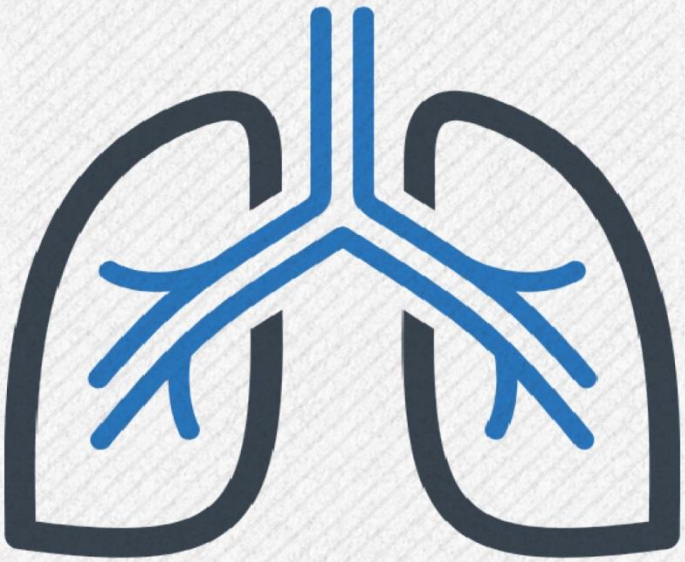

Respiratory system physiology

sheet | handout | slides

Number	7
Doctor	Yanal
Done by	Abdel-Mu’ez Siyam
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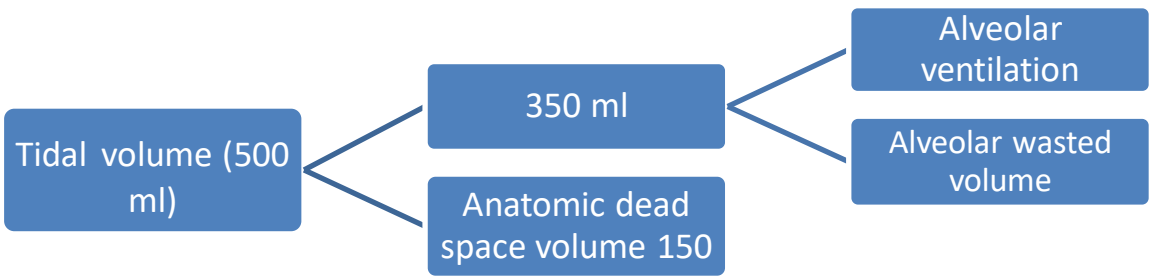
In the name of God, the Most Gracious, the Most Merciful

❖ Physiological dead space (PDS):

- Remember that the tidal volume is the volume of air that enters or leaves the lung per breath, which is normally about 0.5L. When we first take this volume, our conducting system (which includes the parts that just conduct the air, also called Anatomical dead space (ADS) –no gas exchange occur in them) already contains 150 ml, so the first 150 inspired air will push those 150 ml down then another 350 ml enter (so that the last 150 ml entering occupy the conducting system and not participate in gas exchange). So you must know that of the inspired 500 ml, 350 ml make it to downstream respiratory airways while 150 ml fill the ADS without gas exchange.

- The 350 ml which do make it to the respiratory part undergo gas exchange with pulmonary capillaries: O2 diffuses to capillaries, CO2 diffuses to alveoli. **Normally**, all the 350 ml participate in this process. Note that this process requires some conditions: air must reach the alveoli (the alveoli must be *ventilated* with air), these alveoli should be surrounded by capillaries in which blood flows, to bring blood that lacks oxygen and is full of CO2 to that site and make exchange possible (the alveoli must be *perfused* with blood).

- Imagine that some alveoli are ventilated, but something is obstructing the blood flow in the capillaries (no perfusion). In this case, no exchange occurs, because the air filled the alveoli for nothing, and this inspired air out of all the 350 ml that entered was ''wasted''; meaning that it reached the alveoli but did not undergo any exchange.



- Out of the inspired 500 ml, we can say that generally speaking, the volume of air that entered but did not undergo any gas exchange is the volume of the ADS plus the alveolar wasted volume. This volume is called the ***physiological dead space volume.*** Normally, the physiological dead space (PDS) volume is the same as ADS volume, meaning that all the 350 ml that reach the alveoli undergo exchange and nothing was wasted. All parts of the lung which are ventilated are also perfused with blood.

  → This means that the least value PDS volume can have is ADS volume **(it can't be less).**
  → so PDS volume = ADS volume + Alveolar wasted volume.
- In some pathological conditions like emphysema, in which destruction of capillaries might happen → there is ventilation but no perfusion, so the wasted volume is more than zero. Thus, PDS > ADS.

- **Value of PDS volume calculation:**

- PDS volume is always a fraction (part of) the tidal volume, and is calculated as follows:
- VD = VT x ((PaCO2 – PECO2)/PaCO2).
where

VD = Physiologic dead space (mL)
VT = Tidal volume (mL)
PaCO2 = PCO2 of arterial blood (mm Hg)
PECO2 = PCO2 of mixed expired air (mm Hg)

-Mixed Expired Air: we expire a volume of air which is equal to the tidal volume per breath (500 ml). To know the CO2 content of this air, we must divide it into 150 ml (that was filling the ADS at the end of inspiration, so this volume did not undergo any gas exchange, and no CO2 diffused to it from capillaries, so PCO2 in these equals 0), and 350 ml which are the 350 ml that reached the alveoli and underwent exchange, now those are exhaled as part of the 500 ml tidal volume; these have a PCO2 of 40 mmHg. So mixed expired air PCO2 =
((150 x 0) + (350 x 40))/500 = 28 mmHg.
-P arterial CO2 equals 40 mmHg.

So VD = 500 x (40 – 28)/40 = 150 ml

Another way that we'll talk about later is used to calculate ADS volume. From both ways, you can conclude that if PDS volume = ADS volume, then wasted volume is zero.

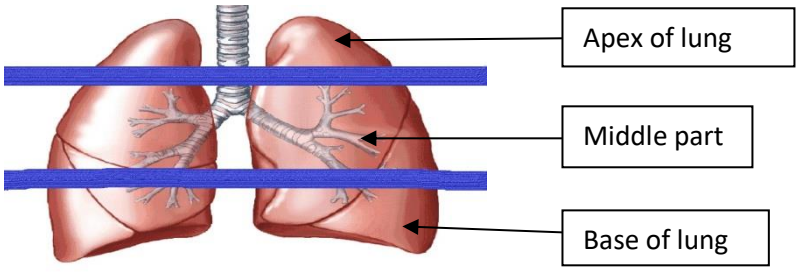
❖ **<u>Ventilation/perfusion Ratio:</u> (V/Q ratio)**

- For normal respiratory function, air must reach the alveoli (the alveoli must be *<u>ventilated</u>* with air), and these alveoli should be surrounded by capillaries in which blood flows, to bring blood that lacks oxygen and is full of CO2 to this site and make exchange possible (the alveoli must be *<u>perfused</u>* with blood). Ventilation that we are talking about is *alveolar* ventilation: remember that we said that per breath you inspire the tidal volume, and you have 12 breaths/minute, so the volume of air that moves into and out of the **lungs** per minute equals 0.5 x 12 = 6L/min. This is called as the Respiratory minute ventilation (RMV). Of these 6L, how much fresh air reaches the *alveoli* equals 0.35 x 12 = 4.2L, which is called <u>Alveolar ventilation</u>, and there also is a volume of 0.15 x 12 = 1.8L, which is the ADS ventilation. So 6L = 4.2L + 1.8L.

- In the best possible scenario, there will be adequate alveolar ventilation, adequate perfusion, and proper V/Q ratio. We don't want an area of the lung to be ventilated and not perfused (wasted ventilation), and we also don't want areas to be perfused but not ventilated (wasted perfusion).

- As an average value for the whole lung: all the alveoli receive 4.2L of fresh air/min (ventilation; V), while all of them are also perfused by a blood volume, which is equal to the cardiac output of the right ventricle (5L/min); Q. So V/Q ratio = 4.2/5 = 0.84. This value means that alveolar ventilation (L/min) is 84% of the value for pulmonary blood flow (L/min) (the capillaries around the alveoli receive X amount of blood per minute and the alveoli during that minute received 0.84X of air) and this in turn, reflects normal PO2 and PCO2 in the alveoli and capillaries, so if this ratio has a different value, these values will change as well (as we'll see in a minute).

- This V/Q ratio is an average value for the whole lung, but it's actually different between different areas within the lungs, as follows (for both lungs together):



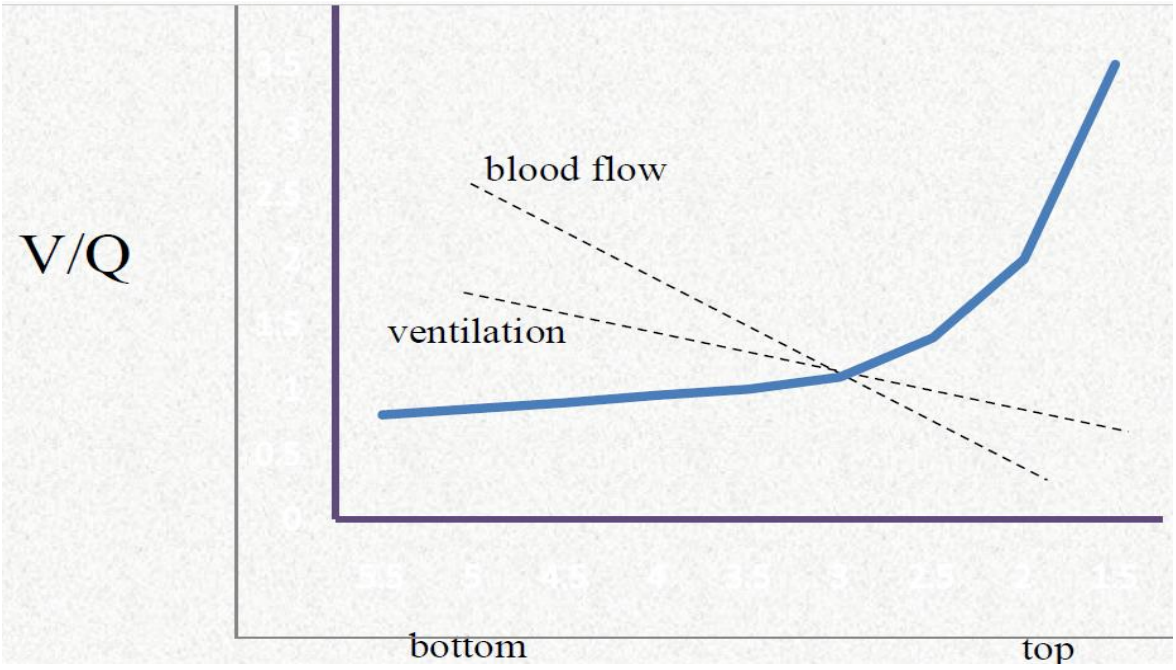
- Don't worry about numbers: In the apex of the lung, Ventilation (V) = 0.24 L/min, perfusion (Q) =0.07 L/min, so V/Q equals 0.24/0.07 = 3.6, which is higher than 0.84.

- As For the base, V= 0.82 L/min, Q = 1.32 L/min, V/Q = 0.6. (less than 0.84)

- We can say that V/Q of apex (3.6) means that the apex is much **better** ventilated, while the base (V/Q = 0.6) is much **better** perfused. Note that we said much better not much more, because as an absolute value, V base > V apex (0.82>0.24), but since the apex has less perfusion, its ventilation is more than enough (*better* ventilated for its perfusion).

- The base is much **better** perfused than the apex, because 0.6 < 3.6, and is also much **more** perfused (as absolute quantity) because 1.32 > 0.07, so the base has much blood than the apex. Note that everything we say describes a normal individual in a standing position. Much more blood is in the base due to gravitational effect (gravity pulls blood down to the base).

  top = apex, bottom = base, the blue line is V/Q.

- 

- We conclude from the figure that:

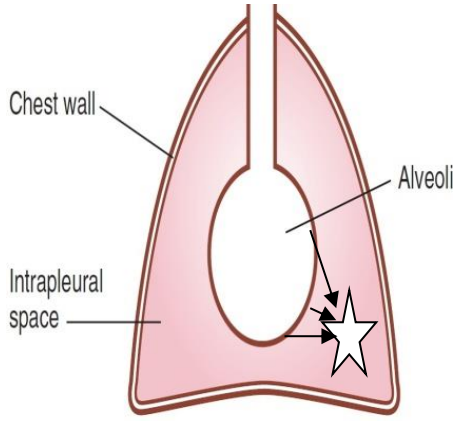
1- V base > V apex (as value, because 0.82 > 0.24)

2- Q base > Q apex (as value, because 1.32 > 0.07)

3- **V/Q ratio: apex > base**. (3.6 > 0.6)

- We said that V base > V apex, but as soon as air enters the lung, it is logical that it will go to the highermost area (apex) of the lung, but actually it goes more to the base, but WHY? (don't forget that this is in a standing person) Some may think it's due to gravity, but air is actually not that affected by gravity (it's more logical for blood because it's heavier).

- The real cause is that in a standing individual, the negative intrapleural pressure in the apex is more negative (recall: positive pressure pushes the content away, like blood pressure which pushes the blood away from the vessel it is in into the downstream vessels and into the organs. Negative pressure by contrast pulls inside (suction), so since the alveoli are surrounded by pleura from the outside of their walls, a negative intrapleural pressure will suck the alveolar wall to the outside, preventing them from collapsing).



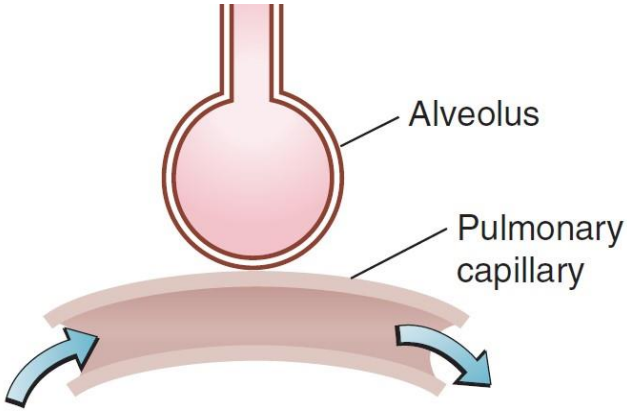
Imagine the point of the star is where the negative intrapleural pressure (it's inside the intrapleural space). Since it's negative, it will suck the alveolar wall outwards (the arrows), and more negative means more suction, meaning a bigger diameter of the alveolus. In the apex, this pressure is -8 (so more suction) while in the base is -2 (less suction). The -8 makes the apical alveoli more ventilated (at rest, before taking the tidal volume, the volume in the lung is distributed so that larger alveoli contain more air so we say more ventilated) while the -2 makes basal alveoli less ventilated (because these are smaller, they contain less air before inspiring air (VT), the air here is from the FRC).

Recall from the compliance curve: it is easy to inflate a partially inflated alveolus (highest compliance), while it's hard to inflate either a collapsed alveolus (like RDS) or a totally inflated alveolus. Because before taking the tidal volume apical alveoli have more air (thus more inflated) than basal alveoli (which are less inflated because they contain less air because their diameter is smaller), now when tidal volume is taken; it is much easier to inflate basal alveoli relative to apical ones, because the compliance of basal alveoli (partially inflated) is higher than the compliance in apical

alveoli (already inflated →cannot bear more air). So when air enters, it is easier for it to fill basal alveoli than to fill the stiff/rigid apical ones.

In summary, ventilation of the base > ventilation of the apex because the alveoli in the apex are already inflated, because the negative IPP around them is higher so when air enters, it will not fill them (thus less fresh air goes to the apex → less V).

- For perfusion, base > apex because of the gravitational effect. If we take the length of the lung as 30 cm (300 mm), and calculate the pressure at the apex and at the base, we'll find that it is much easier for blood to go to the base.



Significance of the V/Q ratio:

The capillary's PO2 = 40 mmHg before the exchange. What about PO2 in the alveolus? To answer this question, assume that the capillary flow is blocked (so no diffusion will occur) + Recall that the outside air PO2 = 160 mmHg. The PO2 in the conducting airways = 150 mmHg. We said previously that PO2 in the alveolus is 100 mmHg, but how did 150 get decreased to 100? By the diffusion of oxygen into the flowing blood of capillaries, so if the capillary flow is blocked → no deoxygenated blood comes → no diffusion of oxygen to that blood → PO2 will not decrease (so PO2 in the alveoli = PO2 in ADS = 150 mmHg because nothing took any oxygen from it). If the blocked capillary opened a little bit, some blood comes, some diffusion occurs, PO2 in alveoli decreases (130 mmHg). If more blood flow, more diffusion, more decrease in alveolar PO2 (120 mmHg). If blood flow is returned to normal, alveolar PO2 = 100 mmHg.

**The question is: in apical alveoli, will alveolar PO2 be more than 100 or will it be less?

➔ It will be more, because they are well ventilated, but less perfused (because V/Q ratio is higher than 0.84), higher ventilated than perfused.

➔ Since PO2 in apical alveoli is more than 100 mmHg, then blood derived from the apex that will go to the left atrium will have PO2 that is more than 100

(the diffusion equilibrium will be at a value more than 100 – for example 130).

- Now for PCO2: before diffusion, capillary PCO2 = 45 mmHg. The alveolar CO2 is derived from capillary diffusion but in the opposite way of oxygen, so if block blood → PCO2 in alveoli = zero, if increase perfusion→increase diffusion of CO2 **into** the alveoli and PCO2 increases. This also means that hyperventilation (relative to perfusion) will diminish the effect of alveolar CO2 and decrease PCO2 in the alveoli.

➔ ***Very important***: The purpose of hyperventilation is to make the composition of alveolar air closer to outside air, so hyperventilated areas have higher PO2 and lower PCO2.

Apical alveolar PCO2 is **less** than 40 mmHg (↑V).

- As for the base (V/Q is less than 0.8). In order to understand we will do the exact opposite: let us block the airways, so that no air enters to the alveoli and that V/Q = zero (because v = zero). What will happen when blood flows in the capillaries? Now, PO2 capillary = 40 mmHg, and PO2 alveolar is very low (only FRC, nothing entered), so oxygen will diffuse from the capillary to the alveoli (OPPOSITE) until PO2 alveolar = 40 mmHg (like blood). PCO2 alveolar will also rise to 45 mmHg (due to diffusion of CO2 from the capillaries to the alveoli).

Now that we've taken the extreme case (V/Q = zero) we saw that PO2 is markedly decreased and PCO2 is increased. So in general, when V/Q is less than 0.8 → PO2 is decreased (< 100 mmHg) and PCO2 is increased.

Let us say that of the base, PO2 = 90 mmHg. So the blood derived from the base will also have PO2 of 90 mmHg. This blood and the blood derived from the apex (PO2 = 130 mmHg) will eventually be mixed in the left atrium. So what is the PO2 in this mixture?
It is wrong to say (130 + 90)/2, because perfusion of the base is higher than the apex, thus the volume of blood that is going to the left atrium from the base is higher than the volume coming from the apex, thus the PO2 value will be closer to the 90 not the 130. If you know that blood is distributed as : (base : apex ratio equals 3 : 1) meaning that ¾ of blood going to the left atrium is derived from basal blood, while ¼ is derived from apical blood, then:
PO2 = ((1x130) + (3x90)) /4 = 100 mmHg…….(Theoretically true, but actually it is around 95 mmHg, why is there this 5 mmHg difference? You're gonna have to

wait till next lecture to get the whole picture).

- To make things more puzzling: expired air has a PO2 of 100 mmHg. If you know that ¾ parts of this air were expired by the base, while ¼ were expired by the apex, we would calculate mixed expired air PO2 as:
  ((3 x 90) + (1 x 130))/4 = 100 mmHg…….which is TRUE. (PO2 expired really equals 100 mmHg). So in terms of air, the hyper ventilated area (apex) managed to compensate over the hypoventilated area (base), and maths worked. But in terms of blood, the apex couldn't compensate for the base, and PO2 was less than 100 mmHg (if direct math → not logical).

- Implications:

1- Aerobic bacteria like TB bacilli prefer the apical regions of the lung (because they have too much O2; because the apex is more ventilated than perfused, V/Q ratio is high, 130 > 90). So on chest X-rays, if you see a shadow in the apex of the lung, you'll have to rule out TB first. While a shadow in the base → rule out cancer first.

2- At the beginning of the lecture (PDS), we put an example of an alveolus ventilated but not perfused, Q= zero and when you divide by zero you approximate to infinity, so in that example, V/Q = ∞

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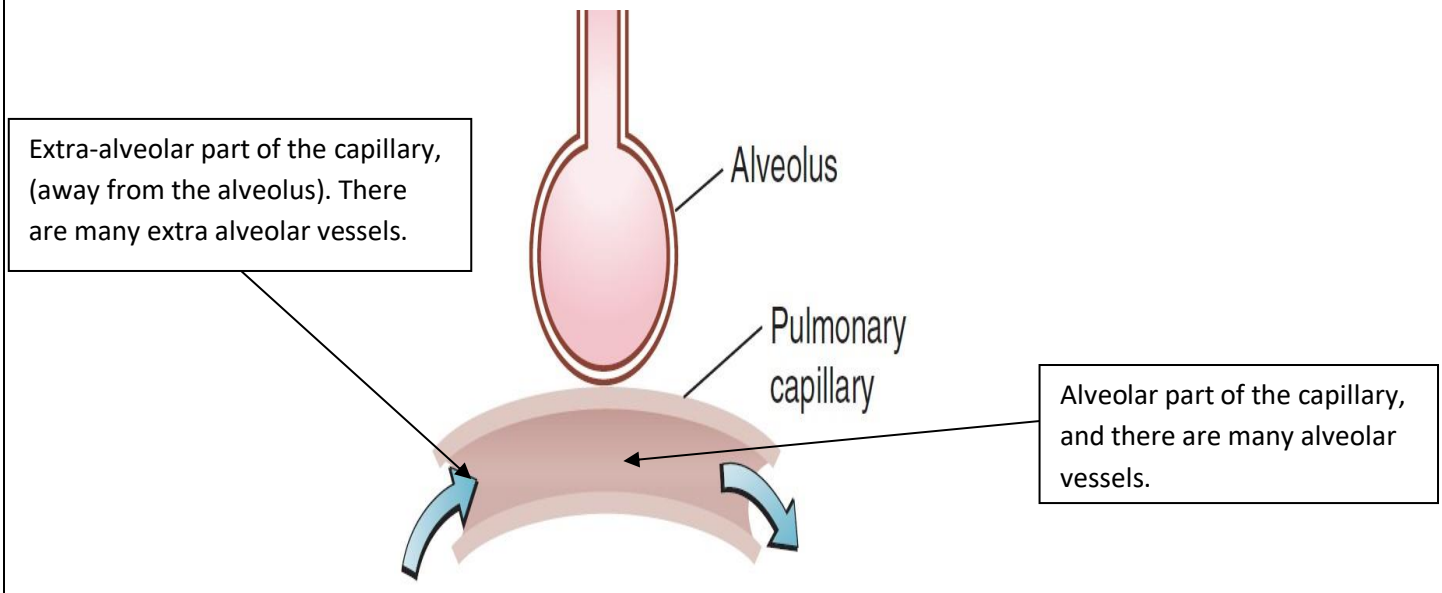
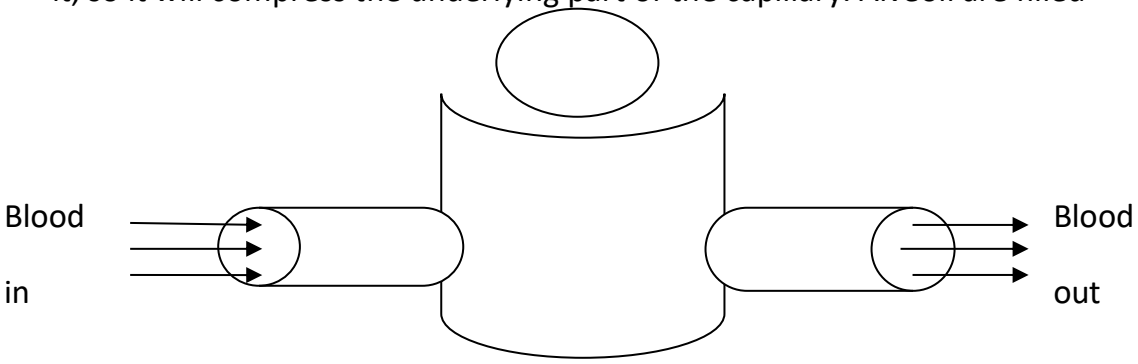
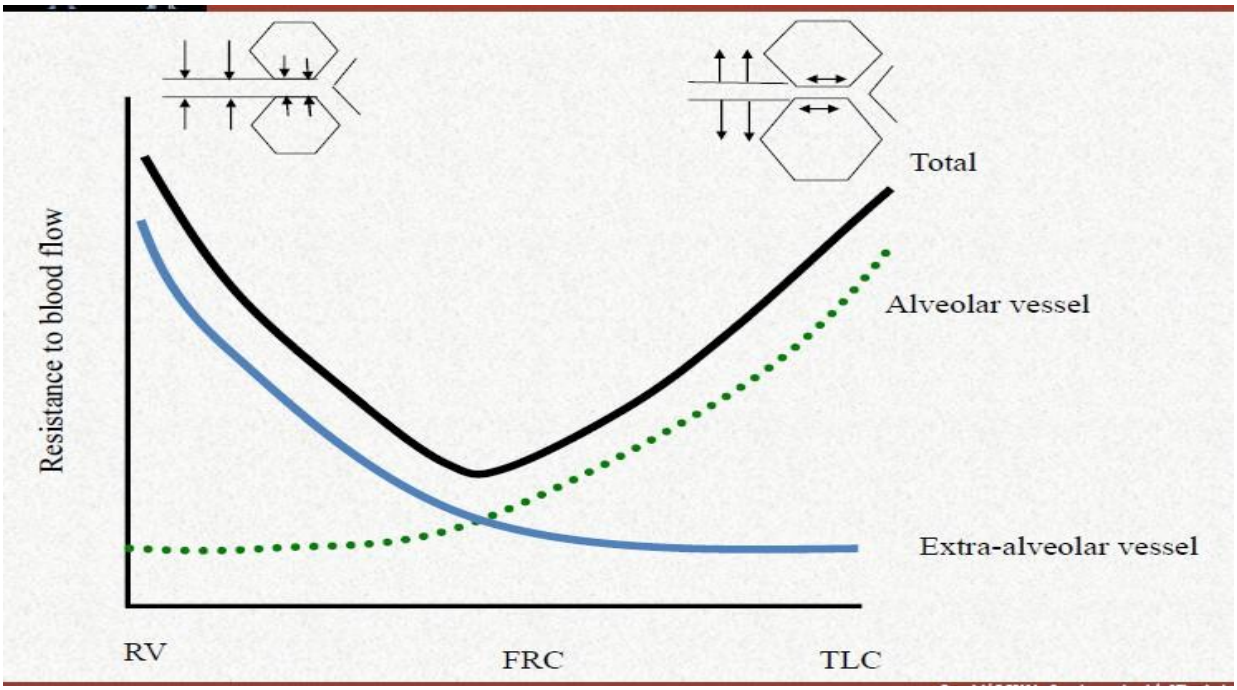


** The below figure shows an alveolus (oval), and a capillary beneath it. When the alveolus is full of air (volume = TLC), this means that there is too much air in it, so it will compress the underlying part of the capillary. Alveoli are filled



to the maximum when the intrapleural pressure is too negative, which caused the alveolus to expand and fill with TLC, thus compressing the underlying part (alveolar part of the capillary) and increasing the resistance to blood flow there. In contrast, extra alveolar parts are affected by the suction of the very negative intrapleural pressure, and are sucked outward (so inc. diameter)→ decrease vascular resistance in extra alveolar vessels.

- When volume in the alveolus equals RV→ less volume fills the alveolus → less compression against the alveolar part of the vessel → resistance to blood flow decrease. But don't forget that at that level, the intrapleural pressure might actually be positive, pushing the walls of the vessel inward (specifically the extra alveolar vessel) and increasing its resistance to blood flow there.



Note from the figure that:

1- Increasing volume of air increases resistance of alveolar vessels.
2- Increasing volume of air decreases resistance of extra-alveolar vessels
3- At any point, total resistance to blood flow = resistance in alveolar vessel + resistance in extra-alveolar vessels.
4- FRC is very important because at FRC, the resistance to blood flow is minimal.

→If pulmonary fibrosis, then FRC is less. At this new value, the extra-alveolar resistance is high (higher than at normal FRC), and alveolar resistance is low, but the total is higher than normal.

→If emphysema, FRC increases. At this new value, the extra-alveolar resistance is less (lower than at normal FRC), and alveolar resistance is high, but the total is higher than normal.

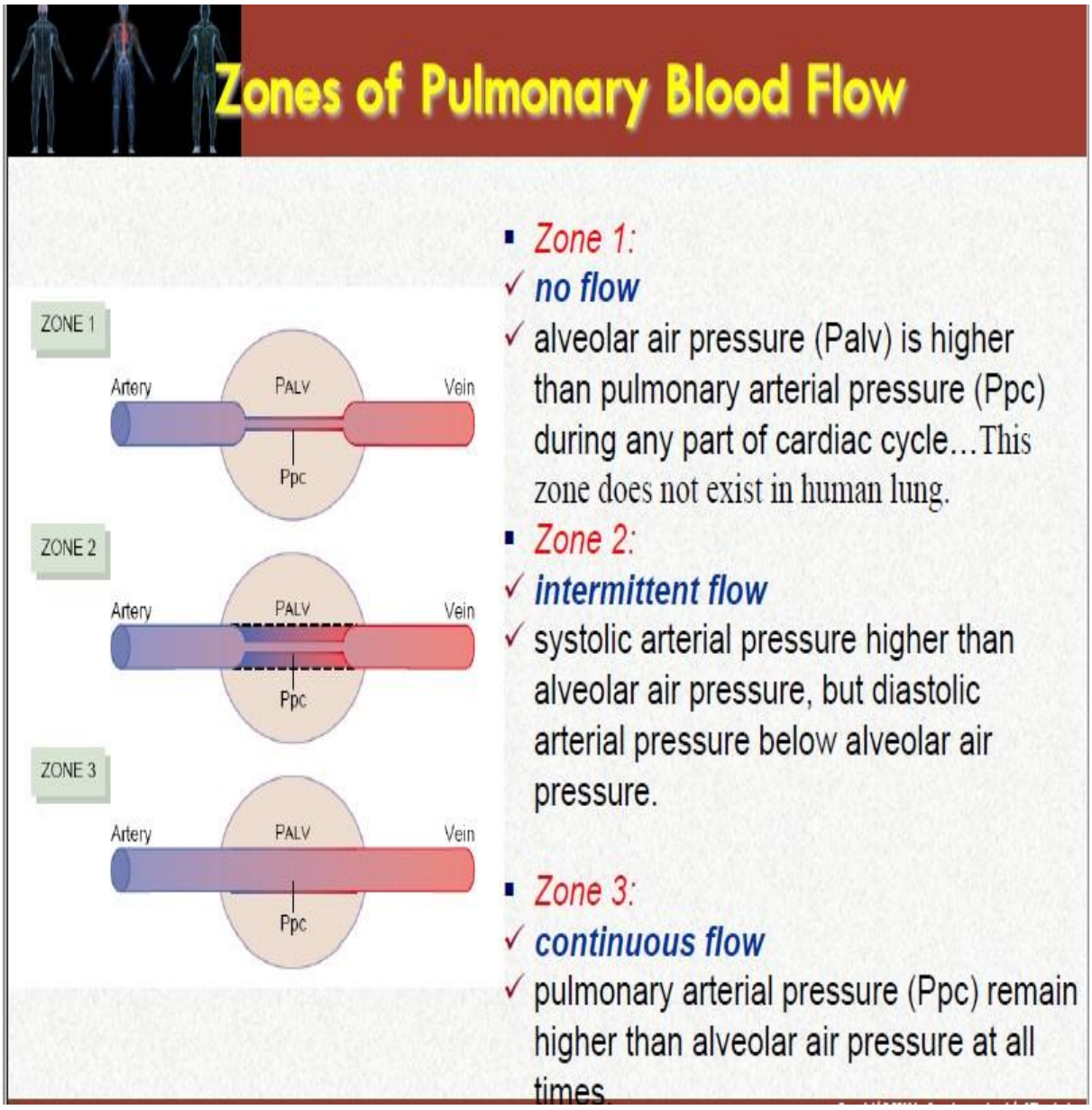
- Capillary blood flow is described as intermittent (increases and decreases only due to relaxation or contraction of the precapillary sphincter, respectively). It is not pulsatile (increases and decreases in regular intervals due to systole and diastole of the heart) nor continuous (there is always flow). This is true in many tissues, but in the lung it is **pulsatile** (because the distance between the lungs and the right ventricle is not long, so the pulsating pressure does not disappear when it travels). This means that pulmonary capillary flow increases during systole and decreases during diastole.

- If the alveolar pressure is higher than the systolic pressure in the capillary → even the highest pressure in the capillary cannot repel the compressing force of the alveolus over the capillary, so the alveolus does compress the capillary, obstructing flow → **No blood flow.**
  If the perfusion status of an area of the lung is like this, we call it zone 1.
  Zone 1: P alveolar > P systolic > P diastolic……. No flow of blood

- Zone 2 : the alveolar pressure is higher than the diastolic pressure of the capillary but less than the systolic. This means that during systole→ the capillary cannot be compressed by the alveolus → there is flow.
  In diastole, the alveolus compresses the capillary → no flow
  so the perfusion status is **intermittent**.

- Zone 3: P systolic > P diastolic > P alveolar
  even when the capillary is at its lowest pressure value, it is enough to prevent the compression by the alveolus → flow is **continuous**.

- In a standing individual with a normal lung, only zones 2 and 3 exist. Zone 1 areas do not exist. Zone 1 only develops if there is bleeding to the extent that systolic capillary blood pressure is less than alveolar pressure in the apical region of the lung. During exercise, all the lung converts to zone 3 (blood flow is continuous at all times).



☺ ***Sorry for the long sheet- Best of luck***