Fundamentals of Fluid Mechanics for Chemical and Biomedical Engineers
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So, in this lecture we are going to discuss about the role of Fluid Dynamics in Biomedical Applications. So, we will discuss the fluid mechanics involved in human physiological system, what are the organ systems in which fluid dynamics play a, an important role in their functioning, in the functioning of various organ systems and then as a consequence the role of fluid mechanics in the design and development of various biomedical devices or diagnosis of diseases or treatment of diseases.

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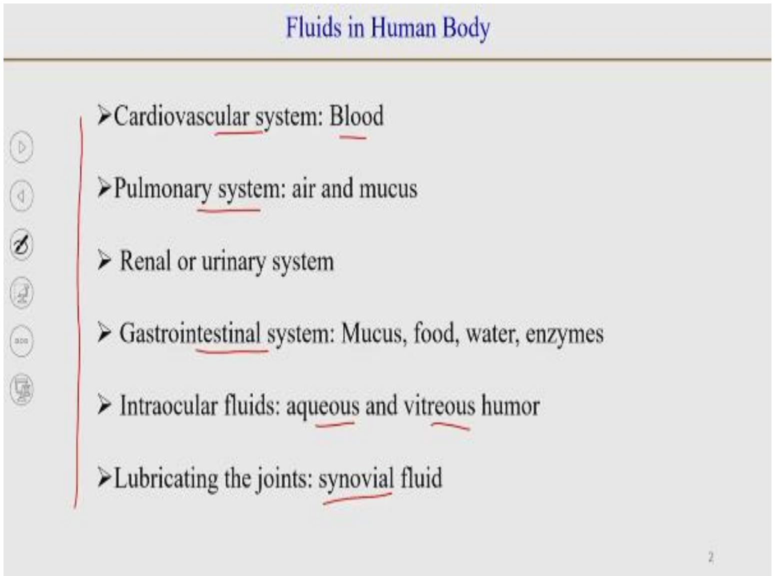

So, as we know that about sixty percent of human body is composed of water and this water is present in the form of various fluids in the human body. So, the first such organ system is cardiovascular system, so in the cardiovascular system the fluid is blood and this blood it is pumped through heart to different organs of the body, where it transports oxygen and other nutrients and collects carbon dioxide and other waste products and, and then transport them back to lung or in case of carbon dioxide and to urinary system or kidneys in case of other waste products.

Now, to facilitate the supply of oxygen we have another fluid system which is called pulmonary system, where through our nose the air is transported to the lungs and this air exchanges carbon dioxide and oxygen with the blood in lungs. So, again the role of flow of air is important in pulmonary system. Then, the urinary system where the filtration of blood happens and the waste products from the blood are filtered out in the form of urine, it also help in maintaining the pressure of the blood in the body.

Then, a Gastrointestinal system, so anything or everything that we eat or drink via our mouth, liquids of course, they are in the form of a liquid, they are in the liquid form, the solid fluid that we eat is converted into a slurry form by adding saliva and chewing or masticating the food, so this slurry is converted in the form of a liquid and is transported through the gastrointestinal system or through our gastric system where it is digested and the nutrients are extracted from it. The transportation itself takes place via peristaltic motion, so and different enzymes or gastric juices are added during the process.

Now, there are number of fluid dynamic aspects apart from of course, biochemical aspects to, to the functioning of gastrointestinal system. For example, the disease piles where the, the blood comes out from, from the anus and that happens because the viscosity of the waste that is secreted, that is released by humans is very high or it is the stool is in the solid form and that causes a lot of shear stress on the muscles resulting in that, that the blood vessels on those tissues surrounding the anus, they come out and then form, form lumps.

So, one of the treatments or all the treatment for such cases they, they direct that the viscosity of the food or, or the person is not constipated, so not constipated means that the viscosity of the stool is reduced significantly for which the, the doctors prescribe for example, dietary fiber diet etcetera. So, what I am trying to say is one of the important aspects in this case is minimizing the shear stress on the tissues and the blood vessels surrounding it. So, that is a fluid dynamic aspect into it.

Then similarly, for our eyes we have two important fluids in eyes. One is called aqueous humor and the other is called vitreous humor. So, aqueous humor is the one that is above our eyes and it, it is continuously produced and then absorbed. So, if its supply is blocked then there is pressure buildup in the eye and that can eventually even may cause loss of vision. On the other hand vitreous humor is a viscoelastic fluid or viscoelastic material which is gel like and with age it becomes more fluid like or its viscosity decreases and it becomes a clear fluid. So, again maintaining the aqueous humor and viscous humor in the right physiological condition is an important part of ocular management.

Then, we have bones 206, 206 bones in our body and a number of joints, so at the joints there is a liquid present between the bones which, which helps in reducing the friction between the bones and this liquid is known as a synovial fluid which is generally a shear thinning fluid and its viscosity decreases when the, when the stresses on it increases. So, all these systems apart from this there are a number of other systems such as say reproductive system or the lymphatic fluids where again the fluid mechanics is or the flow of fluid plays an important role.

I have listed down some of the prominent systems here and in all these systems apart from of course, biochemical reactions etcetera, fluid mechanics also plays a very important role.

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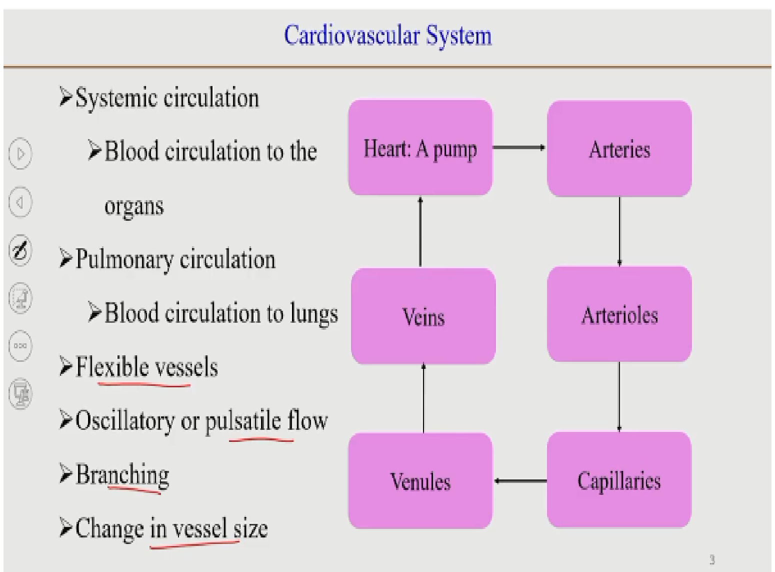

So, if we look at cardiovascular system in particular. So, cardiovascular system is basically a network of pipes, so if, if we look at from fluid dynamics point of view, heart is a pump which is a pumps blood to a large artery first, in case of systemic circulation which refers to a flow of blood to different organs except lungs. So, in the systemic circulation the blood is pumped from heart to aorta which is the largest artery in the human body and from aorta it bifurcates into different arteries and smaller arteries so and from arteries it goes to further smaller arteries which are called arterioles, arterioles are more they, they can change the resistance.

So, they can, they are more flexible when you compare with arteries and of course, they are smaller than arteries and from arterioles they are further goes to smaller capillaries, which are of, their dimension is of the order of 10 micron or so. So, in the capillaries which where the blood is or the nutrients are supplied to organs and the exchange takes place and from capillaries the blood becomes that is where the blood takes carbon dioxide, so it becomes deoxygenated and this deoxygenated blood from capillaries it is supplied to smaller veins which we call venules.

And from venules it goes to larger veins and from all the larger veins to vena cava and from vena cava it goes to heart. So, that is the systemic circulation, so such systematic circulation basically it, it refers to the supply of blood from heart to different organs and it is the supply of fresh blood from the heart.

Whereas, pulmonary circulation refers to the supply of blood to and from lungs, so to the lungs the deoxygenated blood goes to the lungs and it is oxygenated by exchanging oxygen from the, the oxygen exchange takes place in the lungs and the blood become oxygenated and then it comes back to the heart where it is sent to different organs. So, the circulation to the from heart to lungs and back is called pulmonary circulation.

So, when you compare with the, with a conventional piping network, let us say a pumping network in or the piping network in our household, one of the major differences is of course, that the sizes are different, there is a very large network of vessels and these vessels are flexible vessels. Moreover, the flow generally when we look at or any chemical engineering applications, we are looking at a flow which is, which is steady, there might be unsteadiness in the flow at the start or when we stop the flow but during the operation, we tend to have or we would like to have steady flow.

Whereas, in the human system we know that the heart beats 72 times in a normal human being in a normal conditions. So, the flow is pulsatile and the vessels are flexible. And then there is lot of branching and the, the pipes or the vessels, blood vessels they are not in straight whereas they have a curved shape or they are for example, the coronary artery which is following the shape of the heart, so it is a 3-dimensional shape or its not planar geometry. And so all this, all these topics the flow in flexible vessels or the pulsatile flow, the branching and changing vessel size, all these topics are important from cardiovascular point of view.

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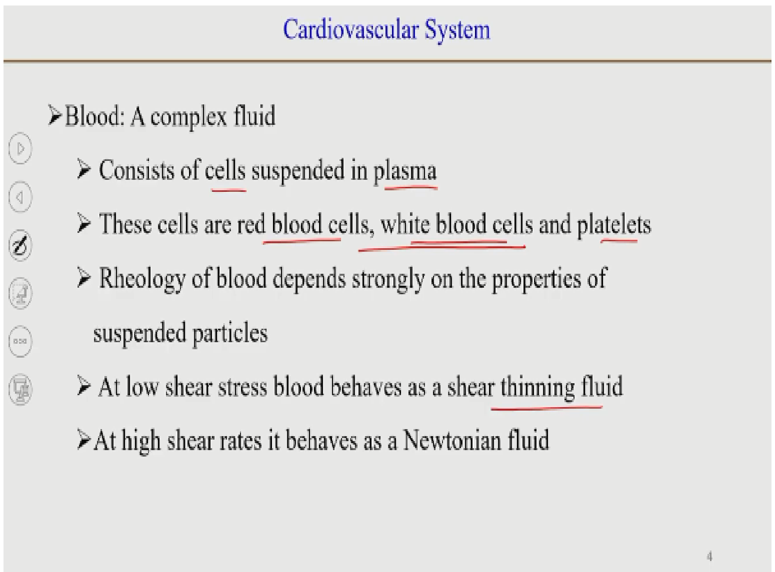

So, if you look at the fluid itself, in the cardiovascular system, blood is a complex fluid, so as we discussed in the other class that when we look at a fluid and we would like to characterize this fluid, so the first characteristic comes by looking at the rheological behavior of the fluid, which is finding out the relationship between stress and rate of strain and if the relationship is linear then we call the fluid to be Newtonian fluid.

So, blood behaves as non-Newtonian fluid and it is a complex fluid because it has, in a liquid which is water like plasma, which has water plus some protein suspended in it and this plasma has a cells and these cells can be red blood cells which we call RBC, white blood cells which we call WBC and platelets in it.

So, the rheology of blood it depends strongly on the properties of these cells which are suspended as well as the concentration of protein in the plasma and that can cause the blood to be viscous or more viscous or less viscous. And if you can imagine that if the blood is thicker that means it is viscous then the power required to pump the blood in the system is more and that will cause the blood pressure to be high. If it is thinner then the power will be lesser, so the blood pressure will be normal in that case.

So, the blood what we know is it behaves differently at different shear stresses, so at low shear stress blood behaves as a shear thinning fluid and that has to do with the orientation of the cells that are suspended in the blood and at high shear rates all the cells suspended in it they, they are aligned with the flow and then blood starts behaving at Newtonian, as a Newtonian fluid.

Now, to give you an idea that what is the concentration of these cells RBC are about 45 percent in healthy normal human being, the concentration of RBC is about 45 percent, so that is very thick, the blood has lot of these red blood cells and then about less than one percent of white blood cells and then even lesser platelets.

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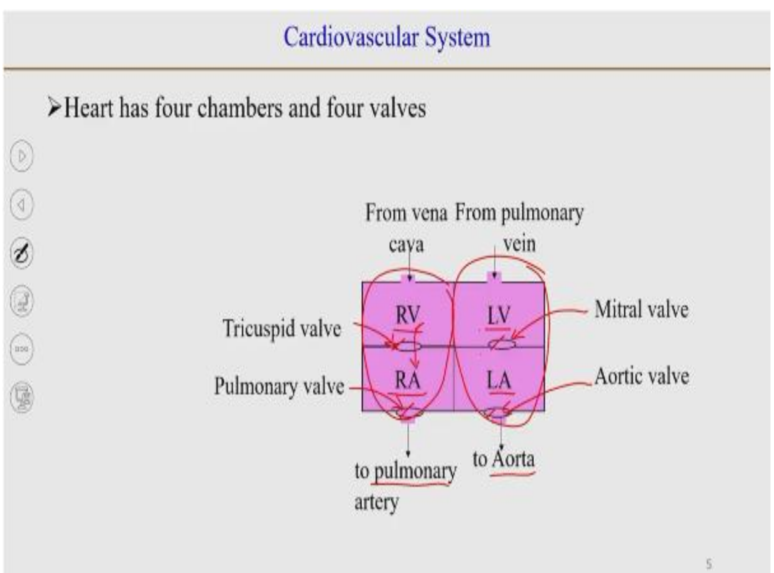

Now, if we look at the heart which is basically a pump, you can say that it has two pumps into it, one which transports blood to the pulmonary system and or the pulmonary circulation and the other which transport blood to the circulatory system or the systemic circulation. So, if we look at the left part where it has two chambers, left ventricle and left atrium and on the right part where it has right ventricle and right atrium. So, it has in total four chambers and out of in these four chambers they are called ventricle, where the blood is collected first and then it is transported to atrium, so that is the right part it supplies blood to a pulmonary system, whereas the left part is supplies blood to the systemic circulation, that is, all the organs.

Now, in all these cases you might see there are four valves present, so these valves, this is what is called tricuspid valve, the valves between right ventricle and right atrium, the valves between left ventricle and left atrium is called mitral valve and the two valves which are supplying blood to the arteries they are named based on the artery on which this blood is supplied, so to which the blood is being supplied, so for example, from right atrium the blood is supplied to pulmonary artery, so this is called the pulmonary valve and from the left atrium the blood is supplied to the largest artery which is called aorta, so this valve was named as aortic valve.

Now, these valve can be a tricuspid or bicuspid depending on that how many leaves do they have and they are one way valve, so this allow the flow of blood only in one direction, it cannot go back.

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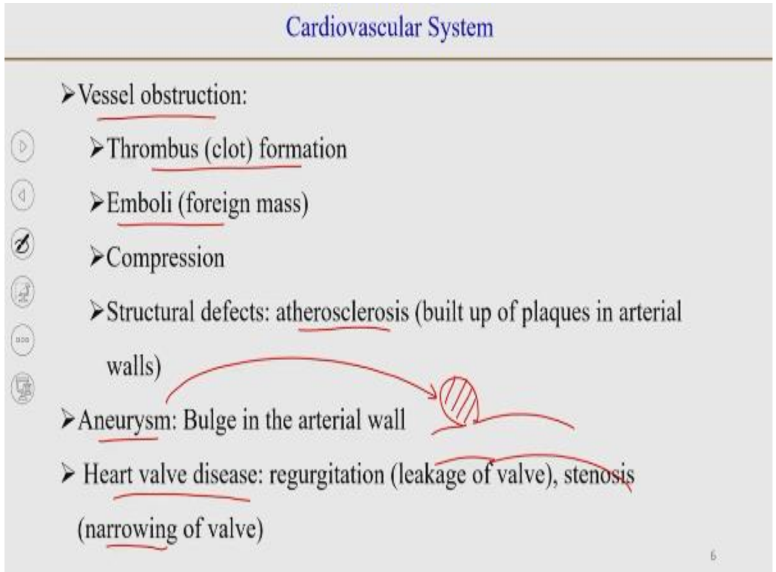

Now, one of the problems one can have is these valves may not function properly, so again these valves need to be replaced by a synthetic valves or what is called prosthetic valves. So, the design of those valves require the understanding of the fluid mechanics in the circulatory system and designed according to the patient's circulatory system. Now, there are different cardiovascular diseases where the role of blood flow is very important, it might be also important in terms of that the disease may occur or the progression or the development of the disease.

So for example, if we categorize a lot of problems in the cardiovascular system happens because the pipe through which the flow occurs is blocked and that can happen for various reasons. So, first reason what I have listed here is what is called thrombus or clot formation, you might have heard of what is called thrombosis, so the thrombus comes that the when, when we have a wound and to supply to the platelets are activated and the blood is clotted there, so that is good for human body or so that the blood supply is stopped automatically.

However, if it happens inside the vessels then the clot may form on the arteries and then it may constrict the flow of blood and if the blood supply is higher this clot may get separated from the artery and it may flow as an emboli in the blood. So, again it the shape of this foreign mass or emboli will be larger and it can stop the flow of blood or it can affect the flow of blood to organs and tissues and if it is in a critical area for example, flow of blood to brain then it can cause strokes.

Or compression if, if at some place for any reason if the artery is compressed, then again the flow of blood will be affected or there can be structural defects, so those structural defects might come over time which is called the atherosclerosis that is building of plaques, hardening of the arteries and building up of plaques by the deposition of cholesterol and other fatty materials in the arterial system, so, that can happen.

Now, the location where these plaques develop is again depends on the fluid dynamics point of view. So, if we look at most of the plaques develop where the shear stress is low, so it has been identified that the shear stress can act as a marker, so for example, of when the artery bifurcates, one artery bifurcates into two arteries, at the bifurcation zone the, the plague formation is generally seen or observed to occur.

So, all these regions, thrombosis, emboli, compression or structural defects they can cause vessel obstruction and affect the flow of blood in different organ systems and can affect the functioning of, the functioning of different organs, for example, when it happens in the coronary artery which supply blood to heart, then one can have heart attack, when, when the flow to brain is affected, then one can have a stroke and so on.

Now, another problem can happen which is called aneurysm, aneurysm is basically refers to, it refers to bulge in the arterial wall, so for example, if you have an artery and at the artery one can develop a bulge which is called aneurysm. Now this aneurysm happens generally when the wall of the artery becomes weaker and that of course, affect the fluid dynamics behavior and when this bulge occurs, it may compress other arteries.

Sometimes it may also burst and that bursting can cause if it is for example, the two, two very important aneurysm from clinical perspective or from human life perspective are cerebral aneurysm, which is aneurysm in the brain and aortic aneurysm and aneurysm near the aorta and they are bursting may cause, cause the functioning of the brain or functioning of the of the lungs and heart affected, so they, there is lot of research from the fluid dynamics perspective in the diagnosis and treatment of aneurysm.

Now, another thing is what I said is heart valve disease, so there are two important diseases in terms of heart valves, one is what is called regurgitation, which is the leakage of, leakage of blood from the valve, so the valve no more acts as a one way valve and some of the blood may leak back or go back to the atrium or to the ventricle depending on which valve it is and the other problem can occur what is called stenosis. So, stenosis refers to the narrowing of valve or stenosis is a general term, so if it is narrowing of an artery there also it is called stenosis and in with respect to valves it is called narrowing of valves. So, the supply of blood may not be adequate if it happens.

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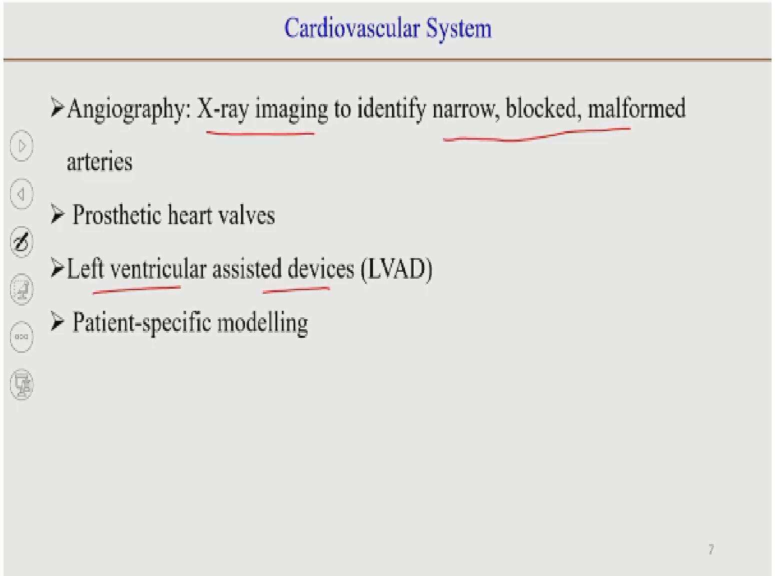

So, there are some techniques which are developed. So for example, angiography, angiography is a common technique which the cardiologists use to identify the blockage in the arteries and this is done using a dye, what they use, using x-ray, they image the arteries and identify that which area of the artery has narrowed down, blocked or it is malformed and if they identify or if they find that there is serious problem, then they can do a treatment there they put a put a stent there which, which can increase the size of the artery and the procedure is called angioplasty.

Then the design of prosthetic heart valves, so if the heart valves need to be replaced by artificial heart valves then they are again the design of prosthetic heart valves is, there is lot of fluid dynamics involved into it and people do lot of CFD or computational fluid dynamics simulations to design these heart valves. Then what is called cardiovascular assisted device or left ventricular assisted device in particular for the, so when for some reason the heart is not pumping enough blood or of during the procedures where some procedure heart has to go through some procedure, then an external device can assist the flow of blood in or through the left ventricle.

So, this is basically a pump, so the design of this pump is again when you are designing a pump keeping in mind the factors that it should be in compatibility with the body fluid and body materials. So, that is what is left ventricle assisted device. Now, in recently, I mean in last 20 years, people have been looking at the patient specific treatments, so in line with that what is called patient specific modeling in cardiovascular systems. So, the structure of arteries or the vascular system for every human being is different and it depends on the race, on the age, on the gender, on the weight and height.

So, for the treatment if one can understand the flow behavior in a patient, then one can have or one would be able to make more informed clinical decisions, finding out for example, if one need to do bypass surgery and one has two or three options, one can quickly do some flow simulations and find out which option is better and to do this what is done is, one can take a three-dimensional imaging using MRI or computed, 3D computed tomography.

And from these images one can construct the real 3D model of the arterial or vascular system and once this is done, the measuring the pressure and velocities or flow rates in these arteries, one can simulate the local flow behavior in an arterial segment. And from that one can identify the velocity field and the pressure field and make clinical decisions apart from of course, developing a lot of understanding of the flow physics and effect of different geometrical parameters.

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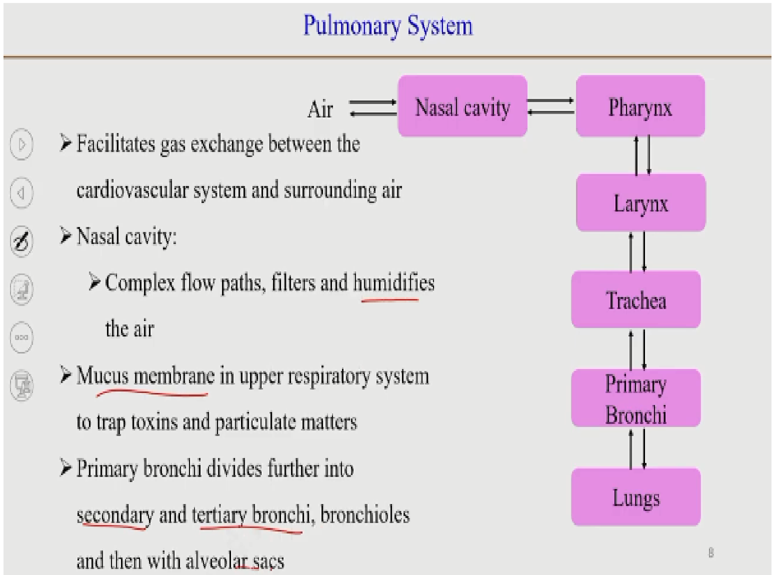

So, another system, a very important system from the fluid dynamics perspective in human body is pulmonary system, which is lungs and or the flow of lungs to and from the nose. So, with this lungs they facilitated the gas exchange between the cardiovascular system and the surrounding air. So, exchange of blood, exchange of carbon dioxide and oxygen between the blood and the air is facilitated by lungs or the pulmonary system. So, when we breathe the air it passes through our nose and that is where nasal cavity is.

Now, first thing that these, the air may have or generally has lot of suspended particles into it, it may have a lot of (both) pathogens, so the first line of defense inside the nose we have is our hairs in the nose and these hairs act as a filter, then the path in this nasal cavity is very tortuous, so while the air can pass through it but, but the solid particles their response time is larger and they generally are trapped in the mucus that is lined on the valves of this nasal cavity.

So, it acts as a filter and it also humidifies the air or it also help in maintaining the temperature of the air that passes through the nose and then from nasal cavity it goes to pharynx, the common area where the food and oxygen can pass through and from there it goes to larynx, so in all these systems pharynx, nasal cavity and larynx which is called upper respiratory system, there is a mucous membrane present and the toxins and particulate matters if they are not trapped in the nasal cavity they can get trapped here.

And from larynx it further goes down to trachea which is also called wind pipe and from there it goes to primary bronchi, so trachea is one pipe and from there it bifurcates into two primary bronchi and these bronchi supply blood, supply air to the two lungs and in the lungs these bronchi are further divided into, this primary bronchi are divided into secondary and tertiary branch bronchi and secondary and tertiary bronchi they are further bifurcated into a different generations, five or six generations of bronchioles and then these bronchioles are then they terminate into what is called alveolar sacs.

So, these are, these alveolar sac they are made of alveolis that is where the transfer of oxygen between the blood and the air happens, the transfer of oxygen and carbon dioxide.

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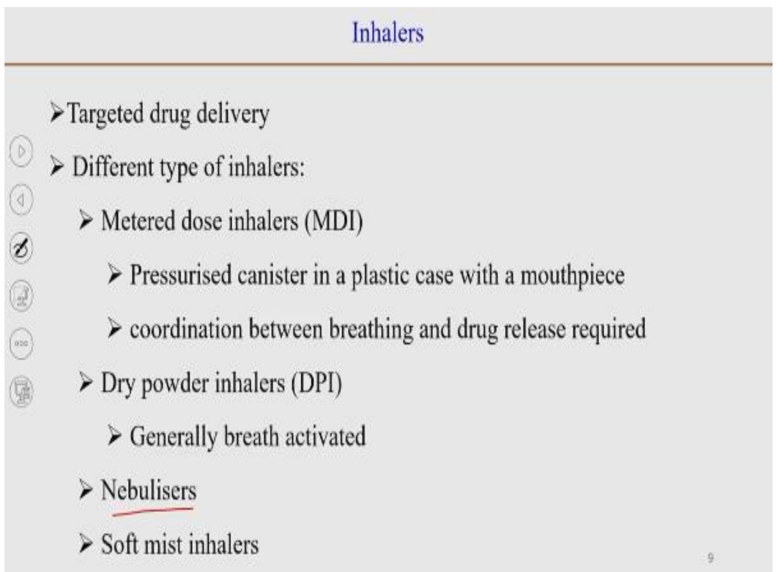

So, one of the very important application of fluid dynamics is in the treatment of pulmonary diseases, in terms of targeted drug delivery. So, for asthmatic patients or for the patients who are suffering from chronic pulmonary obstruction diseases, any disease which, which causes an obstruction to the supply of air to the lungs is called COPD Chronic Obstructive Pulmonary Disease.

So, the treatment of this more and more is being done in a targeted manner, that is in place of giving an oral medication which will be going through the blood and then reach to lungs, the drugs are given directly to the lungs where it is required. And this also helps in avoiding the side effects because the drug is not going to the blood.

So, there are different types of inhaler and you would have seen most of these and they are called say, for example, Metered dose inhaler which is very common, you might have seen in asthmatic patients, so these metered dose inhaler they have is a pressurized canister and which is surrounded by a plastic case and a mouthpiece and this, so once you press the canister, the drug is released.

Now, the trick here is that there should be a coordination between the breathing and the drug release because if that does not happen, then lot of drug that can go wasted and it does not reach the target, it may just get deposited in the mouth. So, that is one of the very important problem from fluid dynamics point of view, that how one can have that this drug release and coordination is not the subject dependent, it is not dependent how the patient or the subject breathes or how he operates the device. So, then you might see that there is a spacer that is now coming that between the device or between MDI and the mouth, there is a spacer so that can help in minimizing the drug going waste.

Another kind of inhaler is what is called DPI Dry Powder Inhaler and they are breath actuated inhalers, so when one breathes and from the breathe the device is activated and the device has the drug plus carrier, generally in the form of lactose, so this drug is released and then it is de-agglomerated in the device and then it is deposited in the human lungs. So, the design of dry powder inhalers is design and optimization of these dry powder inhalers is being done a lot with the help of computational fluid dynamics as well as in vitro experiments.

And then, you might have seen the nebulizers, generally the kids when they have severe cough and cold the drug is given to them with the help of nebulizers. And then there are soft mist inhalers and the design of all these is strongly driven by fluid dynamics because the goal is the release of right amount, right size of drug and depositing it in the lungs at the required targets, it should not be that it is being deposited in the mouth and throat it should be, it should be deposited in the lungs where it is required, in the lower airways.

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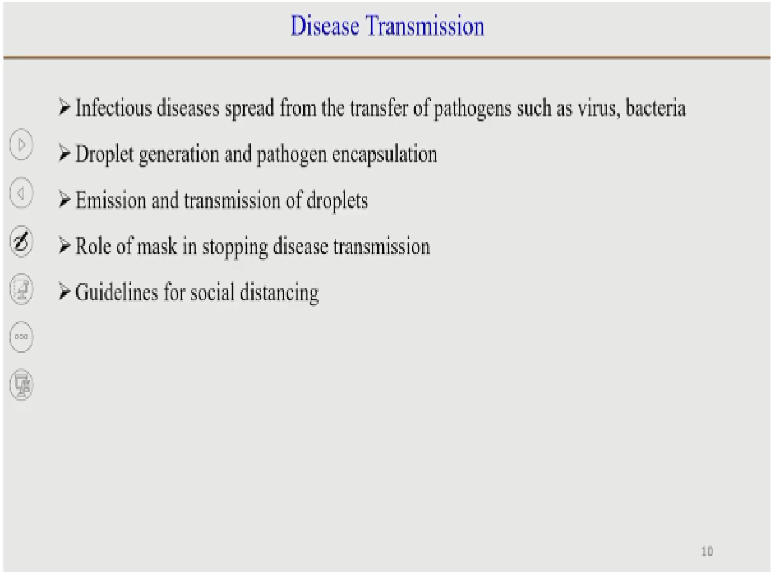

Now, the other and more relevant in today's world is disease transmission. So, Covid19, we have two very important aspects that one is wearing of mask and maintaining social distance and both of them are guided by fluid dynamic principles, social distancing generally one says that 2 meter of distance or 6 feet of distance and that number comes from the fluid dynamic perspective. So, infectious diseases including covid19 they spread from the transfer of pathogens from an infected person via virus or bacteria etcetera.

Now, in every stage, so when these pathogens they exist or the pathogens, viruses and bacteria they are in the mouth area etcetera, so when we speak, when we breathe or when we sneeze the droplets are generated. Now, the size of this droplet, the encapsulation of pathogens in these droplets, all this is driven by fluid dynamic principles and the better we understand the more we will be able to handle or device the method to mitigate the transmission of the disease.

Then, these droplets of course, are emitted in the form of liquids, once the droplet is emitted it may get evaporated, so once the droplet evaporated and before depositing on the surface if the droplet get evaporated it is called droplet nuclei, so this droplet nuclei in the solid form it may remain suspended in the air and then it can go to a, in the airways of another person, so when it goes in the airways of another person or when it reaches, approaches another person, the role of mask is important in this disease transmission. The design of mask is also driven by that how the supply of air is controlled when you when you wear a mask. One also need to understand that wearing a mask, there is not large pressure drop through the mask because it can affect the supply of oxygen to the person and, then so all this also help in devising guidelines for social distancing.

So, in nutshell what we can say that there is lot of role that the fluid dynamics can play and is playing actively in the design and development of biomedical devices in diagnosis of diseases and treatment of diseases. So, we will be understanding fluid mechanics and try to solve some of the problems which are relevant for biomedical engineering, so we will stop here today, thank you.