Introduction to Biomaterials
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Module No. # 01
Lecture No. # 13
Biological testing
(Hemocompatibility, tribological testing)

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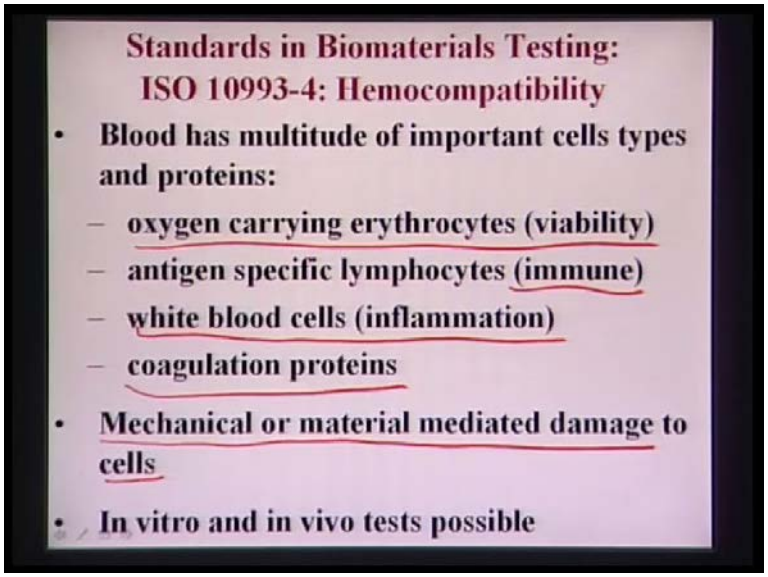

In the last lecture, I have discussed the In vitro cytotoxicity, that is, the cell level toxicity or the potential of the capability of biomaterial to cause cellular apoptosis or as well as the mechanism by which cell material intrusion takes place. That was lastly discussed. Towards the end of the lecture, I also discussed the genotoxicity, that is, the toxicity level at the gene level or in other words, the potential of the biomaterials to cause DNA damage; that was also discussed.

Some results were shown to illustrate that how the genotoxicity property of the biomaterial can be evaluated and to that end, the results of the single cell gel electrophoresis are the comet as it were shown.

Now, in continuation with this discussion of the In vitro biocompatibility assignment, in today's lecture, I will discuss first the hemocompatibility. Hemo means blood and blood compatibility testing. What are the basic principles, what are the typical mythology's that is taken and how to assess that whether the blood contact devices can be bio hemo compatible? That will be discussed.

So, first plot is considered as a tissue, in a sense that blood also contains a large number of cells and these cells present in the blood as well as number of proteins and they too perform certain specific functions. The first one is the oxygen carrying capacity and that gives a viability property. Then, antigen specific lymphocytes that give the immune capability or immune response. Then, white blood cells, the WBC that are in response for the inflammation and then, there are some proteins which help in the coagulation of blood tissue. Then, other things that are important are the mechanical or material mediated damage to cells.

So, this, what it mean by you know that whenever a material experiences some kind of mechanical stress, then that external stress also can cause the damage of the blood tissues. Now, one can prove this blood compatibility test, both the In vitro as well as the In vivo. So, again In vitro means that is the laboratory simulated test. In vivo means, that is the experiments which are conducted inside the animal.

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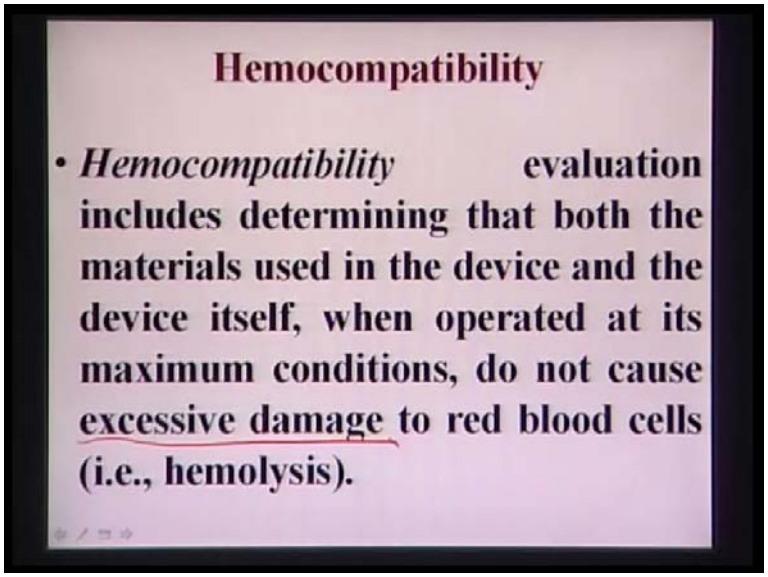

So, this is kind of more specific information of the hemocompatibility and this particular biocompatibility takes, includes determining that both the materials used in the device as well as device itself, when operated at its maximum conditions. They should not cause any excessive damage to RBC's or hemolysis. Again, coming to the fact that you have to you have to underline this excessive damage.

Now, if you recall the discussion of the genotoxicity when I have shown you these results that results, if you go back to the discussion of the genotoxicity yeah.

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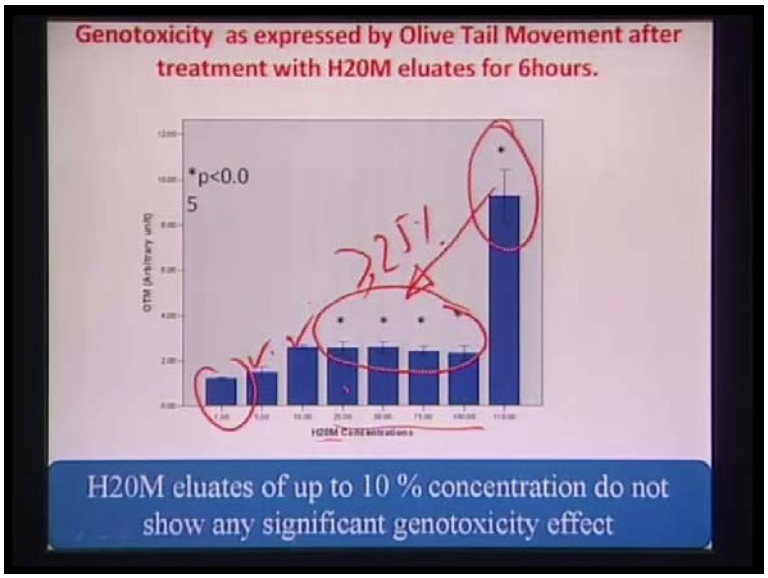

Yeah this is the results of the genotoxicity assay, that is the comet assay and these results are expressed in terms of olive tail movement. Olive tail movement means what is the length of the fragmented DNA and that length depends on what is the eluate concentration. Now, in the x-axis eluate concentration that we have taken, just the hydroxyapatite 20 percentage molar because we have tested that In vitro and In vivo potential.

So, that is the reason, that we have selected this particular eluate composition. Now, if you see that compared to positive control, although these materials, these compositions, they have through compare to the negative control, both these eluate concentrations over greater than 25 percent, greater than equal 25 percent as well as the positive control. They show statistically significant genotoxicity effect because they are damaged, DNA damaged length or the olive tail movement is much higher.

However, that from 25 percent or more, there that it is much less OTM values are much compare to the positive count. If you look at the 5 percent and 10 percent, there also the olive tail movement was measured and then, however they are not that significant compared to the negative control.

So, what I am trying to tell here, that it is important to recognize that whenever you put a material or whenever you inject some drugs or some particles inside the human body or in the In vitro conditions, they will cause some damage to the gene level. Your task is to understand that whether the gene level toxicity is very significant or very much statistical significant compared to the control specimen or not.

So, in the same way, I was trying to explain here that most of the materials are blood contacting devices or blood contacting materials. They will cause some damage to the RBC's, red blood cells. However, your task is to find out or determine, whether this damage is statically significant compared to some control samples or not and you cannot have an ideal material which do not cause any damage to the RBC. That is the bottom line I am trying to tell.

So, therefore, you have to remember that in a blood contacting device and blood contacting material will have some genotoxic effect, but this should not be statistically significantly higher compared to what a control specific control material, they do the damage to the RBC's. So, implant and devices contain materials that are recognized by blood as foreign material.

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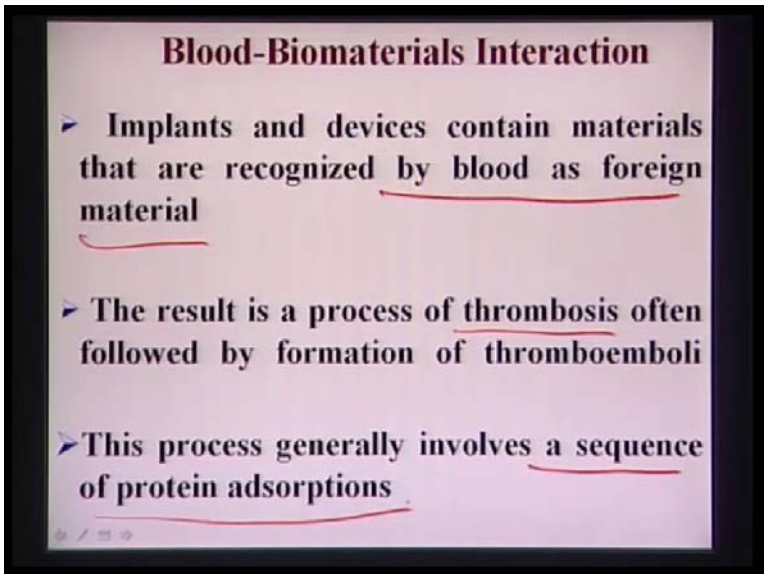

So, what they mentioned that whenever any synthetic material you are used, be it hydroxyapatite, be it polythene or other metals, then they are always called, recognized by the blood as the foreign material. Therefore, there will be some foreign body response that you can expect. Now, the result is the process of thrombosis often followed by the formation of thromboemboli. So, thrombosis means there will be some blood clotting there at the implant site or at the wound side and this positional involved sequence of protein adsorptions.

Remember, these protein absorptions again takes place just like, whenever you put a material inside the body and in case of the blood also contains some proteins. Therefore, proteins will necessarily be absorbed on the material surface, whether it is a blood or whether it is simple human body plasma.

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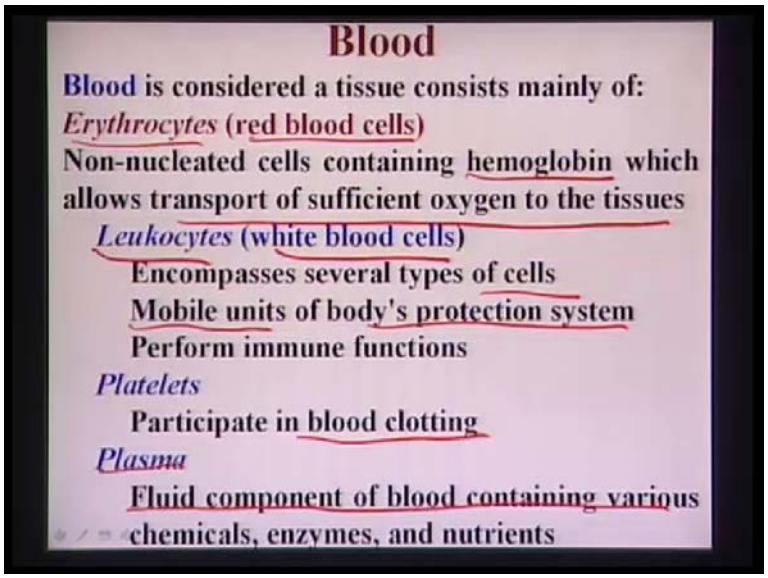

Now, this is what I have already told that blood is considered as a tissue and that primarily consists of erythrocytes. So, red blood cells biological name is erythrocytes and leukocytes, that is, the white blood cell. So, RBC's are generally non-nucleated cells and contains hemoglobin which allows transport of sufficient oxygen to the tissues. Then, how this oxygen is transported? That you know from your basic biology, from school biology, that is oxygen will be attached to the hemoglobin of the RBC's and thereby, will be transported to different parts of the body.

Now, leukocytes that encompasses several types of cells and this leucocytes of the mobile units of the body's protection system and that is why, many times you will see that, you know when you undergo this blood testing, so doctors always tell you to count the RBC, count the WBC. So, WBC's are important for your immune system. Immune means that is actual protection against some external damage or immune system. Therefore, if the WBC's are very less in your blood, then your immunity is very poor.

So, that was the reason why WBC content is also important. Now, WBC content varies for male and female. So, depending on you can see that whenever you are writing your sex as male or female, they will give you the particular limit of the WBC's that in normal healthy human being should have. If it is much lower than that limit, then that means, it is not desirable. Now, there are also blood platelets, they participate in the blood clotting.

Then, fourth one is the plasma. Plasma is like you know considered it as ECM, extracellular matrix. So, plasma here, actually it is a fluid component of the blood. So, that means, it is a kind of matrix. For any tissue, there will be a matrix for the different cells are aggregated together. So, here for the blood, it is the plasma that is the fluid component of blood containing various chemicals, enzymes and nutrients. So, these are like essential for the survival of the cells which are contained in blood ok.

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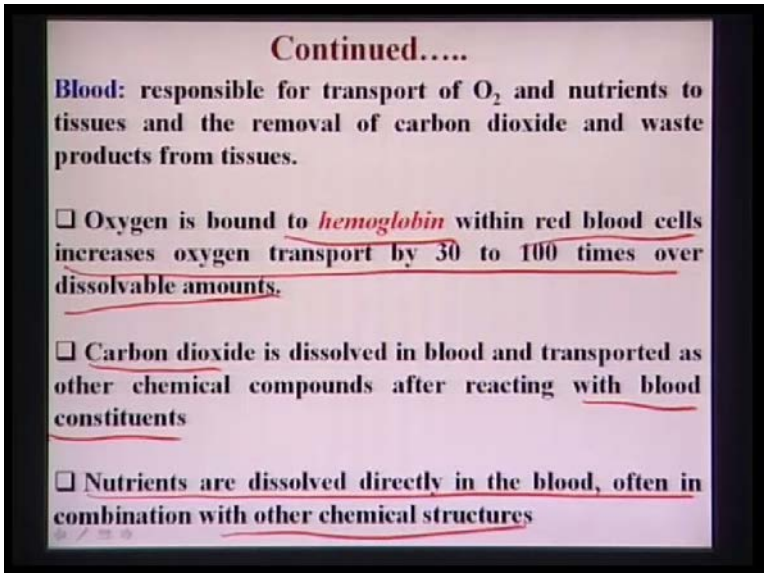

Now, blood as I said earlier, that blood is responsible for transport of oxygen and nutrients to tissues and the removal of carbon dioxide and waste products from tissues. Now, this cycle is dynamic in nature. This cycle means, that is, transport of oxygen into the blood and removal of carbon dioxide through blood. That cycle should be continuously operated for a normal healthy human being. Now, many times for the ailing patients or the patients which undergo surgery or who are not healthy, what happens in the blood oxygen level is reduced and carbon dioxide level is increased.

Carbon dioxide level is increased means, what the carbon dioxide is not being able to be transported to the blood and oxygen level is reduced, means that RBC's which carrying the oxygen, they are not performing its normal function. Thereby, they are not able to supply enough oxygen to the blood and that is the reason that many of the tissues will die subsequently because of the hypoxia. Hypoxia means that is the absence of sufficient amount of oxygen.

Many times if you see doctors or medical professionals, they use the word that patient died because of hypoxia. Hypoxia means, that is, the absence of sufficient level of oxygen in the blood. The next one, oxygen is bound hemoglobin within the red blood cells and that increases oxygen transports by 30 to 100 times over dissoluble amounts. So, the other one's is the carbon dioxide is dissolved in blood and transported other chemical compounds after reacting with blood constituents.

So, all these oxygen also directly bound to the hemoglobin and that is the way, oxygen is transported. Similarly, carbon dioxide is also dissolved in the blood. Blood means it is a blood plasma and then transported as other chemical compounds after reacting with blood constituents and nutrients are dissolved directly in the blood and often in combination with other chemicals structures.

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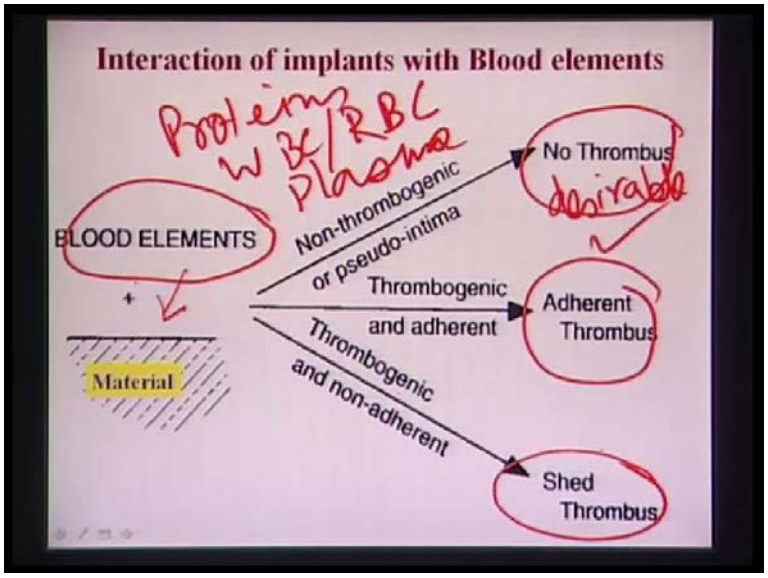

Now, this is your blood elements. Blood elements means you have the proteins, then you have the WBC, then you have the RBC and you have the plasma right. These are like four major elements of the blood. Now, you have the erythrocytes, you have the leucocytes, you have the proteins, you have the plasma. Now, when a material will react with blood, blood means it is a combination of all these. Therefore, the material will be reacting, interacting all these molecules.

What will happen initially? As you know from your basic cell material in fact and the proteins will be absorbed fast on the material surface and these proteins will be different

type, that is, the blood proteins. This will be different type in other cases, simple that when a bone replacement materials are implanted at certain specific anatomic locations.

Now, there can be three types of reactions. One is the non-thrombogenic or pseudo-intima. Non-thrombogenic means there is no thrombus formation. I will come to this. I will show you some slides to show you, illustrate that what is called thrombus. Now, that it is a non-thrombogenic means, it is very good, like you know there is no blood clotting that coagulation of the blood cells does not take place.

Therefore, it is very good that is like desirable. Then, it can be thrombogenic adherent thrombogenic and adherent means you have the thrombus formation and this thrombus will be adhering to the biomaterial surface. Third one is the thrombogenic and non-adherent thrombogenic and non-adherent means thrombus will be formed, but as the blood flow will be continuously. It is a dynamic condition, so the subsequence blood will take away all the thrombus. So, therefore, it is non-adherent.

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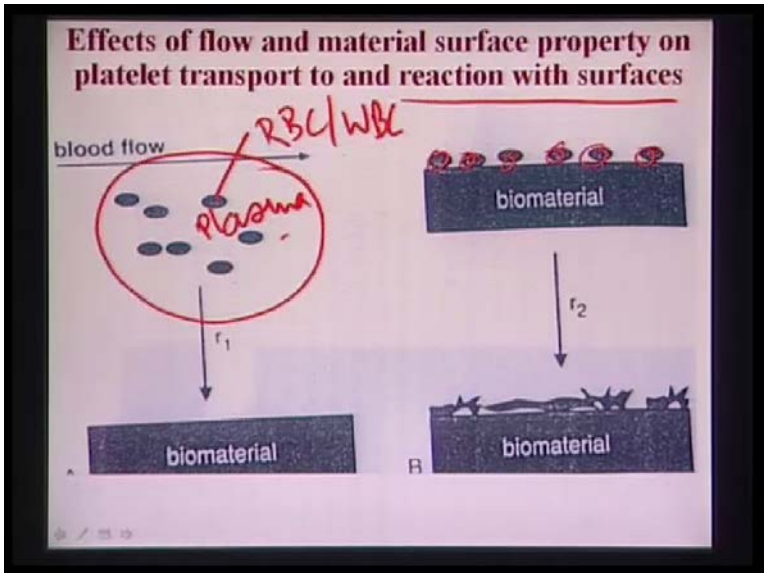

So, this is that effects of the blood flow and the material surface property on platelet transport and reaction with surfaces. Now, what you see? The blood flow. So, essentially the blood flow you can consider that it is a plasma and inside the plasma, you have all these leucocytes or R B C's or W B C's. They are there. This is blood cells and then what will happen? These blood cells initially will be adhering and first will be the protein absorbed and then, after this protein absorbed, then blood cells will be adhering. They

can spread on the surface like away normal cells, like you know fibroblast cells, osteoblast. They spread on the surface.

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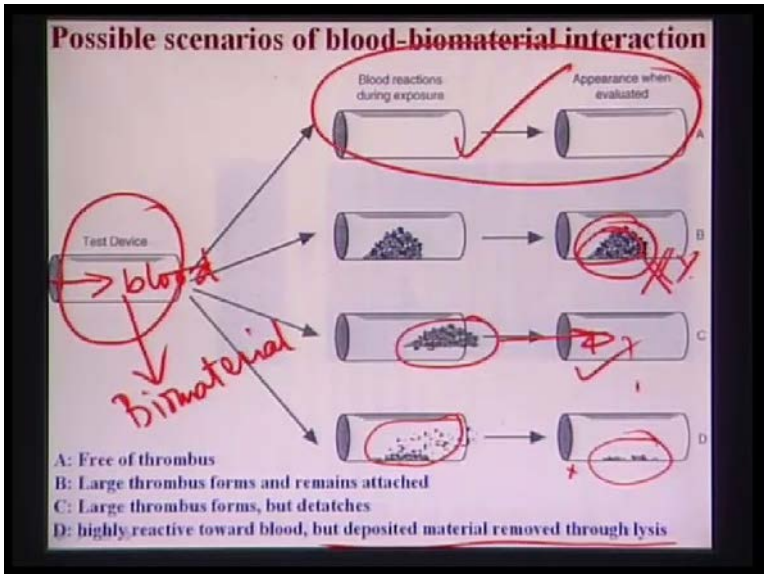

Now, here is what actually I thought, I will first show you, so that you understand what is thrombus and what are the different reactions those are possible. Now, these are like test device. Test device means this is your biomaterial. Now, in this biomaterial, now this is a cylindrical type of object you can see. So, this blood is made to flow at a constant rate through this device. So, that means continuously this biomaterial is in contact with the blood cells, blood proteins, everything blood plasma.

Now, if a biomaterial is strictly hemocompatible like excellent hemocompatible material, then this is the most desirable situation. There is no thrombus formation at all. Now, when a biomaterial is non-hemocompatible, that what you see is that thrombogenic or this cost thrombus formation. Thrombus means that is the aggregate formation of the blood cells and it will be combined to the blood proteins. Then, form a, this is like individual thrombus formation.

Then, last thrombus forms. Then, other scenario is that is the thrombus forms and this thrombus is getting transported. That means this thrombus is not strong enough to sustain the subsequent blood flow because blood is flowing continuously and if the thrombus is not strong enough or is not strongly adhering to the biomaterial surface, then the blood will immediately take it out from the material. Then, fourth one is that, it is highly

reactive toward blood, but deposited material removed through lysis, cell lysis takes place. Therefore, it is blood cells are adhering. They do not form large thrombus and then, blood cells also undergoing cell lysis.

So, that means it is not non-hemocompatible to that extent like this way. So, this is like cross. This is like ok you can have it. This is like you know, it is like mild cross. It is not like very strong cross like this one and the most desirable is that no thrombus formation takes place at any given time during exposer with the blood. So, I hope this is clear to you that you know what is meant by blood-biomaterial interaction with hemocompatibility as such.

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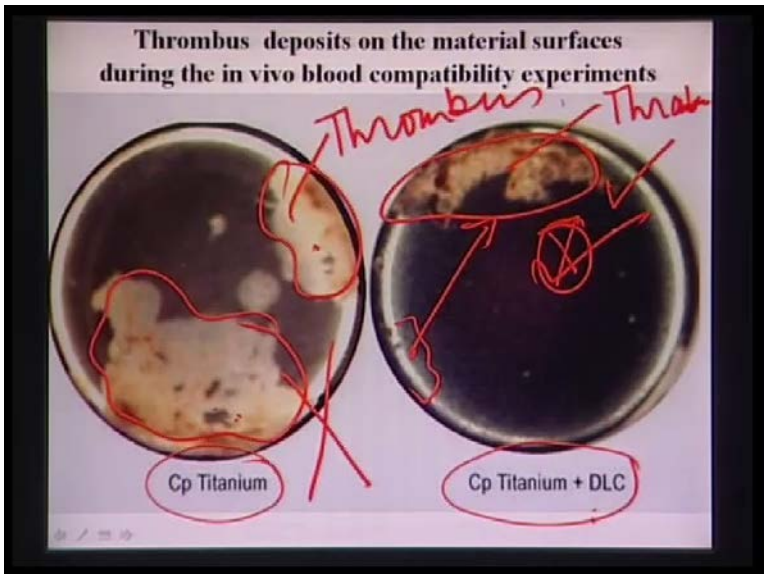

Now, this actually tells you that you know how to select that hemocompatible material. Now, there are two materials that are shown. One is that Cp titanium. Cp means commercially pure titanium. Second one is that commercially pure titanium plus DLC sportive. DLC stands for diamond like carbon. So, that means that diamond like carbon is coated on the titanium surface, but your death surface is the same titanium and that is possible because all this cell material interaction, blood material interaction is essentially surface property driven.

That means it is a surface property that is important in these all these interaction right biological interaction therefore, if you can manipulate the surface properties or if you can manipulate the surface composition, then also you can induce the good biocompatibility

property. Although, your underlying subscript can be non-biocompatibility. Do you understand what I am saying? So, the same thing has been shown here that if you have the commercially pure titanium, you see that these are like thrombus here right. Then, if you have the DLC coating, then that the thrombus formation is also taking place, but if you see that extent or the quantification of this thrombus formation, it is largely non-desirable whether this can be tolerated or this can be (( )). If you take a control sample and then put the same treatment of this In vivo biocompatibility case, you will probably see the same control sample. We will have some kind of thrombus formation, but not to the extent.

So, statistically if you quantify this versus this, control versus Cp titanium plus DLC coating, you will see this will not be statistically significant in that sense. Therefore, you can consider for potential blood contacting device application right. So, this is like you know, some examples that I have taken from literature, that is, you know platelet consumption when exposed to blood for 30 minutes duration.

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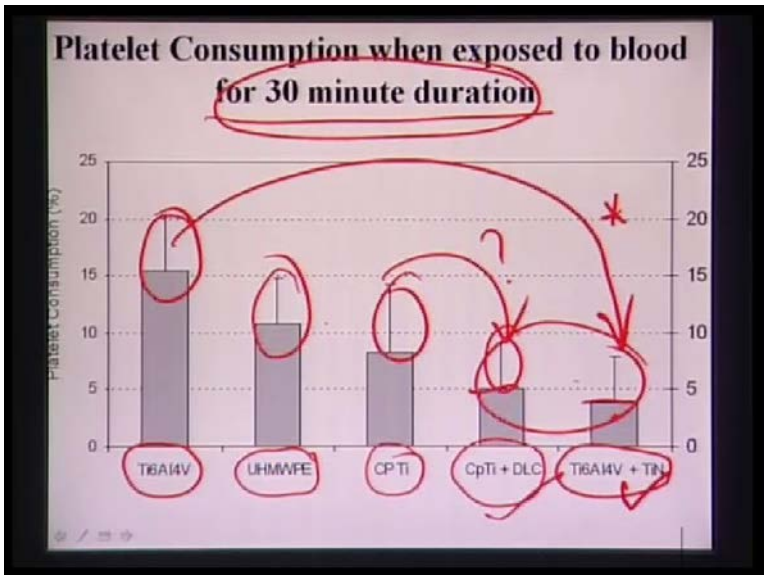

Now, you can see when we want to compare the efficiency or if you want to compare the blood compatibility properties of different materials, then you have to keep all other parameters constant and all other parameters is case duration blood flow rate. So, blood flow rate should be constant. Test duration is here taken as 30 minutes duration.

Now, after 30 minute duration what you see here, Ti6l4V, that is titanium 6 percent, aluminum 4 percent, vanadium all time molecular at polythene, that is UHMWPE, that is ultra high molecular polymer. That is an example of biopolymer commercial pure titanium. That is the third one. I just, I have shown you the previous slide. The commercially pure titanium plus DLC coating, that is, diamond like carbon coatings and titanium 6l4V plus titanium nitrite coating.

So, you have this diamond like coating, you have this titanium nitride coating and those two coatings as you can see here, that their the mean value if you consider, this mean value is much less from this titanium 6 percent, aluminum 4 vanadium or even the ultra high molecular polythene, but seems that (( )) overlap. I do not think, they have very much statistically significant reduction by cooking this coating.

However, if you consider that over all blood compatibility of these materials, you can clearly see because of the presence of titanium nitrate coating on Ti cell 4B. So, if you compare this versus this, then you can put a star. Star means that is statistically significant. However, this versus this, I do not think it will be statistically significant because there error birds almost like overlapped with each other.

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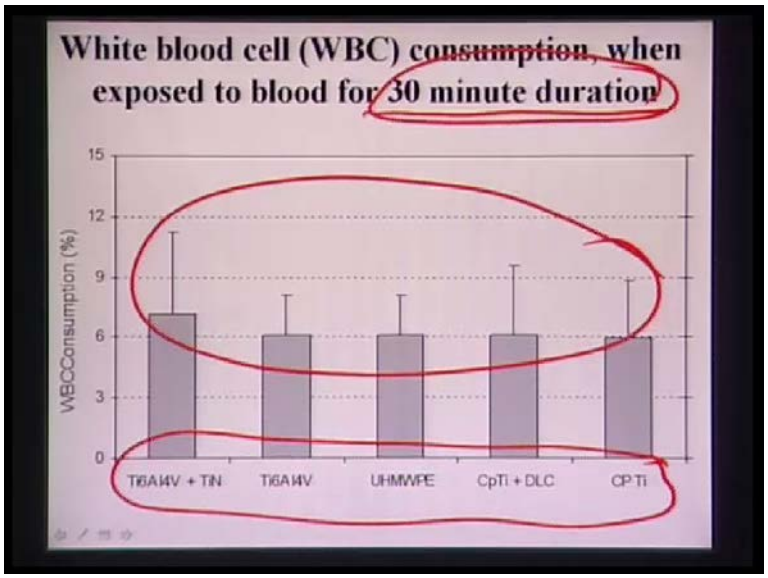

Now, this is WBC consumption, that is, the white blood cells. So, after exposed to blood for thirty minutes duration, you can count that how many WBC's or white blood cells are present on this blood contacting devices.

Again, what you see that all these error bars, they overlap with each other. That means as far as the WBC consumption is concerned, there is no statistically different result that we can obtain. That is statistically significant different result that you can obtain among this particular group of materials for these particular combination of case para.

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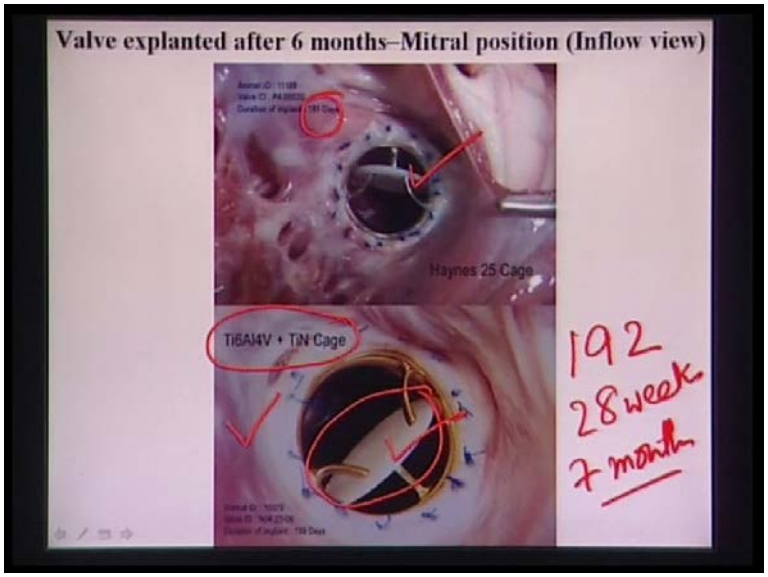

This is the example of this. You know artificial heart valve which is made of this titanium 6, aluminum 4 vanadium that is the alloy plus titanium nitrite coating.

You can see that is that after 192 days, means it is roughly around 28 weeks. So, 28 weeks means, it is roughly around 7 months. So, it was implanted in some animals and this duration of this implant is 7 months and then, here it is one around the same time. So, we are comparing with the titanium nitrite coating and without titanium nitrite coating and this is after valve is explanted after 6 months. Then, what you can see roughly, that this material they have a much better performance compared to the other material.

So, after I completed this, you know In vitro or In vivo hemocompatibility that blood contacting for blood contacting devices.

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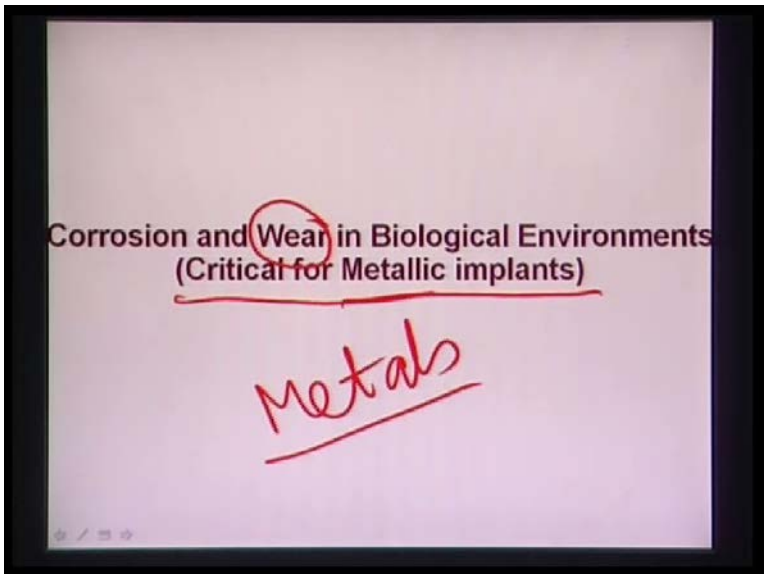

I will now discuss with you that corrosion and wear of materials in biological environments. Now, corrosion and wear are these properties which are important for rough mostly for metallic materials because metals are largely prone to corrosion in the In vitro environment or in the simulated body (( )) environment, where is the progressive material damage at the two surfaces in relative motion. That is the definition of the wear. I will come to this later.

Now, so that is why, I have made this statement here. This is critical for metallic implants like stainless steel titanium. Now, why stainless steel are getting replaced by titanium, although titanium is expensive because titanium has much more or better corrosion resistant compared to titanium. Sorry, titanium has better corrosion resistant than stainless steel because titanium shows active passive behavior. I will show you all those things.

Then, stainless steel and wear resistance wise also mechanical material, they have very, they have lower hardness and have fore this mechanical materials. They have higher wear range.

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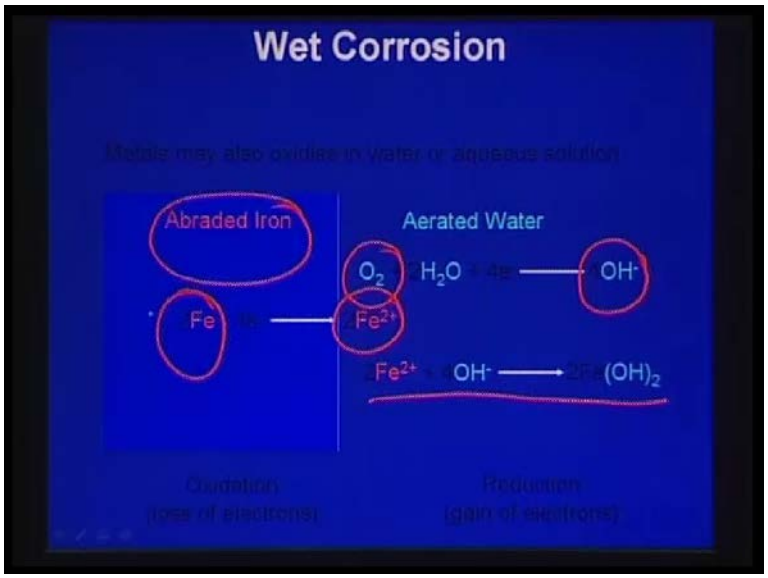

Now, wet corrosion behavior is what is important for metallic materials. Wet corrosion means, for example, this is abraded iron, that is, that iron or iron based steel materials. Now, iron can be oxidized to form Fe plus 2 irons and then, oxygen that is aerated water. Then, can oxygen form dissolve oxygen in the water can form OH minus and Fe plus 2 react to the OH minus to form iron hydroxide.

So, that is the way iron will be continuously leached out from the metals and that is the kind of corrosion mechanism by which that iron will be corroded in aerated water. I mean abraded water.

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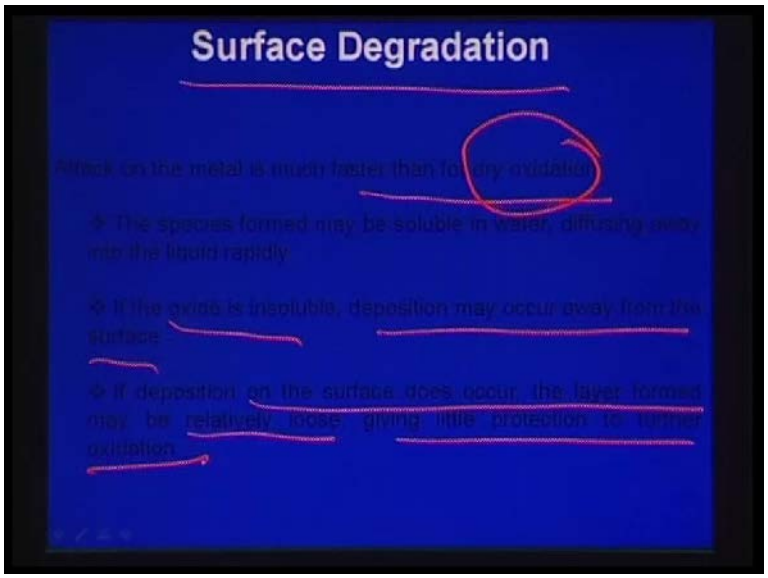

Then, surface degradation, this is attack on these metals which is faster than dry, then for dry oxidation. Now, dry oxidation means, that is, the corrosion which takes place in the absence of any water. That means in the ambient conditions, now if the oxide is insoluble, the deposition may occur away from the surface and if the deposition of the surface does not occur, the layer form may be relatively lose giving the protection to further oxidation. Now, there is a more relevant to the dry oxidation and dry oxidation does not take place in case of the application of the biomaterials.

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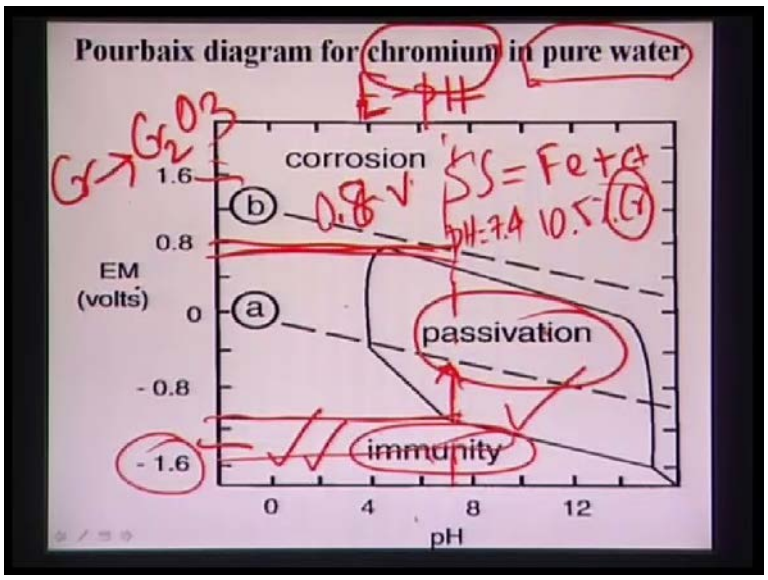

Now, let us see that what Pourbaix diagram is. Pourbaix diagram means that is E versus pH diagram. So, other name of pourbaix diagram is H versus pH diagram. Now, inside the human body or simulated body fluid, there pH is always maintained at 7.4 and inside the human body, your pore pH or the blood pH is the 7.4. That is the reason, why all the In vitro experiments, they are conducted at pH is equal to 7.4.

Now, inside the human body depending on the concentration of ions, then this e value that is the electrochemical potential value, they also vary over a large range. What you can see, that is given for the example of chromium for example, because stainless steel, the stainless, the corrosion resistance of the stainless steel is imparted by the presence of chromium only because stainless steel means that is iron plus carbon. That is always that steel means that is the solid session iron and carbon. If carbon is not there, you cannot call it steel and stainless steel means at least 10.5 percent chromium must be there and this is the chromium which keeps the steel. They require corrosion resistance properties.

So, therefore, it is important to find out that what the stability of chromium is. For example, in pure water as far as the pourbaix diagram is concerned, that is the reason that why I am showing that pourbaix diagram of the chromium. Now, what you see here that at around 7.4 here, this is the line. If I can draw at pH is equal to 7.4, now what you see if the electrochemical voltage is highly negative and then, it is in the immunity region. Immunity means that the stainless steel will not undergo any corrosion. That means stainless steel will be immune to corrosion ok.

So, that means the surrounding environment will not have any corroding effect on the chromium. Now, the moment this is electrochemical voltage at this 7.8 is above around point minus 1.2 or minus 1 or up to this value that is around 0.6 or so. Then, it will undergo passivation. Passivation means, what that means chromium will form chromium oxide or chromium can form other higher oxide also and depending on what is the voltage and what is the conditions. So, passivation is steel immunity is the highly desirable. So, I am putting two ticks.

Passivation is also desirable that means that chromium is protecting underlying material by forming the passivated oxides on the surface. Now, the moment this electrochemical potential at pH is at 7.4 is above 0.8 hold, then your corrosion starts. So, at higher

electrochemical potential range, although there is sufficient amount of chromium which otherwise keeps you good corrosion resistance, that will not service purpose ok.

So, therefore in the human, the message that I am trying to give from this slide is that inside the In vivo conditions or In vivo or inside the human body when if you put the stainless steel, it will not protect you from corrosion. If the electrochemical potential value is one fold or more than one fold, then the stainless steel itself will undergo corrosion. The other thing is that I want to tell, that here all these experiments, all these data points based on your identifying whether it is a immunity region, passivation region corrosion region, they are based on experiments in water, but your simulated body fluid is not a pure aqua's environment. It contains several salt, like sodium chloride, calcium chloride etcetera, potassium chloride and if you want to simulate closely the In vivo condition, then it also contains the protein molecules like serum protein and so on. So, they are the environmental effect because of the presence of the sodium chloride and all they are the environmental effect will be much more significant than pure aqua's environment. Again, it may be so that your passivity region is reduced or it is contracted and therefore, with simple increase in the above 0 volt, the material can go to the corrosion region ok.

So, in that kind of sbf environment or In vivo environment, this particular diagram will not be valid anymore and you need to construct a separate diagram by contacting tests in the pure sbf environment or the body environment simulated. You know where the solution which will simulate very close to the In vivo environment and as I said that knowing the concentration of the sbf or knowing the concentration of the different elements in the In vivo environment, the corrosion region will be expanded, much more expanded. Much more means their passivity region will be narrow and corrosion region will be expanded much more, so that this material can be easily corroded in that kind of environment.

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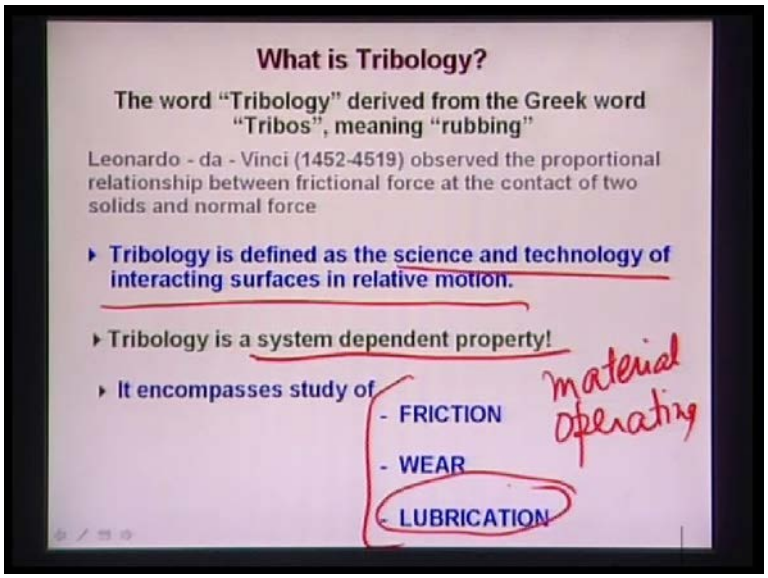

Now, coming to the Tribology, that is the friction and wear kind of tests. So, this tribology is derived from the Greek word tribos, which means rubbing. Rubbing means when two materials, they rub against each other. So, that is the interface. These materials will undergo surface damage and surface damage induces the material removal and that can cause the friction and the wear of the material. It is defined as the science and technology. So, this is the formal definition is defined as the science technology of interacting surfaces in relative motion important thing of tribology say system dependent property system. Dependent property means tribological property. It depends on the material parameters for and at the same time, it depends on the operating parameters.

Now, if somebody will ask you that what the coefficient of friction of steel is, it does not mean anything because coefficient of friction of steel against steel would be different for coefficient of friction of steel against alumina or against zirconia. So, if that other body or the matting body or the counter body is different than coefficient of friction will also change. Therefore, if you make any statement that coefficient of friction of steel is 0.5, it is scientifically wrong. It is meaningless statement. You have to always scale coefficient of friction of steel against what that material. Also, you have to explicitly mention, whenever you mention the tribological profile ok.

The second thing is that operating parameters mean, that is tribological properties are also dependent on the sliding speed. It depends on the load. So, if you change your load or if you change your sliding speed or the prating speed, then tribological properties also

will be different. Now, come back to the same system. Let the steel versus steel. If you change the load from 5 newton to 10 newton, then your friction coefficient also will change. Your wear rate also will change.

If your sliding velocity is changed from 1 meter per second to 4 meter per second, then all the tribological properties also will change because the moment you change the operating parameters, tribological properties will change. The moment you change your counter body or your matting couple, then also tribological properties will change. Now, it encompasses the study of friction, wear and lubrication and lubrication is mostly related to the mechanical engineer. So, we will not be dealing with lubrication here as far as the biomaterials are concerned.

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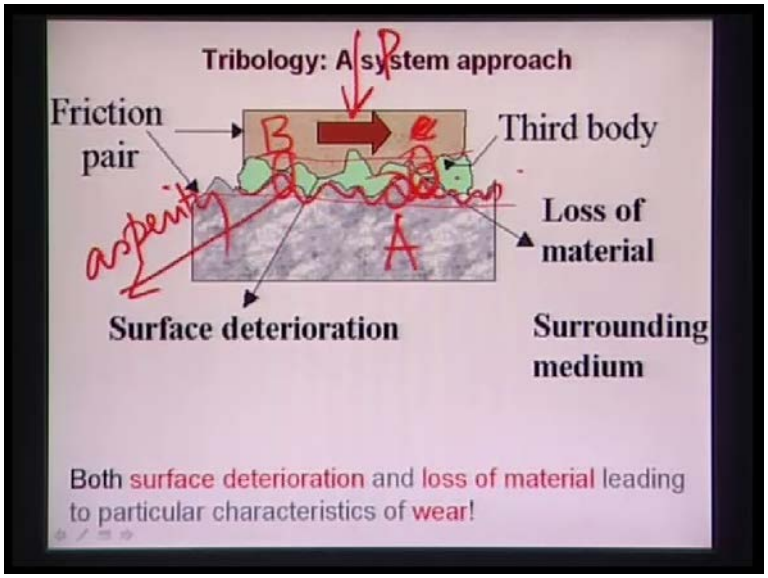

Now, what is meant by system property here? Suppose, this is A, one body and this is another body B. So, these are like two matting couple. Now, if B is different, if B is replaced by C, then your tribological properties also will be changed. The other thing is that I am trying to mention here is that, although these both and if you look at your own eye or naked eyes, you will find that they are like perfectly smooth surface, but microscopically they are not smooth. They always contain this kind of hills and valleys which in scientifically known as asperity. So, this is one asperity and then the other asperity is, for example this or this.

So, each surface contains capital N number of asperities, whether it is a flat body or whether it is a ball surface. Now, tribological interaction actually takes place in these asperities and asperities wherever whenever you will put A load here, then P will make contact with A only at the multiple asperities, not all throughout the surface. .

So, therefore, whatever friction coefficient, whatever where you see that is the result of this physic mechanical infraction between the N number of asperities from the two opposing or two matting solids.

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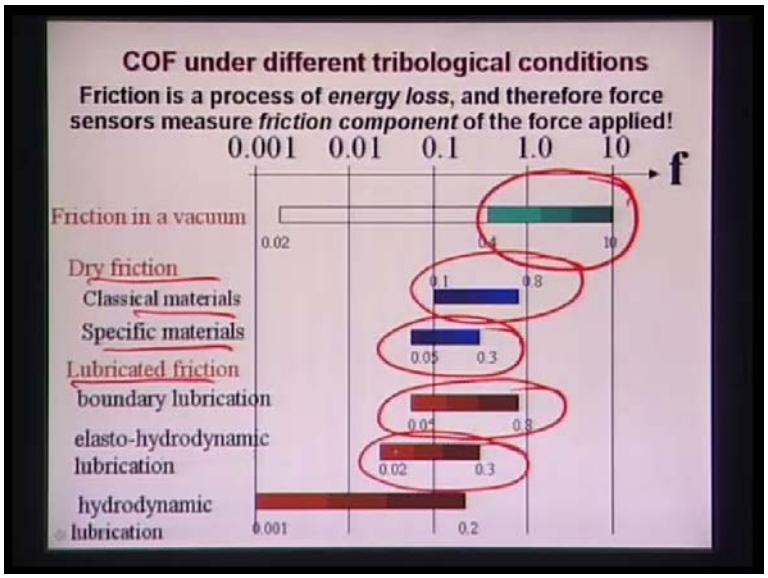

So, this shows that you know friction coefficient on a different tribological conditions for self metal steel. Now, typically friction you know vacuum, they can be very high or that can go up to 10 or so. Dry friction you know classical metals are specific metals. It can vary from 0.1 to 0.8 or 0.05 to 0.3. If lubricated frictions, then it values between 0.05 to 0.8 and 0.02 to 0.3.

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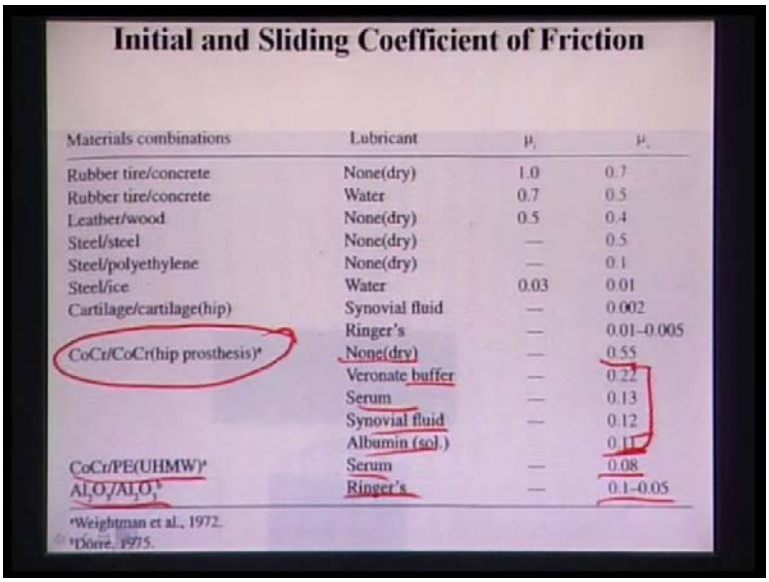

Now, this is the initial and starting coefficient of friction here. You can have different materials for tribological applications. For example, you can see cobalt, chromium. This is used as the cobalt chrome moly and these are used in the knee joint application. In the knee joint applications, if you see in the dry condition that means without any lubricant, it is around 0.55. So, 0.6 is the (( )) friction. The moment you keep the lubricants, like you know serum or synovial fluid or albumin, that is the solution in the protein solution.

In the presence of this serum protein and all tribological properties, friction coefficient is reduced to around 0.1 or so. In the cobalt chrome moly, that is polyethylene. In serum solution, it is 0.08. Now, alumina versus aluminum ringers solution is somewhere around 0.1 to 0.05. So, as you see that if your solution is changed or if your environment is changed, then your coefficient of friction also changes.

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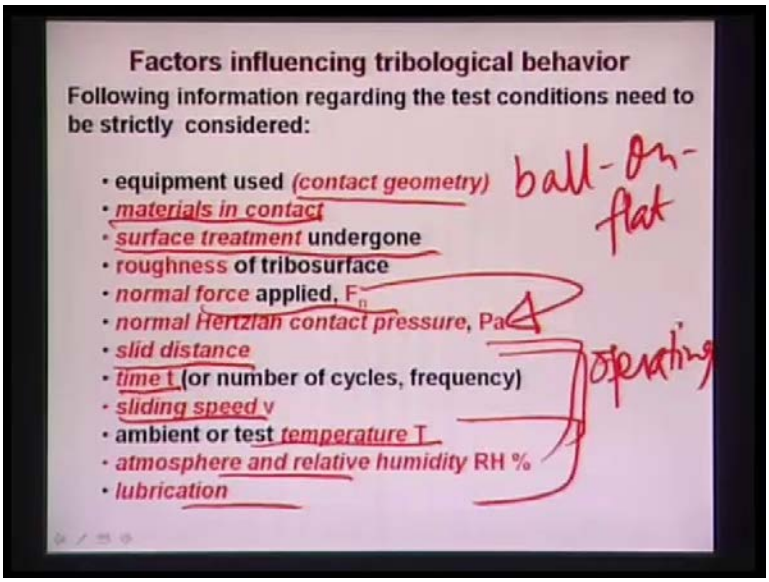

Now, if you look at what are the different factors which will influence the tribological behavior. First one is the contact geometry, whether it is a ball-on-flat type of geometry or whether is undergone. These types of geometry, that is important. Then, materials in contact, as I said the tribology depends on the material parameter as well as the operating parameter.

So, the moment you change, they are matting solid. That is that other material which is in contact with the nominal material, the tribological properties will also change. Now, like biological properties, tribological properties are also surface sensitive. That means underlying substrate can be same. If you do any surface treatment or if you put any coating on the material surface, then tribological properties also will be influenced or also will be checked. For example, you can put titanium, but the moment you put titanium nitrate putting on the same titanium, then the tribological properties will change because then tribological properties will be determined by the properties of the titanium nitride, not the titanium.

Then, roughness of the tribological surface. So, if you remember that what I have shown you, some two slides back, that is any nominally flat surface, always composed of multiple numbers of asperities. Asperities means like those are like hills and valleys. Those are present in the material surface and these asperities actually will interact and at the loaded tribo contact and that leads to the friction and wear of the system.

Fourth and fifth one is the normal force, that is f n. That is applied through when the matting couple, thus depending on the normal load. Then, that will form some hertzian contact diameter. Then, you can find out what is the hertzian contact pressure or the tribal couple? What is the time duration and what is the total sliding displacement? What is the sliding speed? What is the ambient or test temperature and atmosphere and lubrication?

These are all called the operating parameters. Operating parameters means, like this is the load. What is the sliding distance, what is the sliding speed etcetera and as well as the atmosphere?

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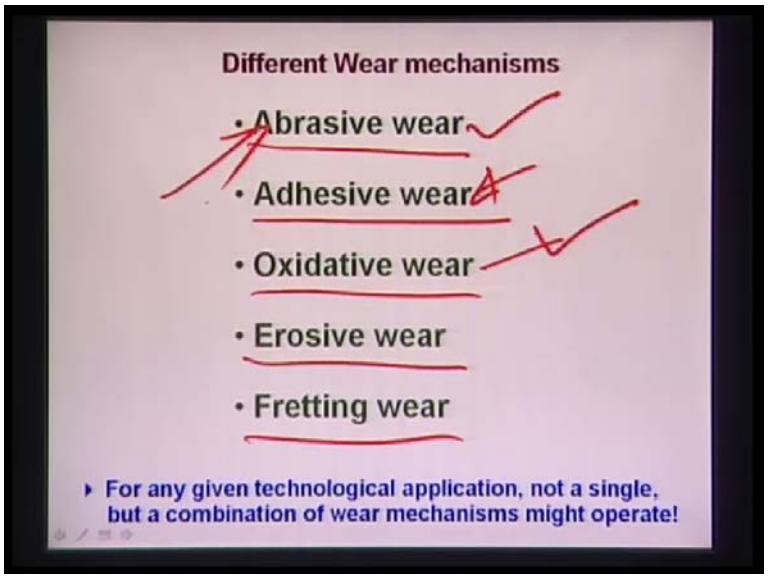

Now, what are the different mechanisms of the wear? Wear can be classified as that 5 primarily distinguishable mechanisms, that is one is that Abrasive wear. Then, it is called Adhesive wear. Then, Oxidative wear and then, Erosive wear. The last one is the Fretting wear. Now, for any given technological applications, it is important that not a single, but a combination of wear mechanisms might operate.

That means, it may be so that abrasive wear is dominant, but you have some contributions from the adhesive wear right. At the same time, it may be. So, your oxidative wear is the dominant wear mechanism, but you have some contribution from abrasive wear. That means there will always be some dominant contribution of particular

wear mechanism. In addition to that, you also have minor or noticeable contribution from the other wear mechanism.

So, you cannot say that for this particular operative combination, operating parameters and for this particular sliding couple, it is only abrasive wear that take place. So, it is a combination of mechanism that takes place.

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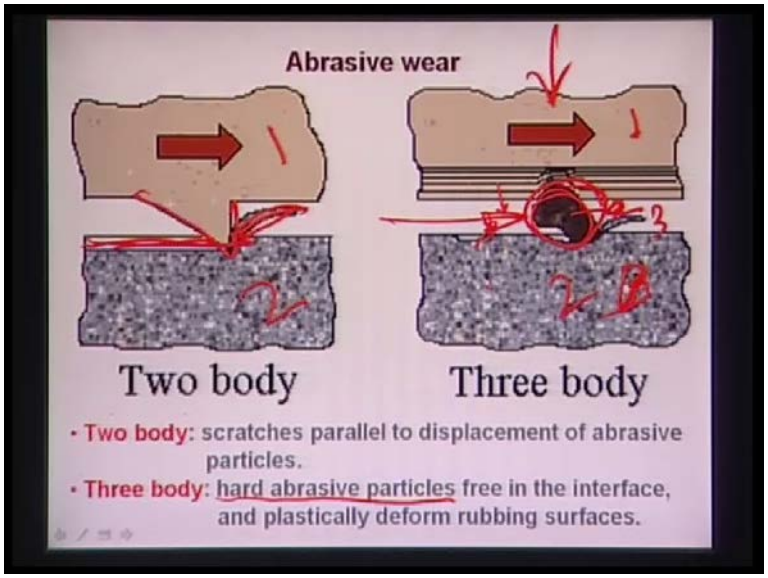

Now, abrasive wear means, like you know you have surface asperities and then, surface asperities are actually upgrading the materials. The other time many time people also described abrasive wear is like a ploughing mechanism. Ploughing means, if you remember the farmers, they plough the ground. Plough means like they take out that mud or they dig the mud and then, that helps in the agriculture.

So, similar things what happens in the abrasive wear in a conical asperity. If you can notice here and then, conical asperity, it abrades away the material and it forms the chips kind of thing. These chips are formed also during the machining of the materials.

Now, this is a called two body operations. Two body operation means, this is body number 1 and this is the body number 2. Now, what is called three body operation? You have this body number 1; this is called body number 2. This is called, sorry this is called body 2 and this is called body number 3. Now, what happens in some abrasive wear, you have these wear particles that is generated. Wear particles means, now whenever the

material will undergo extensive damage, then some part of this material, either from body 1 or either from body 2, they form some kind of wear fragments like wear materials like remove materials and this wear particles is called body 3.

Now, in the loaded contact in this kind of situation, when one body is moving with respect to the another body or one body is in relative motion with respect to the other body, then this is the wear particles which will contribute to the friction and wear. This wear particles are typically hard abrasive particles and these hard abrasive particles either can be intentionally introduced between the two bodies or they can be self generated during the wear experiments itself.

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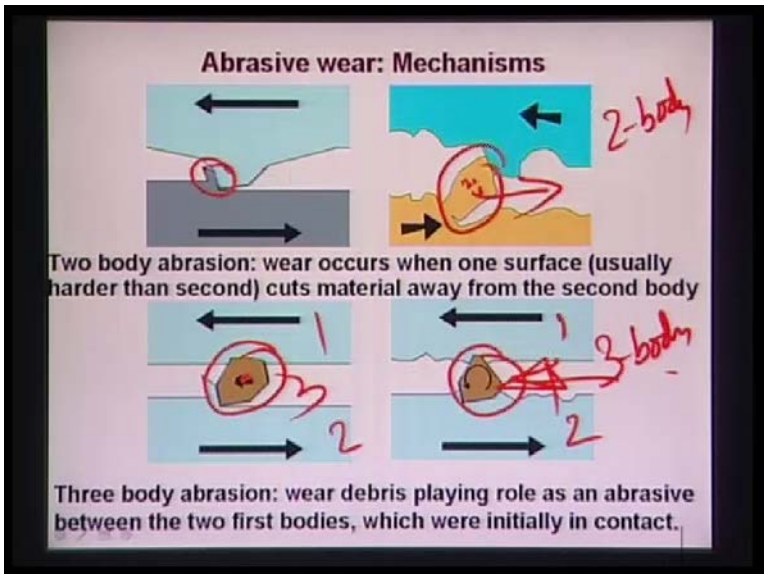

This is little bit more of the abrasive wear mechanisms. This is called two body wear and this is called three body wear. As you can see here, this is the wear fragments. They form and this is the cheap that can be removed immediately during the next impact.

Now, the second three body wear is that it is that external wear particles which are introduced in between the two fast bodies. So, two fast bodies, means this is body 1 and this is body 2 and this is the third body, but here this wear fragment is generated in C2. Here, these wear fragments or this wear particles or this abrasive particles are introduced externally at the inter phase between the two fast bodies.

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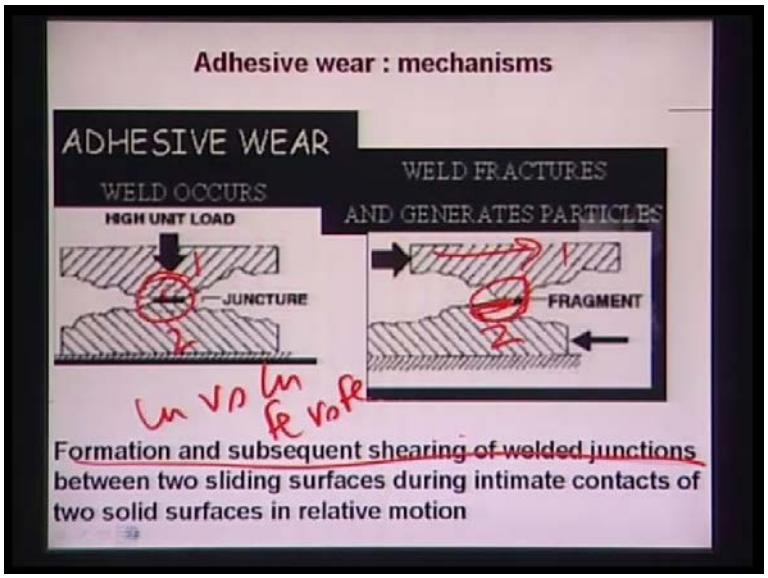

This is another wear mechanism is called adhesive wear. Adhesive wear means that essentially when the two fast bodies, 1 and 2 are made of the same material, for example copper versus copper or iron versus iron. In that case, you have the adhesive wear. The adhesive wear means, they can initially contact. They can initially make welded joint. You know the welding? Welding means when the two materials are joined together. So, similar thing happens because they are the same composition, as I said like copper versus copper or iron versus iron. When they have the two same compositions, that welding can take place very easily.

Then, what will happen when this one body is in relative motion against another body? That relative motion can only take place if this welded joint can be broken as a wear fragment and that is what has been shown here. So, formation as subsequent shearing of welded junctions between two sliding surfaces, that what takes place during that adhesive wear.

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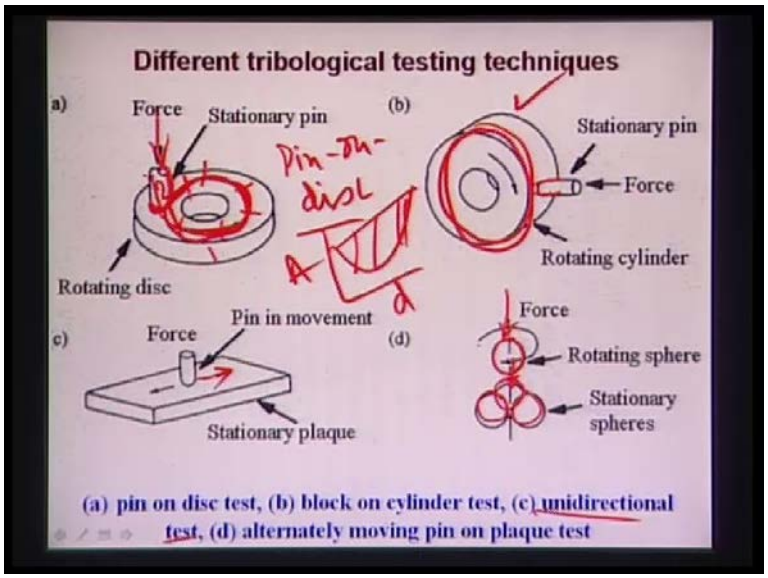

So, this slide shows actually that you know different contact configuration what you can achieve in different phase setup. This first one is called pin on disc type of setup and this pin on disc is most widely used across the world. Essentially, as the names suggest that pin means this is your cylindrical pin and this cylindrical pin is forced against a rotating disc, normally here. As I said, that one body is relative motion against the other, so here the rotating bodies number 1 and pin is number 2, so this call as rotates at certain rotational speed and pin space at rest at a particular position ok.

So, after that what will happen? You will find either wear track is formed. Wear track means this track experiences the material damage or this track is that area, where the material damage under wear has taken place. Then, you can find out if it is a metal which undergoes extensive wear. Then, if you can measure the wear before the case, you can measure the wear after the test. Then, you can find out that what is the mass removal due to the wear test in ceramics that wear volume is much less than what you do after. You do this stage, then you can take at different position that 2d surface profiles using the non-contact surface profilometer, like leather surface profilometer. Then, you can measure the area of this profilometer in each profile and then, you can put this profile, the area as the function of the distance and this will give you this kind of torque.

You can integrate under the curve and that will give you the volume of the wear curve. So, this volume is the wear rate. Essentially, it tells you the wear rate. Now, this b is known as the pin on cylinder type of configuration.

Pin on cylinder means again it is a rotating cylinder and these rotations at it particular speed. That pin is stationary and this pin, actually also experiences where the third one is that unidirectional test. Unidirectional test means, if is not a, you know that rotating type of motion, but it is a linear motion and linear motion that it always takes place in particular direction. The fourth one is that four ball test. Four ball test means this is one ball, this is the other three balls and these balls is in the loaded contact against the three balls. When it rotates, then it causes the friction and wear.

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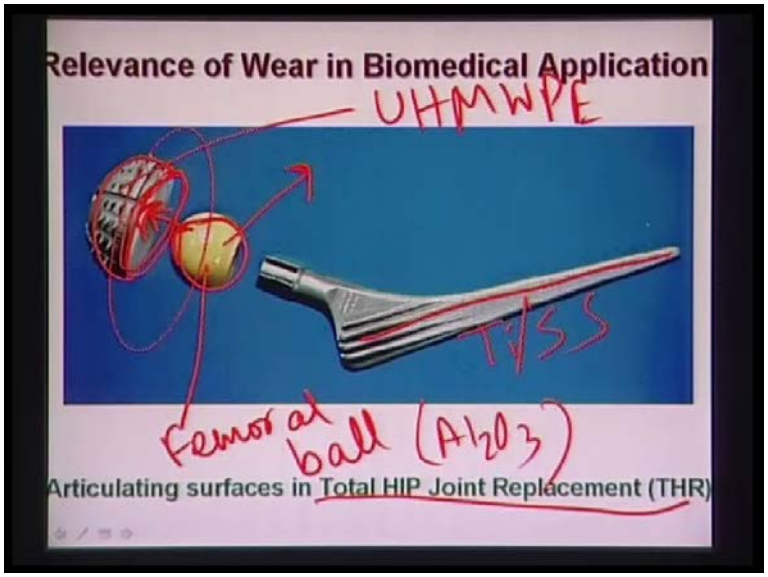

Now, since I have discussed so much on the scientific aspect of what is the wear mechanisms or what is the friction coefficient of the different materials, what are the factors which influences the friction and wear properties. I would like to now give you an example or one important example, where wear causes significant damage of the biomaterials. Now, this example is taken for the total hip joint replacement, THR. This is one of the orthopedic applications.

Now, this is your stem. Now, this stem can be made up of titanium or stainless steel. Titanium is extensive, is very costly. Stainless steel is rather cheap in developing nations like India. People always use the stainless because people cannot afford that costly titanium stem.

However, titanium as you know has much better corrosion resistance than the stainless steel. Therefore, if you use the titanium stem, then it will have a much longer life

compared to that of the stainless steel. Durability or longer life lasting is much better for titanium compared to stainless steel.

Now, this is your femoral ball head. Now, this is your femoral ball and this femoral ball can be made up of either metal, stainless steel or it can be made up of ceramic, like alumina or zirconia. Then, this is your acetabular cup and this acetabular cup is typically made up of ultra high molecular with polyethylene or it can be some ceramic surfaces also. What I am trying to focus on here is that the wear takes place here, primarily here because this ball has to be fitted inside the acetabular cup. During this motion, that human motion what happens, this ball and the acetabular cups face will always make some kind of reciprocity motion or the fretting kind of conditions. So, that is the reason whenever you want to replace this ball material and replace this ultra mated polyethylene cup, you must do wear test in the simulated body feed environment before. You can approve that this material will have a longer life or better biocompatibility property.

So, as I said in the beginning, biocompatibility is a broad term. It encompasses cell toxicity, it encompasses genotoxicity, it encompasses or the hemocompatibility friction corrosion all these properties, but it should be either in the In vitro or In vivo environment. Then, only you can call it as a biocompatibility property.