

Alveolar ventilation and Perfusion



Functions of the Lung

Introduction

The lungs perform several vital functions, but the primary and most important one is:

► Gas Exchange

- The main role of the lungs is to exchange gases between air and blood.
- Oxygen (O_2) diffuses from the alveoli (air sacs) into the blood.
- Carbon dioxide (CO_2) diffuses from the blood into the alveoli to be exhaled.

► Other Functions

- Filtering: The lungs filter out small clots, air bubbles, or other unwanted materials from the blood.
- Metabolic functions: Some metabolic reactions occur in the lung tissue (for example, converting angiotensin I to angiotensin II by ACE enzyme).
- Reservoir for blood: The lungs can store a certain amount of blood, helping to regulate circulation.

Systemic circulation

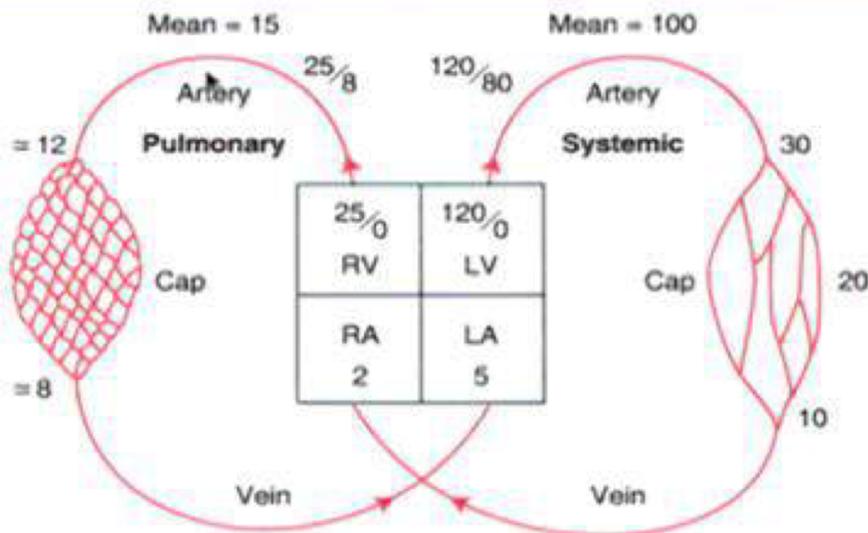
Carries oxygenated blood from the left heart → body tissues → returns deoxygenated blood to the right heart.

Pulmonary circulation

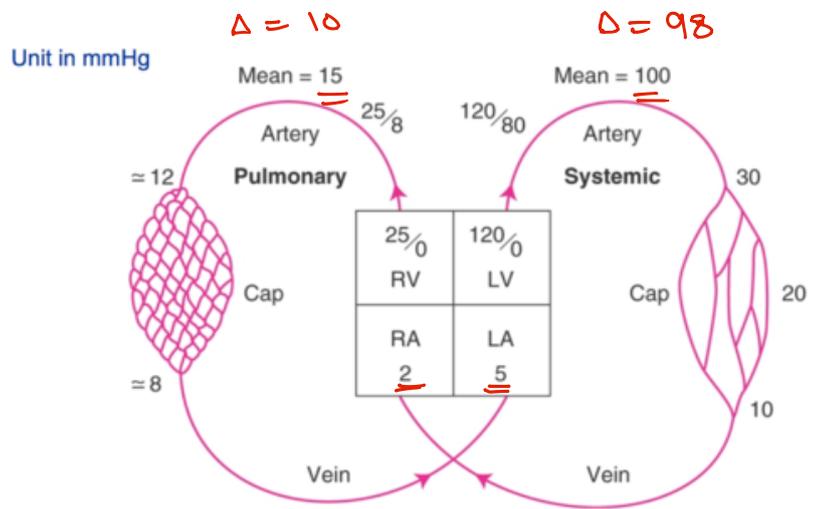
Carries deoxygenated blood from the right heart → lungs → returns oxygenated blood to the left heart.

So, the pulmonary circulation is responsible for bringing blood to the lungs for gas exchange.

Systemic and Pulmonary circulation



* In systemic 10 times
in pulmonary !!
Why?!



Systemic Circulation – High Pressure

- Blood must travel a long distance (to all body tissues).
- Needs strong force to overcome high resistance of many small arteries and arterioles.
- Therefore, left ventricle generates high pressure ($\approx 120/80$ mmHg).

Pulmonary Circulation – Low Pressure

- Blood travels only through the lungs (short distance).
- Pulmonary vessels are thin, wide, and low-resistance.
- So, right ventricle needs only low pressure ($\approx 25/8$ mmHg) to pump blood.

Overall layout and flow

- The diagram shows two closed circuits side-by-side:
- Left side = Pulmonary circulation (right heart \rightarrow lungs \rightarrow left heart).
- Right side = Systemic circulation (left heart \rightarrow body tissues \rightarrow right heart).
- Blood flows in a loop: Systemic arteries \rightarrow systemic capillaries \rightarrow systemic veins \rightarrow right atrium (RA) \rightarrow right ventricle (RV) \rightarrow pulmonary artery \rightarrow pulmonary capillaries (lungs) \rightarrow pulmonary veins \rightarrow left atrium (LA) \rightarrow left ventricle (LV) \rightarrow systemic arteries.

Central box — intracardiac pressures (in mmHg)

The small square in the center shows typical pressures inside the heart chambers:

- RV (right ventricle): 25 / 0 (systolic / diastolic) — RV systolic pressure ≈ 25 mmHg, diastolic near 0–2 mmHg.
- LV (left ventricle): 120 / 80 — LV systolic ≈ 120 mmHg, diastolic ≈ 80 mmHg.
- RA (right atrium): 2 mmHg (mean right atrial pressure).
- LA (left atrium): 5 mmHg (mean left atrial pressure).

Meaning: the left ventricle generates very high pressures to perfuse the systemic circulation; the right ventricle generates much lower pressure because the pulmonary circulation is a low-pressure, low-resistance system.

Pulmonary circulation (left side of the picture)

- At the top: Mean pulmonary arterial pressure ≈ 15 mmHg (label: Mean = 15).
- The pulmonary artery is shown with 25 / 8 mmHg (systolic/diastolic). These are normal PA pressures: systolic ≈ 25 , diastolic ≈ 8 .
- Pulmonary capillary pressures (the capillary drawing on the left) are labeled approximately ≈ 12 mmHg (arteriolar end) and ≈ 8 mmHg (venous end). These are low compared with systemic capillaries.
- The pulmonary veins return oxygenated blood to the left atrium (LA).

Physiological implications:

- Low pulmonary pressures and low capillary hydrostatic pressure normally protect lungs from fluid accumulation (pulmonary edema).
- **If pulmonary arterial or capillary pressures rise (for example in left heart failure or pulmonary hypertension), fluid can leak into alveoli (pulmonary edema / "stress failure" of the blood-gas barrier).**

Systemic circulation (right side of the picture)

- At the top: Mean systemic arterial pressure ≈ 100 mmHg (label: Mean = 100).
- The systemic artery is shown as 120 / 80 mmHg (systolic/diastolic).
- The systemic capillary drawing shows a pressure gradient across the capillary bed: $\sim 30 \rightarrow 20 \rightarrow 10$ mmHg

(arteriolar end higher, venular end lower). This decline along the capillary reflects drop in hydrostatic pressure as blood flows through the microcirculation.

- Systemic veins return blood to the right atrium; venous pressure is very low centrally but veins act as a large blood reservoir.

Physiological implications:

- The higher systemic capillary hydrostatic pressure at the arteriole end favors filtration of fluid out of capillaries into interstitium; venous/oncotic forces favor reabsorption at the venous end (Starling forces).
- Because systemic arterial pressure is high, the systemic circulation experiences much greater mechanical stress and requires thicker, more muscular vessels.

When systemic hypertension occurs, the pressure in the systemic circulation becomes very high.

The **left ventricle** has to pump blood against this high pressure, so it works harder.

Over time, the left ventricle becomes thickened (**left ventricular hypertrophy**) and may later fail — this is called **left-sided heart failure**.

In **pulmonary hypertension**, the pressure in the pulmonary circulation is abnormally high.

This increases the workload on the **right ventricle**, which must push blood into the lungs against the high pressure.

As a result, the right ventricle becomes enlarged and thickened (**right ventricular hypertrophy**) and can eventually fail — this is known as **right-sided heart failure or cor pulmonale**.

Key comparisons & takeaways

1. Pressures

- Systemic arterial pressure (mean ~ 100 mmHg) \gg pulmonary arterial pressure (mean ~ 15 mmHg).
- LV systolic pressure (~ 120 mmHg) \gg RV systolic pressure (~ 25 mmHg).
- Atria have very low mean pressures (RA ≈ 2 mmHg, LA ≈ 5 mmHg).

2. Capillary pressures

- Pulmonary capillaries: low ($\sim 8-12$ mmHg) \rightarrow less tendency for fluid filtration into alveoli at normal conditions.
- Systemic capillaries: higher at arteriolar end (~ 30 mmHg) and fall toward venous end (~ 10 mmHg) \rightarrow net filtration at arteriolar end and partial reabsorption toward venous end.

3. Functional consequences

• The pulmonary circulation's low pressure and low resistance protect the delicate blood-gas barrier and facilitate rapid gas exchange.

- The systemic circulation's high pressure is required to perfuse the entire body but increases filtration forces in tissues.

4. Clinical relevance

• Pulmonary hypertension (elevated pulmonary arterial pressure) or increased left atrial pressure (e.g., mitral stenosis, LV failure) raises pulmonary capillary hydrostatic pressure and predisposes to pulmonary edema.

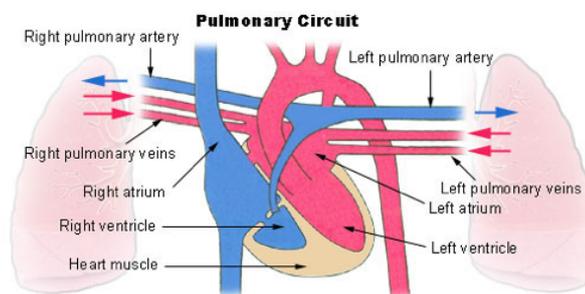
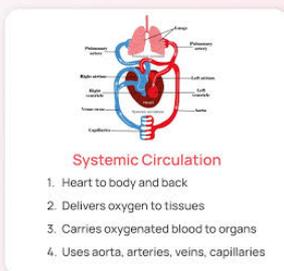
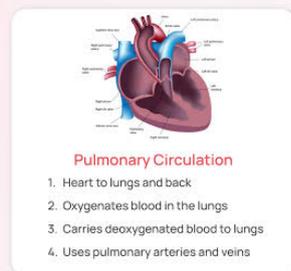
- Right ventricular failure results from chronically increased RV afterload (i.e., pulmonary hypertension).

• Volume distribution: veins (especially systemic veins) contain most of the blood volume and act as capacitance (reservoir) vessels; small changes in venous tone greatly affect venous return and cardiac output.



Difference Between Pulmonary & Systemic Circulation

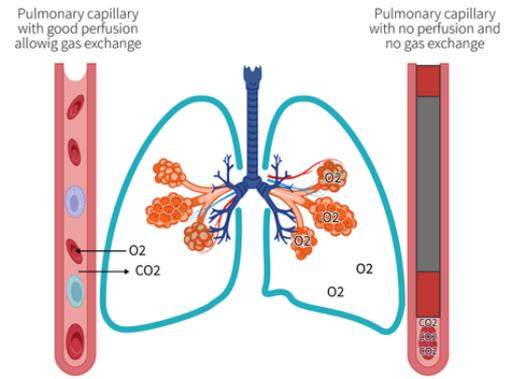
Understanding the Body's Vital Blood Circuits



Facts of Ventilation

Ventilation means the movement of air in and out of the lungs.

- Think of the lungs as a **symmetrical** organ with the blood-gas barrier in the middle:
- Air enters from one side through the airways (ventilation system).
- Blood comes from the other side through the pulmonary circulation (blood system).
- Both systems meet at the blood-gas barrier, where gas exchange occurs.



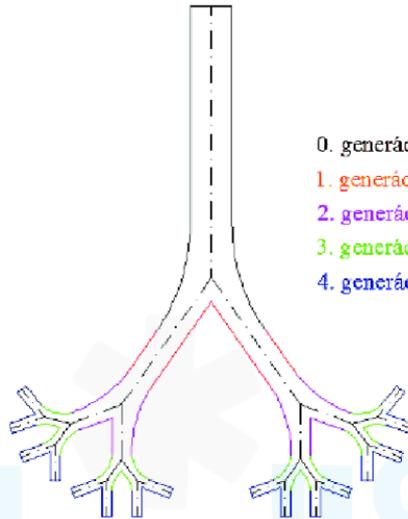
To understand the structure of airways, scientists use the Weibel model.

The Weibel Model of the Airways

Swiss anatomist Dr. Weibel carefully studied and counted the airways in the human lung. He developed an idealized model showing how airways branch and change in size.

► Main Findings (Implications):

- If you plot the total cross-sectional area (sum of all airway diameters) for each airway generation (each branching level), you notice:
 1. **For the first few generations** (like trachea → bronchi), **the total area stays almost the same.**
 2. **In deeper generations** (bronchioles → alveoli), **the total area increases enormously, like a trumpet shape (narrow at first, then widens).**



G	Structure	Category
0	Trachea	Conducting airways
1	Bronchi	
2	Bronchioles	
3		
4		
5	Terminal bronchioles	Acinar airways
16	Transitional	
17		
18	Transitional bronchioles	
19		
20		
21	Alveolar ducts	
22	Alveolar sacs	
23		

Importance of the Weibel Model

- As the **total cross-sectional area increases**, the **velocity of airflow decreases**.
- **Air moves slowly in the small airways and alveoli.**
- This means that convection (bulk movement of air) becomes less effective in small airways.
- Therefore, **diffusion** becomes the main mechanism for gas movement from terminal bronchioles → alveoli.

► Clinical Importance

- **Most pollutants** (e.g., smoke, dust) **settle at the junction between the conducting zone and respiratory zone** — because **air moves slowly here.**
- Example: Coal dust in miners accumulates in terminal bronchioles, not in the alveoli.
- Early signs of chronic bronchitis appear first in these small airways.
- So, although a little dust can reach alveoli, the major deposition occurs in the terminal bronchioles.

Volumes and Flows in the Lung

► Tidal Volume (TV)

- The amount of air inhaled or exhaled in one normal breath.
- Usually about 500 mL.

► Minute Ventilation

- The total amount of air breathed per minute.
- Formula:

Minute ventilation = Tidal Volume × Breathing Rate

Example:

- Breathing rate = 15 breaths/min
- Tidal volume = 500 mL

→ Minute ventilation = 500 × 15 = 7500 mL/min (7.5 L/min)

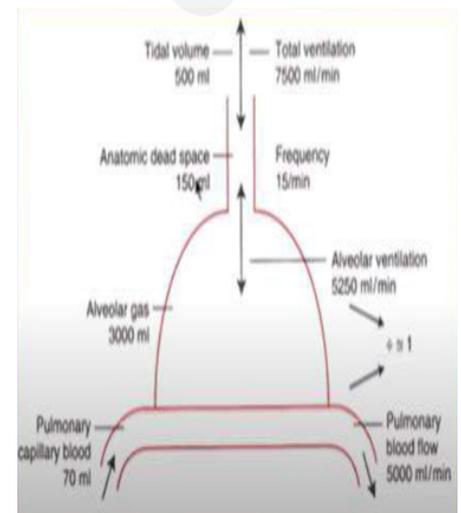
But not all this air reaches the alveoli—some stays in the dead space (airways with no gas exchange).

► Alveolar Ventilation

- Alveolar ventilation = (Tidal Volume – Dead Space) × Breathing Rate
- Dead space ≈ 150 mL
- So alveolar ventilation = (500 – 150) × 15 = **5250 mL/min**

► Comparison with Blood Flow

- Right heart cardiac output ≈ **5000 mL/min.**
- So, **alveolar ventilation ≈ pulmonary blood flow**, giving a ratio (\dot{V}_A / \dot{Q}) ≈ 1.
- This ratio is important for ventilation–perfusion balance.



Alveoli and Capillaries

- The alveoli are tiny air sacs surrounded by capillaries.
- Blood–gas barrier separates:
 - Air (gas) inside alveolus
 - Blood inside capillary
- This barrier is extremely thin—so thin that it cannot be seen clearly with a light microscope.

Electron Micrograph of Pulmonary Capillary

An electron microscope shows:

- Capillary wall running between two alveoli.
- Alveolar gas on both sides.
- Inside the capillary: red blood cells and plasma.
- The blood–gas barrier separates blood from air.
- Thickness: about 1/3 of a micron (0.3 μm).
- (1 micron = 1/1,000,000 meter = 1/1,000 mm)
- Red blood cell = about 7 μm in diameter → can be seen with a light microscope.
- **Blood–gas barrier is polarized:**
 - Capillary side: thinner
 - Alveolar side: thicker

► Clinical Note

Because it is so thin, this barrier is fragile.

If capillary pressure increases abnormally, it can damage the barrier and cause fluid to leak into alveoli — this condition is called stress failure.

If alveolar pressure > capillary pressure

- The air pressure inside the alveolus becomes greater than the blood pressure in nearby capillaries.
- This compresses or collapses the capillaries.
- Blood flow stops or becomes very low in that region.

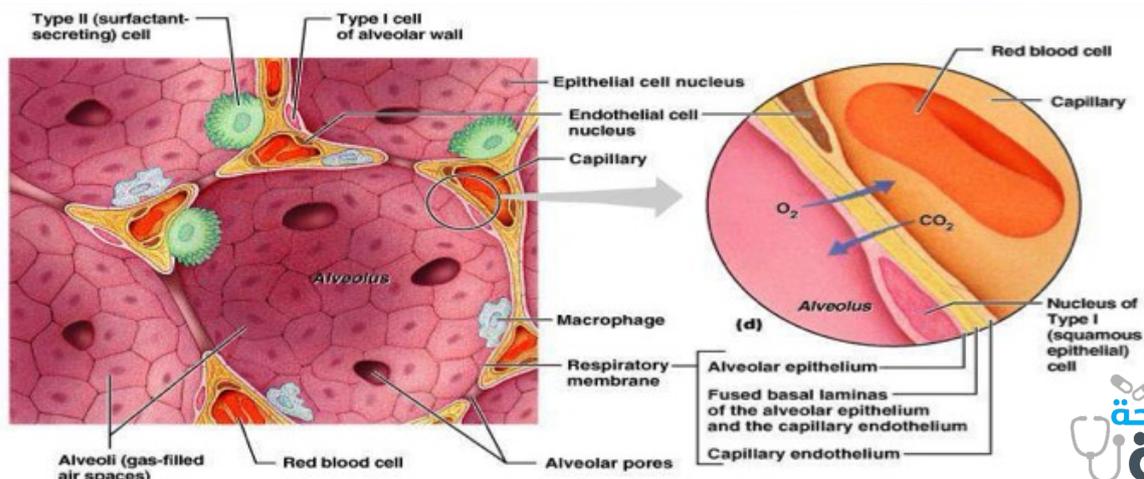
Structure of the Alveolar Wall

- Alveoli are surrounded by elastic fibers, helping them expand and recoil.
- Alveolar macrophages (“dust cells”) move freely inside alveoli to clean debris.
- Type I pneumocytes: thin cells forming most of the gas-exchange surface.
- Type II pneumocytes: secrete surfactant (reduces surface tension and prevents collapse).
- Type IV collagen: provides strength to the basement membrane.

► Air–Blood Barrier (Respiratory Membrane)

This is where gas exchange occurs:

- Oxygen (O₂) diffuses from alveolar air → capillary blood.
- Carbon dioxide (CO₂) diffuses from blood → alveolar air.



Fick's Law of Diffusion

Fick's law describes how gases move **across a membrane** (like the blood–gas barrier).

► According to Fick's Law:

The rate of diffusion is:

- **Directly proportional to:**
- Surface area (A)
- Diffusion constant (D)
- Pressure difference (ΔP) between both sides
- **Inversely proportional to:**
- Thickness (T) of the barrier

So, for efficient gas exchange, **we need:**

- Very large surface area
- Extremely thin barrier

► In the Lung:

- The blood–gas barrier has:
- Thickness: $\sim 0.3 \mu\text{m}$
- Surface area: $\sim 50\text{--}100$ square meters
- Number of alveoli: ~ 500 million

This enormous area and thin structure make gas exchange extremely fast and efficient.

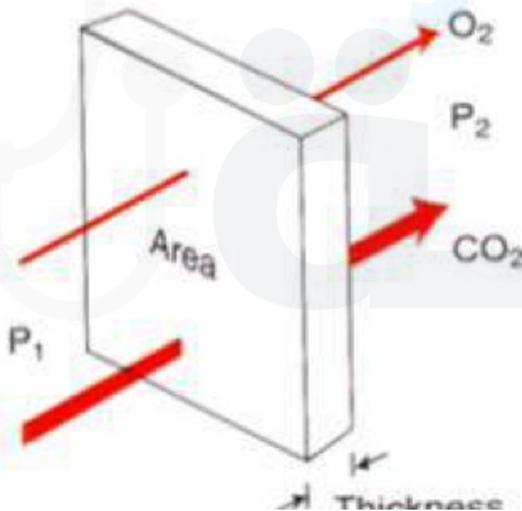


Fick's Law

✓ Diffusion Equation

$$\dot{V}_{\text{gas}} = \frac{D * (P_1 - P_2) * A}{T}$$

- Diffusion Coefficient (D)
- Partial pressure gradient ($P_1 - P_2$)
- Surface area (A)
- Thickness of barrier (T)



$$\dot{V}_{\text{gas}} \propto \frac{A}{T} \cdot D \cdot (P_1 - P_2)$$

$$D \propto \frac{\text{Sol}}{\sqrt{\text{MW}}}$$



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لَا حَوْلَ وَلَا قُوَّةَ إِلَّا بِاللَّهِ

"من كنوز الجنة"

