RS MODULE
PHYSIOLOGY (LECTURE 3)
PULMONARY CIRCULATION

BY

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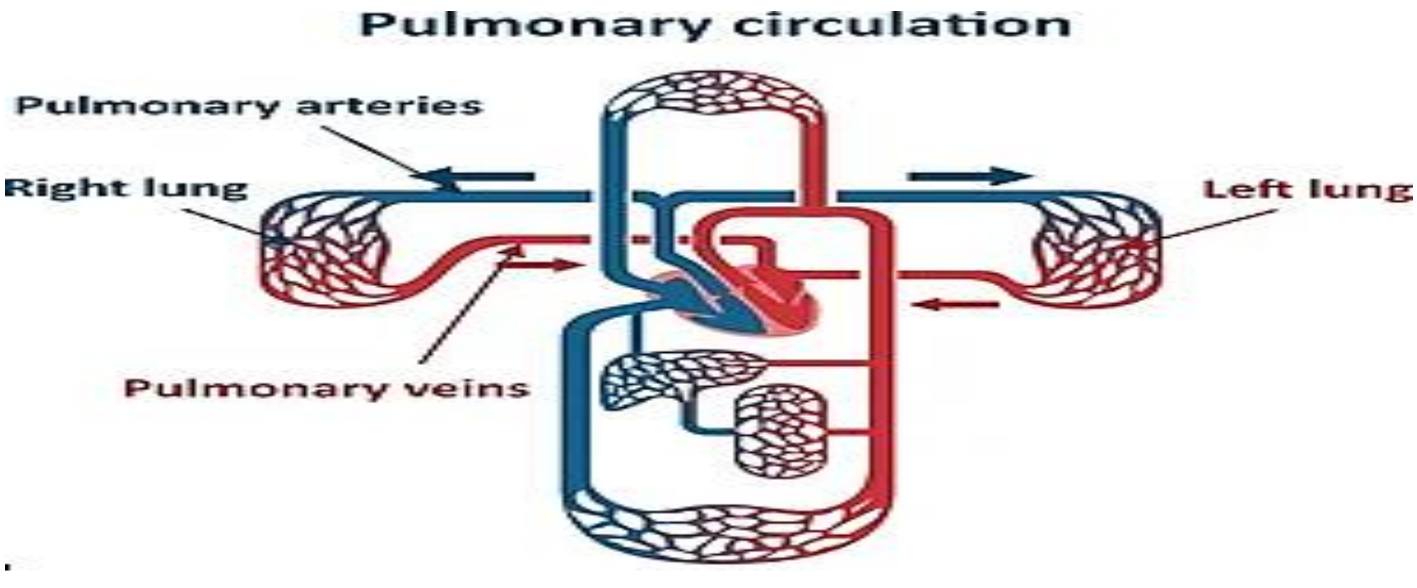
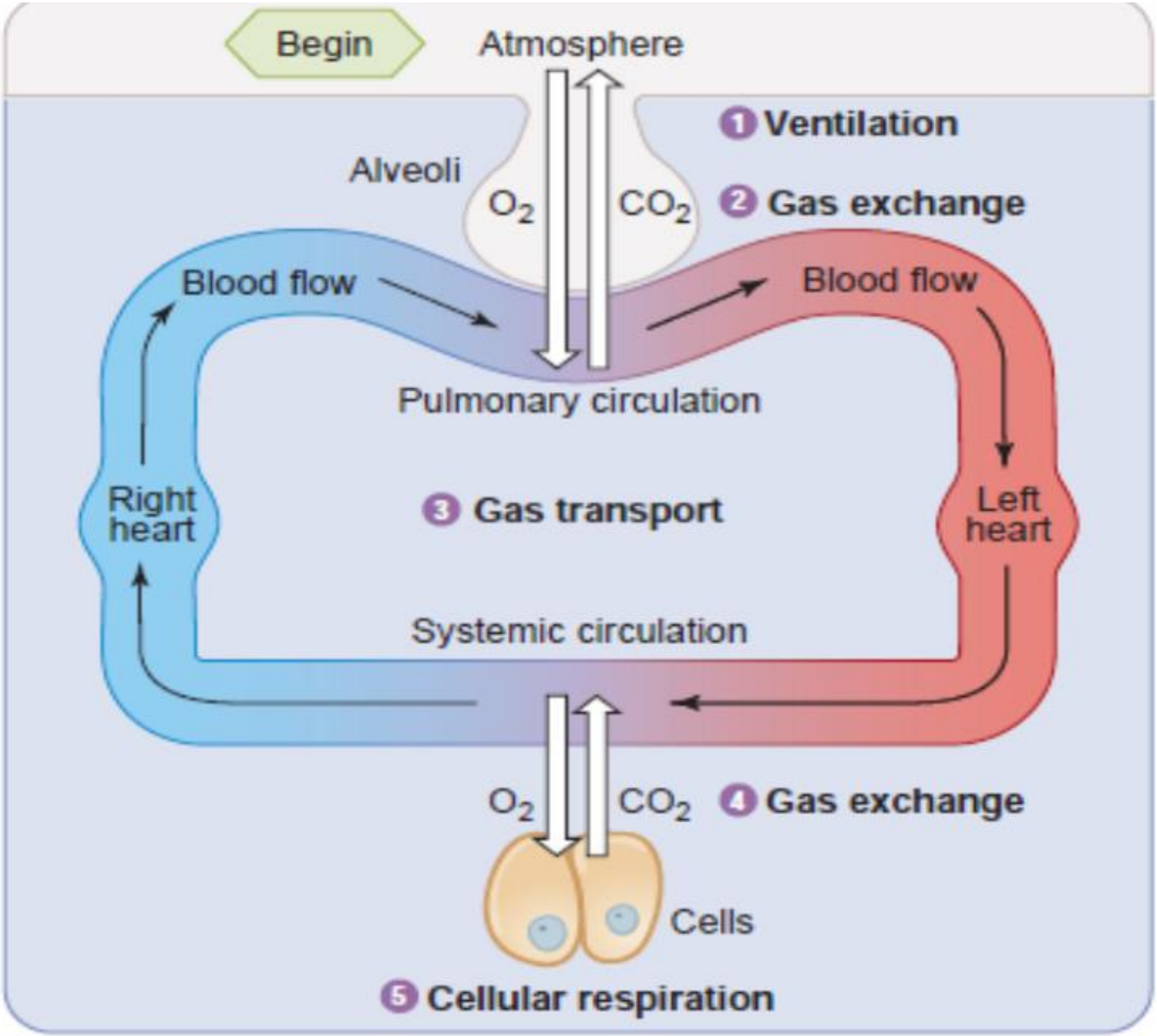


Pulmonary (lesser) Circulation

Functions of the pulmonary circulation:

- ✓ Conduction of blood from the right side of the heart to its left side.
- ✓ Blood oxygenation and wash of CO_2 (= **arterialization of venous blood**).
- ✓ Filtration of various emboli from the venous blood (The lungs contain a fibrinolytic system that lyses blood clots in the pulmonary vessels).
- ✓ Blood reservoir: Because of their distensibility, the pulmonary veins are an important blood reservoir. When a normal individual lies down, the pulmonary blood volume increases by up to 400 ml, and when the person stands up this blood is discharged into the general circulation. This shift is the cause of the decrease in vital capacity in the supine position and is responsible for the occurrence of orthopnea in heart failure.



Begin
Atmosphere
1 Ventilation
Alveoli
O_2
CO_2
2 Gas exchange
Blood flow
Blood flow
Pulmonary circulation
Right heart
3 Gas transport
Left heart
Systemic circulation
O_2
CO_2
4 Gas exchange
Cells
5 Cellular respiration

Characteristics of Pulmonary Vasculature

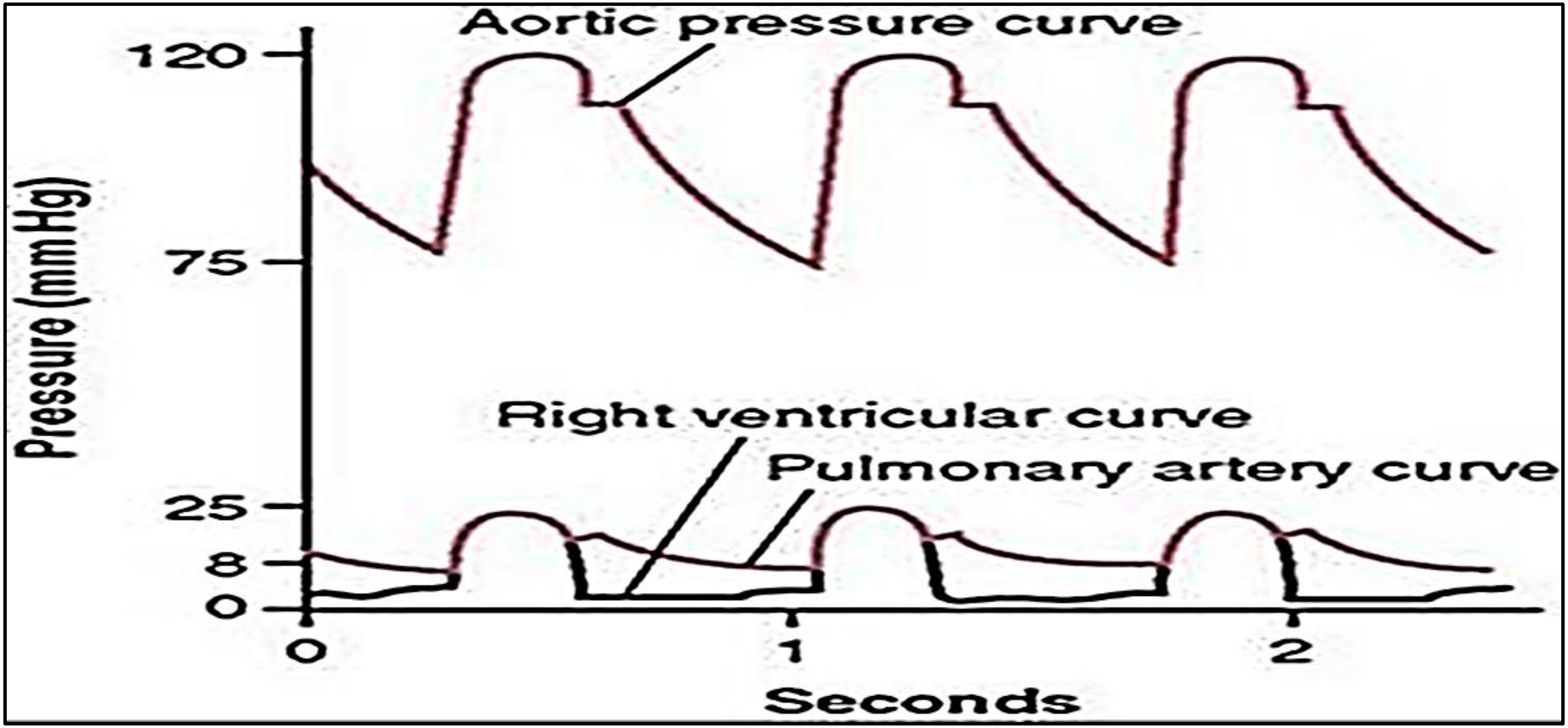
- The pulmonary vasculature has unique characteristics that set it apart from the rest of the vascular system.
- These properties relate directly to the physiologic function of the respiratory system.
- The lungs receive arterial blood from the pulmonary and bronchial arteries and their venous blood is drained mainly by the 4 pulmonary veins.
- **The pulmonary vasculature is characterized by:**

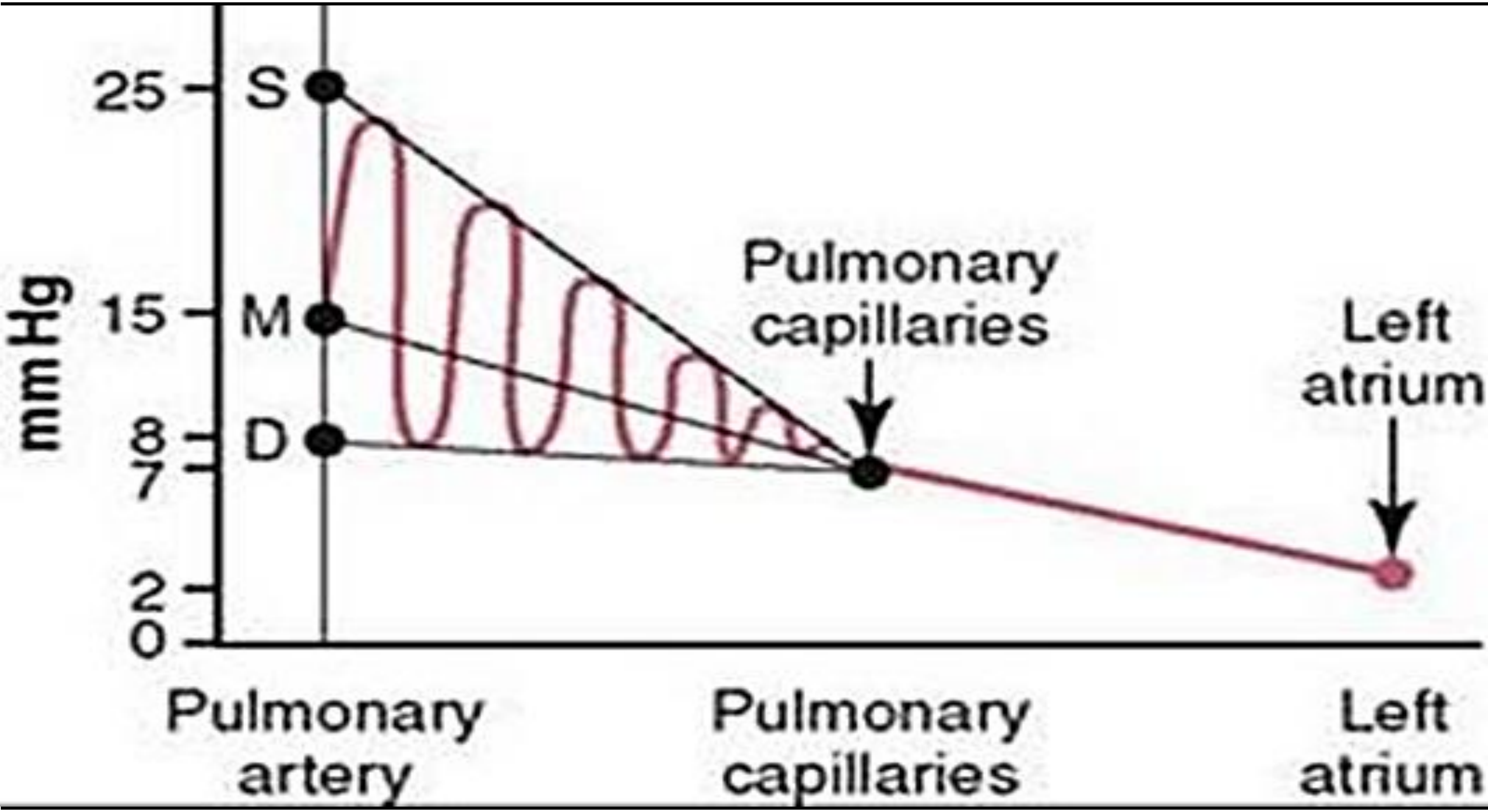
- The walls of the pulmonary artery and its large branches are thin (30 % as thick as aortic wall) while the small pulmonary arteries & pulmonary arterioles are short, wide & have little smooth muscle. These properties render the pulmonary arterial tree highly compliant (i.e. easily distensible).
- The pulmonary veins are short and compliant as systemic veins.
- Considerable anastomoses exist between the branches of the pulmonary and bronchial arteries and most of bronchial blood is drained by pulmonary veins. So, the left ventricular output is normally slightly greater than that of the right ventricle.
- The pulmonary capillaries are large, have a high permeability and an extensive exchange surface area as well as multiple anastomoses, so each alveolus sits in a basket (i.e. a network) of capillaries.
- The lungs are also richly supplied by lymphatic vessels.

Normal Pressures in pulmonary circulation

- In the right ventricle of the normal human being, the systolic pressure averages about 25 mm Hg, while the diastolic pressure is almost 0 mm Hg (values that are only one fifth those for the left ventricle).
- In the pulmonary artery, the **systolic pulmonary pressure** is essentially equal to the pressure in the right ventricle **(25 mmHg)**; about 1/5 that in the aorta because the pulmonary vessels offer a much smaller peripheral resistance.
- The **diastolic pulmonary arterial pressure** is about **8 mm Hg.**
- **The mean pulmonary arterial pressure is 15 mm Hg**.
- **Pulmonary capillary pressure averages 7 mm Hg** (lowest capillary pressure in the body).
- In the **pulmonary veins and left atrium, the pressure range is 1-5 mmHg (average: 2 mmHg)**.

Pressure Pulse Curve in the Right Ventricle and pulmonary artery.





Pressures in the different vessels of the lungs. S, systolic ; D, diastolic; M, mean.

The pulmonary vascular resistance (PVR)

- The PVR is normally low (about 1/6 that in the systemic circulation) because of the large distensibility of the pulmonary vasculature.
- It is determined by the **pulmonary arteriolar diameter**:

Factors that decrease the arteriolar diameter (i.e. produce V.C.), increase the PVR while factors that increase the arteriolar diameter (i.e. produce V.D.), decrease the PVR.

Factors that cause pulmonary V.C.:

- Hypoxia.
- Low pH (i.e. acidosis).
- Sympathetic stimulation.
- Catecholamines (noradrenaline).
- Angiotensin II.
- Thromboxane A_2 and PGF_2.

Factors that cause pulmonary V.D.:

- Vagal stimulation.
- Acetylcholine.
- ANP.
- PGI_2.

N.B. The PVR increases significantly in certain lung diseases e.g. emphysema, pulmonary fibrosis and pulmonary embolism as a result of:
Obliteration of pulmonary vessels.
Local hypoxia in the lungs.

Relation between lung volume & pulmonary vascular resistance (PVR)

PVR changes with lung volume:

- At high volumes, the alveolar vessels are compressed by stretched alveolar walls and contribute more to PVR.
- At low volumes, extra-alveolar vessels are compressed due to increased positive intrathoracic (intrapleural) pressure, contributing to an increased PVR.
- The total PVR is typically lowest at functional residual capacity (i.e. FRC).

Regulation of Pulmonary Blood Flow (PBF)

- The PBF normally equals the cardiac output (about 5.5 liters/minute). i.e. the pulmonary circulation accommodates a blood flow that is equal to that of all the other organs in the body.
- The PBF is regulated as follows:

Overall regulation of the PBF:

This is mostly a passive process e.g. **during exercise**, the cardiac output increases markedly and the pulmonary vessels dilate passively (due to their high distensibility). So, the PVR drops and PBF increases.

- ## Regional regulation of the PBF:

This is controlled by 2 factors:

(1) O_2 tension:

- Local hypoxia (due to obstruction of a bronchus or a bronchiole) causes local V.C. by stimulating the vascular smooth muscle (This is opposite to the effect observed in systemic vessels, which dilate rather than constrict in response to low oxygen).
- Such effect shifts the blood away from the hypoxic area to other normally ventilated alveoli without affecting the total PBF (thus providing an automatic control system for distributing blood flow to the pulmonary areas in proportion to their alveolar oxygen pressures).

- Local CO_2 accumulation produces the same effect. Accumulation of CO_2 leads to a drop in pH in the area, and a decline in pH also produces vasoconstriction in the lungs, as opposed to the vasodilation it produces in other tissues. Conversely, reduction of the blood flow to a portion of the lung lowers the alveolar PCO_2 in that area, and this leads to constriction of the bronchi supplying it, shifting ventilation away from the poorly perfused area.

- This is autoregulatory mechanism in the lungs that shifts blood from the low-ventilated areas to other well-ventilated areas.

(2) Gravity:

Gravity has a relatively marked effect on the pulmonary circulation. In the upright position, the apices of the lungs are well above the heart level while their bases are below it.

By the effect of gravity, this normally creates a gradient in the pulmonary arterial pressure of about 23 mmHg (at the lung apices, the pulmonary arterial pressure becomes about 15 mmHg less than that at the heart level, while at the lung bases, it becomes about 8 mmHg greater than that at the heart level).

Such pressure differences have profound effects on blood flow through the different areas of the lungs. It causes intermittent PBF at the lung apices (only during systole) and a continuous PBF at the lung bases (during both systole and diastole), which leads to an increase of the PBF from above downwards, becoming maximal at the lung bases (= **waterfall effect**).

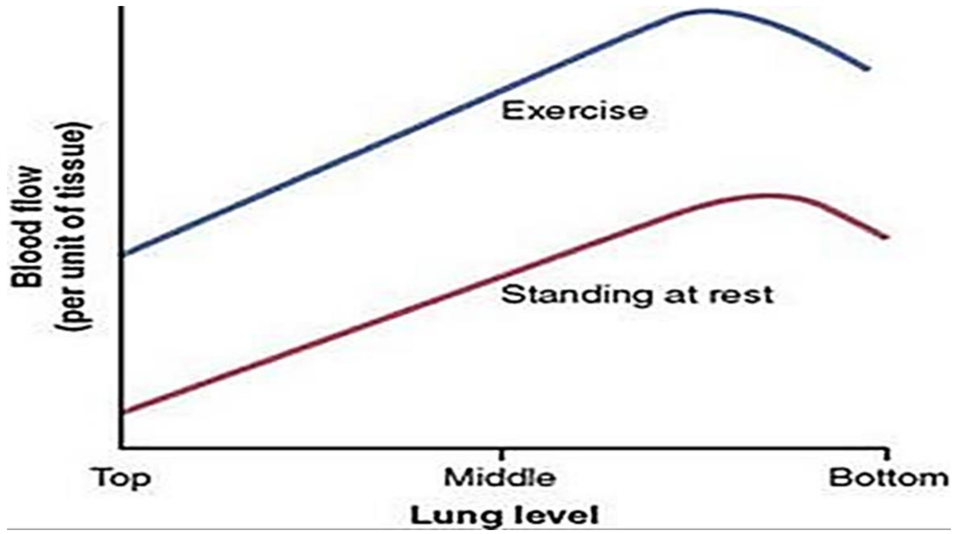


Figure. Blood flow at different levels in the lung of an upright person *at rest* and *during exercise.* Note that when the person is at rest, the blood flow is very low at the top of the lungs; most of the flow is through the bottom of the lung.

To help explain these differences, one often describes the lung as being divided into three zones. In each zone, the patterns of blood flow are quite different.

Zones 1, 2, and 3 of Pulmonary Blood Flow

- The capillaries in the alveolar walls are distended by the blood pressure inside them, but simultaneously, they are compressed by the alveolar air pressure on their outsides.
- Therefore, any time the lung alveolar air pressure becomes greater than the capillary blood pressure, the capillaries close and there is no blood flow.
- Under different lung conditions, one may find any one of three possible zones of pulmonary blood flow, as follows:
- **Zone 1: No blood flow during all portions of the cardiac cycle** because the local alveolar capillary pressure in that area of the lung never rises higher than the alveolar air pressure during any part of the cardiac cycle
- **Zone 2: Intermittent blood flow** only during the pulmonary arterial pressure peaks because the systolic pressure is then greater than the alveolar air pressure, but the diastolic pressure is less than the alveolar air pressure.
- **Zone 3: Continuous blood flow** because the alveolar capillary pressure remains greater than alveolar air pressure during the entire cardiac cycle.

- ✓ Normally, the lungs have only zones 2 and 3 blood flow—zone 2 (intermittent flow) in the apices, and zone 3 (continuous flow) in all the lower areas.
- ✓ For example, when a person is in the upright position, the pulmonary arterial pressure at the lung apex is about 15 mm Hg less than the pressure at the level of the heart. Therefore, the apical systolic pressure is only 10 mm Hg (25 mm Hg at heart level minus 15 mm Hg hydrostatic pressure difference). This 10 mm Hg apical blood pressure is greater than the zero alveolar air pressure, so that blood flows through the pulmonary apical capillaries during cardiac systole. Conversely, during diastole, the 8 mm Hg diastolic pressure at the level of the heart is not sufficient to push the blood up the 15 mm Hg hydrostatic pressure gradient required to cause diastolic capillary flow.
- ✓ Therefore, blood flow through the apical part of the lung is **intermittent**, with flow during systole but cessation of flow during diastole; this is called **zone 2 blood flow**.

- ✓ **In the lower regions of the lungs**, the pulmonary arterial pressure during both systole and diastole remains greater than the zero alveolar air pressure. Therefore, there is continuous flow through the alveolar capillaries, or **zone 3 blood flow**.
- ✓ Also, when a person is **lying down**, no part of the lung is more than a few centimeters above the level of the heart. In this case, blood flow in a normal person is entirely **zone 3 blood flow**, including the lung apices.

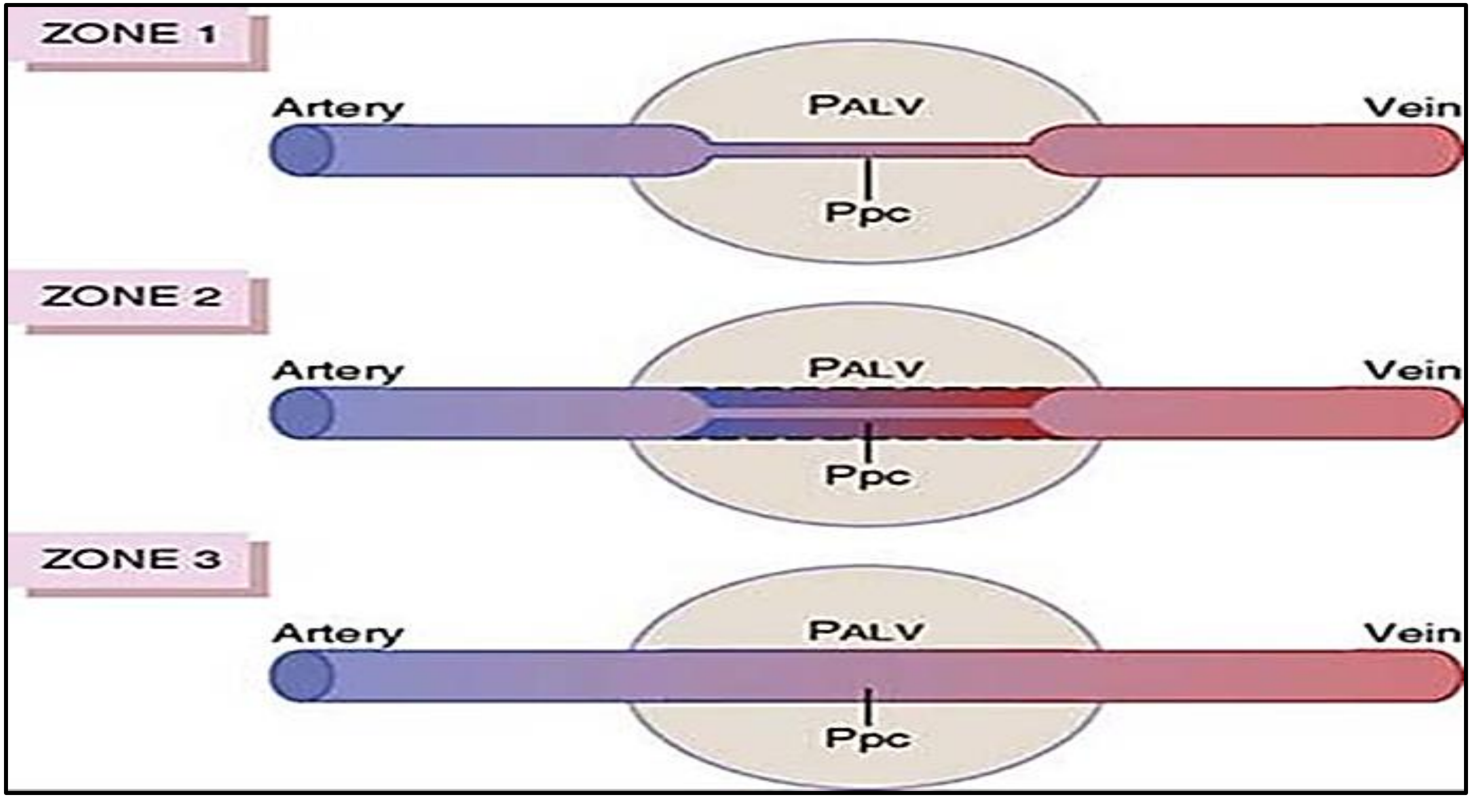


Figure. Mechanics of blood flow in the three blood flow zones of the lung: *zone 1, no flow*—alveolar air pressure (PALV) is greater than arterial pressure; *zone 2, intermittent flow*—systolic arterial pressure rises higher than alveolar air pressure, but diastolic arterial pressure falls below alveolar air pressure; and *zone 3, continuous flow*—arterial pressure and pulmonary capillary pressure (Ppc) remain greater than alveolar air pressure at all times.

Factors affecting pulmonary arterial B.P.

(A) Pulmonary vascular resistance (PVR)

All factors that increase PVR also increase the pulmonary arterial B.P. and vice versa.

The commonest of these factors include the following:

- **Nervous factors:**
  - Sympathetic stimulation causes VC of pulmonary arterioles which increases the PVR and pulmonary arterial B.P.
  - Vagal stimulation produces opposite effects.

- **Chemical factors:**
  - Pulmonary VC substances (e.g. catecholamines) increase the PVR and pulmonary arterial B.P. while V.D. substances (e.g. acetylcholine) produce opposite effects.
  - Systemic hypoxia: this leads to V.C. of pulmonary arterioles which increases the PVR and pulmonary arterial B.P.

- **Respiratory movements:**

During inspiration, the pulmonary arterioles dilate resulting in reduction of both PVR and pulmonary arterial B.P.
During expiration, opposite effects occur.

- **Lung diseases:**

The diseases that cause narrowing of the pulmonary arterioles (e.g. emphysema, pulmonary fibrosis and pulmonary embolism) increase the PVR and pulmonary arterial B.P.

(B) Left atrial pressure:

- ✓ A rise of the left atrial pressure above 7-8 mmHg leads to back pressure in the pulmonary vascular system resulting in elevation of the pulmonary arterial B.P. this commonly occurs secondary to left ventricular failure and severe mitral stenosis.
- ✓ Any increase in left atrial pressure above 7-8 mm Hg increases the capillary pressure almost equally as much. When the left atrial pressure has risen above 30 mm Hg, causing similar increases in capillary pressure, pulmonary edema is likely to develop.

(C) Cardiac output

- ✓ During heavy exercise, the cardiac output increases 4-7 folds. However, this leads to only a small rise of the pulmonary arterial B.P., because the PVR is rather decreased as a result of increasing the pulmonary capacity.

The latter occurs by:

- Distension of all pulmonary capillaries.
- Increase of the number of open pulmonary capillaries as well as the rate of blood flow through them (a red blood cell takes about 0.75 second to traverse a pulmonary capillary during rest, and 0.3 second or less during exercise).

- ✓ This ability also prevents a significant rise in pulmonary capillary pressure, thus also preventing the development of pulmonary edema.

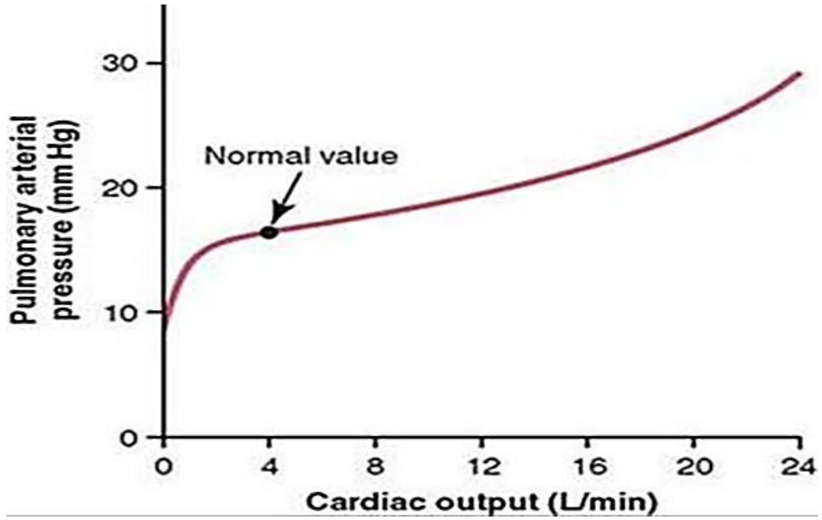


Figure. Effect on mean pulmonary arterial pressure caused by increasing the cardiac output during exercise.

Functional Characteristics of Pulmonary Circulation

- The pulmonary vascular system is a distensible low pressure system.

- It is a high flow circulation (the pulmonary blood flow = cardiac output); it accommodates a blood flow that is almost equal to that of all the other organs in the body.

- Its venous return at the left atrium is 1-2 % greater than the right ventricular output.

- It has a high compliance, acting as blood reservoir of varying capacity.

- The blood flow in the pulmonary capillaries is rapid (about 0.75 second during rest and 0.3 during exercise).

- Both the pulmonary capillary surface area and permeability are great.

- The regional pulmonary blood flow is affected by gravity (it is much greater in the lung bases than in the apices).

- The alveoli are normally kept almost completely dry.

- It has special reactions to gas changes e.g. hypoxia, hypercapnia and excess H^+ produce V.C. and not V.D. as in other tissues.

- The mean velocity of the blood in the root of the pulmonary artery is the same as that in the aorta (about 40 cm/s).

The Physiological Shunts

- These are normal shunts that allow drainage of some systemic venous blood into the pulmonary venous blood (which is arterial blood after equilibration with the alveolar air).

- This systemic venous blood is derived from:

  - The bronchial veins, which drain some of their blood into the pulmonary capillaries and veins.
  - The coronary veins, which drain some of their blood directly into the left side of the heart.

- As a result of these physiological shunts, the Po_2 and % saturation of Hb with O_2 in the systemic arterial blood (about 95 mmHg and 97% respectively) are normally slightly less than their corresponding values in the blood that has equilibrated with alveolar air at the venous ends of the pulmonary capillaries (about 97 mmHg and 97.5% respectively).

Diseases Affecting the Pulmonary Circulation

Pulmonary Hypertension

Sustained primary pulmonary hypertension can occur at any age. Like systemic arterial hypertension, it is a syndrome with multiple causes. However, the causes are different from those causing systemic hypertension. They include hypoxia, inhalation of cocaine and treatment with appetite-suppressing drugs that increase extracellular serotonin.

Some cases are familial and appear to be related to mutations that increase the sensitivity of pulmonary vessels to growth factors or cause deformations in the pulmonary vascular system.

All these conditions lead to increased pulmonary vascular resistance. If appropriate therapy is not initiated, the increased right ventricular afterload can lead eventually to right heart failure and death.

Treatment with vasodilators such as prostacyclin and prostacyclin analogs is effective.


Thank you