Human Physiology
Dr. Sudip Mukherjee
School of Biomedical Engineering
IIT(BHU), Varanasi
Week - 04
Lecture - 03

Hello everyone, welcome to another new class in human physiology. This week, we are discussing the respiration process. We also saw how the lung anatomy is, and how respiration and expiration happen in our body. In this class, we will mostly discuss it as a mathematical class. And also, we will discuss different types of lung capacities. So, we will try to solve some problems related to lung capacity and lung volume.

So, let us stick with it. So, what different content will be covered? Basically, we will see a basic overview of grass transport, and then we will discuss different lung volume capacities. We will have a few problems related to lung volume capacity; then we will discuss different lung volumes, and we will also try to solve different types of problems related to lung volume. So, as we know, gas transport in the lungs involves the diffusion of oxygen into the bloodstream, and eventually, after the cellular respiration process, the carbon dioxide produced by the cells gets dissolved back into the blood, and the blood carries the carbon dioxide back to the lungs for the expiration process.

So, this is like the overall process of gas transport, and in the last class, we already discussed in thorough detail what different factors are responsible for increasing and decreasing the various types of these processes. So let us start with the first problem. Can we calculate the total amount of oxygen present in the human body that is attached to hemoglobin? So, what do we have to kind of calculate here? So, we have to calculate that; let us consider we have a certain amount of hemoglobin present in our body. So, how much is the total amount of oxygen present in an attached condition with hemoglobin? So, there are certain factors to consider that our average volume of blood is about 5 liters. Then that means, like the normal hemoglobin concentration that we have to also consider, is 150 grams per liter.

So, basically, around 15 grams per 100 ml is the hemoglobin concentration. So, per liter, it becomes 150 grams per liter. And also there is this one constant, which is called the Hafner constant, which is basically the amount of oxygen that is attached to 1 gram of hemoglobin, and with 1 gram of hemoglobin, about 1.34 ml of oxygen can attach. So, this is called Hafner's constant.

So, we basically consider like three situations of three factors. The first one is we have 5 liters of blood, the second one is that the Hb concentration of hemoglobin per liter is about 150 grams, and the third one is the known factor, Hafner's constant, which states that for each gram of hemoglobin, about 1.34 milliliters of oxygen can attach during full saturation. Now, we have to calculate the total amount of oxygen present in a bound condition with hemoglobin. So, to solve that, first we have to calculate how much total hemoglobin is present in our body.

So, we already took a condition that we have 5 liters of blood and the hemoglobin concentration was 150 grams per liter. So, if you multiply both, what will happen is we will get about 750 grams of hemoglobin, which is present in 5 liters of blood. And now, the Hafner's constant is said to be that for each ml of hemoglobin, what do we have? For each gram of hemoglobin, we have 1.34 ml of oxygen that can get attached. So, how much of the total hemoglobin can we calculate? We calculated that we have a total of 750 grams of hemoglobin for 5 liters of blood, right? So, if you multiply the total amount of hemoglobin that is present in our body, which is 750 grams, with Hafner's constant, which states that in the case of full saturation, 1 gram of hemoglobin can bind with 1.

34 ml of oxygen. The total oxygen comes to around 1.005 liters or 1005 ml of oxygen. So, basically, an average human body carries about 1 liter of oxygen at a given time, which is attached to hemoglobin. So, one more thing I should tell you is the total amount of oxygen that is basically dissolved or getting attached in our body.

So, if I consider that we have a total of 100 percent of oxygen, which is being transported, out of which 97 percent of oxygen is basically transported via hemoglobin attachment and 3 percent of oxygen is basically transferred in dissolved form. So, what we calculated over here is the total oxygen that is carried via hemoglobin in the attached form. So, this is very important to know, and under regular conditions, how much? Almost 1 liter of oxygen can be transported via its attachment to hemoglobin. Now, we will discuss lung volume capacities. These are like different parameters and factors, or they measure the capacity of the lung.

So, the first one, which is like the total lung capacity, basically refers to the maximum volume of air it can hold after a maximum inspiration. So, if we take a full inspiration, maximum inspiration, and measure how much total air it can hold, it is called TLC. So, basically, what we said is that the maximum volume of air the lungs can hold after a full inspiration, which is approximately around 6 liters, is called TLC or total lung capacity. Then the next one is the vital capacity, or VC, which is basically the maximum volume of air that can be exhaled after a maximum inhalation. So, we can inhale a maximum volume of how much? Around 6 liters for a healthy adult, and what is the maximum exhalation we can do? around 4.

5 liters. So, an amount of about 1 to 1.5 liters is always present that we cannot expel even with a full or maximum exhalation strategy. Then the next one is the functional residual capacity, which is the FRC. This is the air volume that remains in the lungs after normal exhalation. So, if it is a forceful and maximum exhalation, then how much volume is left? It was about 1.

5 liters, right? But the FRC is like if we can do a forceful exhalation, or FRC is basically if we do a normal exhalation, then about 3 liters of air can still be present after a normal exhalation, which is called functional residual capacity or FRC. The next one is that the inspiratory capacity, or IC, is the maximum volume of air that can be inhaled after a normal exhalation. So, if we do a normal exhalation after that, the maximum volume of air we can consume, which is about 3.5 liters, is called IC. So, we have to let ourselves, like all these four factors, try to understand one more time.

So, basically, if we think about our lungs and the total lung capacity, it is 6 liters. So, at most with forceful and maximum inhalation, we can take 6 liters; this is by inhalation. The maximum inhalation for the TLC is 6 liters, so it is the intake. Exhalation, like when we perform maximum exhalation, how much can we actually exhale? About 4.

5 liters. This is a maximum, like a forceful exhalation. But if we do a normal exhalation, then we can exhale roughly about 3 liters. So, basically, 3 liters out of this 6 liters a normal exhalation can remove, leaving another 3 liters of air in the airways or in the lungs. So, basically, this is the FRC, which occurs after normal exhalation. So, after a normal exhalation, which is about 3 liters in volume, the remaining volume, which is left over, is called FRC.

And what is the inspiratory capacity? So, basically, if we do a normal exhalation, that means about 3 liters if we exhale, and it can also be up to 3 to 3.5 liters. After a normal exhalation, we still have some amount left, right? So, we still have about 2.5 to 3 liters of air left in our lungs. So, that means the total capacity is about 6 liters, out of which about 2.

5 to 3 liters are already present. So, the next inhalation we can only take up to 3 to 3.5 liters of inhaling gas, which is called inspiratory capacity or IC. So, hopefully, you understood the different capacity. Please go further through the textbook and web content.

If you have any further questions, please discuss them with us during the live session. Then let us discuss different lung volumes. So, basically, the first one is a tidal volume. The volume of air inhaled or exhaled during normal quiet breathing is approximately 500 ml; this is called tidal volume. Then the next one is the inspiratory reserve volume, which is the additional air volume that can be inhaled forcefully after a normal breath.

So, you remember that we said in the last slide how much normal breathing we can do after a normal exhalation; it is about 3 to 3.5 liters, and the total capacity is about 6 to 6.5 liters. So, the inspiratory reserve volume is the additional air. Furthermore, we can inhale forcefully after a normal breath, which is about 3 liters in the case of males.

What is expiratory reserve volume, which is the additional air volume that can be exhaled forcefully after a normal breath, is about 1.5 liters? So, you remember that we said that a maximum exhalation can remove how much? Total 4.5 liter. And so, if you remember, we said that the maximum exhalation was about 4.5 liters and the normal exhalation was about 3.

5 liters, right? So, this if we subtract this about 1.5 liter that we can further exhale even after a normal exhalation, right. 1.5 liters of air can be forcefully exhaled even after normal exhalation; this volume is called expiratory reserve volume. And then the last one is the residual volume, which is after the maximum exhalation, which totals about 4.

5 liters, indicating how much gas is still left in the lungs, approximately 1.2 to 1.5 liters. Why? Because our total capacity is around 6 liters, out of which, with the maximum exhalation, we can remove basically around 4.

5 to roughly 4.8 liters of gas. So, that means we are still left with around 1.2 to 1.5 liters. That is called residual value, and this residual value volume basically always stays inside our lungs, so a little bit of air needs to be present in the lungs to maintain the surface tension of the lungs so that they do not fall apart and the alveoli cells do not get collapsed. So, let us try to derive the second question.

So, let us consider a person's inspiratory volume, or IRV, which is 3 liters; their tidal volume, or TV, is 500 ml; and the expiratory reserve volume, or ERV, which is 1.1 liters or 1100 ml. So, what is their vital capacity or VC? So, vital capacity if you remember go back. So, what was the vital capacity that we discussed? Vital capacity is the maximum volume of air that can be exhaled after a maximum inhalation. And we discussed that it is generally about 4.

5 liters for a healthy adult. And in the case of VC, the mathematical formula for VC is IRV plus TV plus ERV. So, basically, vital capacity equals inspiratory reserve volume plus tidal volume plus expiratory reserve volume. So, if you sum all three, how much is it coming to? It is coming

to about 4600 ml or around 4.6 liters of air. So, this is the vital capacity, which is the maximum volume of air that can be exhaled after a maximal inhalation.

So, how much is the total maximum inhalation it can be? It can be around 4.5 liters, and maximum exhalation can also be around 4.5 liters, while the total lung capacity, or TLC, is about 6 liters, out of which 4.5 liters can be consumed by inhalation, and there is always about 1.

2 to 1.5 liters of residual volume that remains. So, here in this maximum inhalation, we can basically consume about 4.5 liters; the total lung capacity is about 6 liters, but maximum inhalation and maximum exhalation are close to the same; both are around 4.

5 to 4.6 liters. Then next we will discuss the oxygen content, or it is the arterial oxygen content. It can be arterial or venous oxygen content as well, but basically, oxygen content can be derived from bound oxygen and dissolved oxygen. As you remember, we said that about 97 percent of bound oxygen is with the hemoglobin, and about 3 percent of oxygen generally stays in a dissolved form. So, in the case of arterial oxygen content, it is like bound oxygen plus dissolved oxygen, and the bound oxygen can be derived from 1.

31, which is basically Hafner's constant. You remember we said that it is the amount of oxygen that is attached to it per gram of hemoglobin at full saturation. Then Hb is like the amount of hemoglobin present in basically grams per deciliter of blood. SaO2 is the arterial hemoglobin saturation in percentages. So, 1.31 into Hb into the SaO2, which is the arterial hemoglobin saturation in percent, into 0.

01. So, if you derive this part 1.31 into Hb and multiply by SaO2 by 0.01, it will give you the bound oxygen amount, and for the dissolved oxygen amount, it is 0.0225 times PaO2. 0.0225, which is the solubility coefficient of oxygen at body temperature, and PaO2, which is the partial pressure of oxygen in arterial blood, are measured in kilopascals.

So, if you derive all this considering that we basically have about 15 grams of hemoglobin per 100 ml, if you remember. And if you consider inserting the average figures for a normal adult, these are the things right. So, at sea level, the FiO2 is about 0.

021, and 1 atmosphere is about 101.325 kilopascals. And then the SaO2 value is, let's consider, about 100 percent hemoglobin, which you already said is like 15 grams per 100 ml of blood, and the PaO2, which is the partial pressure of oxygen in arterial blood, is about 13.3 kilopascals. So, if you kind of put all the values together and calculate the arterial oxygen content, it comes out to about 19.95 ml of oxygen in 100 ml of blood. So, this is basically like a total given at a time, which is both bound oxygen plus dissolved oxygen.

Next is the global daily oxygen delivery, or DO2, which is basically how you will calculate the DO2. So, oxygen delivery, or global oxygen delivery, which is the DO2, is equal to cardiac output (CO) multiplied by the arterial oxygen content. So, in the last slide, we already discussed what the amount of CaO2 or the arterial oxygen content is; it is about 19.

95, right? 19.95 ml of oxygen per 100 ml of blood. So, this is the one we discussed in the last slide, which is the CaO2 or the arterial oxygen content. Now, if you multiply it by the cardiac output, right? So, basically, in the case of cardiac output, the CO is about 5 liters per minute. So, you multiply 5 liters per minute by basically like.

So, in cases of 100 ml, if it is 19.95 ml per O2. So, if you calculate for 1 liter, it will come out to 199.5 ml O2. So, now you multiply 5 liters per minute by 199.5 ml of O2 by liters.

So, what we will get into is like this: 997.5 ml per minute. So, this is called the oxygen delivery or the DO2. So, one more time, oxygen delivery, or the global oxygen delivery, which is DO2, is cardiac output multiplied by arterial oxygen content. So, regarding arterial oxygen content, we discussed how much it came to around 19.95 ml of oxygen per 100 ml of blood.

So, if we convert it to per liter, it comes to about 199.5 ml of oxygen per liter of blood, and then the cardiac output, which means how much blood our heart is basically circulating per minute, is about 5 liters. So, in terms of the whole thing, if you multiply 5 liters per minute by 199.5 ml O2 per 1 liter of blood, it gives us about 997.

5 ml per minute. which is called the global oxygen delivery. Okay, this is in case of an adult male. So, let us address this question. So, let us think that a patient has the following measurement. The cardiac output is 5 liters per minute. Hemoglobin: how much is 15 grams per deciliter or 15 grams per 100 ml? The arterial oxygen saturation, SAO2, is 98%.

And the partial pressure of arterial oxygen, PaO2, is like 100 millimeters of Hg. Now, what do we have to calculate? We have to calculate DO2, or the global oxygen delivery. So, remember the formula: DO2 was the CO, the cardiac output multiplied; this was the whole thing, which was the arterial oxygen content, right? So, the DO2, or global oxygen delivery, was the cardiac output multiplied by the oxygen content, and two slides before, we already discussed how to derive the arterial oxygen content. Arterial oxygen content is 1.31, which is Hafner's constant, multiplied by hemoglobin, total hemoglobin, and SaO2, multiplied by 0.

01, plus 0.0225, which is the solubility coefficient, multiplied by PaO2, or the partial pressure. So, we have all the values and the constant; let us see how much, and you also remember this was called bound oxygen, right? So, this was called bound oxygen and this was called dissolved oxygen. So, let us see how much the oxygen delivery affects the global oxygen delivery. So, first you have to calculate how much oxygen is bound to hemoglobin.

So, 1.31, which is Hafner's constant, and 15 grams per deciliter, which is the hemoglobin per 100 ml of blood, and we also discussed how much the arterial saturation is, which is like the SAO2 value, about 95%. So, 98 multiplied by 0.01 gives us this value, which is 19.257 ml of oxygen per 100 ml of blood. In the same way, let us calculate how much total dissolved oxygen is present.

So, this is the solubility coefficient, which is 0.0225 multiplied by 100. 100 is the PaO2 value, the partial pressure of oxygen; we already provided this value as 100 millimeters of mercury. So, 0.0225 multiplied by 100 gives us approximately 2.25 ml of oxygen per 100 ml of blood.

Now, we have to sum it up correctly because this is the CaO2. So, the sum of both components, which is the arterial oxygen present at a given time, includes both bound oxygen, which amounts to 19.257 ml oxygen per 100 ml of blood, and dissolved oxygen, which amounts to 2.25 ml oxygen per 100 ml of blood.

If we total it, we will get 21.507 ml of oxygen per 100 ml of blood. Now, if we convert it to per liter, how much will it be? It will be 215.07 ml of oxygen per liter of blood, and now cardiac output is 5 liters per minute. So, let us multiply 5 liters per minute by 215.07 ml of oxygen per liter of blood. So, if we multiply the cardiac output by the oxygen content, the arterial oxygen content will give us the global oxygen delivery, which is the DO2, and it is about 1075.

35 ml of oxygen per minute. So, you fully understood the solution. The next one is the oxygen consumption, or VO2. So, you can see that what is basically VO2.

CVO2 is 1.31 times HB times SVO2 times 0.01 plus 0.2225 times PVO2, and basically VO2 is cardiac output, which is CO times CO2, which is the oxygen content, which is the oxygen content in the artery, minus the oxygen content in the veins. So, basically the same as CO2, in the two slides before, we discussed how to derive CO2. In the same way, if you replace the SAO2 with the SVO2 and you replace the PaO2 with the PVO2, you can derive the oxygen content in veins. And VO2, which is oxygen consumption, is nothing but cardiac output into CO2 minus CVO2. And in this way, if you put in all the standard assumptions and the number, we get the oxygen consumption of about 254.

5 ml per minute. So, let us see how a soccer player improves their VO2 max from 45 ml per kg per minute to 52 ml per kg per minute. Unless they consider their body weight to be about 70 kg. How much more oxygen in liters per minute can they now consume? So, how will we approach this solution? So, the initial VO2 max we mentioned is about 45 ml per kg per minute, right? And then the final VO2 max is about 52 ml per kg per minute, and their body weight we discussed is about 70 kg. So, what would the initial oxygen consumption be? So, we will multiply 70 kg by the initial oxygen VO2 max, which is 45.

So, it comes out to about 3.5 liters per minute. Then, the final oxygen consumption, if you multiply 70 kg by 52 ml per kg per minute, gives us about 3.64 liters per minute. And how much improvement in oxygen consumption occurs, or how much does the increase in oxygen consumption happen? Basically, if you subtract 3.

64 from 3.15, we get about 0.49 liters or about half a liter per minute, okay. The last kind of factor in the formula discussed is the oxygen extraction ratio. This is a fraction of the oxygen delivered by the cardiovascular system that is actually utilized by the tissues. And this is therefore the ratio of oxygen consumption to oxygen delivery. So, you can see that the O2ER of the oxygen extraction ratio is basically kind of like a formula which is like a ratio between the oxygen consumption and the oxygen delivery. So, VO2 was the oxygen consumption; VO2 was oxygen consumption, and DO2 was the oxygen delivery.

So, O2 here, or the oxygen extraction ratio, is very simple. It is the ratio of oxygen consumption, which is the VO2, divided by the oxygen delivery, which is the DO2. And if you put the VO2 and DO2 here, you remember the VO2 in the last slide we discussed; it was 254. 0.5 ml per minute, and the DO2 we discussed a few slides before was the standard for ml; it was about 997.

5 ml per minute, and if you calculate the O2 here, it comes out to about 0.26 at rest. So, you can see here it comes out to about 0.26 at rest. In a healthy condition, basically only about 20 to 30 percent of the oxygen is delivered to different tissues. So, even if you are consuming about 4 to 5 liters of oxygen at a maximum inhalation, only 20 to 30 percent, roughly about 1 liter or 1.

1 to 1.2 liters of oxygen at a given time is delivered to the tissues, which is called the oxygen extraction ratio. Let us discuss a few more problems and we will end. So, the patient has an arterial oxygen content of 20 ml of oxygen per 100 ml of blood and a venous oxygen content of 15 ml of oxygen per 100 ml of blood. So, what would their OER be? So, OER can also be discussed; do you remember what the OER was? OER was Vo2 by Do2, right? You remember, and then the Vo2 is, so basically, the Vo2 is arterial O2 minus the venous O2.

So, this was the VO2 right, and then the DO2 is how much? So, Do2 is the arterial O2. So, VO2 is the measure of oxygen consumption. So, VO2 is the oxygen consumption, and DO2 is the oxygen delivery. So, arterial O2 minus venous O2 is oxygen consumption, and delivery is arterial O2. So, we have all the given items.

So, for arterial O2, it is 20 ml per 100 ml of blood; then the venous O2 is about 15. So, how much do we get the VO2 then? 20 minus 15, which is 5. That would be divided by the arterial O2 or the DO2.

So, we will get about 0.25 or 25 percent as the oxygen extraction ratio. Hopefully, it is clear. In the same way, if the arterial oxygen content is 19 ml per 100 ml of blood and the oxygen extraction ratio is 30 percent, what would be the venous oxygen content? So, we all know that OER is arterial O2 minus venous O2 divided by arterial O2, and again to kind of point you to this, VO2 is divided by this part, which is DO2. Now, we have to calculate venous O2, right? So, basically, venous O2, if you kind of derive it, like if you rearrange this equation, what is coming? So, venous O2 then becomes arterial O2 multiplied by 1 minus OER. So, 1 minus OER. Like if you calculate venous O2, it is arterial O2 into 1 minus OER.

Now, we are given arterial O2, which is 19 ml per 100 ml of blood. We are also given the OER, which is about 0.

3. So, if we calculate this, it comes to about 19 times 0.7, or 13.3 ml of O2 per 100 ml of blood. So, this is basically what we derive as venous oxygen content. So, it is a very simple problem. The last problem is that a muscle receives about 500 mL of blood per minute. Now, the arterial oxygen content is about 19 mL O2 per 100 mL of blood.

Venous oxygen content is about 9 mL O2 per 100 mL of blood. How much oxygen, in mL, is extracted by the muscle per minute? Can we calculate this? So, let us, the solution, do it. Oxygen extracted per 100 mL of blood would be, so the delivery is 19. And the consumption is about 9. So, basically, the extraction is about 10 ml of O2, right, and the blood flow is about 500 ml per minute. So, if you do the total oxygen extraction, it will be 500 divided by 100 times 10, which becomes about 5 times 10 or 50 ml of oxygen per minute.

So, this is the total oxygen extracted, right? Hopefully, all these problems are clear to you. You may also refer to different textbooks to solve various problems related to lung volumes and lung capacity. This was the mathematics class I knew, but these are also very important to know. Hopefully, you are enjoying different classes in human physiology. Let us meet with you very soon for another new class. Thank you.