Ventilation-Perfusion Relationship

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Lung circulations

- The lung has two circulations, a high-pressure, low-flow circulation and a low-pressure, high-flow circulation.

- The high-pressure, low-flow circulation supplies systemic arterial blood to the trachea, bronchial tree (including the terminal bronchioles), supporting tissues of the lung, and outer coats (adventitia) of the pulmonary arteries and veins.

- The low-pressure, high-flow circulation supplies venous blood from all parts of the body to the alveolar capillaries where oxygen (O2) is added and carbon dioxide (CO2)

Last lecture Question

- The pH of venous blood is only slightly more acidic than the pH of arterial blood because

- (A) CO_2 is a weak base
- (B) there is no carbonic anhydrase in venous blood
- (C) the H^+ generated from CO_2 and H_2O is buffered by HCO_3^- in venous blood
- (D) the H^+ generated from CO_2 and H_2O is buffered by deoxyhemoglobin in venous blood
- (E) oxyhemoglobin is a better buffer for H^+ than is deoxyhemoglobin

Pulmonary blood flow

- The Pulmonary blood flow is the cardiac output of the right heart, which is equal to the cardiac output of the left heart.

- Pulmonary blood flow is directly proportional to the pressure gradient between the pulmonary artery and the left atrium and is inversely proportional to the resistance of the pulmonary vasculature

Regulation of pulmonary blood flow

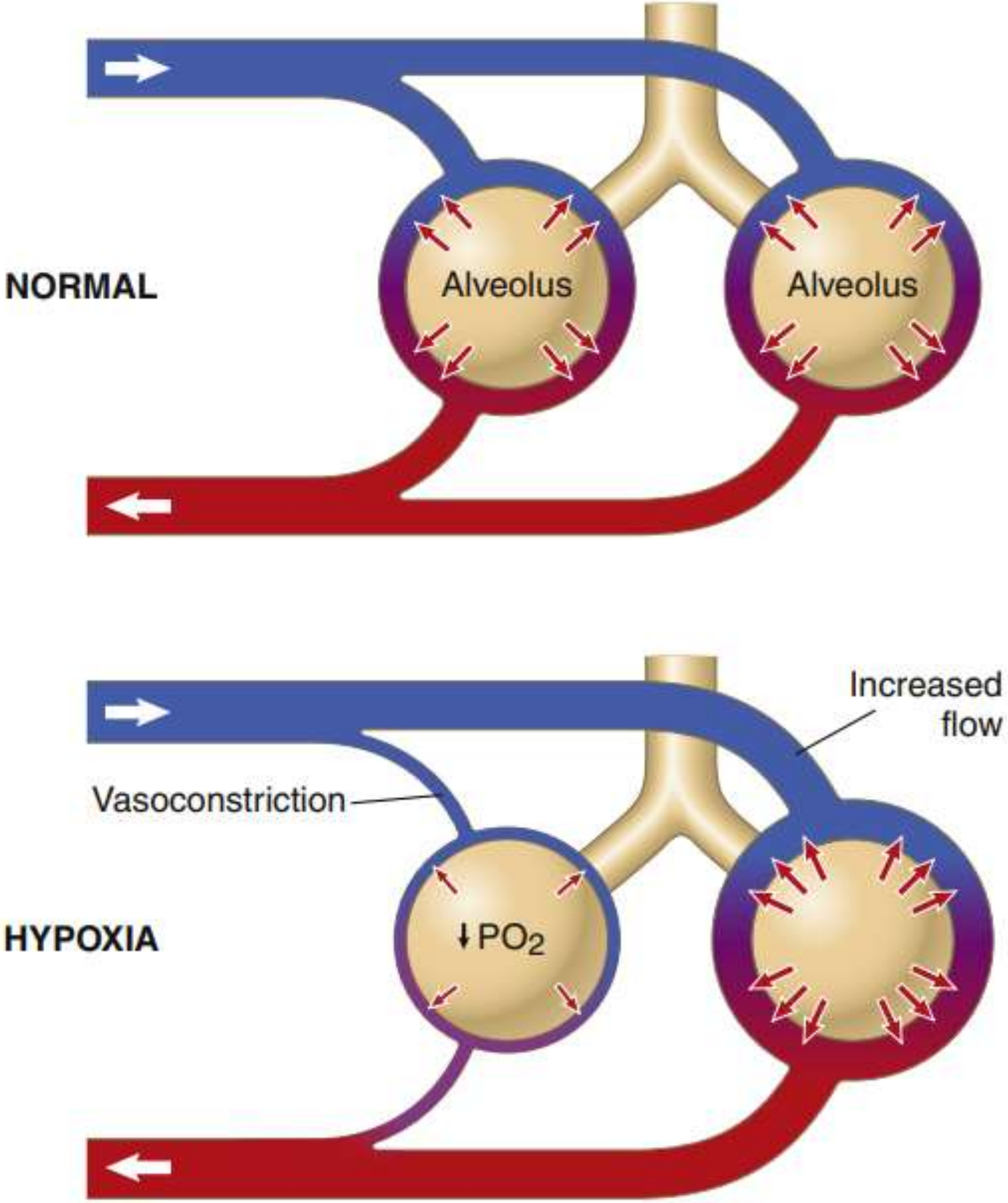
- By far, the major factor regulating pulmonary blood flow is the partial pressure of O_2 in alveolar gas, PAO_2.

- Decreases in PAO_2 produce pulmonary vasoconstriction (i.e., hypoxic vasoconstriction).

Hypoxic vasoconstriction

- In the lungs, hypoxic vasoconstriction occurs as an adaptive mechanism, reducing pulmonary blood flow to poorly ventilated areas where the blood flow would be "wasted."

- Pulmonary blood flow is directed away from poorly ventilated regions of the lung, where gas exchange would be inadequate, and toward well-ventilated regions of the lung, where gas exchange will be better.


NORMAL
Alveolus
Alveolus
HYPOXIA
Vasoconstriction
↓PO2
Increased flow

Hypoxic vasoconstriction

- In certain types of lung disease, hypoxic vasoconstriction serves a protective role because, within limits, blood can be redirected to alveoli that are well oxygenated without changing overall pulmonary vascular resistance.

- The compensatory mechanism fails, however, if the lung disease is widespread (e.g., multilobar pneumonia); if there are insufficient areas of well-ventilated alveoli, hypoxemia will occur.

Hypoxic vasoconstriction

- hypoxic vasoconstriction can function locally to redirect blood flow to well-ventilated regions of the lung.

- It also can operate globally in an entire lung, in which case the vasoconstriction will produce an increase in pulmonary vascular resistance.

- For example, at high altitude or in persons breathing a low O_2 mixture, PAO_2 is reduced throughout the lungs, not just in one region.

Hypoxic vasoconstriction

- Fetal circulation is another example of global hypoxic vasoconstriction.

- Because the fetus does not breathe, PAO_2 is much lower in the fetus than in the mother, producing vasoconstriction in the fetal lungs.

- This vasoconstriction increases pulmonary vascular resistance and, accordingly, decreases pulmonary blood flow to approximately 15% of the cardiac output.

- At birth, the neonate's first breath increases PAO_2 to 100 mm Hg, hypoxic vasoconstriction is reduced, pulmonary vascular resistance decreases, and pulmonary blood flow increases and eventually equals cardiac output of the left side of the heart (as in the adult).

Hypoxic vasoconstriction

- The mechanism of hypoxic vasoconstriction involves a direct action of alveolar PO_2 on the vascular smooth muscle of pulmonary arterioles.

Vasoactive substances

- Thromboxane A2 is a powerful local vasoconstrictor of both arterioles and veins.

- Prostacyclin (prostaglandin I2) is a potent local vasodilator.

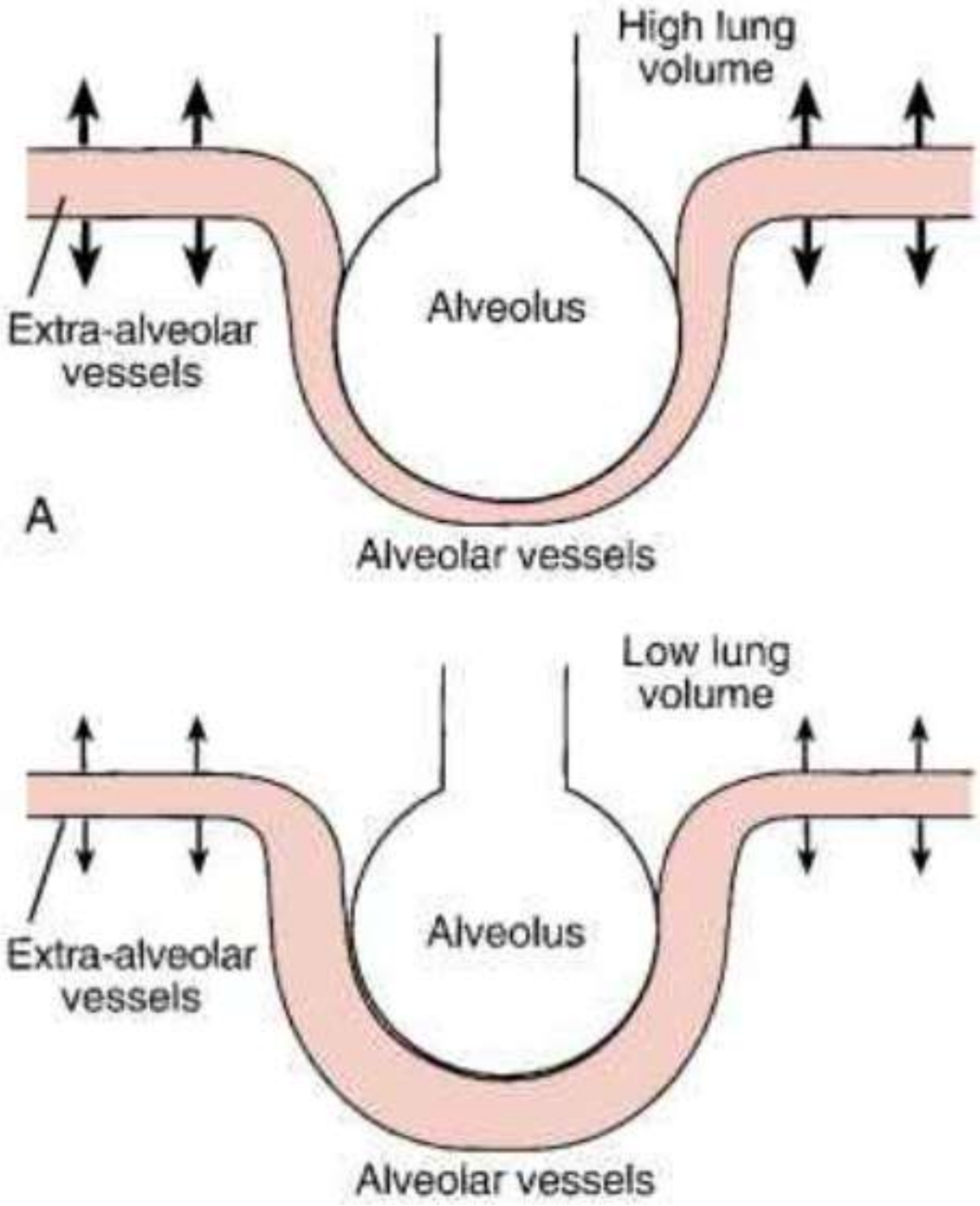
- The leukotrienes cause airway constriction.

Pulmonary blood vessels

- The Pulmonary blood vessels include **alveolar** vessels (i.e., capillaries) that are surrounded by alveoli and **extra-alveolar** vessels (e.g., arteries and veins) that are not.

- Increased lung volume affects the two types of vessels differently: It crushes the alveolar vessels, increasing their resistance, but it pulls open the extra-alveolar vessels, decreasing their resistance.

- Because total pulmonary vascular resistance is the sum of alveolar and extra-alveolar resistances, the effect of increased lung volume depends on which effect is larger.


High lung volume
Alveolus
Extra-alveolar vessels
A
Alveolar vessels
Low lung volume
Alveolus
Extra-alveolar vessels
Alveolar vessels

Distribution of pulmonary blood flow

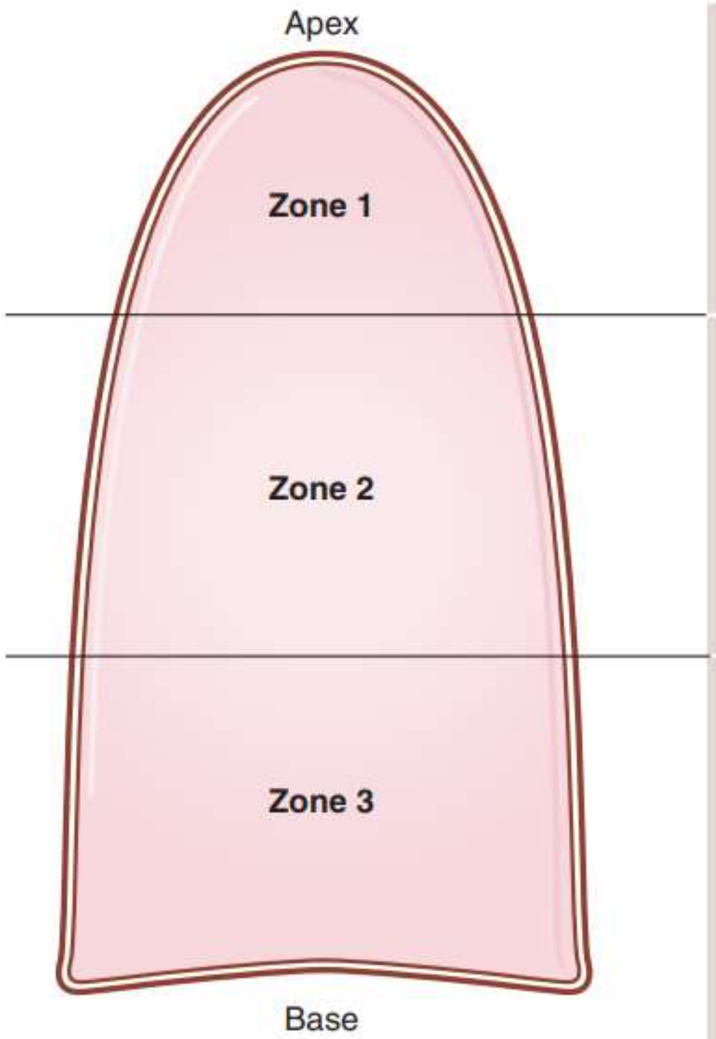
- The distribution of pulmonary blood flow within the lung is uneven and the distribution can be explained by the effects of gravity.

- When a person is supine, blood flow is nearly uniform because the entire lung is at the same gravitational level.

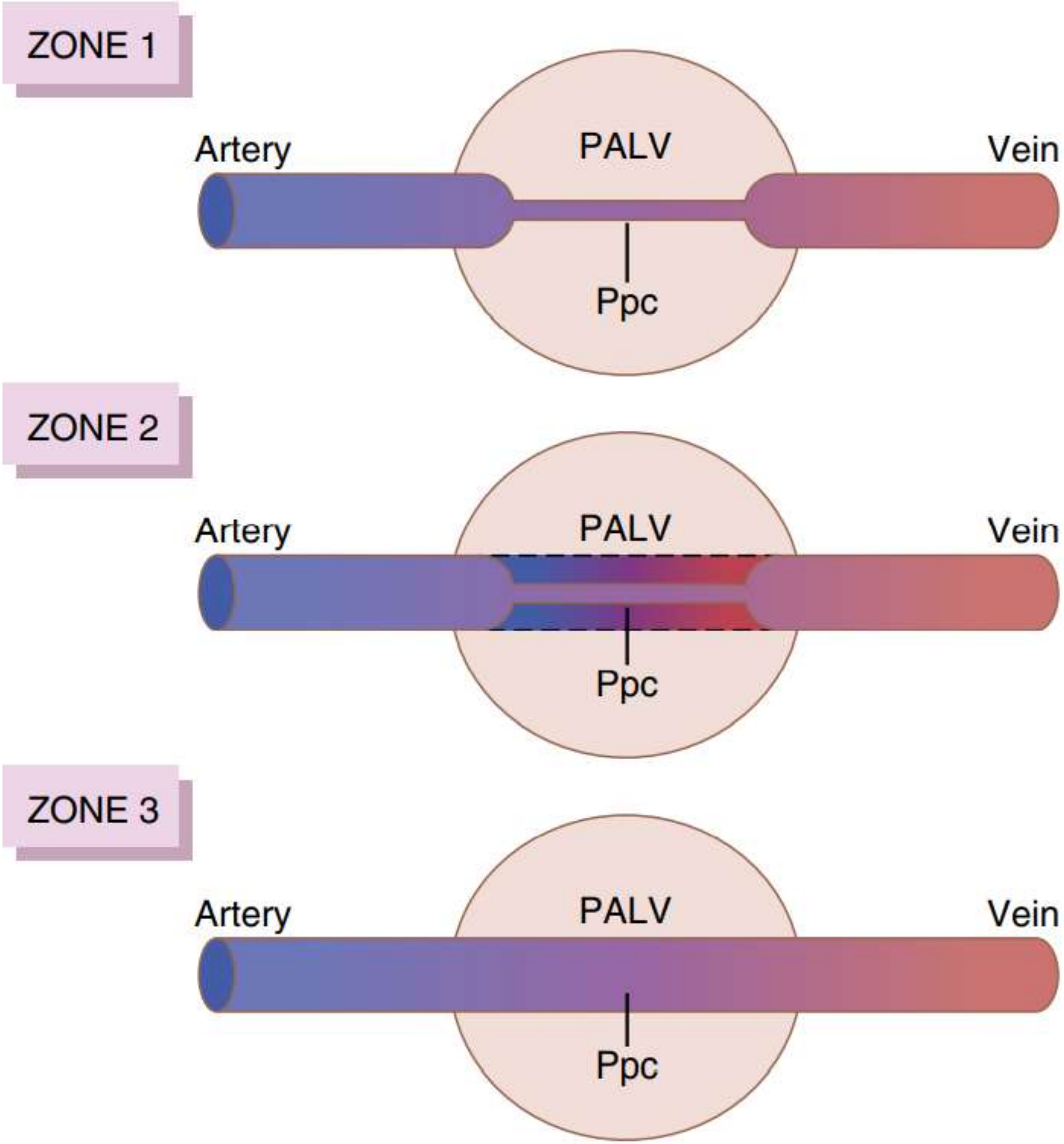
- However, when a person is upright, gravitational effects are not uniform and blood flow is lowest at the apex of the lung (zone 1) and highest at the base of the lung (zone 3).

- (Gravitational effects increase pulmonary arterial hydrostatic pressure more at the base of the lung than at the apex.)

BLOOD FLOW DISTRIBUTION IN THE LUNG



	Blood Flow	Pressures Driving Blood Flow
Zone 1	Lowest	$P_A \geq \boxed{P_a} > P_V$
Zone 2	Medium	$\boxed{P_a} > P_A > P_V$
Zone 3	Highest	$\boxed{P_a} > P_V > P_A$


ZONE 1
Artery
PALV
Vein
Ppc
ZONE 2
Artery
PALV
Vein
Ppc
ZONE 3
Artery
PALV
Vein
Ppc

Zone 1

- If Pa is lower than PA, the pulmonary capillaries will be compressed by the higher alveolar pressure outside of them.

- This compression will cause the capillaries to close, reducing regional blood flow.

- Normally, in zone 1, arterial pressure is just high enough to prevent this closure, and zone 1 is perfused, albeit at a low flow rate.

Zone 1

- However, if arterial pressure is decreased (e.g., due to hemorrhage) or if alveolar pressure is increased (e.g., by positive pressure breathing),

- then PA will be greater than Pa and the blood vessels will be compressed and will close.

- Under these conditions, zone 1 will be ventilated but not perfused.

- There can be no gas exchange if there is no perfusion, and zone 1 will become part of the physiologic dead space.

Zone 2

- The Because of the gravitational effect on hydrostatic pressure, Pa is higher in zone 2 than in zone 1 and higher than PA.

- Alveolar pressure is still higher than pulmonary venous pressure (PV).

- Although compression of the capillaries does not present a problem in zone 2, blood flow is driven by the difference between arterial and alveolar pressure, not by the venous pressure (as it is in systemic vascular beds).

Zone 3

- In zone 3, the pattern is more familiar.
- The gravitational effect has increased arterial and venous pressures, and both are now higher than alveolar pressure.
- Blood flow in zone 3 is driven by the difference between arterial pressure and venous pressure, as it is in other vascular beds.
- In zone 3, the greatest number of capillaries is open and blood flow is highest

Shunts

- A shunt refers to a portion of the cardiac output or blood flow that is diverted or rerouted.

Physiologic shunts

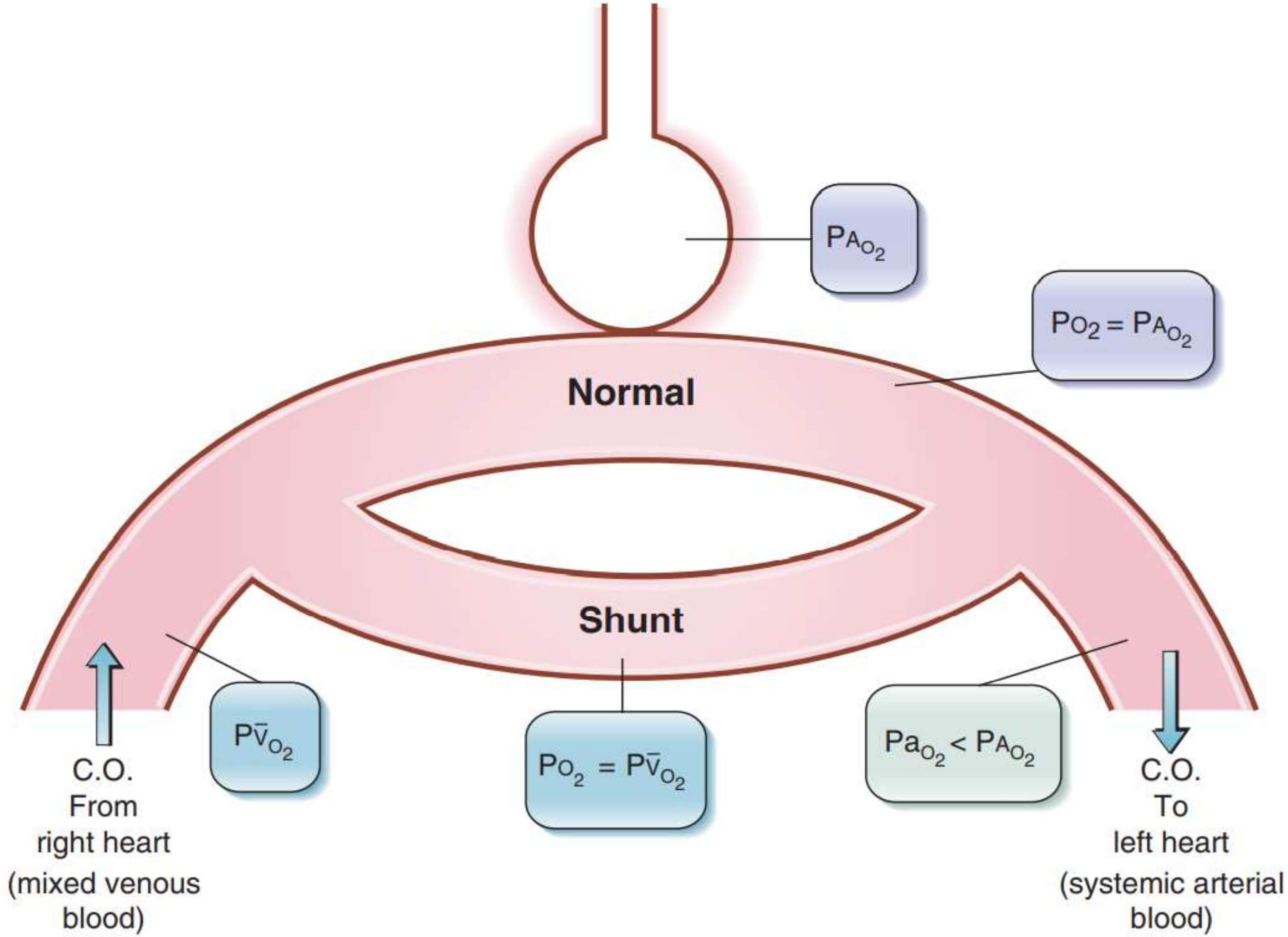
- The Small physiologic shunts are always present, and PaO_2 will always be slightly less than PAO_2.

Rt to Lt shunts

- Hypoxemia always occurs because a significant fraction of the cardiac output is not delivered to the lungs for oxygenation.

- The portion of the cardiac output that is delivered to the lungs for oxygenation is "diluted" by the low O_2 shunted blood.

- A defining characteristic of the hypoxemia caused by a right-to-left shunt is that it cannot be corrected by having the person breathe a high-O_2 gas (e.g., 100% O_2) because the shunted blood never goes to the lungs to be oxygenated.



PA_{O_2}
$PO_2 = PA_{O_2}$
Normal
Shunt
$P\bar{V}_{O_2}$
$PO_2 = P\bar{V}_{O_2}$
$Pa_{O_2} < PA_{O_2}$
C.O. From right heart (mixed venous blood)
C.O. To left heart (systemic arterial blood)

Rt to Lt shunts

- The shunted blood will continue to dilute the normally oxygenated blood, and no matter how high the alveolar PO2, it cannot offset this dilutional effect.

- hemoglobin saturation is nearly 100% in this range, breathing 100% O2 adds primarily dissolved O2 to pulmonary capillary blood and adds little to the total O2 content of blood.)

- However, having a person with a right-to-left shunt breathe 100% O2 is a useful diagnostic tool; the magnitude of the shunt can be estimated from the extent of dilution of the oxygenated blood.

Rt to Lt shunts

- **Usually, a right-to-left shunt does not cause an appreciable increase in $PaCO_2$** (although it may seem that it should because of the high CO_2 content of the shunted blood).

- $PaCO_2$ changes only minimally because the central chemoreceptors are sensitive to changes in $PaCO_2$.

- A small increase in $PaCO_2$ produces an increase in ventilation rate, and the extra CO_2 is expired.

- Chemoreceptors for O_2 are not as sensitive as those for CO_2 and are not activated until the PaO_2 decreases to less than 60 mm Hg.

Rt to Lt shunts

- The blood flow through a right-to-left shunt can be calculated with the shunt fraction equation, where flow through the shunt is expressed as a fraction of pulmonary blood flow, or cardiac output, as follows:

$$\frac{Q_S}{Q_T} = \frac{O_2 \text{ content ("normal" blood)} - O_2 \text{ content (arterial blood)}}{O_2 \text{ content ("normal" blood)} - O_2 \text{ content (mixed venous blood)}}$$

Lt to Rt shunts

- The Left-to-right shunts are more common and do not cause hypoxemia.

- Among the causes of left-to-right shunts are patent ductus arteriosus and traumatic injury.

- If blood is shunted from the left side of the heart to the right side of the heart, pulmonary blood flow (right-heart cardiac output) becomes higher than systemic blood flow (left-heart cardiac output).

Lt to Rt shunts

- In effect, oxygenated blood that has just returned from the lungs is added directly to the right heart without being delivered to the systemic tissues.

- Because the right side of the heart normally receives mixed venous blood, the PO2 in blood on the right side of the heart will be elevated.

Ventilation- Perfusion ratio

- The ventilation/perfusion ratio ($\dot{V}/\dot{Q}$) is the ratio of alveolar ventilation ($\dot{V}A$) to pulmonary blood flow ($\dot{Q}$).

- Matching ventilation to perfusion is critically **important for ideal gas exchange**: It is useless for alveoli to be ventilated but not perfused or for alveoli to be perfused but not ventilated.

Normal Ventilation- Perfusion ratio

- The normal value for $\dot{V}/\dot{Q}$ is 0.8.

- This value means that alveolar ventilation (L/min) is 80% of the value for pulmonary blood flow (L/min). The term "normal" means that if breathing frequency, tidal volume, and cardiac output all are normal, $\dot{V}/\dot{Q}$ will be 0.8.

- In turn, if $\dot{V}/\dot{Q}$ is normal, then PaO_2 will be its normal value of 100 mm Hg and $PaCO_2$ will be its normal value of 40 mm Hg.

- If $\dot{V}/\dot{Q}$ changes due to an alteration of alveolar ventilation or an alteration of pulmonary blood flow, or both, then gas exchange will be less than ideal and the values for PaO_2 and $PaCO_2$ will change.

V/Q distribution in the lung

- The value of 0.8 for $\dot{V}/\dot{Q}$ is an average for the entire lung.

- In fact, **in the three zones of the lung, $\dot{V}/\dot{Q}$ is uneven**, just as blood flow is uneven.

- These variations in $\dot{V}/\dot{Q}$ have consequences for PaO_2 and $PaCO_2$ in blood leaving those zones.

V/Q distribution in the lung

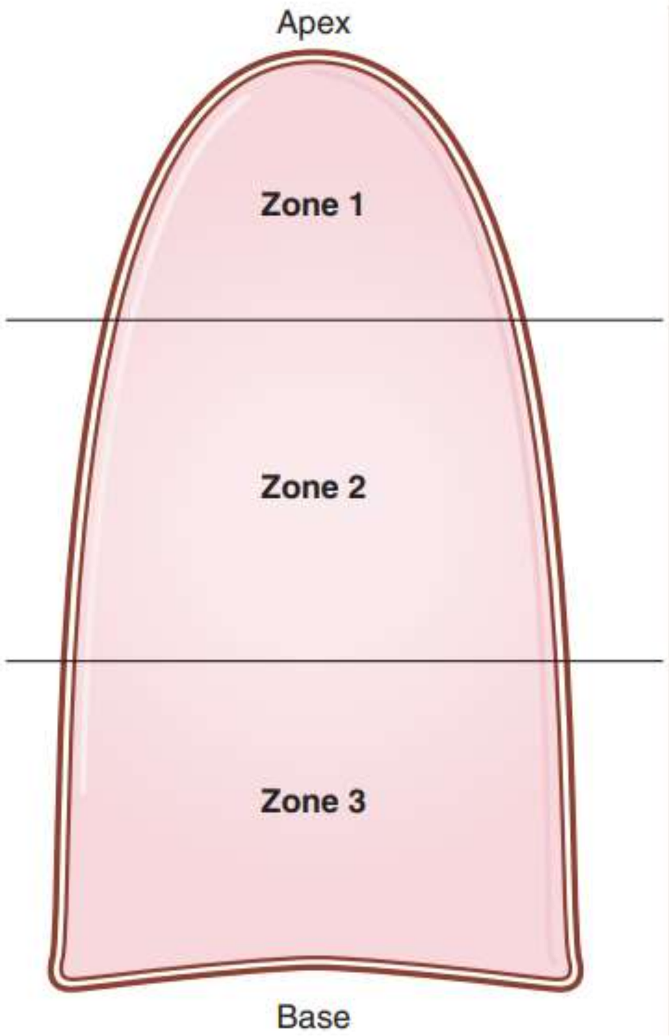
- Zone 1 has the lowest perfusion, and zone 3 the highest.

- Alveolar ventilation also varies in the same direction among the zones of the lung. Ventilation is lower in zone 1 and higher in zone 3, again due to gravitational effects in the upright lung.

- While the regional variations in ventilation and perfusion in the upright lung are in the same direction, the regional variations in ventilation are not as great as regional variations in perfusion.

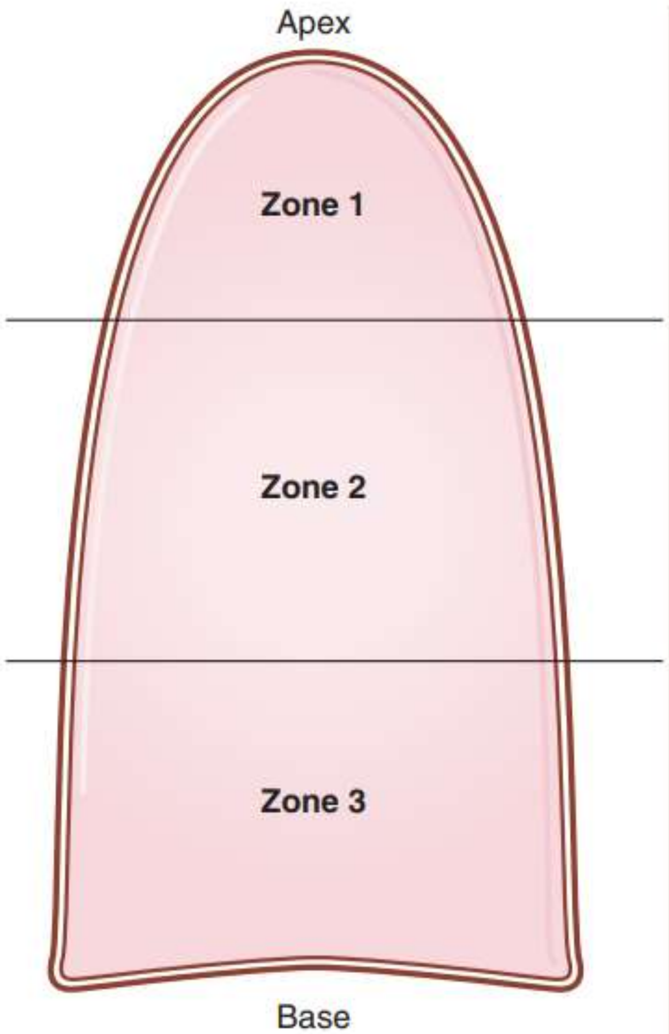
- Therefore, the $\dot{V}/\dot{Q}$ ratio is highest in zone 1 and lowest in zone 3, with the average value for the entire lung being 0.8.

$\dot{V}/\dot{Q}$ DISTRIBUTION IN THE LUNG



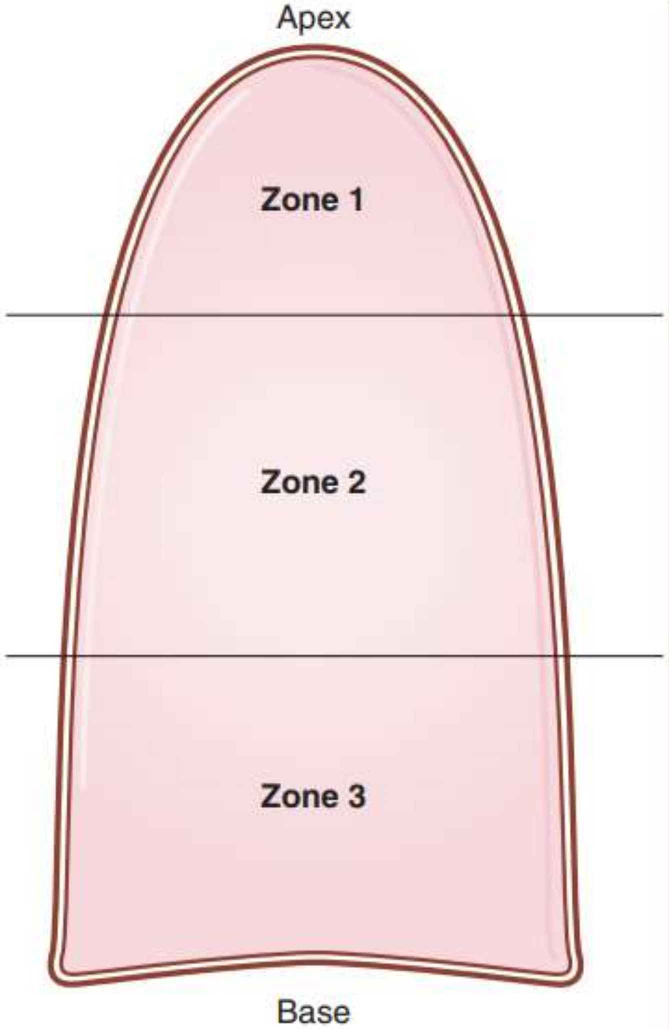
Blood Flow ($\dot{Q}$)	Alveolar Ventilation ($\dot{V}$)	$\frac{\dot{V}}{\dot{Q}}$	Pa_{O_2}	Pa_{CO_2}

$\dot{V}/\dot{Q}$ DISTRIBUTION IN THE LUNG



	Blood Flow ($\dot{Q}$)	Alveolar Ventilation ($\dot{V}$)	$\frac{\dot{V}}{\dot{Q}}$	Pa_{O_2}	Pa_{CO_2}
Zone 1	Lowest	Lower	Highest (3.0)	Highest (130 mm Hg)	Lower (28 mm Hg)
Zone 2	—	—	—	—	—
Zone 3					

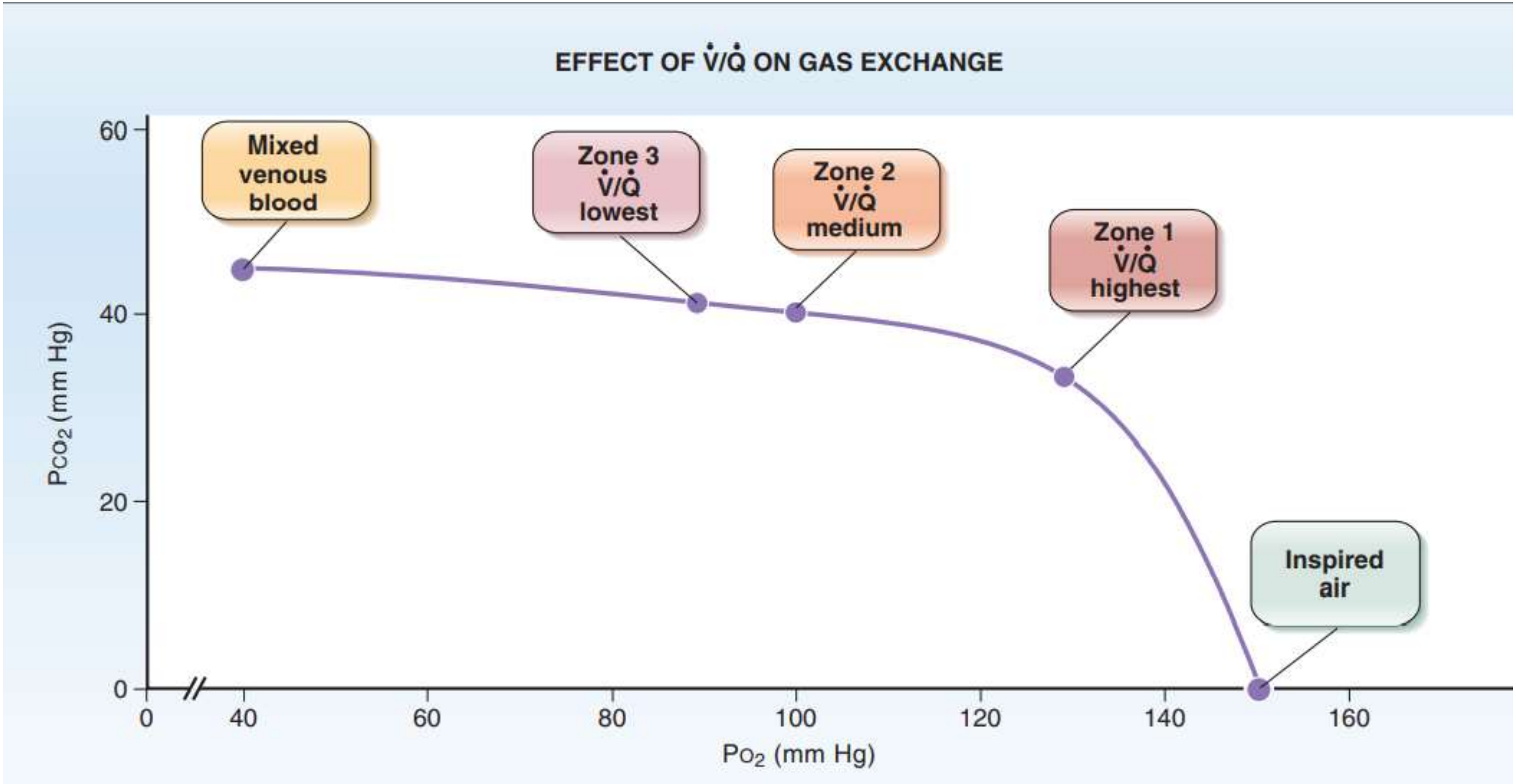
$\dot{V}/\dot{Q}$ DISTRIBUTION IN THE LUNG



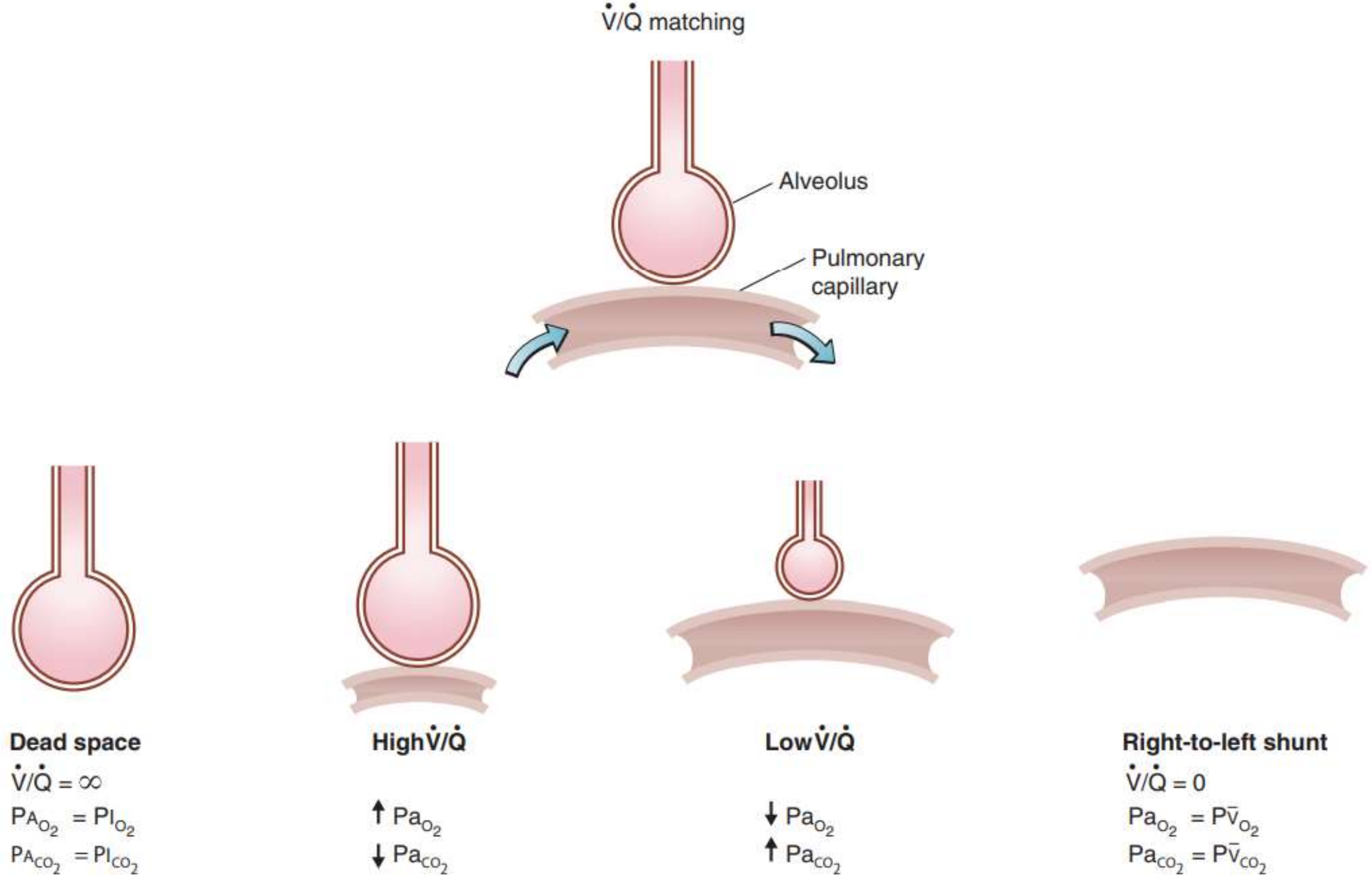
	Blood Flow ($\dot{Q}$)	Alveolar Ventilation ($\dot{V}$)	$\frac{\dot{V}}{\dot{Q}}$	Pa_{O_2}	Pa_{CO_2}
Zone 1	Lowest	Lower	Highest (3.0)	Highest (130 mm Hg)	Lower (28 mm Hg)
Zone 2	—	—	—	—	—
Zone 3	Highest	Higher	Lowest (0.6)	Lowest (89 mm Hg)	Higher (42 mm Hg)

V/Q distribution in the lung

- The O2-CO2 diagram derived from the alveolar gas equation. Notice that the regional differences in PaO2 are much greater than regional differences in PaCO2.
- In zone 1, where $\dot{V}/\dot{Q}$ is highest, PaO2 is highest and PaCO2 is lowest.
- In zone 3, where $\dot{V}/\dot{Q}$ is lowest, PaO2 is lowest and PaCO2 is highest.
- These regional differences are present in healthy lungs, and the blood leaving the lungs via the pulmonary vein (representing the sum of blood from all zones) has an average PaO2 of 100 mm Hg and an average PaCO2 of 40 mm Hg.


EFFECT OF V̇/Q̇ ON GAS EXCHANGE
Mixed venous blood
Zone 3 V̇/Q̇ lowest
Zone 2 V̇/Q̇ medium
Zone 1 V̇/Q̇ highest
Inspired air
60
40
20
0
P_{CO_2} (mm Hg)
0
40
60
80
100
120
140
160
P_{O_2} (mm Hg)

$\dot{V}/\dot{Q}$ DEFECTS



V/Q defect (mismatch)

- Dead space ($\dot{V}/\dot{Q} = \infty$).
- Dead space is ventilation of lung regions that are not perfused. This ventilation is wasted, or "dead."
- No gas exchange is possible in dead space because there is no blood flow to receive O_2 from alveolar gas or add CO_2 to alveolar gas.

V/Q defects

- Dead space is illustrated by **pulmonary embolism**, in which blood flow to a portion of the lung (or even the entire lung) is occluded.

- In regions of dead space, because no gas exchange occurs, alveolar gas has the same composition as humidified inspired air: PAO2 is 150 mm Hg and PACO2 is 0.

V/Q defects

- High V̇/Q̇ .

- Regions of high V̇/Q̇ have high ventilation relative to perfusion, usually because blood flow is decreased.

- Unlike dead space, which has no perfusion, high V̇/Q̇ regions have some blood flow.

- Because ventilation is high relative to perfusion, pulmonary capillary blood from these regions has a high PO2 and a low PCO2.

V/Q defects

- Right-to-left shunt ($\dot{V}/\dot{Q} = 0$).
- Right-to-left shunt is perfusion of lung regions that are not ventilated.
- No gas exchange is possible in regions of shunt because there is no ventilation to deliver O_2 to the blood or carry away CO_2 from the blood.
- Shunt is illustrated by airway obstruction and right-to-left cardiac shunts.
- Because no gas exchange can occur with a shunt, pulmonary capillary blood from these regions has the same composition as mixed venous blood: PaO_2 is 40 mm Hg, and $PaCO_2$ is 46 mm Hg.

V/Q defects

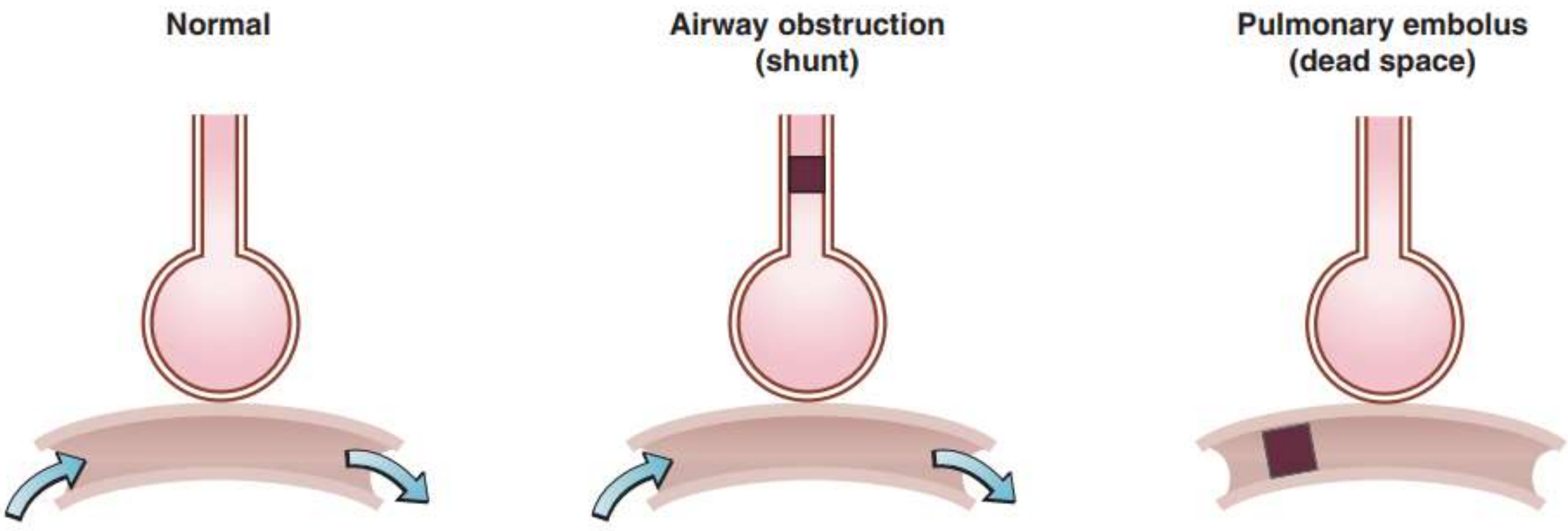
- Low V̇/Q̇ .

- Regions of low V̇/Q̇ have low ventilation relative to perfusion, usually because ventilation is decreased.

- Unlike shunt, which has no ventilation, low V̇/Q̇ regions have some ventilation.

- Because ventilation is low relative to perfusion, pulmonary capillary blood from these regions has a low PO_2 and high PCO_2.

$\dot{V}/\dot{Q}$ DEFECTS

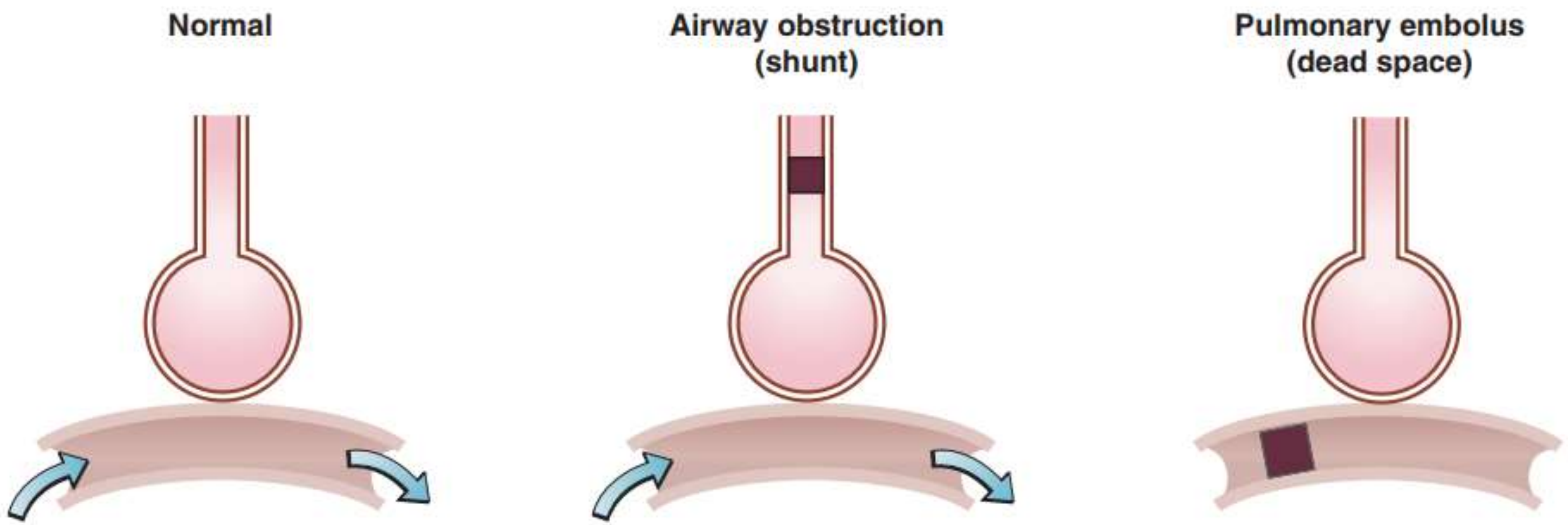


	Normal	Airway obstruction (shunt)	Pulmonary embolus (dead space)
$\dot{V}/\dot{Q}$			
P_{AO_2}			
P_{ACO_2}			
Pa_{O_2}			
Pa_{CO_2}			

$\dot{V}/\dot{Q}$ DEFECTS

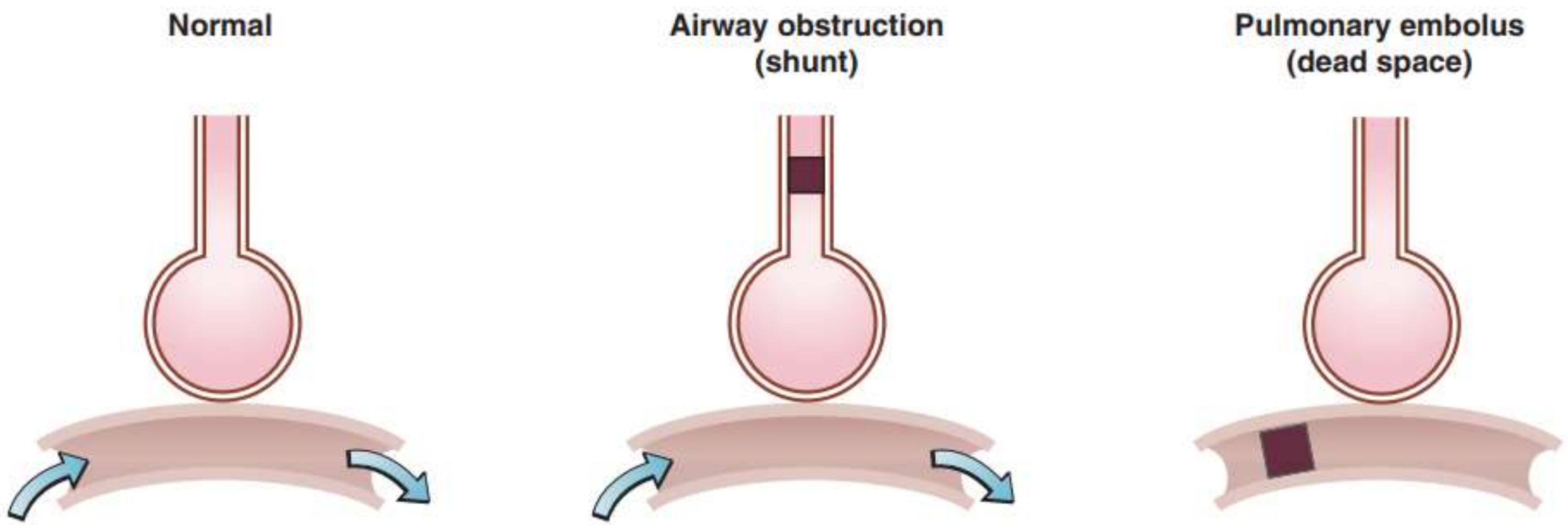
$\dot{V}/\dot{Q}$	0.8	0	∞
$P_{A_{O_2}}$			
$P_{A_{CO_2}}$			
Pa_{O_2}			
Pa_{CO_2}			

$\dot{V}/\dot{Q}$ DEFECTS



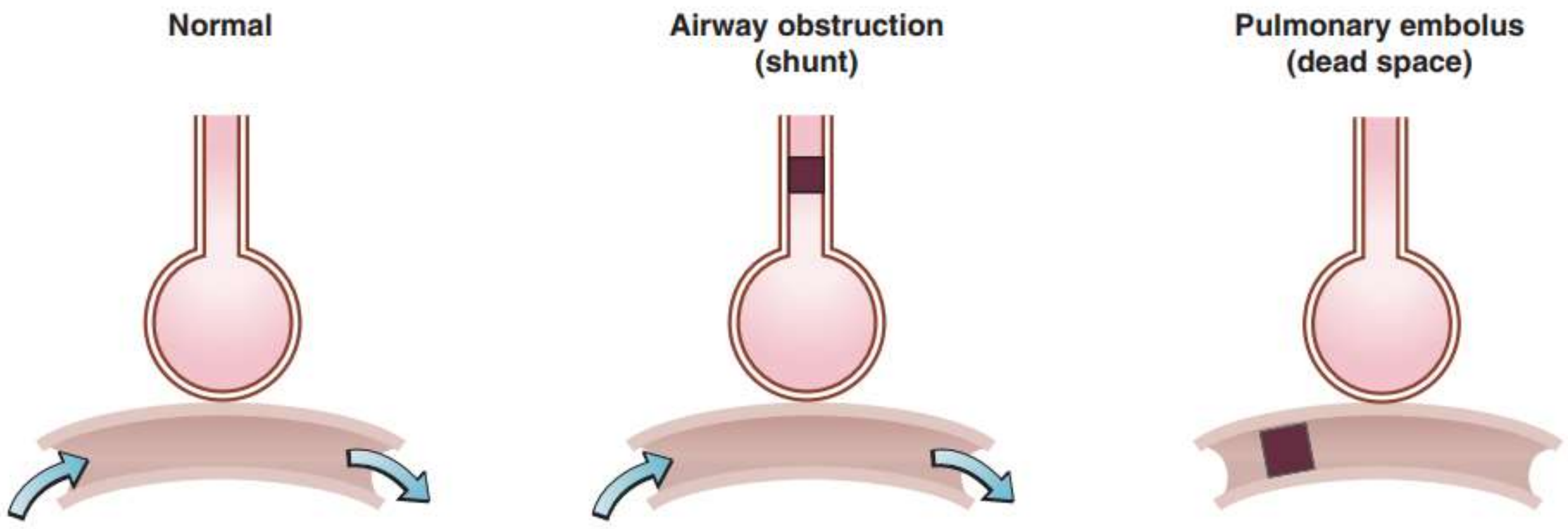
$\dot{V}/\dot{Q}$	0.8	0	∞
$P_{A_{O_2}}$	100	—	150
$P_{A_{CO_2}}$			
Pa_{O_2}			
Pa_{CO_2}			

$\dot{V}/\dot{Q}$ DEFECTS



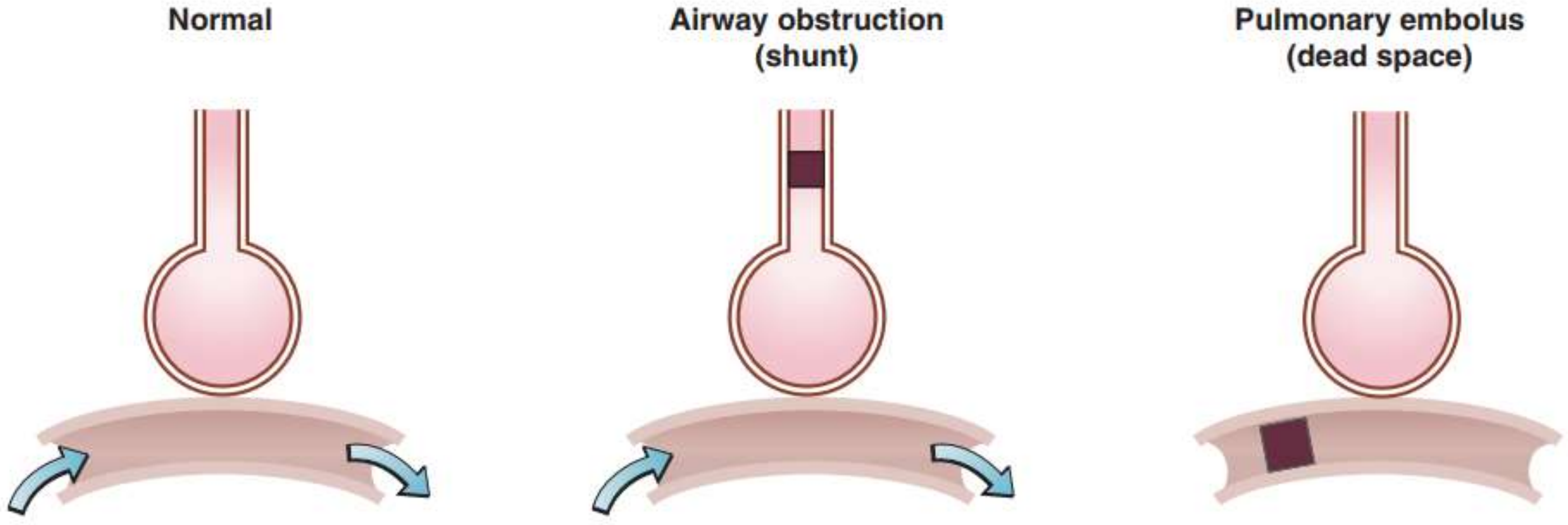
	Normal	Airway obstruction (shunt)	Pulmonary embolus (dead space)
$\dot{V}/\dot{Q}$	0.8	0	∞
P_{AO_2}	100	—	150
P_{ACO_2}	40	—	0
Pa_{O_2}			
Pa_{CO_2}			

$\dot{V}/\dot{Q}$ DEFECTS



$\dot{V}/\dot{Q}$	0.8	0	∞
$P_{A_{O_2}}$	100	—	150
$P_{A_{CO_2}}$	40	—	0
$P_{a_{O_2}}$	100	40	—
$P_{a_{CO_2}}$			

$\dot{V}/\dot{Q}$ DEFECTS



	Normal	Airway obstruction (shunt)	Pulmonary embolus (dead space)
$\dot{V}/\dot{Q}$	0.8	0	∞
P_{AO_2}	100	—	150
P_{ACO_2}	40	—	0
Pa_{O_2}	100	40	—
Pa_{CO_2}	40	46	—

Thank you