Cardiovascular Fluid Mechanics
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Lecture – 01
An Introduction

Hello, this is a short course on Cardiovascular Fluid Mechanics. So, there are a two terms here, you can say cardiovascular and fluid mechanics. And they come from to entirely different fields or so to understand the fluid mechanics in a cardiovascular system, one need to understand the cardiovascular system as well as the fluid mechanics.

So, cardiovascular system one needs to understand the biology and the terms that has a used in the medical fraternity, whereas fluid mechanics is a field from physics and used by engineers to develop and design various devices including biomedical devices. So, cardiovascular means cardiac, cardio means heart and vascular is the blood vessels. So, the flow in a heart as well as blood vessels is what we are concerned about in this course.

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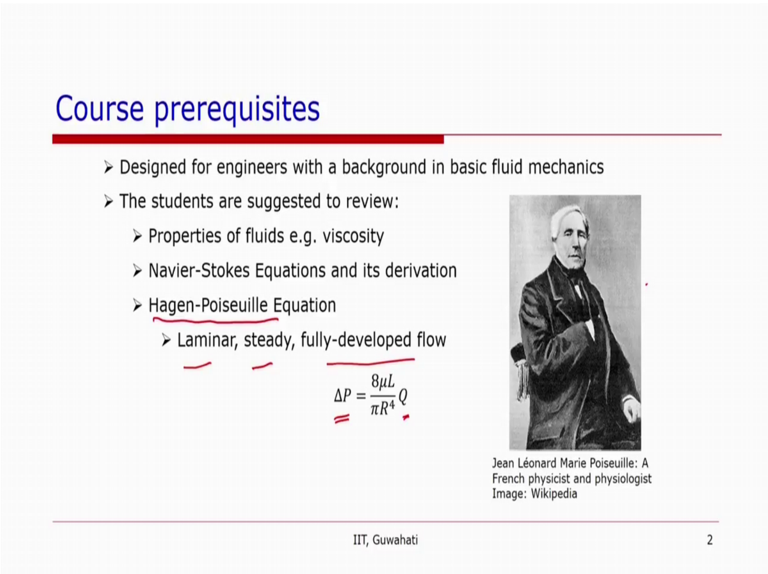

So, to start with this course is primarily designed for engineers with a background in basic fluid mechanics. The course can be studied by different stakeholders including doctors, biomedical engineers, fluid dynamists, physicists, mathematicians, chemical engineers. This course to understand before going to the course to understand the course in entire tree the person from one field especially there you can have two bifurcations that there are two a fields, one is a biomedical field or medical field where doctors or clinicians or the practice nurse are there, and the other is engineers and scientists who are understanding who have understanding of fluid mechanics. And at the other spectrum is biologists and medical specialist who have done the understanding of cardiovascular system.

So, to understand that fluid mechanics of cardiovascular system, one need to understand the terminology of the other field. So, because this course is primarily designed from engineers, so we assume that the engineers will be familiar with the terminology used in basic fluid mechanics and would have undergone at least one course in basic fluid mechanics. So, the students are advised and suggested to review some of the concepts here, the properties of the fluid, what is viscosity. And also it will be helpful if they can go through the derivation of Navier-Stokes equation.

One of the popular equations in fluid mechanics is Hagen-Poiseuille equation which was given independently by Hagen and Poiseuille. Interestingly this guy here Mr. Poiseuille, he was a French physicist and physiologist. And he was interested understanding the blood flow in vessels, and to understand that he developed the Poiseuille equation which is used to study or which can be derived from Navier-Stokes equation itself for laminar, steady and fully-developed flow in a channel. And this relationship is between the pressure drop and Q is the volumetric flow rate. So, one is suggested to understand at least these basic concepts in fluid mechanics; coming to the cardiovascular system.

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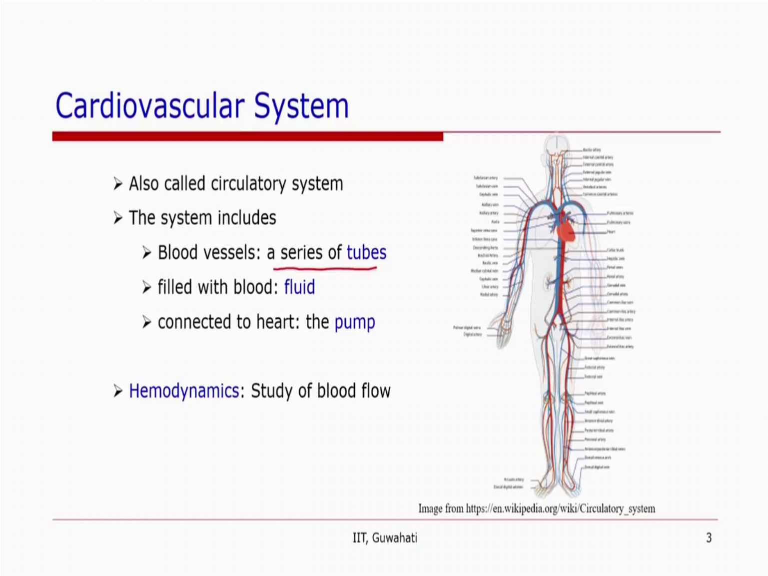

So, cardiovascular system is also called circulatory system, because it is the transport system which circulates blood in the entire body. The system includes it is a fluid dynamic system; from a engineering point of view it is a closed system of pipes which includes a pump which can flow the fluid in the network of pipe or a network of tube which are arteries, arterioles, capillaries, venules, veins and so on.

And what it transport it transports blood which is again a very complex fluid because it behaves differently under different shearing conditions at different flow rates in different pipe diameters. And this fluid is being pumped or it is pumped by heart. So, let us look at this in further detail in biology term or in medical terminology the study of blood flow is also known as hemodynamics.

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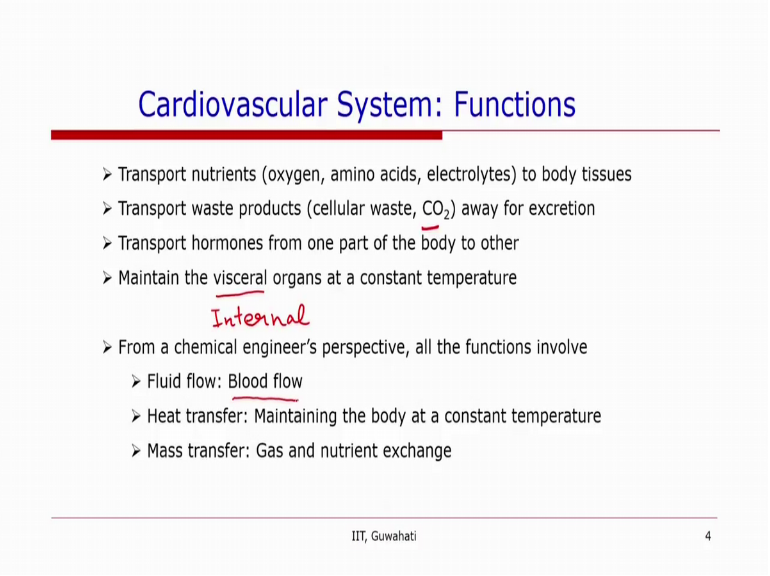

So, the functions of cardiovascular systems they are transporting as I said they are transporting the nutrients from lungs and different parts of the body to different body tissues. So, the oxygen is picked up in the lungs and the waste carbon dioxide is released when the blood exchanges oxygen and carbon dioxide in the lung. And the phrase carbon dioxide or the oxygenated blood is circulated in the entire body and it is supplied to different body tissues.

At the same time, it also transport the waste products of the cells for the excretion from the kidneys. It also transport hormones from one part of the body to another; and the vascular system or the cardiovascular system also has the responsibility to maintain the visceral organs at a constant temperature. So, visceral here is a term which the engineers might not be a familiar with and it just means the internal organs.

So, from an engineer's perspective, and more specifically from a chemical engineers perspective for whom the transport phenomena that is fluid flow heat and mass transfer is a very important subject. The cardiovascular system involves fluid flow that is flow of a complex fluid, which is blood. Heat transfer, that body is to be maintained at a constant temperature. And mass transfer the exchange of gases with the blood in the lungs as well as nutrient exchange in different body parts.

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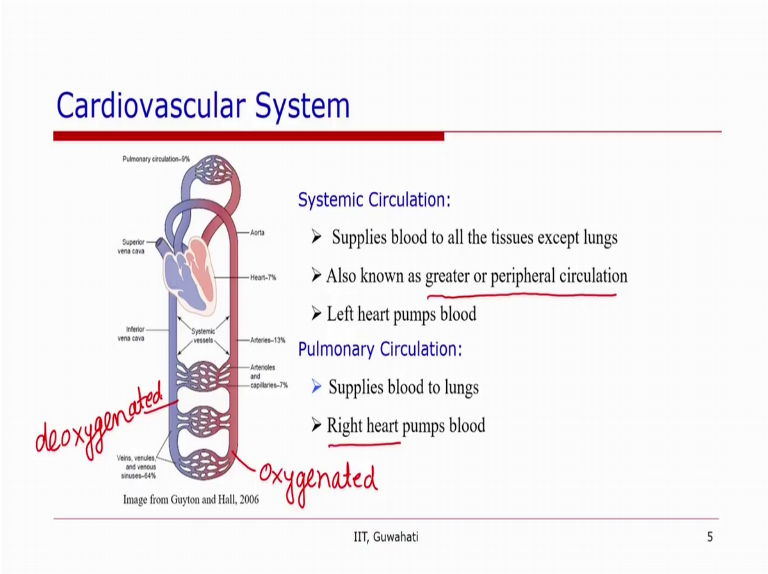

So, the cardiovascular system can be divided into two broad categories, one is called systemic circulation and another is pulmonary circulation. So, systemic circulation is the supply of fresh blood or the oxygenated blood to all the tissues except lungs. This is because this supply blood to the large part of the body, so this is also known as greater or peripheral circulation because it supplies bloods to blood to peripheral organs. The heart has that we will see in the later slides; the heart has two pumps in series.

So, the left part of the heart it pumps the blood in the systemic circulation that is it supplies blood to all parts of the body the fresh blood to all parts of the body except lung. Pulmonary circulation - pulmonary circulation, it supplies the deoxygenated blood to lungs; and this pumping is carried out by the right heart. As you might notice in this color coding here the oxygenated blood it is shown in red, whereas deoxygenated blood it is shown by a blue color.

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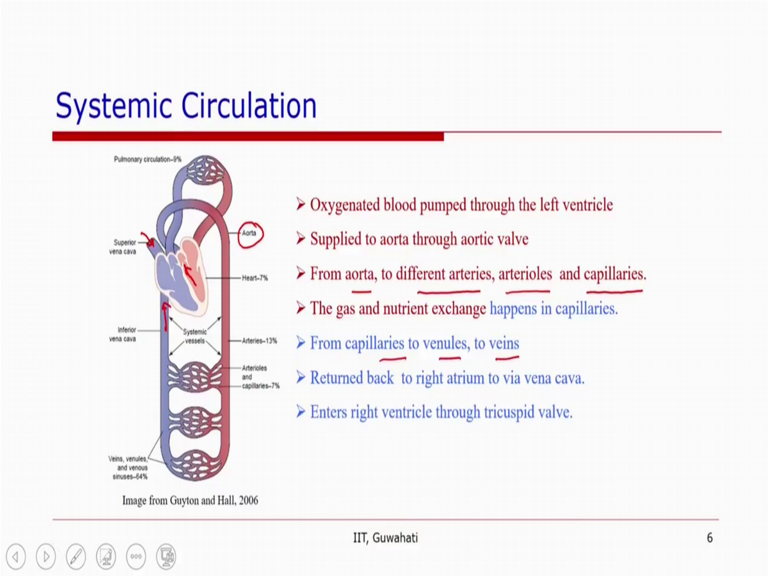

So, at the start of a cardiac cycle, the oxygenated blood is pumped through the left ventricle from it is supplied to aorta. And from aorta, the blood is supplied to further smaller arteries; and the arteries bifurcate into further smaller arteries and then it goes to different organs said the organs it is called arterioles; and further arterioles divide into a smaller vessels they are which are called capillaries; and in capillaries the exchange of gas happens.

So, the gas exchange happens and the oxygen is given to the different tissues and the carbon dioxide from there is taken, so the gas exchange happens in capillaries. And then from capillaries the blood comes to venules; and from venules, it is collected in veins. And from veins, the blood is returned back to right atrium via to parts superior vena cava from the upper part of the body, then from the inferior vena cava from the lower part of the bodies. So, this enters to the right ventricle through tricuspid valves.

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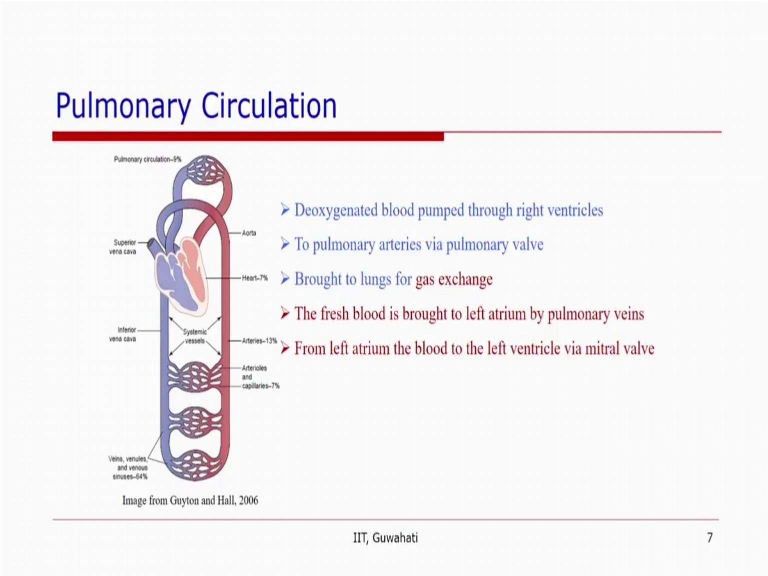

And the deoxygenated blood, it is pumped through the right ventricle and it goes to pulmonary arteries by a pulmonary valve. And the gas exchange happens here, the oxygen is absorbed by the blood, and the carbon dioxide is released in the lungs which are taken out by the atmosphere by ventilation process. So, the oxygenated phrase, oxygenated blood is brought back to the heart via pulmonary veins. And then it comes to the left atrium. And from left atrium, the blood is again sent to left ventricle and then from this one which called mitral valve from there again the next cardiac cycle begins.

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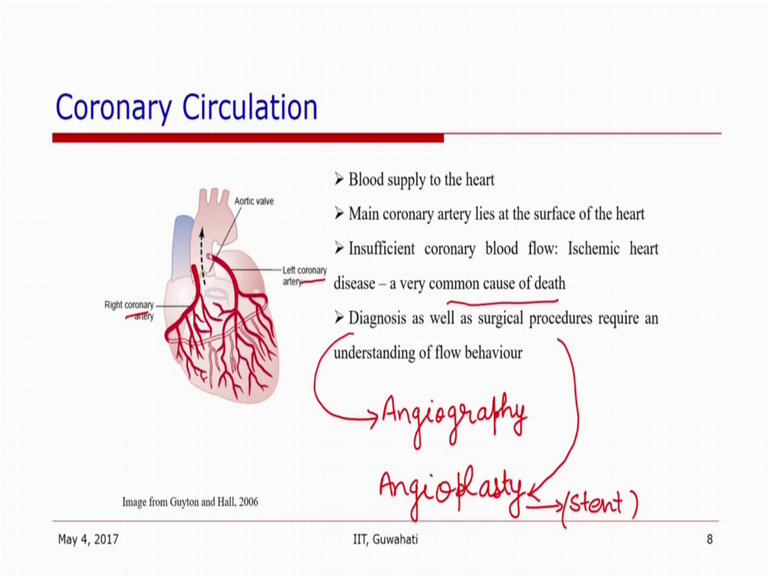

So, just to give you two examples of the tissues where the blood flow is supplied and the understanding of the fluid mechanics is important one of the important tissues is heart itself. So, heart the arteries, which supply blood to the heart are known as coronary arteries. And there are two arteries you see, right artery and left artery. So, the main coronary artery it lies at the surface of the heart and the heart stroke or heart attack that occurs generally when one of these arteries or the bifurcation from these arteries is blocked, and this is a very common cause of death.

So, to understand the blockage which is the diagnosis of the blockage as well as the surgical processes? So, a generally they such done by angiography that is understanding or finding out the blockage, and then putting the stent in the arteries is called angioplasty. So, both of these process during both the processes diagnosis as well as surgical procedure or the stent putting a stent requires understanding of the fluid dynamics while this is happening.

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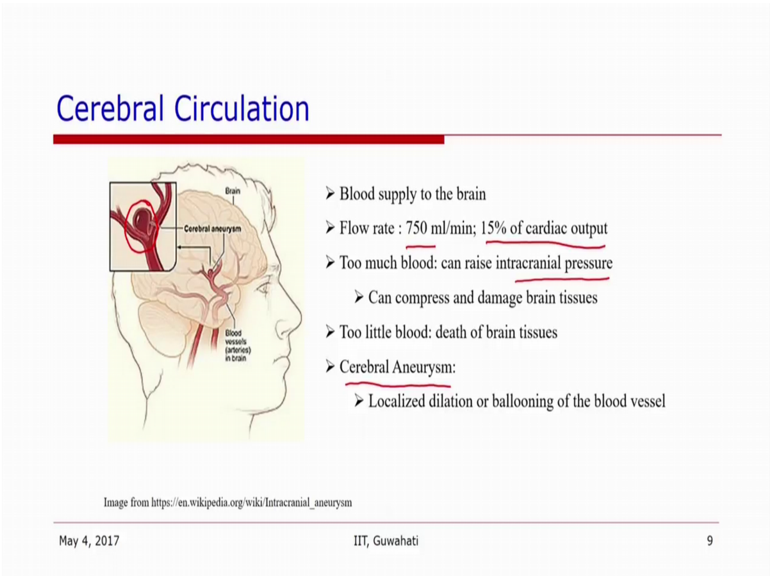

Another important organ were blood flow is important is known as cerebral circulation which is blood supply to the brain. It is very important to have continuous and regulated supply to the brain. Generally on an average about 50 percent of the cardiac output which is 50 percent of the blood that is coming out per minute from the heart is supplied to the blood. So, which is about 750 ml per minute and if this blood is too much then it can increase the pressure in the brain which is called intracranial pressure. And then it can compress and damage the tissues in the brain. If the amount of blood is too little, then it can cause death of the brain tissues. So, both the processes are harmful. If the blood is too little or too a high and this is regulated by the body tissues or which is a auto regulated.

One of the problems one of the diseases which are quite common is called cerebral aneurysm. You see here. What happens there is a localized dilation or localized bulge or ballooning of the blood vessels when the vessels it may be an artery or it may be a vein it becomes weak and ballooning can occur. So, to treated, it is a again very important to understand the fluid dynamics for the entire process. So, these are the two example we will look at the these some of the research work being done on both of these processes as the course progresses.

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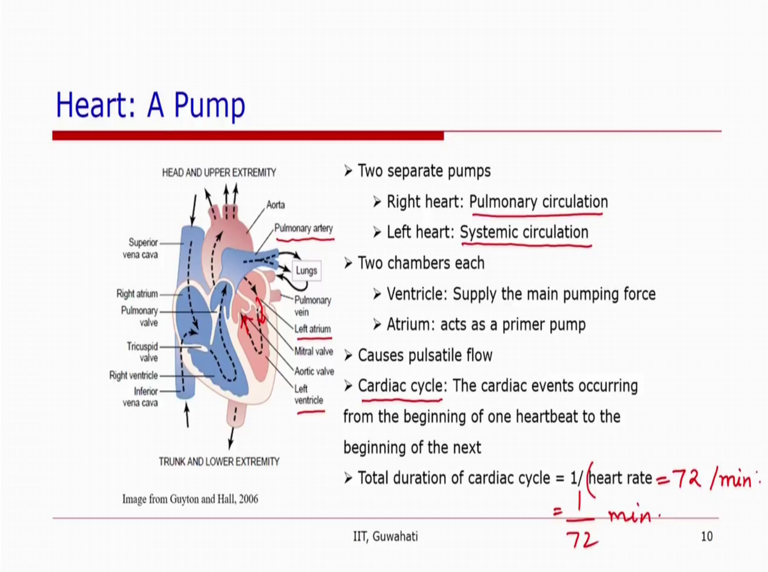

So, as we discussed at the start that there are three components of the cardiovascular system a pump. So, this pump has two separate pumps in series. One is what is called pulmonary pump or right pump which is used for the pulmonary circulations. So, you can see that pulmonary circulation which is taking blood away from the heart towards the lungs using pulmonary artery. And the, another pump is left heart which is supplying blood to the systemic circulations. So, pulmonary circulation you might remember pulmonary circulation is supply of blood to the lungs. And this blood is deoxygenated it is not fresh blood, and then it removes carbon dioxide and bring oxygen from the lungs, so that is pulmonary system and this work is done by right heart.

And from the left heart, systemic circulations it supplies blood to all the peripheral organs. So, it of course, it will need to do more work. Both the pumps they have two chambers as you can see left ventricle left chamber have left ventricle and left atrium. So, the left ventricle gets blood from the atrium and then it supplies to aorta (Refer Time: 17:56) aortic valve. And atrium it acts as a primer pump. So, when the left ventricle is supplying ventricle supplying blood to aorta or to the body, atrium collects a blood. And when the entire blood is ejected during the relaxation process, it again fills the ventricle similar function is done by the right heart.

So, the first component in the heart, there are two pumps which are in series and each pump has two parts, one acts atrium acts as a primer pump and the ventricle it supplies it provides the main pumping force. And this is a pulsatile flow. It oxalates or it varies periodically and the one cycle is known as cardiac cycle. In a normal human being on an average there are 72 beats per minute and this cardiac cycle can be defined as from beginning of one heart beat to the beginning of the next. So, during one cycle both the pumps work or both the left and right ventricle supplies blood to the organs where they are suppose to supply.

For example, the left heart supplies blood to the different organs and the right heart supplies blood to different lungs. Total duration of one cardiac cycle is 1 over heart rate. So, the heart rate in a normal human being is about 72 per minute. So, duration of one cardiac cycle is 1 over 72 minutes.

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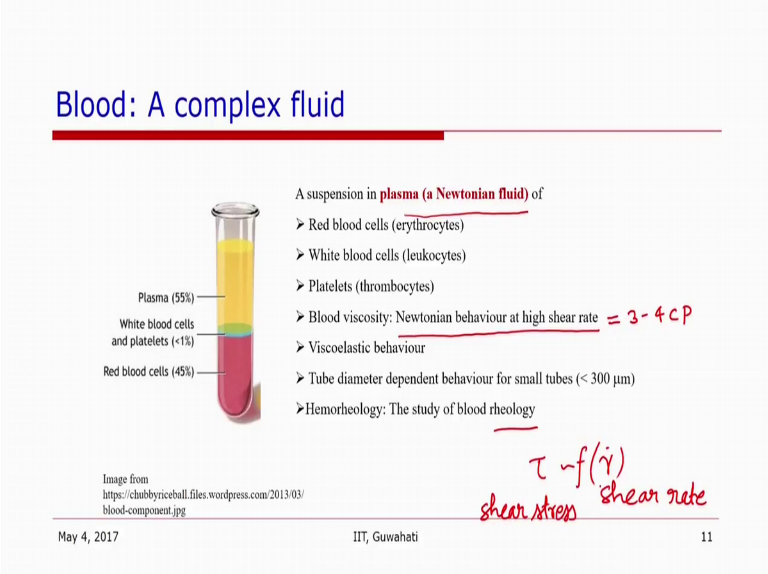

So, the next component of the cardiovascular system we have looked at the pump, and then next component is the fluid. So, if we take the blood, and let it settle and separate out its different components, so it turns out that blood is a suspension of different particles in water like fluid. So, this water like fluid is known as plasma. And plasma is a Newtonian fluid which has very much of which has properties very much similar to that of water. And in this blood, there are different particle suspended, red blood cells which are also known as erythrocytes, white blood cells and platelets. So, when these particles are suspended in the blood, blood behaves in a different way depending on the shear conditions.

So, for example, at high shear rate, blood behaves as a Newtonian fluid and the viscosity of blood at high shear rate can be taken as about 3 to 4 centipoises, because the particles which are suspended in the blood the highest percentage is of red blood cells which is about 45 to 55 percent. And remaining are white blood cells and platelets they are soft particles and have viscoelastic nature, so blood also source viscoelastic behavior. The sizes of these particles are about 8 microns. So, when the size of the vessels in which the blood is flowing, it becomes very small say less than about 300 micron.

Then the vessels, then the behavior does not look a continuum behavior anymore and the behavior of the or the flow behavior of the particles affect the rheology of blood that is the viscosity of the blood. So, we will look at all these aspects of the viscosity and rheology of the blood in further detail and this aspects or this branch of the cardiovascular fluid mechanics is known as hemo rheology under which when study the rheology of blood. So, rheology is a understanding the relationship between shear stress and shear rate.

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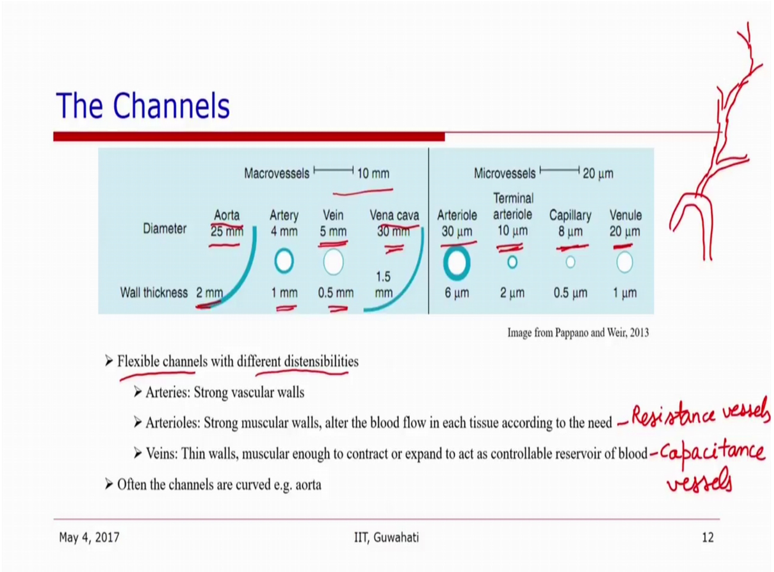

Then the third main component of the cardiovascular cell system is the channels and the channels can be of different type. So, the blood is taken from the heart to different parts of the body by aorta which is the largest artery, and it is about 25 mm in size. Now, this because the pressure in the heart is high, so the pressure in the aorta is of course is going to be high.

And then it will reduce as we will see in after few slides as we go to the arteries and then in other systems. So, the valves of the arteries are thicker the thickness of the aorta is typically about 2 m and the then thickness of the arteries decreases to 1 mm. So, the size of that artery all these numbers which are given they are just an indication of the size, and you can say an order of magnitude because the size of the arteries can vary significantly say from few mm to about 10 mm.

The size of the veins is also about 5 mm, but their thickness is very small, because the veins they have relatively very low pressure. So, the size of the thickness of the vein is smaller. And then vena cava which takes blood to back to the heart; it has a size of about 30 mm and the thickness is about 1.5 mm. So, all these large size of the millimetre size channels or vessels are known as macro vessels; and the smaller arteriole terminal, arteriole capillaries and venules they are known as micro vessels, because they have size of few microns or arteriole is about 10, 30 micron. Whereas, capillaries are of the same size about what is the what is the size of the red blood cells and venules they are slightly larger than the arteries sorry slightly larger than the capillaries the terminal venule oh sorry terminal arteriole is the last artery after which it bifurcates into become capillaries.

So, all the channels are generally arranged like aorta has this shape and from aorta it goes to different arteries and from arteries to further they bifurcates into a smaller artery and so on and so forth and then finally, it becomes into capillaries. So, all these channels they are flexible in nature in general in the fluid mechanics course the flow phenomena that we study, is in rigid tubes. But one complexity that is brought in cardiovascular system is the channels are of a flexible nature. They have depending on what their role is they will have different distensibilities or a different capability to expand or contract.

For example, as I said arteries they have a strong vascular wall and arterioles they have a strong muscular wall and then they can expand a lot because they are the once that control the blood supply to different tissues and control the resistance. Veins, they have very thin walls and they are muscular enough to contract. They are also known as capacitance vessels. So, they can store lot of blood in them. Arterioles, they are known as resistance vessels. And many a time the channels are curved.

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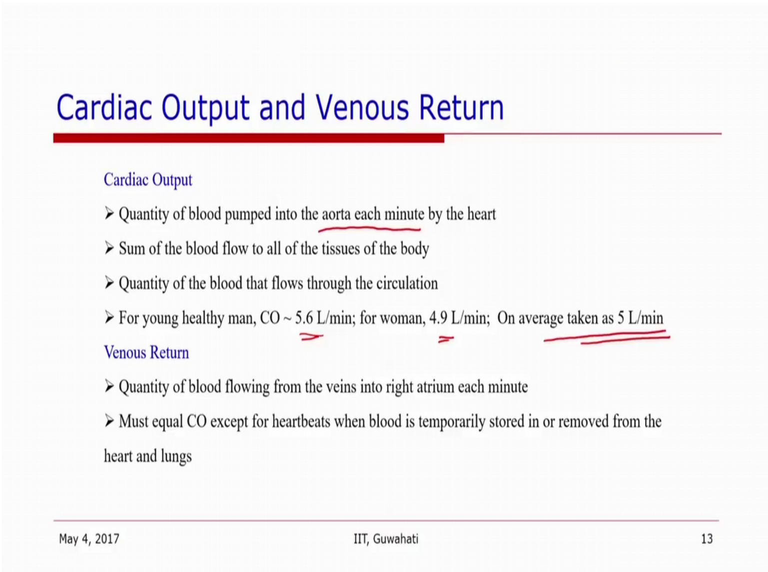

So, the flow rate the entire flow that is coming out from the heart is known as cardiac output of course, it will vary during a cardiac cycle. So, on an average the quantity of blood that is pumped into the aorta each minute. So, flow average flow per minute is known as cardiac output, the blood flow that is coming out of the heart. And this is on an average it is taken as about 5 litres per minute; in a young healthy man, it can be about 5.6 litres per minute; and women about 4.9 litre per minute. So, on an average we can take these number 5 litres per minute.

And the venous return the quantity of blood that is returned from the veins into the atriums called venous return. So, it up to satisfy the mass conservation because whatever flow is going out from the heart, it has to come back through the veins otherwise there will be a problem enough blood will not be there for supply or the blood will be lot of blood will be stored in the veins. So, on an average, they have to be equal so quantity of blood flowing from the veins venous return this will be generally equal to the cardiac output.

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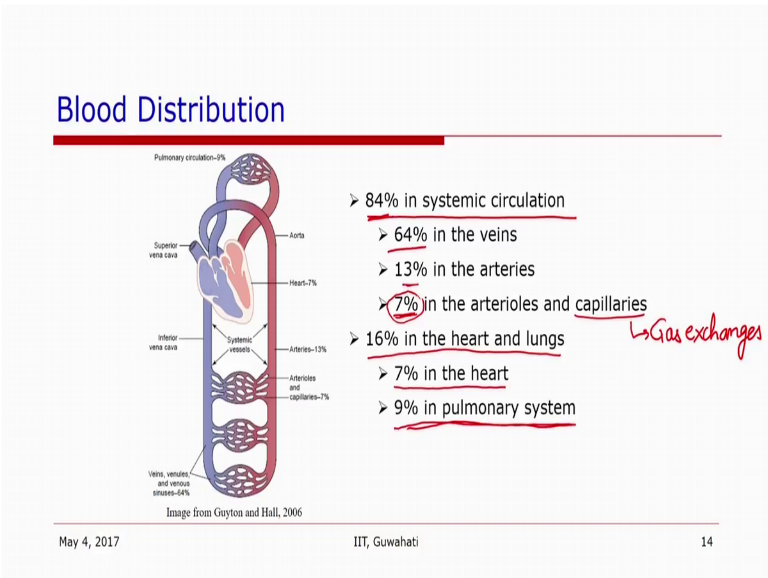

So, this is the typical distribution percentage distribution of the blood in the different parts about 84 percent of the blood goes in the systemic circulations. So, at any time 85 percent of the blood is in the systemic circulation in the peripheral organs and only 16 percent is in the hearts and lungs. So, out of that 9 percent is in the pulmonary system, whereas 7 percent blood is in the heart. Out of this, note that out of 84 percent blood that is there in the systemic circulation 64 percent 64 percent blood is in the veins; and 13 percentage in the arteries, and only 7 percent which is where the exchange is happening 7 percentage in the arteriole and capillaries.

So, very little amount of blood in the capillaries that is where the gas exchange happens and that the exchange process must be very efficient. So, that even though small little amount of blood is there in the arteries or in the capillaries for very small time even though in spite of that only in spite that the gas exchange process happens efficiently.

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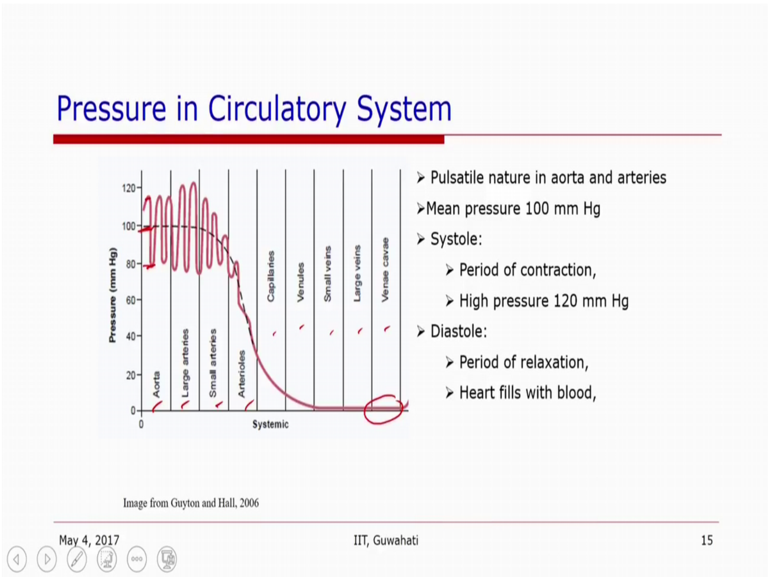

So, we have looked at the flow rates. Now, let us look at the pressure in the circulatory system. So, as we have seen that the heart contracts and expands so 72 times on an average in a minute. And the flow is of course, going to be of pulsatile nature in the aorta and the arteries. Here you see the pressure in different organs, aorta, large arteries, smaller arteries, arteries up to capillaries venules small veins large veins and finally, vena cava.

So, you might notice that blood the when the blood is returned to the heart, the pressure has almost reduced to 0. Whereas, when it is starts from the heart in the aorta the average pressure is about 100 or mean pressure is about 100, and it is pulsatile in natures. So, you might see the maximum pressure is called a it is about 120 mm Hg and the minimum pressure is about 80 mm Hg. So, the maximum pressure is known as systole, and the minimum pressure is known as diastole. Maximum pressure will occur when the heart is contracting and the blood is coming out with the full force, so that is period of contraction of the heart and when heart relaxes the minimum pressure will be there which is 80 mm of Hg.

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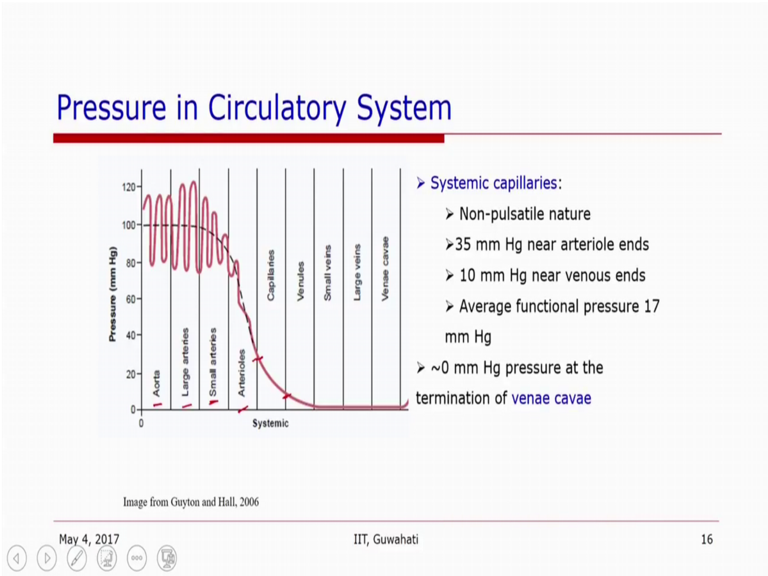

You might further notice that in the capillaries the flow is or the pressure is pulsatile in aorta large arteries and smaller arteries. And from arteriole onwards where the oscillations or pulsatile nature of the pressure and the flow is gone and the flow is smooth in capillaries you might notice the non pulsatile nature. The pressure in the capillaries at the entrance which about 35 mm Hg and when it comes out from the capillaries this has pressure about 10 mm Hg. So, about the average prefer in the capillaries about 17 mm Hg. And as I said earlier z about the pressure has almost 0 mm Hg pressure at the termination of vena cava.

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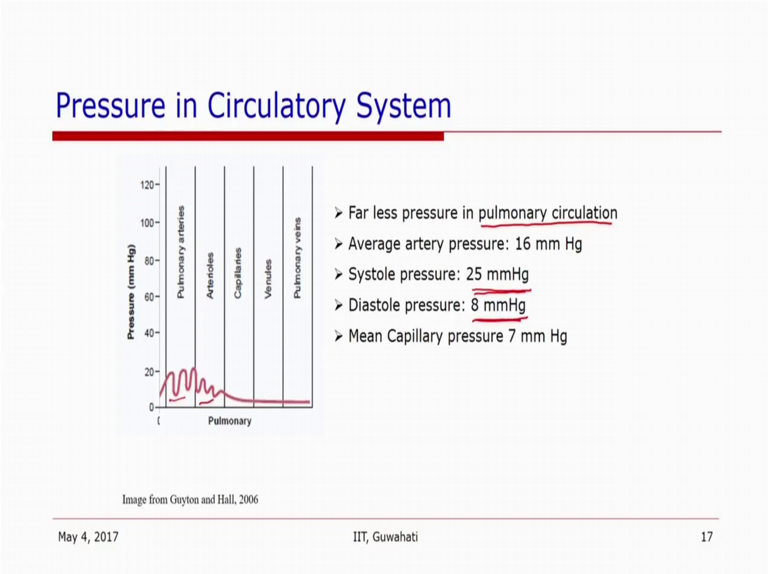

In the circulatory, in the pulmonary system, the trained of the pressure it is same you might see that pressure is pulsatile in nature in the pulmonary arteries as well as arterioles. And the pulsatile nature has gone in the capillaries. However, the numbers or the magnitude of pressure is low, the systole pressure is only 25 mm Hg and diastole is 8 mm Hg as compared to 120 80 in the systemic circulation.

When the blood supply if you might remember that the pulmonary circulation is the blood supply to the lung, you need only 25 mm Hg, 8 mm Hg systole and diastole pressure; whereas for the peripheral circulation the pressure requirement is high, 120 to 80 mm Hg.

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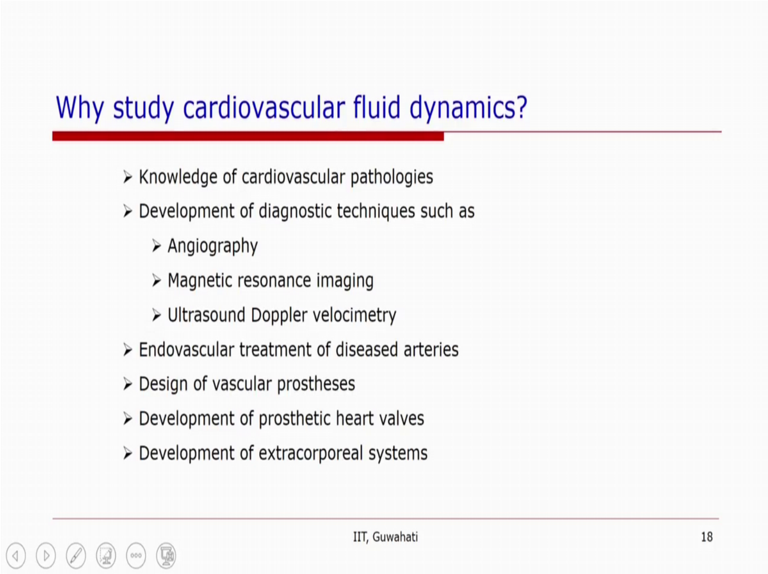

So, with this understanding of the cardiovascular system, what we have looked at that the cardiovascular system is composed of three main components. The heart which has two chambers, right heart and left heart and act as a pump. Then the fluid which is s suspension of small soft particle in water like Newtonian fluid. And flexible pipes ranging their size from few centimetre 2 to 3 centimetre to few microns. So, it is a multi scale nature of the problem. So, why should we study this complex flow, what is the motivation we will look at some of these applications further in detail as we go our progress in the course.

What I have listed down here is some of the applications. So, the knowledge of cardiovascular pathologies, so pathologies means understand the cause and effect of different diseases that is what is done in the pathologies when we when we go and gave our blood there and the blood test is done. And then after the testing based on the report the doctors or the clinicians or the pathologist they find out what diseases can be there or what can be the cause of the disease.

So, to understand that one need to understand the rheology of blood or different characteristics of the blood. At the same time for different diagnostic techniques for example, when the surgeons they carry out bypass, heart surgery or angioplasty, they need to understand the flow rates or they need to have the access to the arteries or they need to image the arteries. So, this is done by different techniques angiography, MRI, or

Ultrasound Doppler, velocimetry. So, to develop these techniques and use it clinically one needs to understand the flow behavior in normal condition, as well as in disease conditions.

Endovascular treatment is that diseased arteries, they need to be treated or they need to be removed, and new arteries is to be put in there or the strands need to be put in there. So, the treatment of the blocked arteries for that also one needs to understand the fluid dynamics fluid mechanics behavior. Design of vascular prostheses, prostheses is artificial organs. So, the design of different or new are organs, this again requires an understanding one understand what functions at what flow rate with what rheology a different a natural organ is behaving then only one can design a artificial organ or a synthetic organ which can replace a part of the model.

Development of prosthetic heart valve again heart valve which also an organ and development of extracorporeal systems, so extracorporeal system if one need to put in a system outside the body for some time for different medical purposes. Say for example, if the heart is to be replaced and the system is to be brought into a artificial heart for some time during the operation then that is to be done by an extracorporeal system.

So, development of such extracorporeal system also requires the understanding of fluid mechanics behavior. So, there are number of there is lot of motivation from the medical fraternity to understand the cardiovascular fluid mechanics and a lot of progress has been made in this direction.

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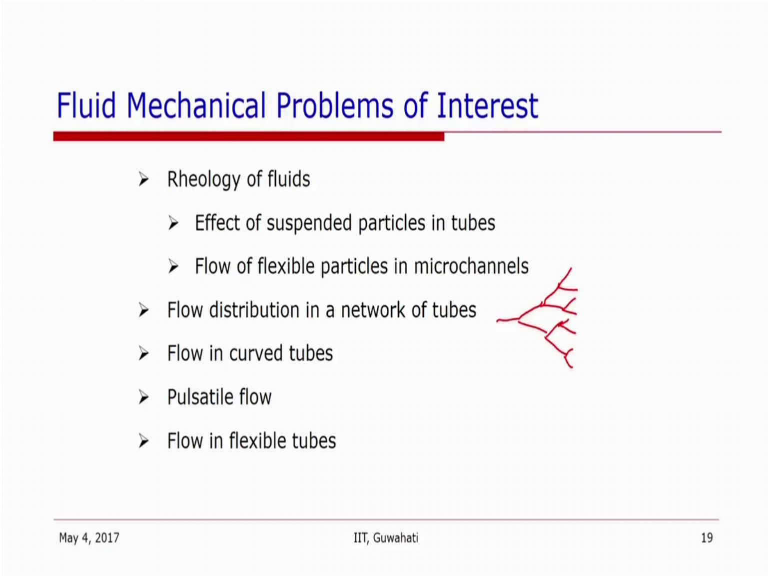

So, what are the problems of interest that we will study in this course? Of course one needs to understand the properties of the fluid that is flowing there. So, rheology of fluid, effect of different suspended particles, the morphology of blood we need to understand and then how these different soft particles affect the rheological behavior of the blood under different shear rates. And how does the flexible nature of the particle affect the rheology of blood.

Then as we have seen that the cardiovascular system is a network of a number of tubes where the tubes bifurcate multiple times. So, we need to also understand the nature of this bifurcation and the shear stress distribution pressure distribution during the bifurcation flow rate distribution. Then a flow most of these tubes are curved in nature, so the flow in curve tubes. The flow is always pulsatile. So, we need to understand the pulsatile flow and flow in flexible tubes. As I said earlier that most of the study or most of the equations that we derived in a basic fluid dynamics course is for flow in rigid tubes, here we also need to understand flow in flexible tube and their effect.

So, we have looked at the rheology of the blood or what we have discussed is the rheology of fluid and the flow in different types of channels. Apart from that we also need to understand the flow in the heart and that will be, we will cover that part also briefly. So, with this, we will stop this lecture.

And in the next lecture, we will further look at the applications and some basic non-dimensional numbers.