University of Al-Qadisiyah

College of Dentistry

Branch of Basic sciences

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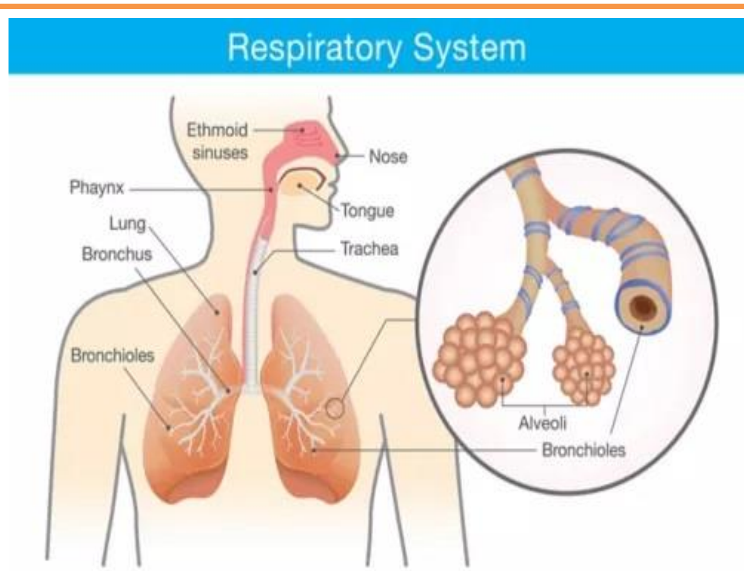
The physics of the lungs and breathing



Introduction

The human " machine " really consists of billions of very small "engines " the living cells of the body .Each of these a miniature engines must be provided with fuel ,O_2 ,and a method of getting rid of the products . The blood and its vessels (cardiovascular system) serve as the transport for these engines .The lungs (pulmonary system)serve as the supplier of O_2 and disposes of the main by product - CO_2 .The blood takes the O_2 to the tissues and removes the CO_2 from the tissues ; it must come in close contact with the air in the lungs in order to exchange its load of CO_2 for a fresh load of O_2 .

The function of the Lungs

1. Exchanging of O_2 and CO_2 .

2. Keeping the PH (acidity) of the blood constant .

3. Heat exchange .

4. Keeping the fluid of the body balance by warming and moisturizing the air we breathe .

5.Controlled the flow of air for talking , coughing ,sneezing , sighing , laughing , and sniffing .

6 . Voice production .

Breathing

1- **We breathe about 6 liters of air per minute .**
2- **Men breath about 12 times per minute at rest .**
3- **Women breath about 20 times per minute .**
4- **Infants breath about 60 times per minute .**

The air we inspired is about 80% N_2 and 20% O_2 .

The Expired air is about 80% N_2 ,16% O_2 and 4% CO_2 .

We breathe about 10 Kg of air each day .Of this the lungs absorbs 400 liters of O_2 (0.5 Kg) and release a slightly smaller amount of CO_2 .

Air ways

The principal air passage into the lungs are shown in figure (1) . Air normally enters the body through the nose where it is warmed , filtered and moisturized .The air then passes through trachea .The trachea divides into two to furnish air to each lung through the bronchi . Each bronchus divides and re divides about 15 times , the resulting terminal bronchioles supply air to millions of small sacs called alveoli .

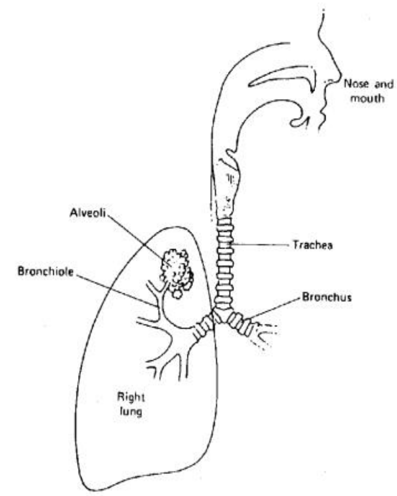


Figure 7.2. A schematic diagram showing the principal air passages into the lungs.

figure 1

The alveoli is small interconnected bubbles are about 0.2 mm in diameter and have walls only 0.4 µm thick (figure 2) .They expand and contract during breathing ; they are in the exchanging of O_2 and CO_2 .Each alveolus is surrounded by blood so that O_2 can diffuse from the blood into the air in the alveolus .

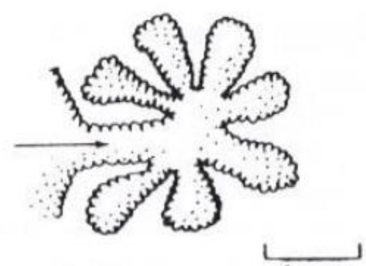


Figure 7.3. The structure of the alveoli.

Figure (2)

How the blood and lungs interact

The transfer of O_2 and CO_2 into and out of the blood is controlled by the physical law of diffusion .All molecules are continually in motion. In gases and liquids , and to certain extent even in solids , the molecules do not remain in one direction .Molecules of a particular type diffuse from region of higher concentration to a region of lower concentration until the concentration is uniform In the lungs we are concerned with diffusion in both gas and liquids .In the O_2 and CO_2 exchange in the tissues we are concerned only with diffusion in liquids .The molecules in a gas at room temperature move at about the speed of sound . Each molecule collides about 10^{10} times each second with neighboring molecules . The distance D of molecule will travel from its origin after N collisions is

$$D = \lambda \sqrt{N}$$

Where λ is the mean free path.

λ is defined as the average distance between collision .

in air $\lambda = 10^{-7}$ m in tissue $\lambda = 10^{-11}$ m

Example (1)

What is the typical value of D in air and in tissue for an O_2 molecule after 1 sec if $N = 10^{10}$ in air and in tissue $N = 10^{12}$?

In air $D = 10^{-7} (10^{10})^{1/2} = 10^{-2}$ m

In tissue $D = 10^{-11} (10^{12})^{1/2} = 10^{-5}$ m

Diffusion depends on the speed of the molecules , the speed of molecules increases with temperature . Since N is proportional to the diffusion time Δ t . (N α Δt) we can write that (D α √ Δt) or (Δt α D ²) In the lungs the distance to be traveled in air usually a small fraction of a millimeter ,and diffusion takes place in a fraction of a second .The diffusion of O_2 and CO_2 in tissue is about 10,000 times slower than it is in air , but the tissue thickness of the molecules must diffuse through in the lungs is very small (0.4µm) and diffusion through the alveolar wall takes place in much less than 1 sec .To understand the behavior of gases in lungs it is necessary to know Dalton' s law of partial pressures .Dalton's law state that if you have a mixture of several gases , each gas make its own contribution to the total pressure as though it were all alone.

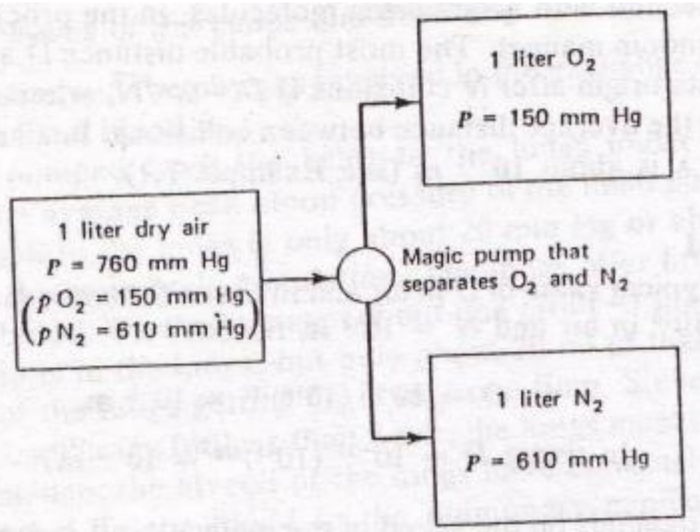


Figure 7.4. A schematic illustration of Dalton's law of partial pressures. A liter of air at 760 mm Hg pressure can be thought of as a mixture of 1 liter of O_2 at a pressure of 150 mm Hg and 1 liter of N_2 at a pressure of 610 mm Hg.

Henry's Law of Solubility of Gases

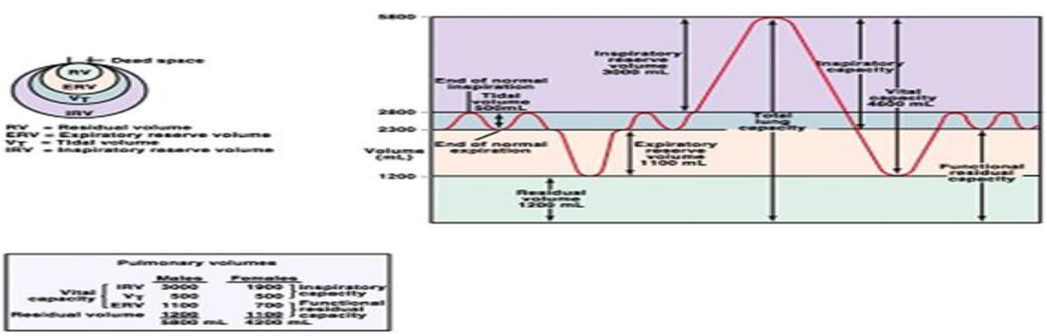
Henry's law states that the quantity of a gas going into simple solution at constant temperature is proportional to the pressure .if we have a closed container of blood and CO_2 ,It found that some of O_2 molecules collide with blood and are dissolved .After a while the number of O_2 molecules that are escaping from the blood each second is the same as the number that are entering it .The blood then has a PO_2 equal to that of the O_2 in contact with it .If PO_2 in the gas phase is doubled , the amount of O_2 dissolved in the blood will also double . This proportionality is Henry's law of solubility of gases .The amount of gas dissolved in blood varies greatly from one gas to another .Oxygen is not very soluble in blood or water .The different solubility of O_2 and CO_2 in tissue affect the transport of these gases across the alveolar wall. A molecule of O_2 diffuse faster than a molecule of CO_2 because of its smaller mass . However , because of greater number of CO_2 molecules in solution , the transport of CO_2 is more efficient than the transport of O_2. The mixture of gases in the alveoli is not the same as the mixture of gases in ordinary air .The lungs are not emptied during expiration .During normal breathing the lungs retain about 30 % of their volume at the end of each expiration . This is called the functional residual volume (FRC).At each breath 500 cm^3 of fresh air (PO_2 of 150 mm Hg) mixes with 2000 cm^3 of stale air in the lungs to result in alveolar air with a PO_2 100 mm Hg .The PCO_2 in the alveoli is about 40 mm Hg .Expired air includes about 150 cm of relatively fresh air from the trachea that are not in contact with alveolar surface , so expired air has a slightly higher PO_2 and lower PCO_2 than alveolar air .

The percentages and partial pressures of O_2 and CO_2 in inspired ,alveolar and Expired .

	% O_2	PO_2 (mmHg)	% CO_2	PCO_2 (mmHg)
Inspired air	20.9	150	0.04	0.3
Alveolar air	14.0	100	5.6	40
Expired air	16.3	116	4.5	32

Measurement of lung volume

Spirometer: **It is a device used to measure air flow into and out of the lungs and record it on a graph of volume versus time.**



Tidal volume (TV) is the amount of air inspired or expired with each breath

Inspiratory Reserve Volume (IRV) is the maximum amount of additional air that can be inspired beyond a normal inspiration.

Expiratory Reserve Volume (ERV) is the maximum amount of additional air that can be expired beyond a normal expiration.

Residual Volume (RV) is the amount of air remaining in the lungs after an extended or complete expiration. RV cannot be measured with a Spiro meter. RV is decreased by restrictive lung diseases like pulmonary fibrosis, lung cancer, and pneumonia, and its increased by obstructive lung diseases such as Chronic Obstructive Pulmonary Disease (COPD), emphysema, asthma.

Total Lung Capacity (TLC) is the amount of air in the lungs at the end of an extended or complete inspiration. TLC is the sum of all four lung volumes discussed above. (RV + IRV + TV + ERV = TLC).

Vital Capacity (VC) is the maximum amount of air that can be forcefully expelled from the lungs after an extended or complete inspiration. VC is the sum of IRV, TV, and ERV. (IRV + TV + ERV = VC)

Both obstructive and restrictive lung diseases can cause a reduction in VC because sufficient amounts of air cannot be inhaled or exhaled from the lungs. VC is also affected by the body's position. Lying in a prone position (flat on the back), decreases the VC because the pulmonary blood volume increases and the diaphragm is pushed downwards.

Functional Residual Capacity (FRC) is the amount of air remaining in the lungs at the end of a normal expiration. FRC is the sum of RV and ERV. (RV + ERV = FRC).

Inspiratory Capacity (IC) is the maximum amount of air that can be inspired after a normal expiration. IC is the sum of TV and IRV. (TV + IRV = IC)

***Body plethysmography*:**

It is a modern device used to get a better understanding of how the lungs are functioning, pulmonary function tests, where Lung volume measurements give an indication as to whether a lung disease is present, and if so, which lung disease.

Anatomical and physiological dead spaces

They are spaces in the respiratory system at which air does not provide O2 to the body.

Anatomical dead space: In the conducting airways (nose, mouth, pharynx, larynx, trachea, bronchi and bronchioles) there is no significant exchange of O_2 & CO_2 between gas and blood, the internal volume of the airways is called the anatomic dead space. The volume of air in the anatomical dead space= 150 cm^3.

Physiological dead space: In some diseases, some air reach the alveoli are poorly perfused by the blood capillary, result in poor ventilation-perfusion relationship increasing the physiological dead space. The volume of air in the physiological dead space= 350 cm^3 .

Compliance:

It is the change in lung volume produced by a small change in pressure

$$C = \frac{\blacktriangle V}{\blacktriangle P}$$

In normal adults, the range of compliance= 0.18-0.27 liter/ cmH_2O. Elderlies over age 60 have about 25% greater compliance than younger men, in women there is a little change in compliance for Elderlies. A fibrotic (stiff) lung has low compliance, while a flabby lung has large compliance

Airways Resistance

Airway resistance is a concept used in respiratory physiology to describe mechanical factors which limit the access of inspired air to the pulmonary alveoli, and thus determine airflow. It is the amount of pressure required to deliver a given flow of gas and is expressed in terms of a change in pressure divided by flow. During inspiration the forces on the airways tend to open them further, during expiration the forces tend to close the airways and thus restrict airflow. For a given lung volume, the expiratory flow rate reaches a maximum and remains constant; it might even decrease slightly with increased respiratory force. Resistance is greatest at the bronchi of intermediate size, in between the fourth and eighth bifurcation.

Air way resistance can be calculated by using Ohm's law:

$$Ra = \frac{\text{Pressure Difference}}{\text{Rate of Air Flow}} = \frac{P\ \text{mouth} - P\ \text{alveoli}}{\text{Rate of Air Flow}}$$

$$Ra = \frac{\blacktriangle P \quad (cmH_20\ )}{V^{\bullet} \quad (\text{Liter/ sec})}$$

$$V^{\bullet} = \blacktriangle V/ \blacktriangle t\ (\text{liter/ sec})$$

Ra depends on:

a. **The dimensions of the airway**
b. **The viscosity of the gas**

For typical adult Ra= 3.3 cmH_2O/ (liter/ sec).
It accounts 50% in the nasal area,
20% in the trachea,
10% in the bronchi & alveoli
20% of the airway resistance is related to the viscosity of the gas we breathe.

The Time Constant

When the respiratory system is subjected to ΔP, time is needed until ΔV occurs, and the time necessary to inflate 63% of its volume is called the **time constant**. The time constant of the lung is related to the airway resistance & the compliance

TC (sec) = Ra x C

The time constant (T) of the lung is complicated, since many parts of the lungs are interconnected. If one part has large (T) than others parts, it will not get its share of the air and that part of the lung will be poor ventilated.

Work of Breathing

The amount of work done in normal breathing accounts for a small fraction of the total energy consumed by the body (2% at rest)

Components of Work

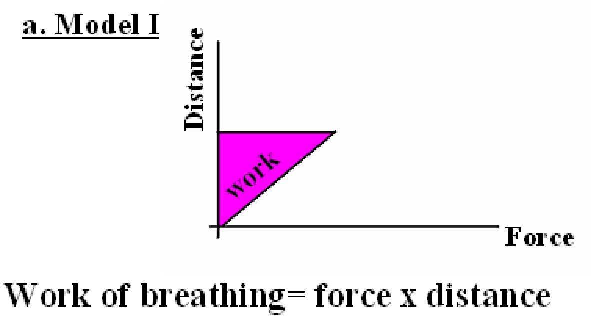
1- **Elastic work - work to overcome:**
- **lung elastic recoil**
- **thoracic cage displacement**
- **abdominal organ displacement**
-

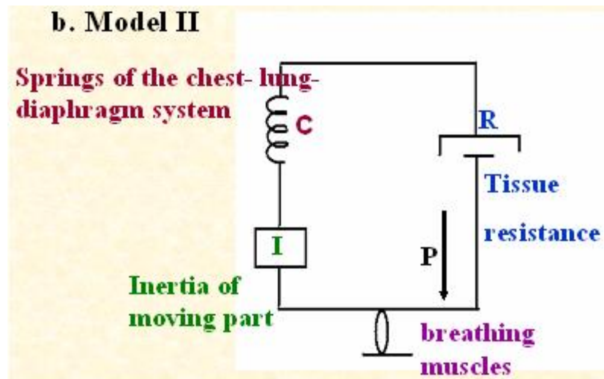
2- **Frictional work - work to overcome:**

- **air-flow resistance (major)**
- **viscous resistance (lobe friction, minor)**

3-**Inertial work - work to overcome:**

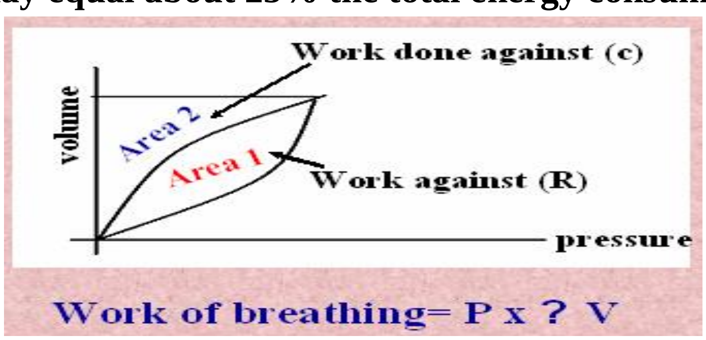
- **acceleration and deceleration of air (negligible due to low mass of air)**
- **acceleration and deceleration of chest wall and lungs (negligible due to over damping)**





The primary work of breathing can be thought of as the work done in stretching the springs representing the lung-chest wall diaphragm system. The resistance of the gas flow produce heat; these can be represented as (R). The springiness of the lung-chest is represented by the spring C, the inertia (I) of the mass of the lungs and chest wall must also be overcome; at normal breathing rates, the inertia can be neglected, but at maximum breathing rates (over 100 breath/ min) it is a significant factor.

During normal breathing, no work is done during expiration; the muscles relax and spring "snap back "to expel the air. The energy dissipating in tissue resistance (R). While during exercise. The muscles are used to expel the air and the work may equal about 25% the total energy consumption



Physics of some lung diseases

Emphysema

Emphysema is a long-term, progressive disease of the lung that primarily causes shortness of breath. In people with emphysema, the lung tissues necessary to support the physical shape and function of the lung are destroyed. It is included in a group of diseases called chronic obstructive pulmonary disease or COPD. Emphysema is called an obstructive lung disease because the destruction of lung tissue around smaller airways, called bronchioles, makes these airways unable to hold their shape properly when you exhale.

- **The no. of lung springs has been greatly reduced, the divisions between the alveoli broken producing large lung spaces. The lung become flabby and expands. The tension reduced allows the chest wall to expand to the resting volume.**
- **In emphysema, the lungs become more compliant, The tissue don't pull very hard on the airways, permitting the narrowed airways to collapse easily during expiration (i.e. increased Ra)**
- **The increased size of the lungs increases the FRC & the RV**.

Asthma

It is a chronic disease involving the respiratory system in which the airways occasionally constrict, become inflamed, and are lined with excessive amounts of mucus, often in response to one or more triggers. These episodes may be triggered by such things as exposure to an environmental stimulant such as an allergen, environmental tobacco smoke, cold or warm air, perfume, pet dander, moist air, exercise or exertion, or emotional stress. In children, the most common triggers are viral illnesses such as those that cause the common cold. This airway narrowing causes symptoms such as wheezing, shortness of breath, chest tightness, and coughing.

The basic problem is the expiratory difficulty due to increase (Ra). Increasing (Ra) is due to:

- **Swelling and mucus in the smaller airways.**
- **Contraction of the smooth muscle around the large airways.**

In asthma the lung *compliance* doesn't change (over the normal value). The *FRC is higher than normal,* because the patient often start to inspire before

completing a normal expiration

Fibrosis of the lungs

Pulmonary fibrosis describes a group of diseases which produce interstitial lung damage and ultimately fibrosis and loss of the elasticity of the lungs. The membrane between the alveoli thickens. It is a chronic condition characterized by shortness of breath,

This has two marked effects:

- **The compliance of the lung decreases**
- **The diffusion of O_2 into the pulmonary capillaries decrease.**