Chapter 2
Physiology of Inflation and Deflation

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The process of breathing, spontaneous or mechanical, involves the physical movement of air in and out of the lungs. Interaction of various physical factors is involved in the way this process occurs physiologically. It is important to understand these factors as they relate to diagnosis and management of lung disease.

2.1 Equation of Motion

A pressure gradient (Δ pressure) is required to move air in and out of the lung. In normal spontaneous respiration, air is drawn from the atmosphere into the alveoli because of negative intrapleural pressure generated by contraction of the diaphragm and intercostal muscles during inspiration and released from alveoli into the atmosphere during expiration by pressure generated from elastic recoil of the lung. During mechanical ventilation, gas flows into the lungs from positive pressure created by the ventilator during inspiration and exhalation results from alveolar pressure generated by elastic recoil of the lung and chest wall.

The original version of this chapter was revised with correct equation at page 17.
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Regardless of the site where it is generated, the pressure necessary to move air is expended for two opposing mechanical factors: (1) *elastance* (inverse of compliance) and (2) *resistance* (Fig. 2.1). Major component of resistance is experienced in generation of airflow across the airways and a minor component is from frictional resistance of tissues. Pressure to overcome elastance is measured by determining the change in volume (Δ volume) after pressure has equilibrated at both ends and flow has ceased. Alveolar pressure is determined in the proximal airway by performing the inspiratory occlusion technique. This means that both the Δ volume and the Δ pressure are determined when pressure has equilibrated throughout and airflow has ceased. Resistance on the other hand is experienced only when airflow is occurring. Thus, the pressure to overcome resistive forces is measured by determining the Δ pressure applied at the source and the flow that results from this. When compliance is measured at a point where there is no flow, it is referred to as static compliance (C_{STAT}). When measured while the flow is occurring, it is referred to as dynamic compliance (C_{DYN}).

2.2 Time Constant

For airflow to occur, a pressure gradient has to be created from one end to the other (proximal airway and the alveoli). Flow will continue as long as the pressure gradient remains between the two ends. When pressure equilibrates at two ends, flow ceases. The equilibration of pressure does not occur instantaneously. It takes some time for pressure to equilibrate at two ends. The time required for pressure

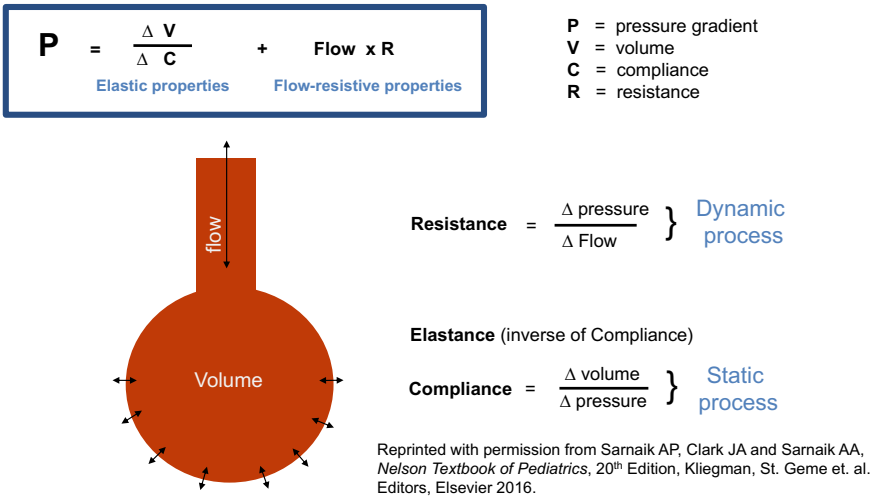

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Fig. 2.1 Equation of motion. Pressure required to move air in and out of the lung is to overcome Resistance (dynamic process) and Elastance (static process)

gradient depends on two variables: (1) compliance and (2) resistance. When compliance is low (meaning elastance is high), the elastic recoil pressure of the lung is increased. During inspiration, inflow of air is opposed by high lung recoil (decreased compliance) and during exhalation; outflow of air is aided by it. This results in quicker attainment of pressure and equilibration volume with cessation of flow in a relatively short time. On the other hand, when airway resistance is increased, longer time is required for pressure/volume equilibration and cessation of air flow to occur. Time constant is a reflection of the time necessary for pressure/volume equilibration to occur and airflow to cease. Thus, the required time is directly proportional to both compliance and resistance. Greater the compliance and resistance, longer the time needed and vice versa. Indeed, time constant is calculated as:

$$\tau(Time\ Constant) = Compliance \times Resistance$$

$$\tau = \frac{\Delta V}{\Delta P} \times \frac{\Delta P}{Flow}$$

$$\tau(\mathrm{s}) = \frac{\cancel{mL}}{\cancel{cms}} \times \frac{\cancel{cms}}{\cancel{mL}/s}$$

Thus, time constant is appropriately represented as time (Fig. 2.2).

It takes one time constant for 63%, two time constants for 86%, 3 time constants for 95% and 5 time constants for almost complete pressure or volume equilibration to occur. Since time constant is a product of compliance and resistance, patients with increased airway resistance require greater time during inspiration and

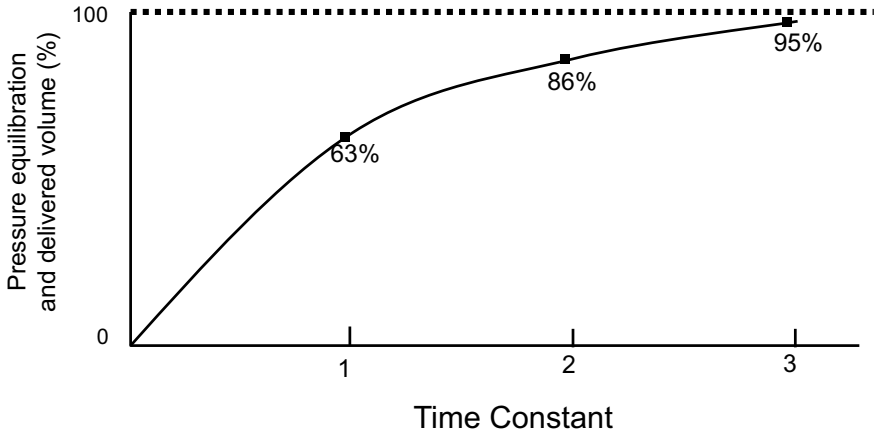


Fig. 2.2 The time required for % of pressure equilibration (and therefore the volume delivery) depends on the time constant of a given system

expiration for pressure and volume equilibration to occur and airflow to cease. Conversely, in patients with diseases of decreased compliance, pressure and volume equilibration occurs quicker. Airways expand during inspiration and narrow during exhalation. Thus, expiratory time constant, because of increased airway resistance is greater than inspiratory time constant. This discrepancy becomes more pronounced in diseases of increased airway resistance (asthma, vascular ring etc.) where expiratory time constant is markedly increased to the point pressure equilibration at the end of expiration does not occur resulting in hyperinflation and auto-PEEP (see below).

The effects of compliance and resistance on time constant are presented in Fig. 2.3. Let's consider that based on compliance and resistance of a normal lung the time constant is X seconds. This would mean that if a pressure of 10 cm H_2O is applied at one end it would take 3X seconds for the other end to receive 9.5 cm H_2O (95% of the driving pressure). The expiratory time constant will be greater than inspiratory time constant because airway resistance is greater in exhalation as they become narrower compared to during inspiration. In diseases with decreased compliance, the time constant will be less than X seconds. Although the volume delivered will be less than in a normal lung, the pressure equilibration is quicker. The inspiratory and expiratory time constants are closer to each other because of greater lung recoil pressure. In diseases of increased airway resistance, the time constant is greater than X seconds as the proximal pressure takes more time to

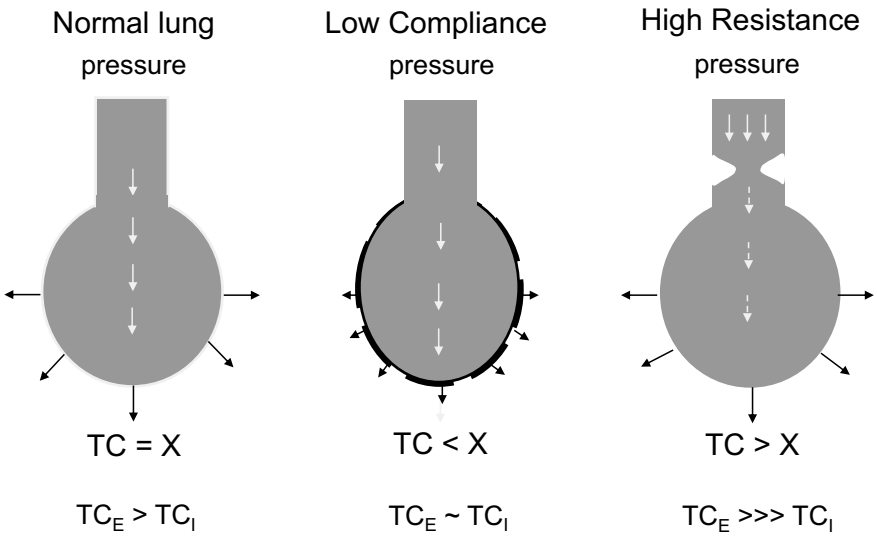


Fig. 2.3 Effect of decreased compliance and increased resistance on time constant (TC). Normally, TC is longer during exhalation as airways get narrower compared to inhalation. Diseases with decreased compliance have decreased TC with expiratory TC (TC_E) getting closer to inspiratory TC (TC_I). Diseases of airway obstruction have prolonged TC with TC_E far exceeding TC_I

overcome airway resistance. In intrathoracic airway obstruction which gets worse during exhalation, the expiratory time constant is much more increased compared to the inspiratory time constant.

Even though a disease can be classified as that of increased resistance (e.g. asthma) or decreased compliance (e.g. ARDS), most lung diseases are often heterogeneous in nature.

Normal lung units are interspersed with units with prolonged time constants (increased resistance) and those with short time constants (decreased compliance). The effect of time on the delivered volume after application of pressure is shown in Fig. 2.4. The units with short time constants fill up (or empty) quickly, with negligible change in volume as time is increased from A to B. The units with increased time constants however fill up (or empty) much slower with greater volume change with time B compared to time A. Consideration of time constant is extremely important when choosing respiratory rate and I:E ratio during mechanical ventilation.

2.2.1 Auto-PEEP and Dynamic Hyperinflation

Auto-PEEP and dynamic hyperinflation exist when exhalation is incomplete and the alveolar pressure has not had sufficient time to equilibrate with atmospheric (or ventilator) pressure during exhalation. As a result, the lung volume is increased above the potential FRC when lung recoil is complete. This occurs in two situations: (1) in patients with airway obstruction such as asthma, time constant is

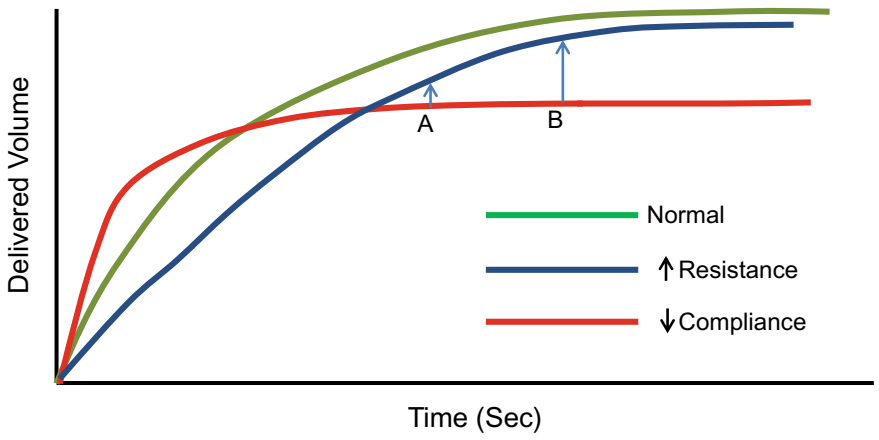


Fig. 2.4 Change in volume delivery in lung units with different time constants. Increasing time from A to B will result in greater volume change in lung units with prolonged time constant (increased resistance) compared to the little change in volume in those units with short time constant (decreased compliance) where pressure equilibration has already occurred

prolonged, much more so during exhalation, preventing complete alveolar emptying. Inspiration occurs either spontaneously or is delivered mechanically before alveolar pressure approximates proximal airway pressure at end expiration. This is termed auto-PEEP and (2) at high respiratory rates, the decrease in expiratory time is not sufficient for complete alveolar emptying to occur. This is referred to as dynamic hyperinflation. Neonates, with their high respiratory rates experience dynamic hyperinflation. Dynamic hyperinflation also results during exercise where both tidal volume and respiratory frequency are increased.

2.3 Work of Breathing

2.3.1 Pressure–Volume Work

In physics, work is defined as the product of force and distance. In the context of respiratory mechanics, work of breathing (WOB) is defined as the product of pressure and volume. It represents the energy required to move air in and out of the lungs. In spontaneous breathing, the work is done by the patient whereas in controlled mandatory breaths, the work is done by the ventilator. Except in situations when expiration is active (obstructive lung disease and forced expiration), WOB is performed during inspiration while the exhalation is passive and the work is accomplished by elastic recoil of the lung. In obstructive lung disease, the patient has to perform expiratory work by creating positive intrapleural pressure by diaphragmatic and intercostal contraction. Calculation of WOB requires consideration of pressure–volume relationship. As stated in equation of motion, one component of pressure required to effect a change in lung volume is to overcome its elastance and the other is to overcome its flow-resistance properties. In the Fig. 2.5, where spontaneous respiration is presented, the red line represents the static pressure volume relationship when there is no flow. Area covered by ACDA represents the inspiratory elastic work (W_{ELAST}) whereas the area covered by ABCA represents the work that represents the flow-resistive work (W_{RESIST}). The total WOB for a given breath is the sum of W_{ELAST} and W_{RESIST}. Total WOB/min is WOB for each breath X respiratory rate. As tidal volume is increased, W_{ELAST} increases since greater amount of volume is moved at higher pressure. W_{RESIST} on the other hand is greatest at maximum flow. At faster respiratory rates, there is less time for air movement to occur. Therefore, air needs to be moved at a higher flow rate. Thus, W_{RESIST} increases at higher respiratory rates. In health as well as in disease, a given minute alveolar ventilation [(Tidal volume—Dead space) X Respiratory rate] is accomplished at a combination of tidal volume and respiratory rate that necessitates the least amount of energy expenditure. Young infants have a larger W_{ELAST} than W_{RESIST} compared to older children and adults. This is not because their lungs have greater elastic recoil (less compliance), but because their chest wall is more compliant and it tends to retract inwards in response to negative intrapleural pressure

during inspiration making lung inflation more difficult. The total WOB is lowest at a rate of 35–40/min for neonates and 14–16/min for older children and adults.

W_{ELAST} increases disproportionately in diseases with decreased compliance and W_{RESIST} increases in diseases with increased airway resistance. Respirations are therefore shallow (low VT) and rapid in diseases of low compliance and deep and relatively slow (decreased flow rate) in diseases of increased resistance in order to minimize energy expenditure. In healthy children, the energy cost of WOB is only approximately 2% of total body expenditure. In children with chronic lung disease, WOB may contribute to as much as 40% of total energy expenditure.

2.4 Airway Dynamics in Health and Disease

Airways in infants are much more compliant compared to older children and adults resulting in greater changes in airway diameter when subjected to similar transmural pressure changes. To understand the phasic dynamic changes during the respiratory cycle, the airway can be divided into 3 anatomic parts: the extra-thoracic airway from the nose to thoracic inlet, the intrathoracic-extrapulmonary airway from the thoracic inlet to the main stem bronchi, and intrathoracic airway which is embedded in the lung parenchyma. Transrespiratory pressure ($P_{AW} - P_{ALV}$) is responsible for air movement. Please note that P_{AW} refers to proximal airway pressure which is same as mouth or atmospheric pressure during spontaneous ventilation and pressure applied to patient-positive pressure interface (ET tube, face

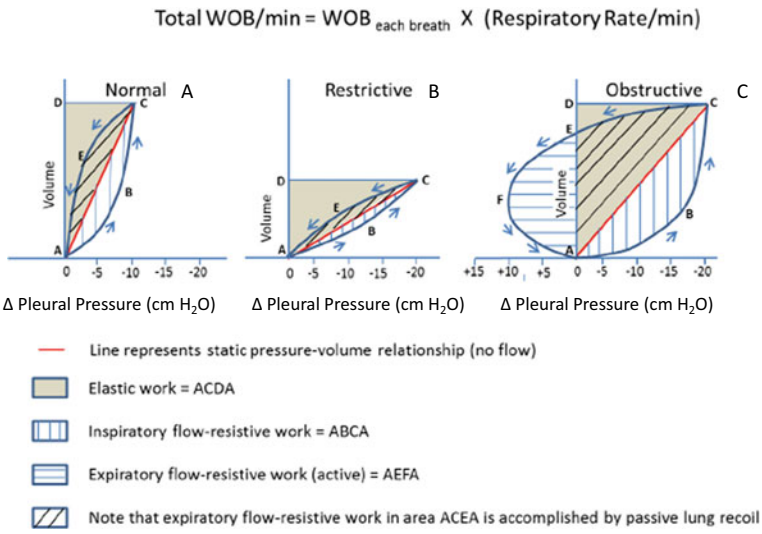
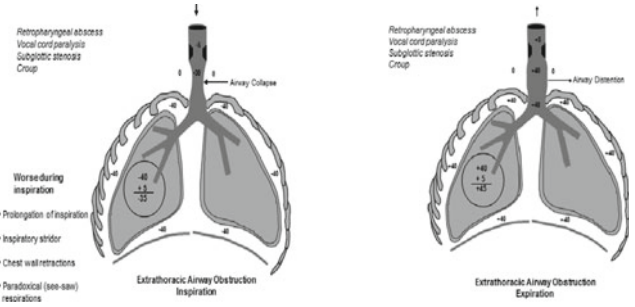


Fig. 2.5 Work of Breathing (WOB) in normal state (**a**), restrictive disease (**b**), and obstructive disease (**c**)

mask, nasal cannula etc.) during mechanical ventilation. P_{ALV} depends on two factors; P_{PL} and recoil pressure of the lung. Lung recoil pressure is greater at higher lung volume and increased elastance (decreased compliance). For the purpose of simplicity, we will assign the value of +5 cm H_2O to lung recoil pressure in order to describe transmural pressures the airways are subjected to during respiration.

During normal spontaneous respirations, intrathoracic airways expand in inspiration because of negative intrapleural pressure, and somewhat narrower during exhalation as they return to the FRC. In diseases characterized by increased airway resistance, a much greater change in intrapleural pressure is required to generate adequate airflow. The transluminal pressure that the walls of the airway are subjected to increase proportionate to the extent the intrapleural pressure is increased. During mechanical ventilation, airways are subjected to positive pressure during inspiration. During exhalation however, it is the positive pressure in the pleural cavity that the alveoli and intrathoracic airways are subjected to. The changes in the size of the airways, which are softer and more compliant, are accentuated in young infants during respiration.

In extra-thoracic (ET) airway obstruction, (retropharyngeal abscess, laryngotracheitis, vocal cord paralysis etc.), most of the increased negative transrespiratory pressure (P_{TR}) during inspiration is transmitted up to the site of obstruction beyond which it is rapidly dissipated. The ET airway below the site of obstruction is subjected to a marked increase in negative intraluminal pressure resulting in collapse. This leads to inspiratory difficulty, prolonged inspiration and inspiratory stridor. Increase in negative intrapleural pressure results in suprasternal, intercostal and subcostal retractions. During exhalation, the increased P_{TR} is again transmitted to the site of obstruction resulting in distension of the ET airway and amelioration of obstruction (Fig. 2.6).

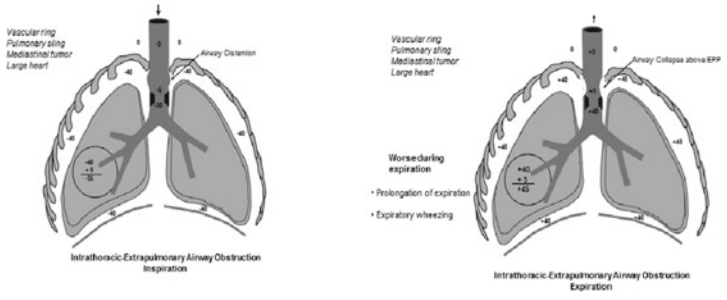


During inspiration, increased negative pleural pressure is transmitted to all airways including the extra-thoracic. This results in collapse of the extra-thoracic airways distal to the site of obstruction. The end result is increased inspiratory resistance and worsening of obstruction.
During exhalation, positive pleural pressure is transmitted to all airways including the extra-thoracic. This results in distention of the airway below the site of obstruction and improvement of symptoms.
Pressures are presented relative to atmospheric pressure (0 cm H_2O). Distal airway pressures are taken as pleural pressure plus lung recoil pressure (arbitrarily taken as +5 cm H_20 for simplicity).

Fig. 2.6 Airways dynamics in extra-thoracic airway obstruction

These symptoms are especially pronounced in newborns and infants with their compliant chest wall and airways. One may observe paradoxical or see-saw respiration as the chest wall retracts inwards and abdomen bulges out due to diaphragmatic descent during inspiration and the converse occurring during exhalation. In obstruction of intrathoracic-extrapulmonary (IT-EP) airways such as vascular ring, pulmonary sling, mediastinal mass etc. the equal pressure point (EPP) is displaced distally and the intrathoracic airway above the obstruction is subjected to an excessive positive intrathoracic pressure (Fig. 2.7).

This results in intrathoracic airway collapse above the EPP, worsening the obstruction leading to the signs and symptoms of expiratory difficulty and wheezing, prolongation of expiration and hyperinflation. During inspiration, there is relatively less obstruction as the IT airway above the obstruction is surrounded by much more negative extraluminal pressure than intraluminal and thus tends to distend with improvement in symptoms. The classic findings of expiratory wheezing in IT-EP obstruction has led to the axiom "all that wheezes is not asthma". In unilateral IT-EP obstruction, such as in foreign body aspiration, the clinical manifestations are predominantly at the site of the lesion. In IP airway obstruction such as with asthma and bronchiolitis, the EPP moves further into the distal airways causing a widespread intrathoracic collapse during expiration resulting in expiratory wheezing, prolonged expiration, air trapping and hyperinflation (Fig. 2.8).



During inspiration, increased negative pleural pressure is transmitted to all structures inside the chest including the airways up to the site of obstruction beyond which it is rapidly dissipated. This results in distension of the intra-thoracic airways proximal to obstruction as it is surrounded by even greater negative intrathoracic pressure. During exhalation, the increased airway pressure rapidly dissipates above the obstruction. There is a collapse of the intrathoracic airway above the obstruction because of markedly increased positive intrathoracic pressure outside the airway making the obstruction worse during exhalation. Equal pressure point (EPP) is the point at which intra and extra luminal pressures during exhalation are equal.
Pressures are presented relative to atmospheric pressure (0 cm H_2O). Distal airway pressures are taken as pleural pressure plus lung recoil pressure (arbitrarily taken as +5 cm H_20 for simplicity).

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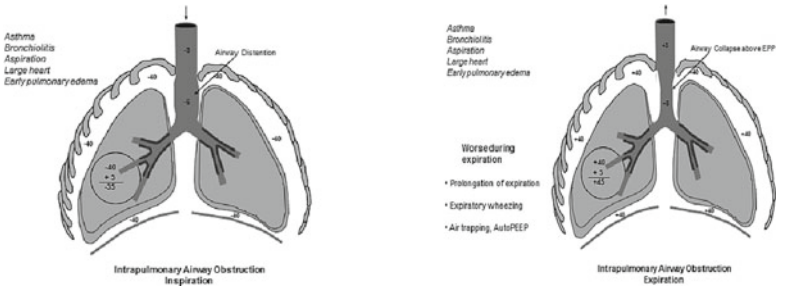
Fig. 2.7 Airway dynamics in intra-thoracic extrapulmonary airway obstruction



During inspiration, increased negative pleural pressure is transmitted to all structures inside the chest including the airways. The intrathoracic extraluminal airway pressure is more negative especially above the site of obstruction resulting in airway distension. During exhalation, the positive intrathoracic pressure rapidly dissipates above the site of obstruction and the equal pressure point moves distally towards the alveoli. The end result is widespread airway collapse and worsening of symptoms. Pressures are presented relative to atmospheric pressure (0 cm H_2O). Distal airway pressures are taken as pleural pressure plus lung recoil pressure (arbitrarily taken as +5 cm H_20 for simplicity).

Fig. 2.8 Airway dynamics in intra-thoracic intrapulmonary airway obstruction

Suggested Readings

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