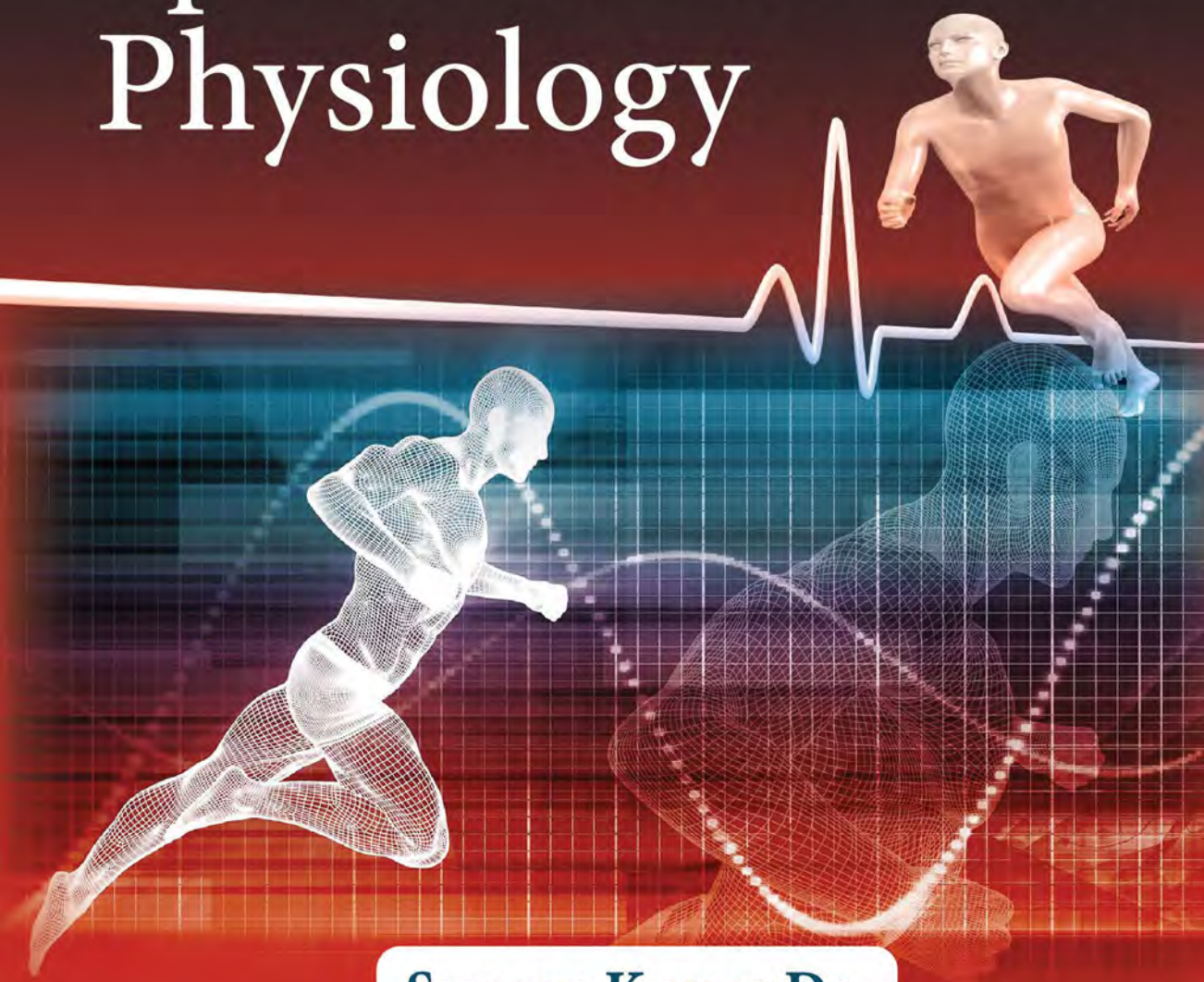
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A Textbook of Sports & Exercise Physiology



Swapan Kumar Dey

2nd Edition

JAYPEE

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4

CHAPTER

Respiratory System

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CHAPTER OUTLINE

- Structure of Human Respiratory Organ (Lungs)
- Phases of Respiration (External and Internal Respiration)
- Pulmonary Ventilation
- Hyperventilation and Breath Holding
- The Respiratory Muscles
- Mechanism of Breathing
- Functional Aspect of Respiration
- Lung Volume and Capacities
- Expirograph (Spirometry)
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- Respiratory Regulation of Acid-Base Balance
- Artificial Respiration

RESPIRATORY SYSTEM

The system formed by the organs which are concerned for the exchange of gases between the environment and living organism is called the respiratory system.

Respiration is the process by which oxygen from the lungs is carried by the blood to the tissue and carbon dioxide formed in the tissues by metabolic activity is carried by the blood to the lungs and is expired out. The transportation of gases involves four different processes. These are as follows:

i. Breathing is the movement of air into and out of the lungs.
ii. Diffusion is the exchange of gases between the lungs and the blood.
iii. Transport of gases (O_2 and CO_2) through blood
iv. Exchange of gases from blood to active tissues and vice versa.

The first two processes are referred to as external respiration because they involve moving gases from outside the body into the lungs and then the blood. Once the gases are in the blood, they must travel to the tissues and the fourth step of respiration occurs. This gas exchange between the blood and the tissues where food particles are burned and produce energy is called internal respiration.

STRUCTURE OF HUMAN RESPIRATORY ORGAN (LUNGS)

The respiratory system consists of the following structures **(Fig. 4.1)**:

1. *The air conducting passage:* The air passage mainly consists of nostril, nasal cavity,

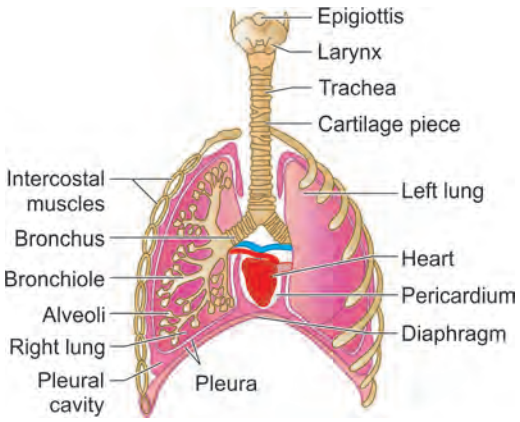


Fig. 4.1: Structure of human lungs.

bronchi, and bronchioles. The air from the atmosphere enters through the ***nostrils***, which open through the internal areas into the ***pharynx***. From the pharynx, the air passes through the cartilaginous chamber known as ***larynx***. This structure is also associated with the production of sound.

Trachea

The main air conducting passage is known as ***trachea***. It is about 12 cm long and 15–18 mm diameter cartilaginous and membranous windpipe. It is kept potent by incomplete C-shaped rings of cartilage on its anterior wall, which keeps air tubes open. The trachea containing numerous mucus glands along with goblet cells trap dust in the inspired air and air is moistened. The cilia beat spontaneously and by their movement it drive out the foreign particles and bacteria to the mouth to entry the clean air to the alveoli. It begins from the lower part of the larynx and ends by separating into right and left ***bronchi***.

Bronchus

The trachea then divides into two branches which are called bronchi which enter into the right and left lungs. The right ***bronchus*** is little larger than the left. Within lungs, the right bronchus is divided into three bronchioles, whereas the left bronchus is divided into two bronchioles. These bronchioles are again subdivided into a number of respiratory terminal bronchioles.

Bronchioles

Each terminal bronchiole opens into a thin-walled respiratory bronchiole of equal diameter which communicates with some alveoli situated on its wall. However, for the most part, each respiratory bronchiole opens into several alveolar ducts; these later open into dilated spaces called pulmonary atrium which further extends to the pulmonary alveoli.

Alveoli

Each alveolus is a thin-walled sac filled with air measuring from 75 to 300 μm in diameter. The capillaries of the pulmonary blood vessels ramify around the walls of the alveoli. The alveolar tissue contains fibers of elastin and collagen and the fluid lining the alveoli has the surface tension. As a result, the lung is elastic and is held expanded by keeping the pressure around it lower than the alveolar pressure **(Fig. 4.2)**.

Schematic representation of airway passage:
Nostril → Trachea → Primary bronchus → Secondary bronchus → Tertiary bronchioles → Terminal bronchiole → Atrium → Alveolus.

2. *Lungs:* Lungs are essential organs for respiration. The lungs are paired, spongy structures, which are situated in the thoracic cavity just above the diaphragm and lateral to the heart. The right lung consists of three lobes and the left lung is divided into two lobes. The membrane, which covers the lungs, is called ***pleura***. There are two such membranes covering (double layered) lungs; the outer membrane is called ***parietal pleura*** and the inner membrane is called ***visceral pleura.*** Space, i.e., pleural cavity between these membranes, is filled with a fluid called ***pleural fluid***.

The normal intrapleural pressure, i.e., pressure in the pleural cavity, is negative and amounts to –2.5 mm Hg at the end expiratory position. This means that the lungs are not completely collapsed and that alveoli remain partially inflated even after complete expiration.

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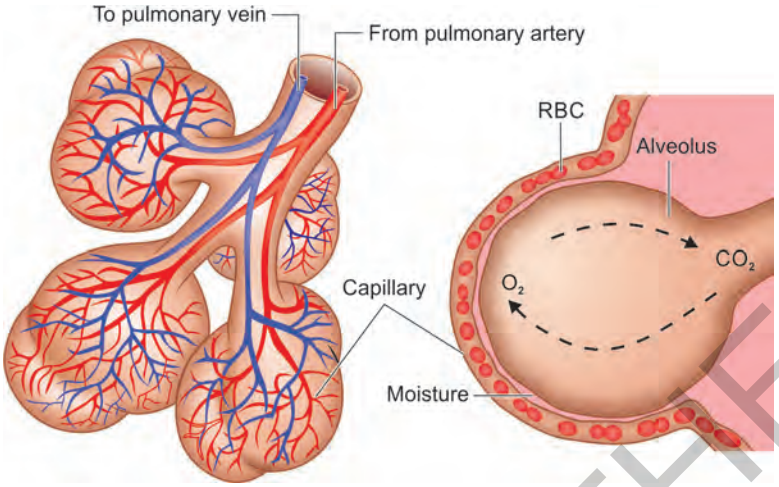


Fig. 4.2: Ventilation and perfusion of respiratory and pulmonary capillary in the alveolar air with the blood-gas barrier.

The factors responsible for negative intrapleural pressure are: a) elastic recoil and b) surface tension of the intra-alveolar fluid. Due to the presence of elastic fibers, the lung tissue has a continuous tendency to recoil away from the chest wall. The tendency naturally increases during inspiration with inflation of the alveoli. On the other hand, due to the intramuscular attraction of the surface layer of the fluid lining the alveoli, they have got a tendency to collapse. The collapsing force of the millions of the alveoli produces a summated effect resulting in tendency of the whole lung to recoil away from the chest wall.

The pleural fluid resists friction of the membrane during breathing. The membranes show elasticity. In the lungs, the bronchioles terminate into the blind sacs known as ***alveoli***. Alveolus is the physiological unit of the lung. Alveoli are lined by a thin layer of squamous epithelium cell. Each alveolus is surrounded by a network of capillaries. Oxygen and carbon dioxide readily diffuse through the thin and moist walls of the alveoli.

3. *Associated respiratory organs:* The ***thorax***, which contains the lungs, is bounded by the ***rib cage***. On the lower side of the thorax, lungs are attached with a dome-shaped sheet of skeletal muscle, the ***diaphragm***. In between the ribs, ***intercostal muscles*** are present. They are of two types: external intercostal and internal intercostal muscle. These muscles are called ***muscles of respiration*** **(Fig. 4.3)**.

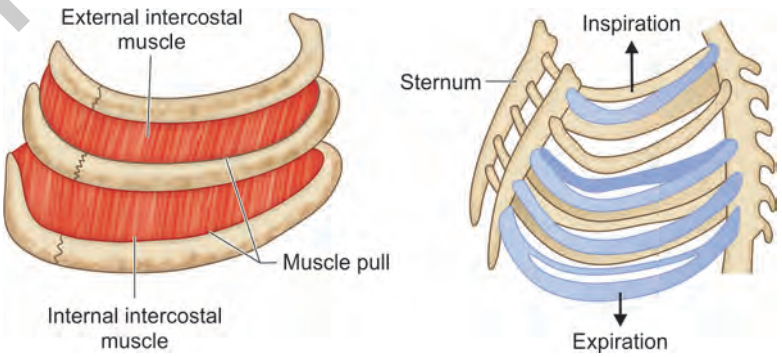


Fig. 4.3: Intercostal muscles and movements of ribs during inspiration and expiration.

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Functions of respiration: The following functions are performed by the respiratory system:

- Transfer of O_2 from the alveoli to the venous blood and CO_2 from venous blood to the lungs.
- Maintain the arterial pressure of CO_2 at 40 mm Hg, which is essential for many vital functions of the body.
- It regulates the acid-base balance (pH of blood) of the body.
- Excretion of certain volatile gases from the body.
- Pumping action to assist in drawing blood from the lower part of the body to help in maintaining venous inflow to the heart.

PHASES OF RESPIRATION (EXTERNAL AND INTERNAL RESPIRATION)

- ***External respiration:*** External respiration is the physical process of interchange of gases between the organism and its environment. Oxygen enters into the body of the organism from the surrounding by diffusion, while carbon dioxide diffuses out from the organism to the environment around. Various respiratory organs, such as trachea, bronchi, and lungs, take part for this purpose.
- ***Internal respiration:*** Internal respiration is the physical process of interchange of gases between the body fluid and tissue cells. In this phase, O_2 enters into the tissue cells by diffusion and is utilized for oxidative process in the cells' mitochondria. This is also called tissue oxidation or tissue respiration. It produces CO_2, which diffuses out from the tissue cells and ultimately diffuses to the venous blood.

PULMONARY VENTILATION

Pulmonary ventilation is the process by which air is moved into and out of the lungs.

Inspiration: It is an active process through which the diaphragm and the external intercostal muscles increase the dimension and thus, the volume of the thoracic cage is reduced and this decreases the pressure in the lungs and draws air in.

Expiration: Normal expiration is a passive process. The inspiratory muscles relax and the elastic tissue of the lungs recoils, returning the thoracic cage to its smaller, normal dimension. This increases the pressure in the lungs and forces air out.

Respiratory Quotient or RQ

Definition: It is the ratio of the volume of carbon dioxide evolved to the volume of oxygen taken in (consumption) during the process of respiration. Therefore, RQ is represented as CO_2/O_2. It depends on the nature, amount of O_2 present in the respiratory substrate, and extent to which the respiratory substrate is broken down. Examples-RQ of carbohydrate is 1.0 whereas in fat it is 0.7 and for a mixed diet it is 0.85.

HYPERVENTILATION AND BREATH HOLDING

If a person breath-holds after a normal exhalation, it takes approximately 40 seconds before the urge to breathe increases enough to initiate inspiration. The stimulus to breathe comes primarily from increased arterial pCO_2 and H^+ concentration, *not* decreased pO_2 in the breath-holding condition. The break point for breath holding corresponds to an increase in arterial pCO_2 to approximately 50 mm Hg.

If one consciously increases ventilation above the normal level (**hyperventilation**) before breath holding, alveolar air composition becomes more like ambient air. Alveolar pCO_2 decreases from its normal value of 40 mm Hg to a low of 15 mm Hg. This creates a considerable diffusion gradient for carbon dioxide runoff into the alveoli from venous blood that enters the pulmonary capillaries. Consequently, a larger than normal quantity of carbon dioxide leaves the blood and arterial pCO_2 decreases. Hyperventilation extends breath-holding duration until arterial pCO_2 and/or H^+ concentration rises to levels that again stimulate the urge to breathe.

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Swimmers and divers use hyperventilation and subsequent breath-holding to improve performance. In sprint swimming, for example, many sprinters hyperventilate on the starting blocks to prolong the breath-hold during the swim and avoid taking a breath. In sport diving, hyperventilation offers a similar effect—to extend breath holding time. Tragedy while diving can occur with extended breath holding from hyperventilation. As the length and depth of a dive increase, the blood's oxygen content decreases to a critically low level before arterial pCO_2 rises enough to stimulate breathing and signal ascent. The diver, unfortunately, often loses consciousness before surfacing.

THE RESPIRATORY MUSCLES

The respiratory muscles play an important role in respiration. Two types of respiratory muscles are involved during respiration: muscles of inspiration and muscles of expiration. The details of these muscles are discussed in the following text.

Muscles Used in Inspiration

- ***Diaphragm:*** The *diaphragm* is believed to be the most important single muscle of inspiration. During resting conditions, it makes a dome shape over the liver and stomach. When it contracts, it causes the bottom of the thorax to flatten (increases the vertical dimension of the thorax). In other words, the domed area is lowered.
- ***External intercostal muscles* (Fig. 4.4):** During strenuous work when heavy breathing is required, the *external intercostal muscles* are brought into play much more extensively. They raise the ribs and sternum in order to create additional enlargement of the anteroposterior and lateral diameters of the chest cavity.
- ***Scalene:*** During exercise, the large volume of inspired air is also aided by contraction of other inspiratory muscles. For instance, contraction of the *scalene* muscle helps to raise the first two ribs.
- ***Sternocleidomastoid:*** The other inspiratory muscle involved during exercise and contraction of the *sternocleidomastoid* muscle helps to raise the sternum.
- ***Extensor muscles:*** It should also be pointed out that the *extensor muscles* of the back and neck help to facilitate inspiratory breathing during vigorous work.
- ***Trapezius:*** The large *trapezius* muscle also helps to facilitate inspiratory breathing during vigorous work.

Muscles Used in Expiration

During normal resting conditions, expiration is primarily due to the elastic recoil of the inspiratory muscles (diaphragm and external

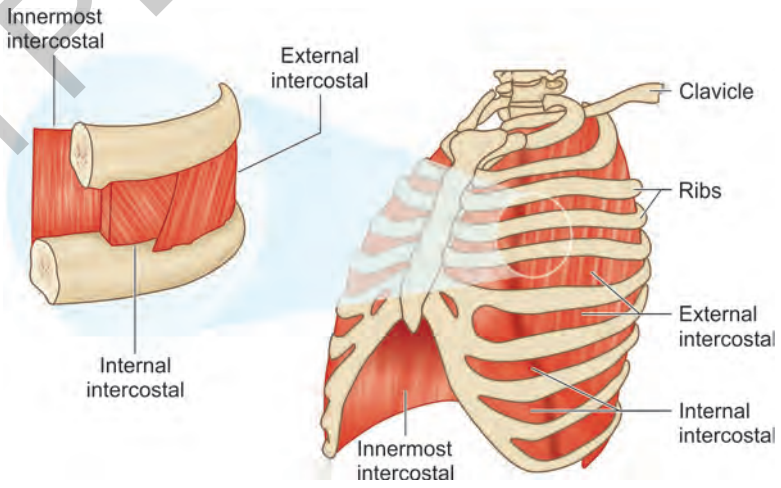


Fig. 4.4: External and internal intercostal muscles.

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intercostal muscles) as they return to their resting positions. This means that during normal resting conditions, expiration plays a passive role while inspiration plays a more active role. However, during exercise, expiration is aided by contraction of the expiratory muscles, thus making it an active process **(Fig. 4.5)**.

- ***Abdominal muscles:*** The abdominal muscles are the most important muscles of expiration during heavy work. When these muscles contract, they not only flex the trunk but also press down the lower ribs. These, in turn, help raise the pressure inside the abdomen.
- ***Diaphragm:*** The diaphragm is then forced upward into the thoracic region, thus reducing the overall size of the thoracic area and aiding in expiration.
- ***Internal intercostal muscles:*** In addition to the abdominal muscles, the internal intercostal muscles are also brought into play during heavy breathing. During the contraction of above muscles, they will pull the ribs down, thus bringing them close to each other. Hence, the combined action of the abdominal muscles and the internal intercostal muscles aids in reducing the size of the thorax and thus facilitates the role of expiration **(Table 4.1)**.

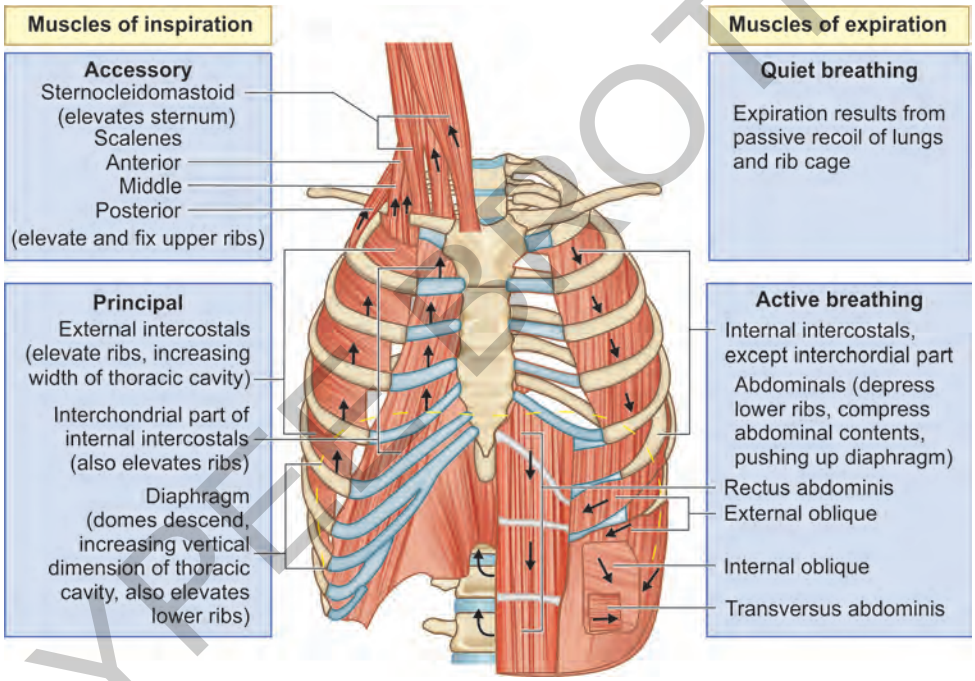


Fig. 4.5: Respiratory muscles (muscles of inspiration and expiration).

TABLE 4.1: Major respiratory muscles involved during rest and exercise.

Respiratory phase	*Muscle acting during rest*	*Action*	*Muscle acting during exercise*
Inspiration	i. Diaphragm	i. Flattens	i. Diaphragm
	ii. External intercostals	ii. Raises ribs	ii. External intercostals
		iii. Elevates first and second ribs	iii. Scalene
		iv. Elevates sternum	iv. Sternocleidomastoid
Expiration	None	i. Lowers ribs	i. Internal intercostals
	None	ii. Depresses lower ribs and forces diaphragm into thorax.	ii. Abdominal

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MECHANISM OF BREATHING

a. *Intra-alveolar pressure:* The respiratory muscles cause pulmonary ventilation by alternatively compressing and distending the lungs, which in turn causes the pressure in the alveoli to raise and fall. During inspiration, the intra-alveolar pressure becomes slightly negative with respect to atmospheric pressure (–3 mm Hg) and causes air to flow inside. During expiration, the intra-alveolar pressure rises and causes air to flow out. During maximum inspiratory and expiratory effort, the intra-alveolar pressure reduced (–80 mm Hg) and increased (100 mm Hg) respectively.

b. *Fluid pressure in the intrapleural cavity:* The normal pressure of the fluid in the intrapleural space is between –10 and –12 mm Hg. This negative pressure acts as a force to hold the visceral pleura of the lungs tightly against the parietal pleura of the chest wall. Due to enlargement and shortening of the chest cavity, this negative pressure causes the lungs also become large and short.

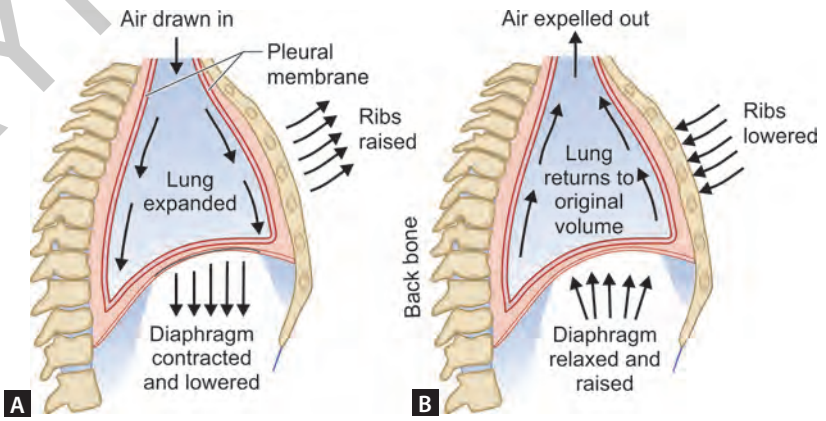
The cause of the very negative intrapleural fluid pressure is the continual tendency of the pleural capillaries to absorb fluid from the intrapleural space. This is particularly true of the visceral pleural capillaries, because these are part of the pulmonary circulatory system and have a very low capillary pressure (about 7 mm Hg) that causes rapid absorption of fluid.

c. *Recoil tendency of the lungs and intrapulmonary pressure:* The lungs have a continual tendency to collapse and therefore to recoil away from the chest wall. This tendency is caused by two different factors:
   i. Elastic fiber: Constantly stretched and shortened.
   ii. Surface tension: Due to intramolecular attraction of the surface layer of the fluid of alveoli, they have got a tendency to collapse. This collapsing force of the millions of alveoli produces a summated effect resulting in tendency of the whole lung to recoil away from the chest wall.

d. *The diaphragm and the abdominal muscles **(Figs. 4.6A and B)**:* Inspiration is an active process by which the air is taken from the atmosphere into the lungs. Normal inspiration is caused principally by the contraction of diaphragm. This muscle is bell-shaped so that contraction of any of its muscle fibers pulls it downward to cause inspiration.

Expiration is the passive process by which the air is given out from lungs to the atmosphere. During expiration, the relaxation of intercostal and diaphragm muscles takes place. The diaphragm and the thoracic wall return to their former position.

e. *Muscles that raise and lower the chest cage:* Three different groups of muscles *cause*



Figs. 4.6A and B: Contraction of diaphragm muscle during (A) inspiration and (B) expiration.

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inspiration by elevating the entire chest cage. The sternocleidomastoid muscles lift upward on the sternum; the anterior serrati muscle lift many of the ribs; and the scalene lifts the first two ribs.

To cause expiration, the abdominal recti, in addition to helping to compress the abdominal contents upward against the diaphragm, also pull downward the lower ribs, thereby decreasing the anteroposterior (AP) diameters of the chest. Thus, these muscles act as muscles of expiration both by depressing the ribs cage and by compressing the abdominal contents upward.

The ribs during expiration are angled downward, and the external intercostals are stretched in a forward and downward direction. As they contract they pull the upper ribs forward in relation to the lower ribs, and this caused leverage on the ribs to rise them upward. Conversely, in the inspiratory position, the internal intercostal muscles are stressed and their contraction pulls the upper ribs backward in relation to the lower ribs. This causes leverage in the opposite direction and lowers the chest cage.

FUNCTIONAL ASPECT OF RESPIRATION

- *Gaseous exchange:* Process of respiration supplies oxygen from the atmosphere to the tissue and removes carbon dioxide from the body to the atmosphere.
- *Excretory functions:* In addition to the carbon dioxide some volatile metabolic waste products, such as acetone, ammonia, oils, alcohol, and water vapor, are also excreted through expiration.
- *Regulates water balance:* During expiration, a large amount of water (about 700 mL) is lost as water vapor.
- *Regulates acid-base balance:* The normal pH of the body/blood is 7.4. Any change of pH alters the rate and depth of respiration.
- *Regulates body temperature:* Certain amount of heat is lost from the body during expiration.
- *Controls metabolic functions:* For metabolism, oxygen is the most important constituent, which is taken up during inspiration.

LUNG VOLUMES AND CAPACITIES

The various lung volumes reflect one's ability to increase the depth of breathing. To obtain these measurements, the subject breathes through Expirograph, which is shown in **Figure 4.7**. Lung volumes are basically divided into static and dynamic lung volumes.

1. *Static lung volume:* The bell of Spirometer, shown in **Figure 4.7**, falls and subsequently rises as air is inhaled and exhaled to record the ventilatory volume and breathing rate. The volume of air moved during either the inspiratory or the expiratory phase of each breathe is termed Tidal Volume. Such volumes are called static lung volume.
2. *Dynamic lung volume:* In appraising the adequacy of pulmonary ventilation, the important consideration is the ability to sustain high levels of air flow rather than the quantity of air moved in a single breath which is termed as dynamic lung volume.

Factors Affecting Lung Volumes and Capacities

Several factors affect lung volumes and capacities, some that can be controlled and some that cannot. These factors include: age, gender, body height, body surface area, smoking, altitude, etc. **(Table 4.2)**.

A person who is born and lives at sea level will have a smaller lung capacity than a person who spends his/her life at a high altitude. This is because the atmosphere is less dense at higher altitude and therefore, the same *volume* of air contains fewer molecules of all gases, including oxygen.

In response to higher altitude, the body's diffusing capacity increases in order to be able to process more air.

When someone from sea level travels up to the higher parts of the earth (e.g., the Andes, Mexico City, Tibet, and the Himalayas), they will often develop a condition called altitude sickness because their lungs cannot process enough oxygen for their body's needs.

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TABLE 4.2: Factors affecting lung functions.

Factors	*Larger volumes*	*Smaller volumes*
Gender	Males have greater lung volumes and capacities.	Females have smaller lung volumes and capacities.
Age	Age up to maturity increases lung volumes and capacity linearly.	As increase in age (after 40 yrs. of age) lung functions decrease.
Body height	Body height has got linear relation with lung volumes and capacities, i.e., taller people have larger volumes.	Shorter people have got smaller lung volumes and capacities.
Body surface area	Body surface area has also got linear relationship with lung volumes and capacities, i.e., the people having bigger surface area have larger volumes and capacities.	People having smaller body surface area have smaller lung volumes and capacities.
Smoking habit	Nonsmokers show higher values of lung volumes and capacities.	Smoking has got deleterious effects on lungs. So, smokers have lower lung volumes and capacities.
Lung disease	People who do not suffer from any respiratory disease have bigger lung volumes and capacities.	Respiratory diseases like asthma, emphysema and bronchitis reduce lung volumes and capacities.
Sports training	Physical training improves the lung volumes and capacities, e.g., athletes.	Sedentary nature of life does not improve lung function parameters, e.g., nonathletes.
High altitude	People living at high altitudes have bigger lung volumes and capacities.	People living at low altitudes have less lung volumes and capacities as compared to people live at high altitude.

On the other hand, cigarette smoking is inversely related to the lung volumes and capacity along with the flow rates. Cigarette smoke containing more than 200 chemicals identified and the carbon monoxide has got the most deleterious effects on the respiratory system.

Taller height and larger surface area of the body are linearly related to lung volumes and capacities as males have reported more lung volumes and capacities as compared to females because of their body height and bigger surface area.

Measurement of lung function: Pulmonary ventilation constitutes the first part of respiratory process, and ventilation has the dimensions of both volume and time. Ventilation occurs as a result of a pressure difference between the alveolar and oral ends of the airways. This ventilation can be measured with a machine called "spirometers" which consists of an inverted bell jar over a double-walled chamber, with water in between two walls. The details of Expirograph are given in the following text **(Fig. 4.7)**.

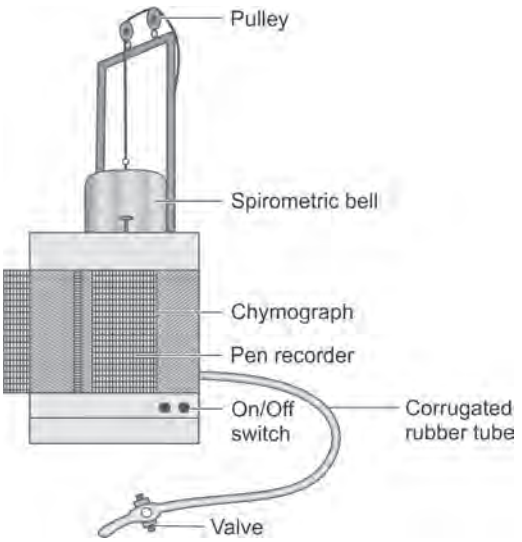


Fig. 4.7: A modified expirograph machine.

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EXPIROGRAPH (SPIROMETRY)

The lung functions are studied by Spirometer/ Expirograph machine. The Spirometer bell, balanced by a counter-weight, is moved through a pulley within the water container when a subject breathes into this closed system. The displacement of the Spirometer is recorded on a kymograph. A special type of recorder pen, very sensitive and having low friction, is used. The kymograph has two different speeds of 60 and 1,200 mm per minute. The soda-lime canister is placed inside the machine which is generally removed during the experiments in order to reduce the resistance to air flow. A corrugated breathing rubber tube is about 40 cm long and a smooth inner lining and an inside diameter of 3.2 cm is fixed with the machine. A valve is fixed with the one end of the tube where the mouth piece is tight while the other end is attached with the machine. The subject breathes through the mouthpiece, and Spirometric bell moves up and down along with the pen recorder and produces graph from which different parameters are calculated **(Fig. 4.8)**.

LUNG FUNCTION

The abbreviations of lung volumes and lung capacities those are commonly used in the Spirometric measurements along with average values of men and women are given in **Table 4.3**.

Breathing reserve: Breathing reserve = MVV (maximum voluntary ventilation) – RMV (respiratory minute volume) = about 136 L/ min. When the breathing reserve falls to 60–70% of MVV, dyspnea will result.

TRANSPORT OF RESPIRATORY GASES

Gases in our body are dissolved in fluids, such as plasma. They dissolve in liquids in proportion to their partial pressure depending also on their solubility in the specific fluids and on the temperature. But the solubility and the temperature in the blood are constant. However, the most critical factor for gas exchange between the alveoli and the blood is the pressure gradient.

The total pressure of respiratory gases (mm Hg) in atmosphere, trachea, alveoli, arterial blood, and venous blood averages to 760 mm Hg. The partial pressure of respiratory gases in expired air is of nitrogen 566 mm Hg, oxygen 120 mm Hg, carbon dioxide 27 mm Hg, and water is 47 mm Hg **(Table 4.4)**.

Transport of Oxygen

The oxygen content of the arterial and venous blood and relevant data are given in **Table 4.4**.

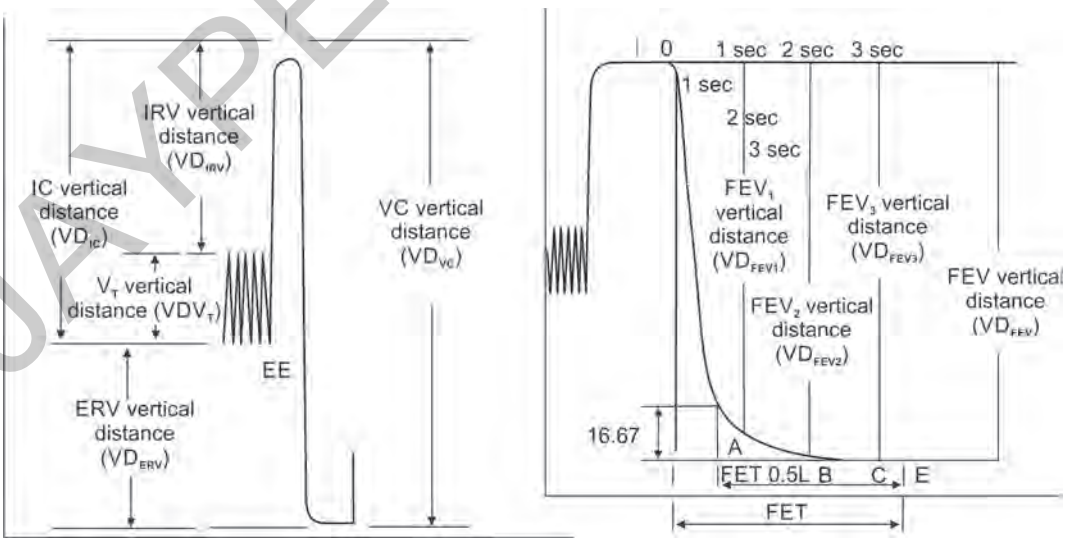


Fig. 4.8: Forced expiratory spirogram for the measurement of various lung function parameters.

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TABLE 4.3: The symbols, terms, definitions, and the normal values of lung function parameters.

Symbols	*Term used*	*Definitions*	*Average values (mL)*	
			Men	Women
V_T	Tidal volume	Volume of gas inspired or expired during each respiratory cycle.	600	500
VC	Vital capacity	Maximal amount of gas that can be expelled from the lungs following a maximal inspiration	4,800	3,500
IC	Inspiratory capacity	Maximal amount of gas that can be inspired from resting expiratory level.	3,600	2,500
IRV	Inspiratory reserve volume	Maximal volume of gas that can be inspired from end tidal inspiration.	3,000	1,900
ERV	Expiratory reserve volume	Maximal volume of gas that can be expired from resting expiratory level.	1,200	800
FVC	Forced vital capacity	Volume of gas expired after full inspiration, expiration being as rapid and complete as possible.	4,800	3,500
FEV_1	Forced expiratory volume (1 sec)	This is the volume of air that can be exhaled out within first 1 seconds of maximum expiration.	4,500	2,900
FEV_1%	Percentage of forced expiratory volume (1 sec)	This is the ratio between FEV_1 and FVC and expressed in percentage.	90–95%	90–95%
FEV_T	Forced expiratory volume, qualified by time interval (sec)	Volume of gas exhaled over given time interval during the performance of a forced vital capacity.	2.5–3.0 sec.	2.5–3.0 sec.
$PEF_{25-75\%}$	Forced mid-expiratory flow	The volume of air per unit of time exhaled during the middle half of the expired volume of the forced expiratory spirogram.	295 L/min	275 L/min
MVV_F	Maximum voluntary ventilation (uncontrolled)	Volume of air which a subject can breath with voluntary maximal ventilatory effort per unit of time.	120–130 L/min	110-120 L/min
PEFR	Peak expiratory flow rate	This is the maximal flow, which can be sustained for a period of 10 milliseconds during a forced expiration starting from total lung capacity.	450 L/min	350 L/min

TABLE 4.4: Partial pressure of oxygen in arterial and mixed venous blood.

	O_2 content (%)	*Oxy Hb (%)*	*O_2 in sol (%)*	*pO_2 (mm Hg)*
Arterial blood	19.3	19	0.3	40
Mixed venous blood	14.2	14	0.2	100

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About 98% of oxygen is present in the blood in chemical combination with hemoglobin and only 0.3 mL in arterial blood (about 2%) is in physical solution in water of the plasma. However, this small quantity in physical solution is responsible for tension of oxygen in the plasma. It is the oxygen tension in the blood, which is responsible for transfer of this gas from alveolar air to the venous blood across the alveolocapillary membrane and also for transfer of this gas from arterial blood to tissue fluid across the capillary membrane. Further, it is the tension of oxygen in plasma, which controls the amount of oxyhemoglobin present in the blood.

Hemoglobin is remarkable in that it can combine with oxygen forming a loose chemical compound known as oxyhemoglobin, which differs from oxide of hemoglobin known as methemoglobin and the fact that the O_2 in methemoglobin is firmly fixed with the hemoglobin molecule.

The amount of O_2 of the hemoglobin will combine with forming oxyhemoglobin is dependent upon the tension of oxygen in the medium where hemoglobin is placed. If the O_2 tension is high a large amount of oxyhemoglobin will be formed whereas on a medium of low O_2 tension the oxyhemoglobin will break down liberating O_2, itself being converted into reduced hemoglobin.

O_2 capacity: One gram of hemoglobin, when fully saturated, will combine with 1.34 mL of O_2. Since the blood contains approximately 15 grams of Hb per 100 mL, the oxygen content of the blood when fully saturated will be about $15 \times 1.34 = 20$ mL. This is called O_2 capacity of the blood. Naturally, the O_2 capacity depends upon the amount of hemoglobin in blood.

O_2 content: It is usually determined by Van Slyke's manometric apparatus in which 1 mL of blood is treated anaerobically with potassium ferricyanide solution in the chamber of the apparatus. The pressure exerted by the liberated oxygen after absorption of CO_2 on a manometer attached with the apparatus is noted and is used for calculation of the oxygen content.

If the blood is first agitated with air so that the Hb gets fully saturated with O_2, the result will indicate O_2 capacity. Percentage saturation of Hb with O_2 = (O_2 content × 100)/ O_2 capacity.

Oxygen exchange in the lungs: The tension of O_2 in the alveolar air is 100 mm Hg and that of the dissolved O_2 in the plasma of the mixed venous blood is only 40 mm Hg.

Due to the tension gradient, O_2 diffuses rapidly from the alveolar air to the mixed venous blood increasing the quantity and also tension of O_2 in the plasma in the venous blood. Rise of O_2 tension of the mixed venous blood is followed by rapid increase in O_2 saturation of the hemoglobin. The oxygenated blood leaves the pulmonary capillaries in tension equilibrium with alveolar air, that is, with O_2 tension of 100 mm Hg and with hemoglobin 98% saturated with oxygen **(Table 4.5)**.

1. The gaseous composition of blood is different in different veins of the body. O_2 content of blood of veins draining metabolically active tissues (e.g., muscles, heart) is low whereas the O_2 content of blood of veins from skin and brain is rather high. The term mixed venous blood

TABLE 4.5: Partial pressure of different gases in alveoli, arterial, and mixed venous blood.

Partial pressure	*In atmospheric air*	*Humidified tracheal air*	*In alveoli*	*In arterial blood*	*In venous blood*
Partial pressure of O_2	159 mm Hg	149.3 mm Hg	104 mm Hg	100 mm Hg	40 mm Hg
Partial pressure of CO_2	0.3 mm Hg	0.3 mm Hg	40 mm Hg	40 mm Hg	46 mm Hg
Partial pressure of H_2O	3.7 mm Hg	47 mm Hg	47 mm Hg	47 mm Hg	47 mm Hg
Partial pressure of N_2	597 mm Hg	564 mm Hg	569 mm Hg	573 mm Hg	573 mm Hg

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A Textbook of
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