V/Q equal to zero in C. Coming into the pulmonary circuit on the left is blood returning from the body and having a low PaO_2 (40 mm Hg) and a high $PaCO_2$ (46 mm Hg). Mixed blood returning from the lungs is not fully saturated with O_2 because of venous admixture from the low. V/Q unit C, where the lack of ventilation leaves the PaO_2 unchanged (40 mm Hg); SO_2 of 75% at a PaO_2 of 40 mm Hg, and a PaO_2 of 55 mm Hg at a SaO_2 of 86% (Figs 1.2 to 1.5).

(Adapted from Goldsmith: Physiological principles pg 56)

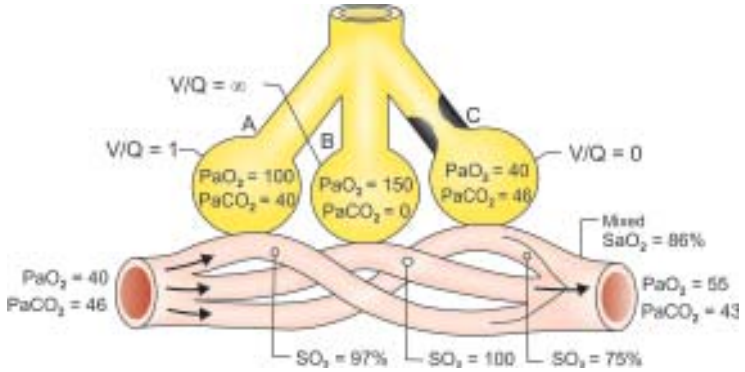
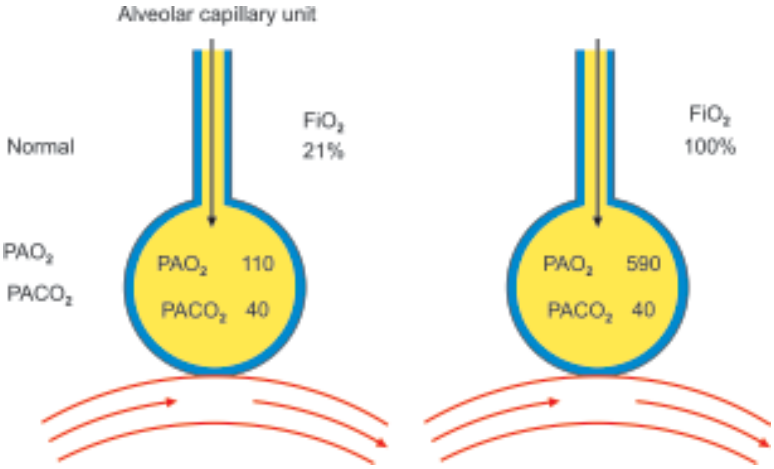
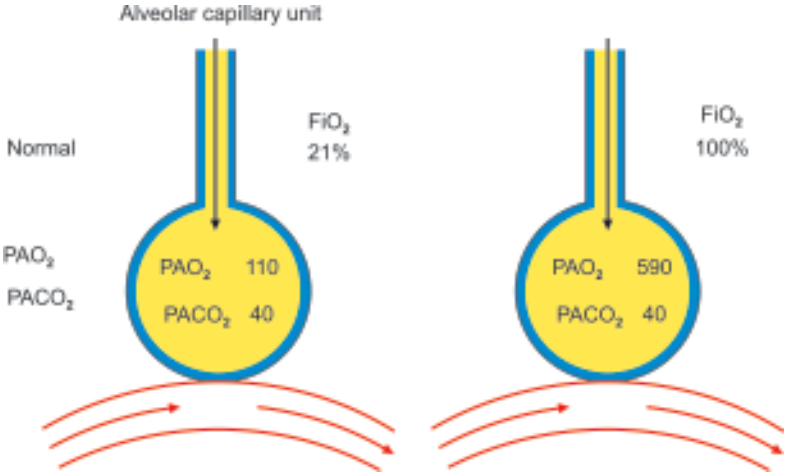


Fig. 1.2: Effect of ventilation: Perfusion (V/Q) on oxygenation in lungs



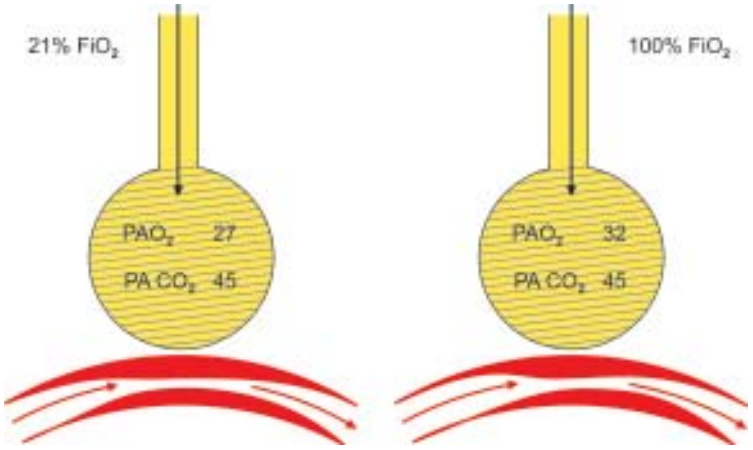
Mixed venous blood	Pulmonary venous blood	Mixed venous	Pulmonary venous
pH 7.35	pH 7.4	pH 7.35	pH 7.4
$PvCO_2$ 45 mm Hg	$PaCO_2$ 40	$PvCO_2$ 45	$PaCO_2$ 40
PvO_2 40 mm Hg	PaO_2 110	PvO_2 40	PaO_2 590
O_2 sat 75%	O_2 sat 98%	O_2 sat 75%	O_2 sat 100%

Fig. 1.3: Normal alveolar—Capillary unit



Mixed venous blood	Pulmonary venous blood	Mixed venous blood	Pulmonary venous blood
pH 7.40	pH 7.40	pH 7.40	pH 7.40
$PvCO_2$ 46	$PaCO_2$ 42	$PvCO_2$ 45 mm Hg	$PaCO_2$ 42 mm Hg
PvO_2 40	PaO_2 50	PvO_2 40 mm Hg	PaO_2 300 mm Hg
O_2 sat 75%	O_2 sat 82%	O_2 Sat 75%	O_2 sat 98%
			PaCO

Fig. 1.4: Alveolar—capillary unit with V/Q mismatch



Mixed venous blood	Pulmonary venous blood	Mixed venous blood	Pulmonary venous blood
pH 7.40	pH 7.40	pH 7.40	pH 7.4
$PvCO_2$ 45	$PaCO_2$ 45	$PvCO_2$ 45	$PaCO_2$ 45
PvO_2 27	PaO_2 27	PvO_2 27	PaO_2 32
O_2 sat 50%	O_2 sat 50%	O_2 sat 50%	O_2 sat 60%

Fig. 1.5: Alveolar—Capillary unit with shunt

Ventilation perfusion mismatch is the most common cause of hypoxemia in the newborn with atelectasis. Only perfusion with reduced or absent ventilation tends to hypoxemia. On the contrary ventilation without perfusion is equivalent to dead space ventilation and this does not lead to hypoxemia, but if severe lead to CO_2 retention.

Shunt: This implies one extreme of ventilation perfusion (V/Q) mismatch in which there is perfusion with no ventilation. This leads to unoxygenated blood being shunted from the right side of the heart to the left side of the heart causing severe hypoxemia. In this situation in crossing the FiO_2 will not improve the oxygenation as there is absolutely no ventilation to this shunted area.

The clinical implication of this is that increasing the FiO_2 will improve oxygenation in V/Q mismatch but not in case of shunt. Examples of intrapulmonary shunts are pneumonia, hyaline membrane disease and extrapulmonary shunt are PFO with PPHN.

Alveoli are Optimally Distended 'Normal Lung Under Ideal Conditions'

The pulmonary arterioles unfurl completely and perfuse the alveolar bed completely (Fig. 1.6)

V/Q = 1 CO_2 40-45 mm Hg

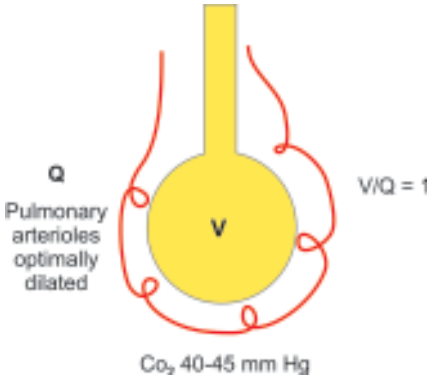


Fig. 1.6: Normal lung

ALVEOLI IS ATELECTATIC

The pulmonary arterioles are coiled up leading to less perfusion to those alveoli (Pulmonary hypertension) and if atelectasis is more profound perfusion proportionately is reduced leading to *intrapulmonary shunting* due to admixture of mixed venous blood into the systemic circulation. The density of the haziness on the X-ray is a rough estimate of the blood CO_2 levels (Fig. 1.7)

V/Q < 1 CO_2 55-70 mm Hg

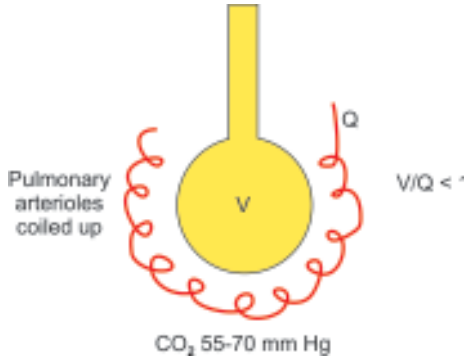


Fig. 1.7: Atelectasis

ALVEOLAR OVERDISTENTION

On the other hand, if the alveoli is overdistended due to inappropriate pressures on the ventilator (CPAP), the pulmonary arterioles got stretched to a point where narrowing of their lumen causing pulmonary hypertension leading, to decreased perfusion in the lung and intrapulmonary shunt. The blood pCO_2 initially remains low to rise after sometime to values above 50 mm Hg. The X-ray shows hyperlucent lung fields (Fig. 1.8).

V/Q >1 (up to infinity)
CO_2 = 25-30 mm Hg

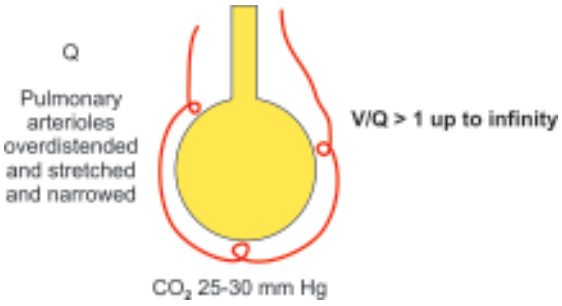


Fig. 1.8: Overdistended lung

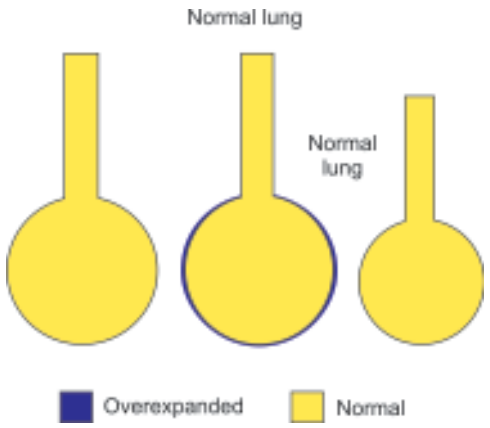


Fig. 1.9: Conceptual model of lung disease in (RDS)

CONCEPTUAL MODELS OF APPLIED PHYSIOLOGY

It would be over-simplification of the lung units and the surface area for gas exchange by presenting a model of lung units with 3 generations of alveoli, the collapse of which present with increasing oxygen requirements in atelectatic lung disease (Fig. 1.9).

Oxygen Requirements > 40% ($FiO_2 > 0.4$)

One generation of alveoli may be collapsing and it would be appropriate to institute assisted ventilation ideally CPAP or Synchronized intermittent mandatory ventilation (SIMV) at this stage. This would recruit lung volume and optimize gas exchange and prevent morbidity and air leaks (Fig. 1.10)

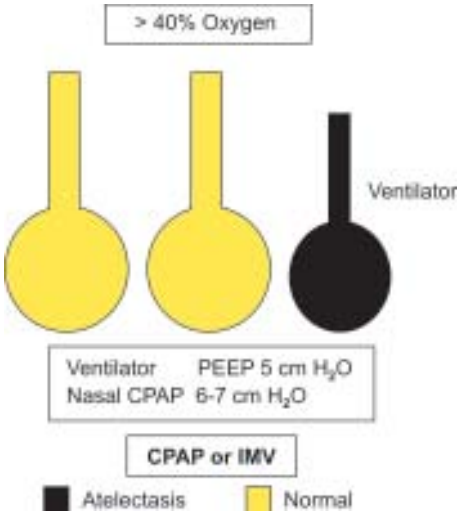


Fig. 1.10: Synchronized intermittent mandatory ventilation (SIMV)

Oxygen Requirements > 60% (FiO_2 > 0.6)

Two generations of alveoli have collapsed and unless interfered, actively with intubation and ventilation (IMV), air leaks, pulmonary hypertension and morbidity could occur (Fig. 1.11).

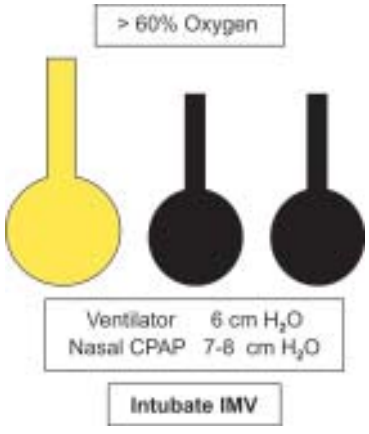


Fig. 1.11: CPAP or IMV

Oxygen Requirements > 70-80% (FiO_2 > 0.7-0.8)

Most generations of alveoli have collapsed and only approximately 1/3 alveolar surface area is available for gas exchange. It would be inadvisable to allow a neonate with RDS to progress to this stage. When ventilation (IMV) is resorted to at this stage air leaks, severe pulmonary hypertension and pulmonary hemorrhage could occur (Fig. 1.12).

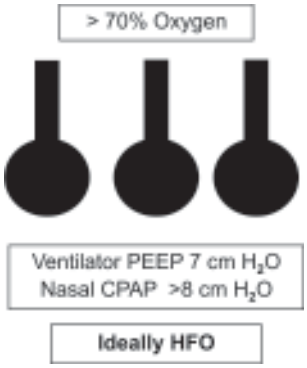


Fig. 1.12: Ideally high-frequency oscillation (HFO)

From the previous discussion, it is apparent that early recruitment of lung volume is essential for optimum ventilation and prevention of morbidity. The early and optimal addition of PEEP or CPAP in lung disease is the sine qua non of ventilatory care and reflects the great variability in morbidity and mortality of various centers dealing in newborn care.

A thumb rule in this lung volume recruitment strategy is highlighted in Table 1.1 which is basically intended for atelectatic lung disease.

Table 1.1: Lung volume recruitment strategy

FiO_2	*PEEP*	*CPAP*
FiO_2 > 0.4	5 cm H_2O	6 cm
FiO_2 > 0.5-0.6	6 cm H_2O	7-8 cm can be tried
FiO_2 > 0.7	7-8 cm H_2O	Not recommended

ANATOMICAL CONSIDERATIONS

The closing volume of alveoli is larger than the FRC until 6-8 years of age. This causes an increased tendency for airway closure at end expiration. Thus, neonates and infants generally benefit from use of continuous positive airway pressure (CPAP) in suitable conditions. For the most part, neonates are preferential nose breathers, which easily facilitates the application of nasal CPAP. CPAP is accomplished by inserting nasopharyngeal tubes, affixing nasal prongs, or fitting a nasal mask to the patient (Fig. 1.13).

PHYSIOLOGICAL CONSIDERATIONS

The application of assisted ventilation requires the basic understanding of a few physiological parameters which are to be assessed in order to optimally ventilate a baby with CPAP.

Airway Resistance

Lung Compliance

The respiratory tract can be simplified into a tube and balloon model to understand the basic concepts of application of CPAP. The baby's ventilation is influenced by the caliber of the airways (airway resistance) and the stiffness of the lung which is reflected by alveolar collapse (atelectasis) this indicates the lung compliance (Figs 1.14 and 1.15)

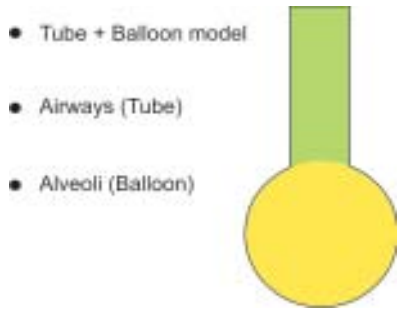


Fig. 1.13: Tube and balloon model—Lung concept

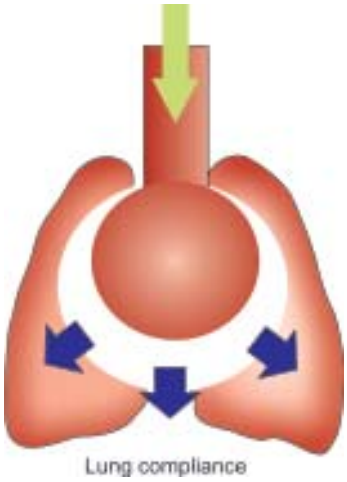


Fig. 1.14: Airway resistance and lung compliance

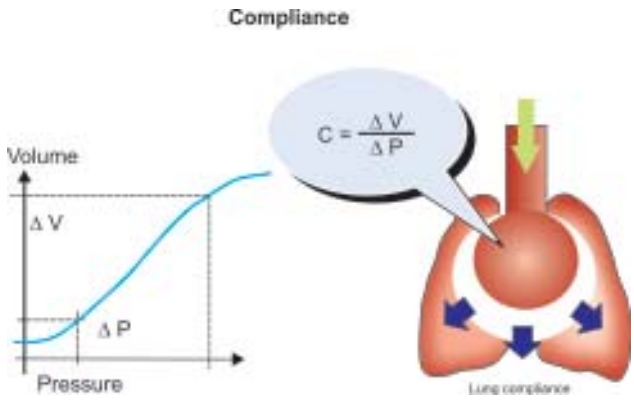


Fig. 1.15: Compliance: Property of distensibility of the lungs and chest wall

Compliance is defined as the unit change in volume for a given unit change in pressure. In hyaline membrane disease (HMD), compliance is extremely low and at the lowest point of the pressure-volume curve.

Where R = Resistance of airways

ΔP = Pressure difference between upper airway and alveoli

ΔF = The difference in flow between upper airway and alveoli

Airway resistance is directly correlated with the tube length, and divided by the fourth power of tube radius (Fig. 1.16). Inspiratory flow resistance is always less than expiratory flow resistance as the airways dilate during inspiration. In meconium aspiration, the airway resistance is very much increased due to airway debris and bronchospasm, which reduce the cross-sectional diameter of the airways significantly.

The work of breathing is best displayed on a pressure-volume curve of one respiratory cycle. Figure 1.17 shows the different pathways for inspiration and expiration, known as hysteresis. The total work of breathing of the cycle is the area contained in the loop.

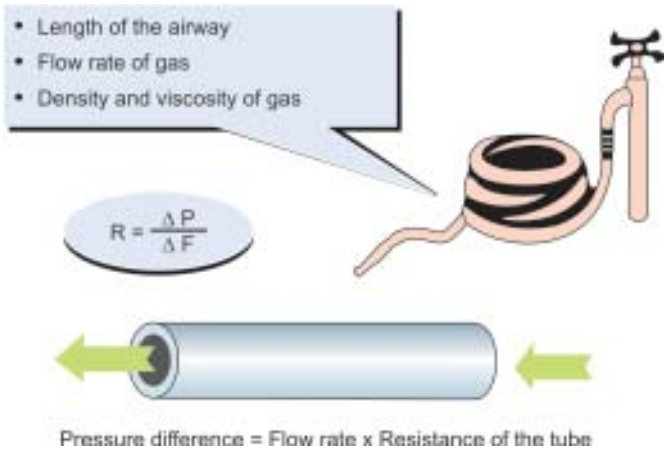


Fig. 1.16: Airway resistance: Property of airways to offer restriction to airflow

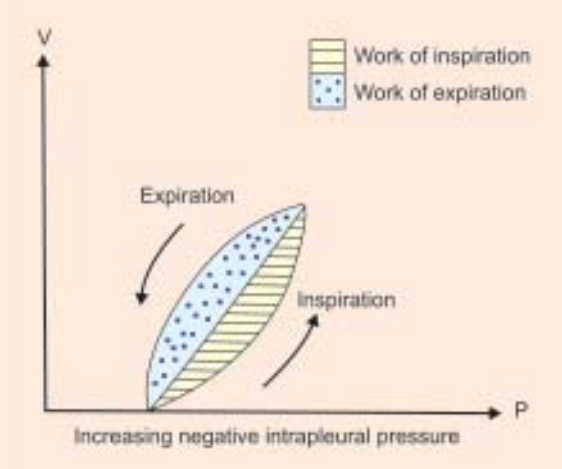


Fig. 1.17: Pressure volume loop: Effect of increasing pressure on volume

Pressure Volume Loop in Hyaline Membrane Disease (HMD)

The normal lung exhibits good change in volume for a given unit change in pressure. This is in sharp contrast to the atelectatic (HMD) lung which shows minimal change in volume per unit pressure change. The direction of arrows show inspiration and expiration respectively (Fig. 1.18)

Relationship of Lung Condition with Pressure-Volume Loop

The pressure-volume curve as it moves towards residual volume (RV) will indicate the severity of atelectasis. The degree of improvement in functional residual capacity (FRC) moves the point towards the middle of the pressure volume curve indicating good change in volume for unit change in pressure. It is evident that as the FRC gets overexpanded with excessive CPAP, the change in volume is again reduced for unit change in pressure. TLC denotes total lung capacity.

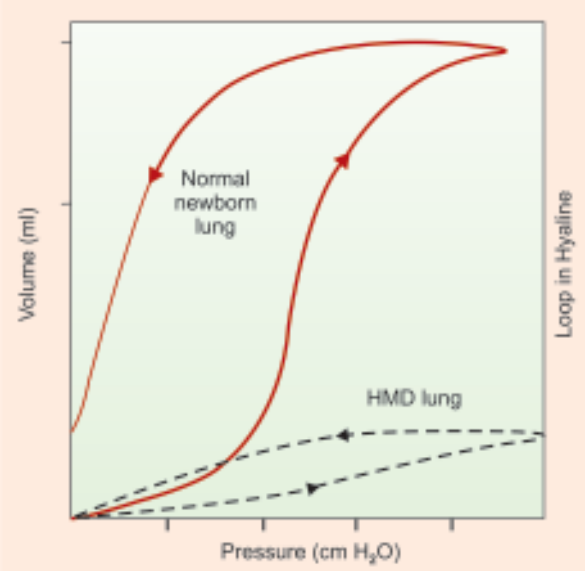


Fig. 1.18: Pressure volume loop in hyaline membrane disease (effect of HMD an PV loop)

CPAP is the major factor determining lung volume. At low CPAP, low lung volumes are evidenced as in RDS and compliance is low. At optimum, lung volumes compliance increases. At still higher volumes (overdistention) compliance again decreases. Optimum FRC results in optimum compliance and the lowest work of breathing. Optimum CPAP is indicative of optimum FRC (Fig. 1.19).

Lung volume is also related to airway resistance. At low lung volumes (insufficient CPAP) airway resistance is high and since atelectasis is not resolved, work of breathing is high. At optimum lung volumes airway resistance is low. Thus CPAP can improve distribution of ventilation to optimize FRC and therefore optimize both lung compliance and airway resistance.

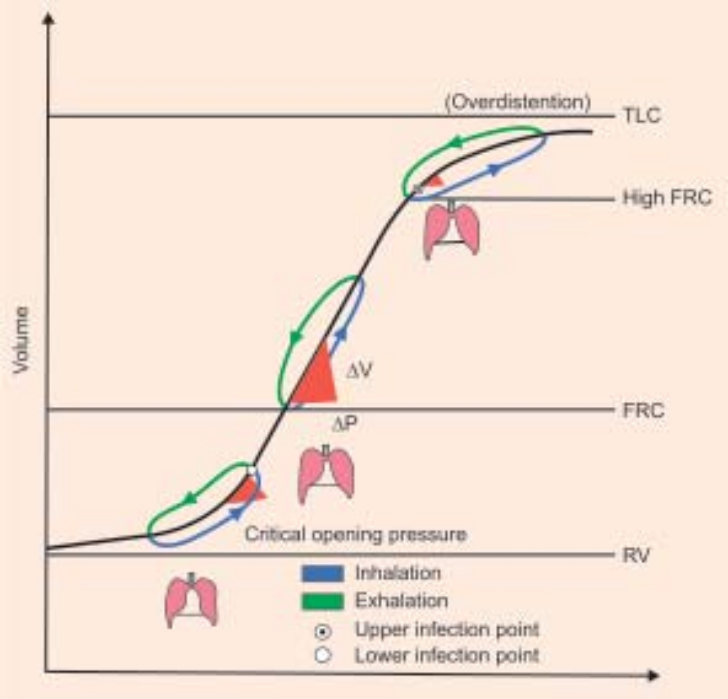


Fig. 1.19: PV loops in various stages of lung expansion

The effect of CPAP is primarily to improve oxygenation and its effect on CO_2 is secondary to the primary event of improving surface area for gas exchange.