Optical Fiber Sensors
Professor V Jagadeesh Kumar
Department of Electrical Engineering
Indian Institute of Technology Madras
Professor Balaji Srinivasan
Department of Electrical Engineering
Indian Institute of Technology Madras
Pulse-Oximeter

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Professor Balaji Srinivasan: Good morning everyone, it is really a pleasure to host Professor V Jagadeesh Kumar, Department of Electrical Engineering IIT Madras, who kindly accepted our invitation to come and share his thoughts on Pulse-oximetry. Of course, as Dean of Academy courses in IIT Madras, he has is a very, very busy person, but in spite of his busy schedule he could accommodate this lecture.

So, just to give a brief introduction Professor Jagadeesh Kumar got his BA in 1978 from College of Engineering Guindy, followed by M-Tech and PhD from IIT Madras, he got his PhD in 1986. He is a professor in Department of Electrical Engineering since 2000 at IIT Madras and is presently heading the central electronics center as well as, as I mentioned, Dean of Academy courses at IIT Madras.

Received the Young Scientist Award from the Department of Science and Technology in 1988 and Dart fellowship in 1997. He has guided 10 PhD scholars, 11 MS research scholars, and

published 60 journals, mostly in IEEE journals, actually the top rate journals there and presented 120 papers in international conferences. He has 6 patents to his credit, and is traveled widely across the globe.

He spent a considerable amount of time at the King's College in London, Asian Institute of Technology in Bangkok, University of Braunschweig, and University of Arts in Germany. His interests are in Measurement, Sensors, Instrumentation and Biomedical Engineering. And that is a formal part but I also want to mention that he is a teacher par excellence. And I still very fondly remember a lecture that I sat in a few years ago on RLC circuits, the concepts that he taught and then the lecture itself is still very fresh in my mind. He is an excellent teacher and we are really glad to have you here, sir. To look forward to your talk. Over to you.

Professor V Jagadeesh Kumar: Thank you, Professor Balaji. I am going to talk about a lot of work that has been done you can see from the title itself in the past 25 years. It started, the ODC started in 1995 and I am grateful to all my students who work with me in this ODC starting from Ramanda Rao, Rezuana, Ashoka Reddy, Leo Mariappan, Bobby George. Bobby George is currently a professor in our group, Madhu Mohan, Gaurav, and Albina and of course few more students who are watching now.

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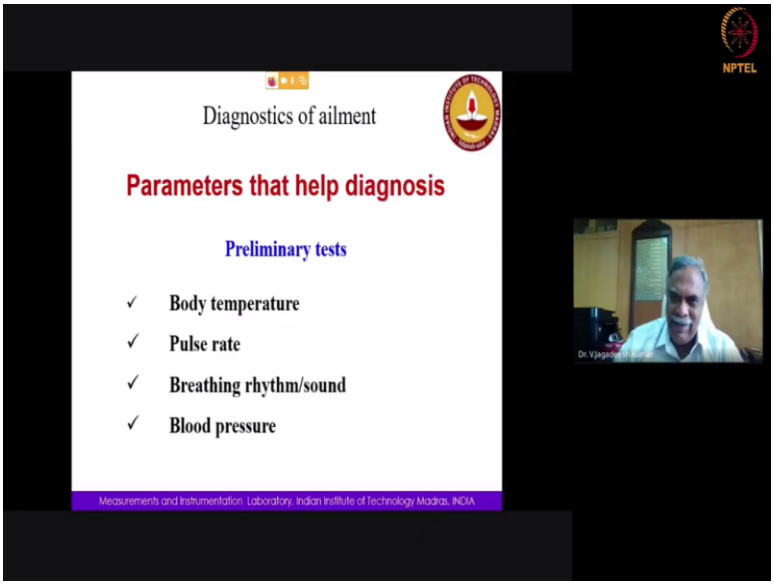

Now, if you look at medical diagnostics, the moment you become sick, of course, you go to the doctor, he takes your temperature, it takes your pulse rate, looks for the breathing rhythm sound

with a stethoscope and if you are above 40, of course, you will also take your blood pressure and makes the diagnostics.

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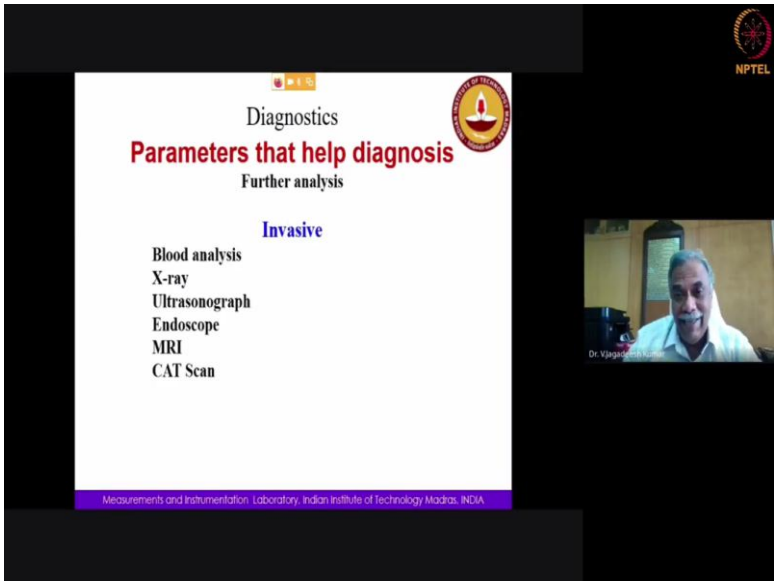

And if that does not help him, he will give you further analysis. He may send you to a lab to take your blood sample and look for whatever pathogens he is looking at or he will ask you to take an X ray, Ultrasound, Endoscope, MRI, CAT scan of course now today, it is really, really endless set of tests, including the virus that we are now suffering from even though we are not having the virus we are still suffering from the effects of it on the society.

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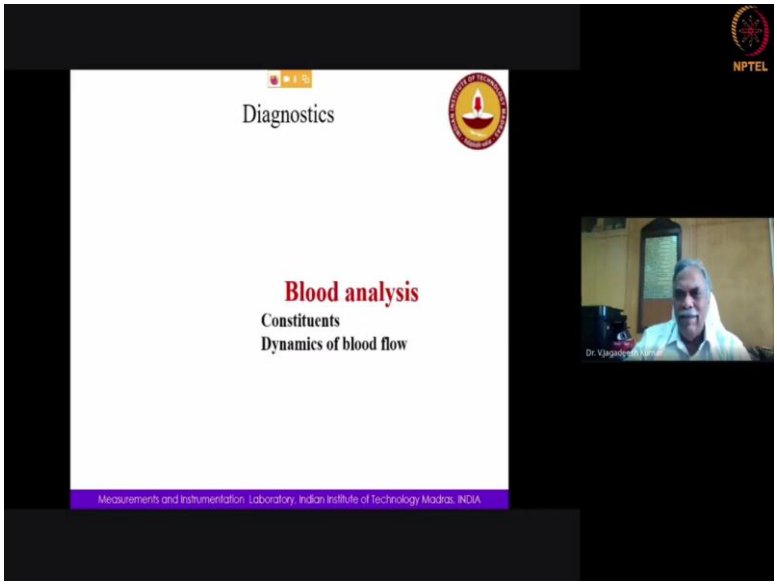

So, if you look at blood analysis, the first part that is you look at what are all the constituents of a blood, whether you have enough amount of hemoglobin, whether you have iron deficiency, all those things. Whether your Eosinophil is at the right level. These are all one type of test. The other one is the dynamics of blood flow itself. That is another part of test that many are not really very familiar with.

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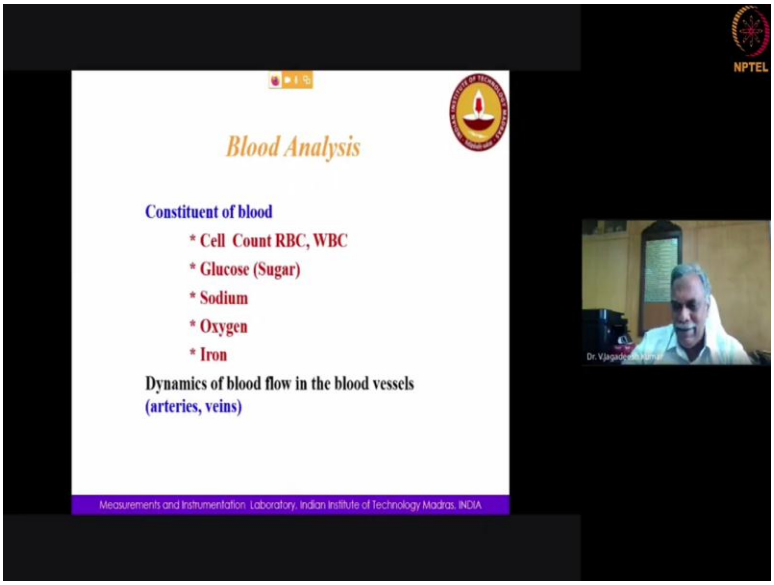

So I am going to talk about the second part, this is the standard test that you do on blood.

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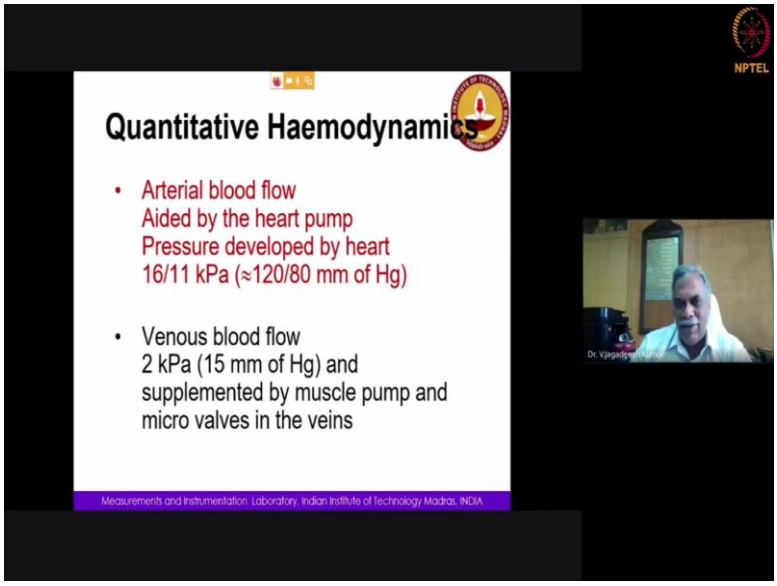

The second part is the Dynamics. When blood flows through the artery, of course, you have huge pressure, I do not know how many of you have really looked at what is 120 millimeter of mercury pressure. It is quite high. In fact, the very first way they measured pressure was puncture an artery and put a capillary. And they kept on increasing the capillary height, and the pressure stabilized at about 3 meters.

I have published a book where this photograph is there, the old photograph, maybe if you are interested, you can look at it. The second is the Venous blood flow. Blood in the veins, when it comes to from the capillaries is very low pressure, it is only about 15 millimeters of mercury. And obviously, it is not enough to move the blood. So the movement of the blood in the veins is aided by the muscle pump as well as the micro valves in the brain. Because when I have blood in my veins in my leg as I am sitting now, that has to come back to the heart, how does it come back to the heart?

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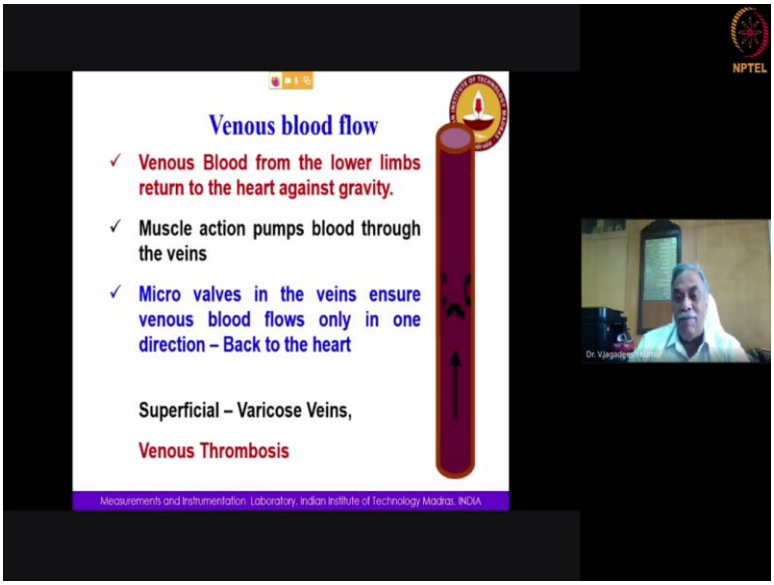

Because the muscle contracts and squeezes the veins and they, there are a large number of micro valves in the vein that permit only the venous blood flow in one direction that is towards the heart. As anything can go wrong, these micro valves also can go wrong or the veins become stiff as you age and if there is a problem with this, then you have two conditions one is called Varicose veins. The other one is called Venous Thrombosis. Varicose veins is provided is with anybody who is above 60 years old to various degrees, but Venous thrombosis is a life threatening, not, if you get it you should be very, very careful. That you removed as soon as possible.

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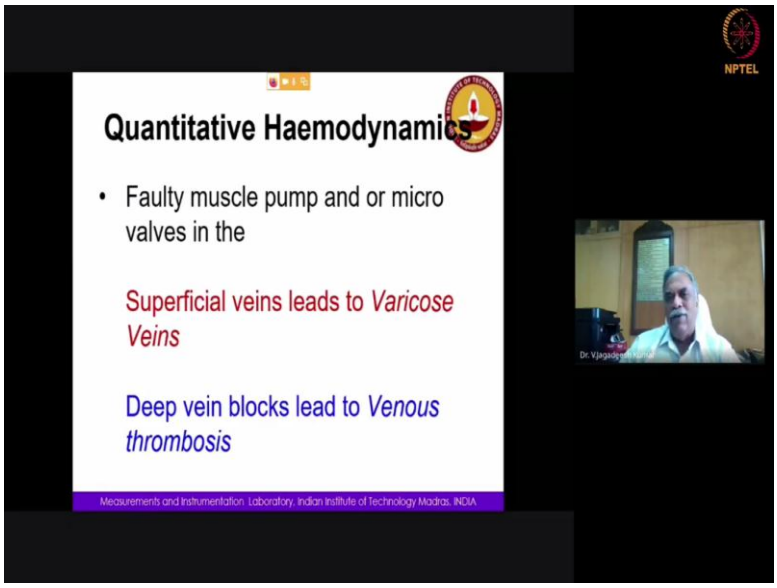

So how do you test that you are, you do not have this problem? There are two standard tests.

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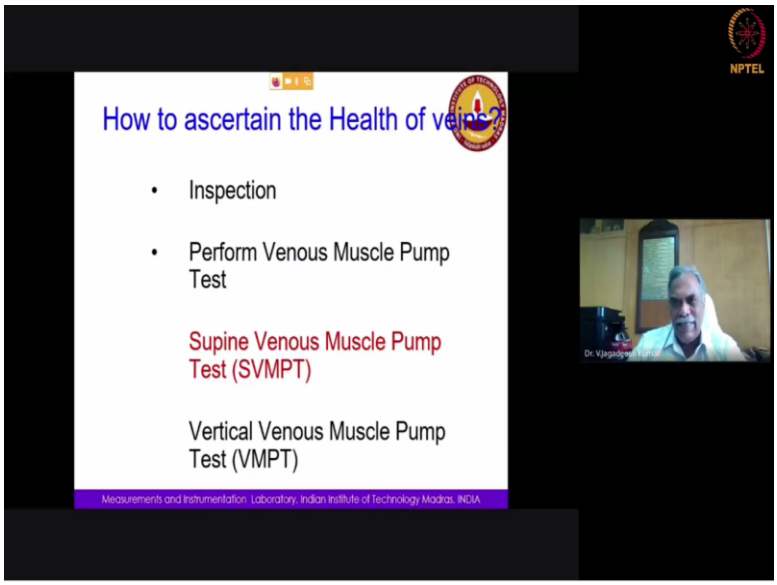

So the tests are called Venous Muscle Pump test Supine and Vertical. The Supine Venous Muscle Pump test is very old and is no longer used. The one that is current is VMPT, which is the Venous Muscle Pump Test.

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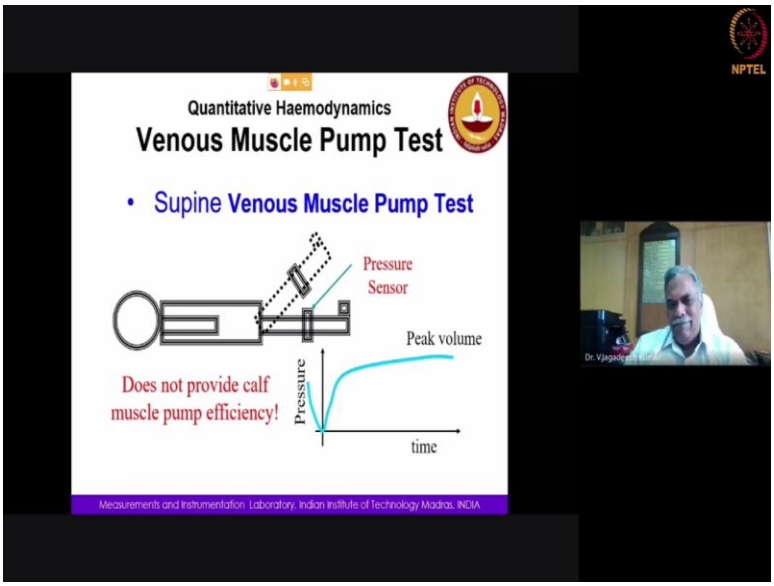

So let me look at in the Supine Venous Muscle Pump Test, you just attach, attach a pressure sensor to a knee, near the knee. Ask the student to, ask the, I am saying student, ask the patient to lie on a board and measure the pressure. Ask the patient to lift the leg. Obviously, the moment the patient lifts the leg due to gravity, the venous blood will flow out. So you will get a pressure drop. Again, you ask the patient to keep the leg horizontal and you take the time required for the pressure to come back. Because this as I said this is no longer used, let us not discuss this, mainly because it does not provide many parameters the other test.

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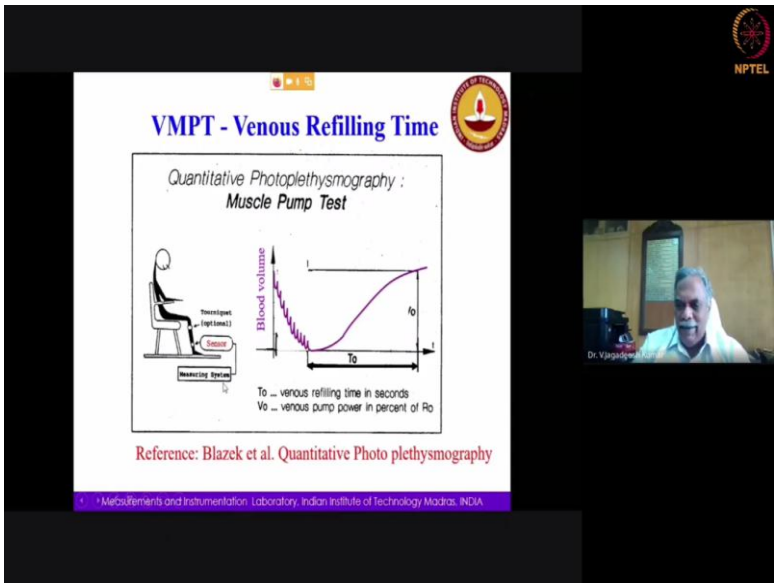

The other test, of course pioneered by my colleague, my friend at the University of Wuhan, Professor Vladimir Blazek, who is the father of this technology. So here you make the patient sit on a chair, put the sensor just below the knee and ask the patient to perform the dorsiflexion that is you lift your foot and tap 8 to 10 times. So if you do that the muscle pumps will get activated and the blood volume in your leg will go down and you ask the patient after he has done ask the patient to stop.

Once the patient stops the blood volume will again increase, blood will flow from the capillaries and reach so you find out this amplitude and the time taken for the Venous to refill. So we call it as Venous Refilling Time VRT and this is V naught is called the Muscle power, Muscle Pump Power and these two give the physicians whether the patient is alright in terms of Varicose veins, venous thrombosis problems. So now, the sensor here traditionally it was a pressure sensor.

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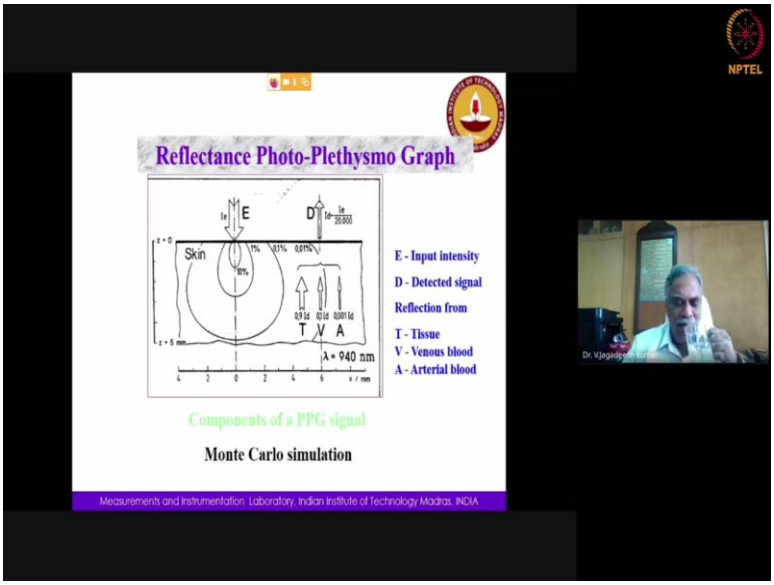

And then Professor Blazek started working on optical sensors. And used just light to get the signals. So if I put a light on the skin, the light goes in and comes out. Of course, most of this light comes out, that is why our color of the skin we see, but quite a few millimeter inside, the light penetrates and comes out. So if I look at the light that comes out it reflect some tissue, venous blood as well as arterial blood.

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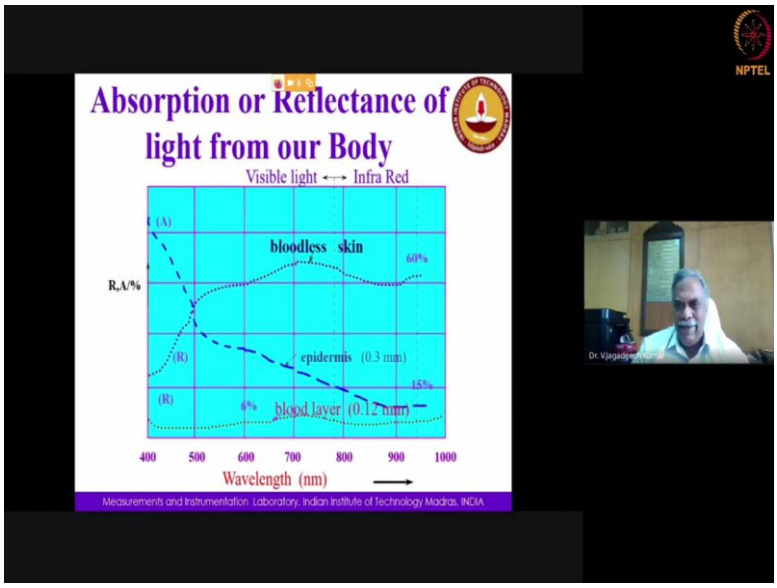

So, in terms of the absorptions or reflectance of light from our body, especially on the top layer near skin, of course, this is the wavelength dependence on epidermis and this is bloodless skin, about 60 percent. And if you look at this blood layer, about 120 micron inside, and very little light comes out of the blood if there is blood layer within this window (()) (11:44), what does it mean? So this was the first experiment I conducted way back in 1996.

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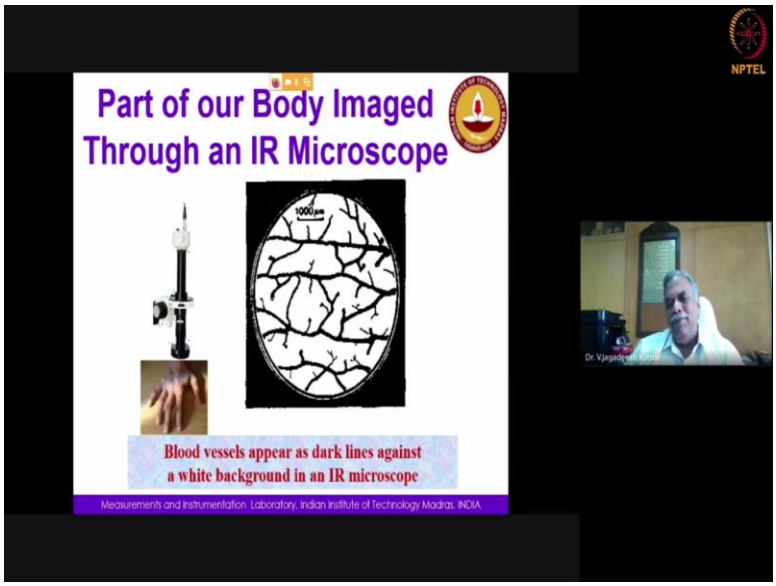

We actually this is my right hand, I had to put the right hand mainly because the microscope the IR microscope, the adjustment was on the left. I do not know why they did that. The photograph

that you see is actually about 4 or 5 millimeters of my right hand top and you see that if I take it at the IR I see only blood vessels as dark lines against a white background. This is no, no gimmicks done just the IR photograph of my hand. What does it mean? Which means if I now look at the infrared light that is coming out and the attenuation of that light is only due to blood vessels. So any measurement I do on this light, there is a big contrast, nothing else really contributes only blood vessels contributes.

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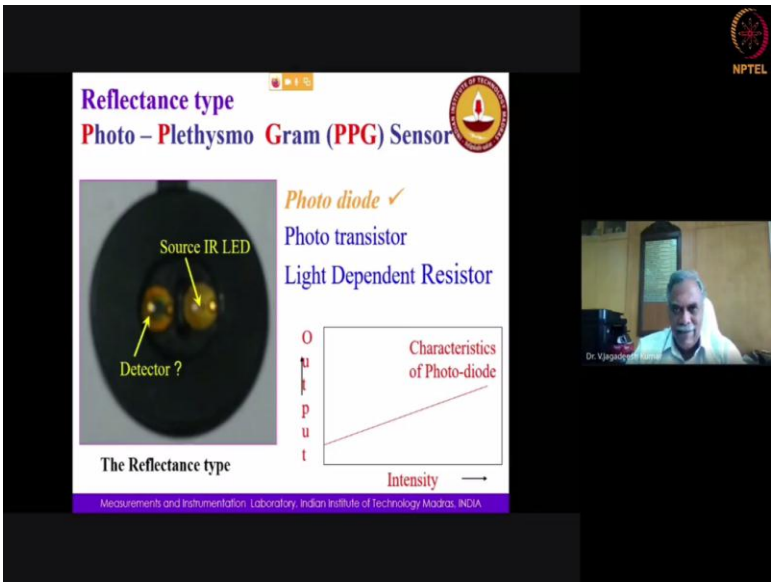

So we can now make a sensor. This is the optical sensor before I started this lecture I was talking to Professor Balaji I told him in terms of optical sensor, the sensor that I use is really nothing. It is just a photodiode. So, I have a small sensor where I send infrared light into the skin and detect and we use a photodiode mainly because the photo transistor and light dependent resistor, they have nonlinear characteristics. Photodiode has a very linear characteristics with this particular (()) (13:37). That is it.

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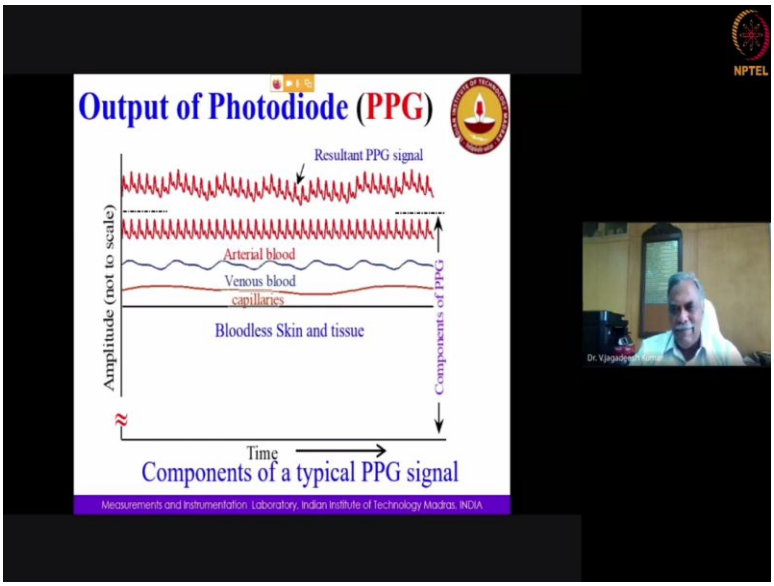

So, if I detect the signal, what will be the components in the signal? There will be large amount of light that comes from the epidermis dermis, then a small amount comes from the slow moving blood in the capillaries and slightly higher frequency from venous blood. And of course arterial blood would be pulsating with respect to the heartbeat. So you can detect all this. I will show you the actual signals later.

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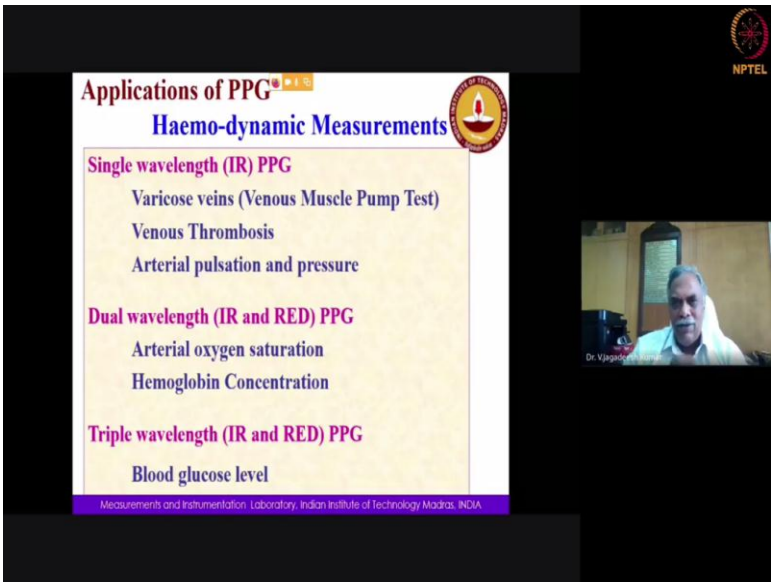

So what can we do with the single wavelength? Only with IR, you can detect varicose veins. And with IR as well as the tourniquet, you can detect venous thrombosis. You can also measure

arterial pulsation and pressure. When I say arterial pressure, you cannot measure systolic and diastolic you can measure only an average pressure. With two wave lengths we have already worked on it arterial oxygen saturation and hemoglobin concentration both my group has worked I will explain how this is done.

And in principle with three wavelengths or more than three wavelengths, you can measure blood glucose level, this is a very big challenge at least 15 20 groups all over the world are working to crack this. It is a very difficult problem. So if somebody crack this, they will become a billionaire. Because right now the only way you can measure blood glucose is to drop blood, either a drop of blood on very inaccurate blood glucose meter or a 1 CC of blood for titration using sodium lauryl sulfate method.

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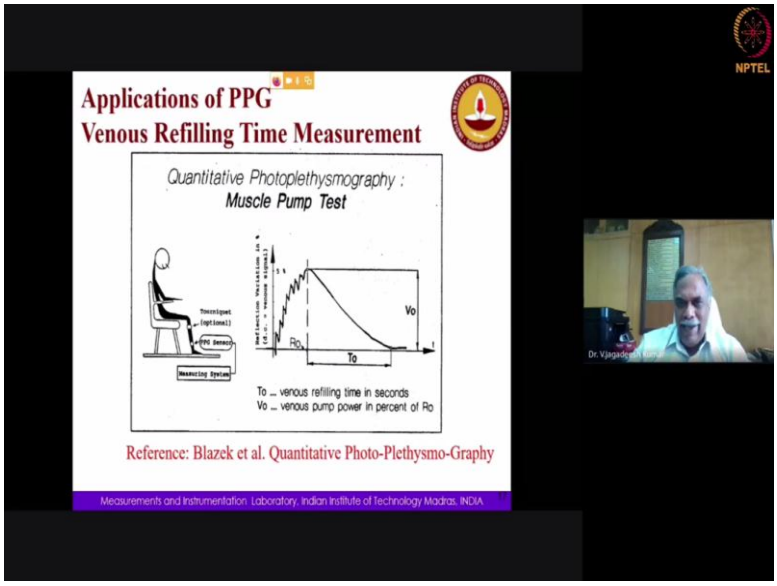

So this, we already said, how to measure venous refilling time, you simply put a PPG sensor and measure the changes in the reflected light. But it is not that easy. Why?

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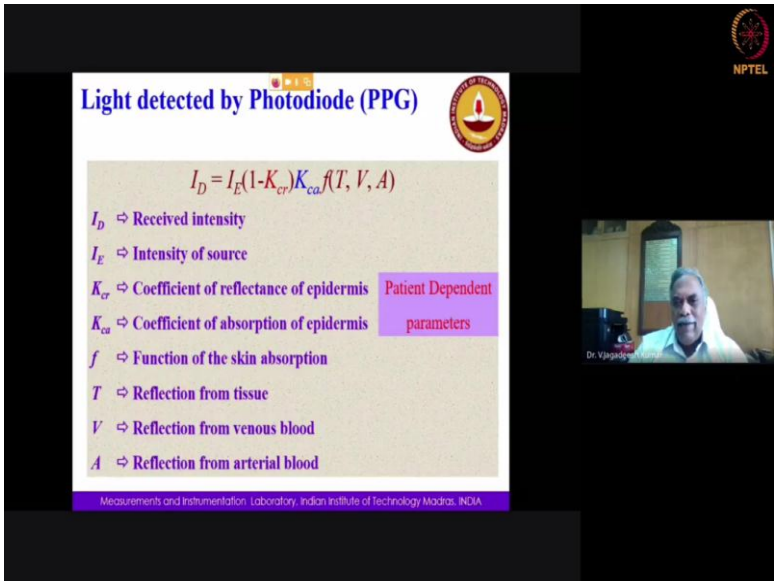

Because if I look at the deducted light, the deducted light is emitted light intensity, attenuated by the epidermis absorption or reflectance and then the coefficient of absorption, then it is a function of tissue, venous blood, arterial blood. But what is the problem? The problem is these two parameters depend on patient. If I have a white skin patient, why does the skin look white, because most of the light is reflected back. That is why we see the patient skin as white, if I look at an African origin person, his shin really looks black. That is because most of the light is absorbed by his skin.

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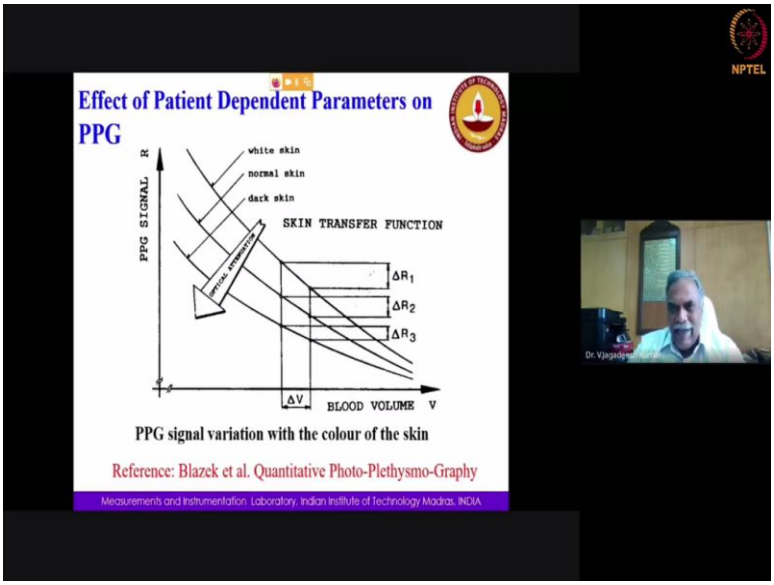

So if I look at a particular volume of blood here and look at the reflected light, if I have white skin, I get a large reflection, if I have a very dark skin, the black person, I get a small one and of course this is somewhere in between. So I cannot make any measurements because of this particular problem. But whenever there is a problem, there is a solution.

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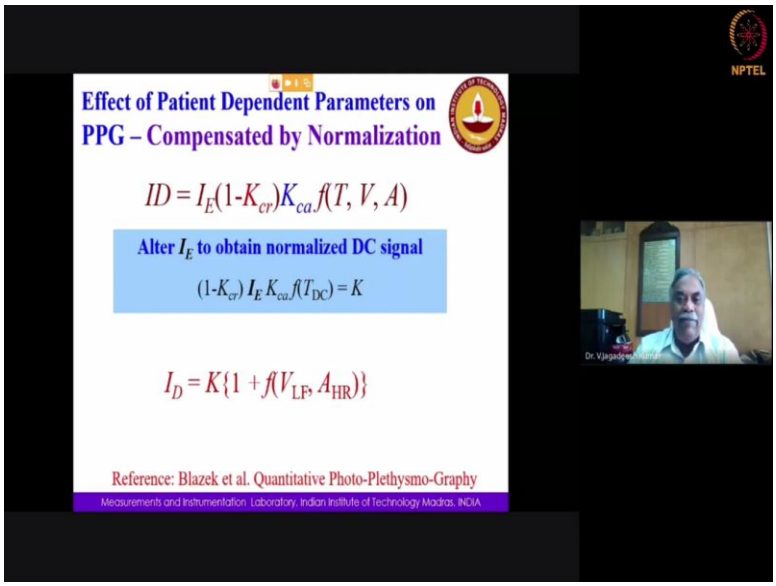

So the first solution, this was actually done by Professor Blazek, so that is why I have given the reference here. We looked at this the detected light or this must be I suffix D is a emitted light into all this. Now, if I look at this, this portion is DC if I make this portion constant for all the patients, what does it mean if I make the constant I just IE so that this portion IE into 1 minus Kcr into Kca become constant then the detected light I can put it as K into 1 plus the function of tissue Venous and that. Now you remember this K is a constant. So I can now make measurements, differentiate between patients with.

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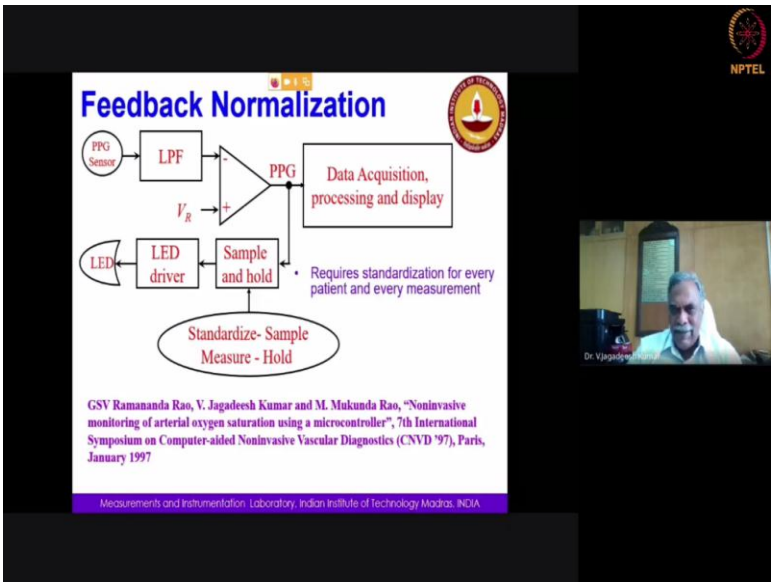

So, how do I make that a constant? I take the PPG sensor; take the low pass filter I get only DC. I compare the DC with the reference voltage, if the reference voltage is more than the PPG DC voltage I decrease the LED driving current and if it is not I (()) (18:32), so this continuously adjust, so that the DC value of the detected diode output voltage is constant for all patients. So which means I have removed the patient dependent parameters I can make measurements. So at this point, of course, I started collaborating with Professor Blazek.

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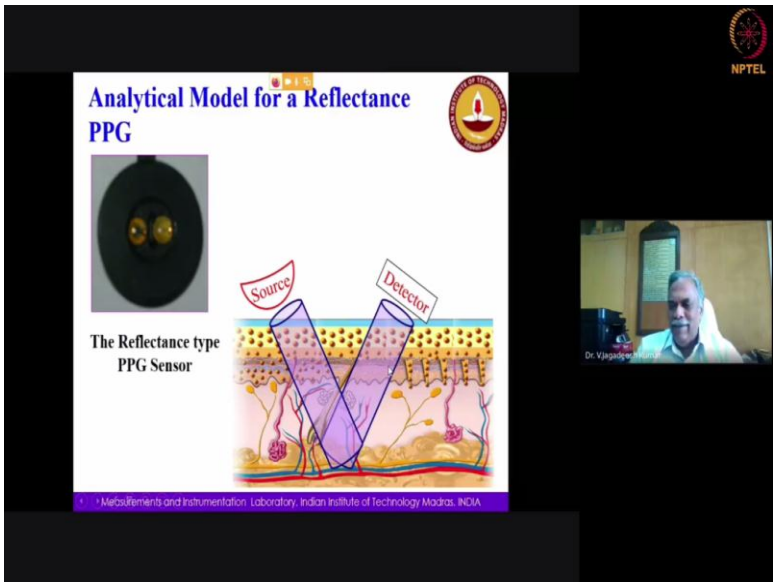

This was the first work done by Leo Mariappan. Is it possible to model this process? I have the light that goes in and comes out. And of course it does not happen like this, like this thing. It is just scatters around it and comes up. So, the thing is, if you put scattering modeling becomes very difficult. So, from the detector, if I look at out I we made that to be just like this way.

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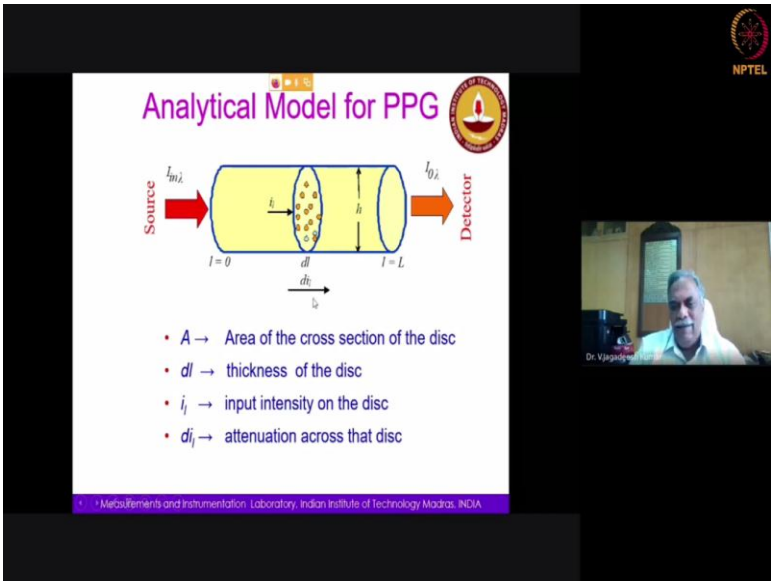

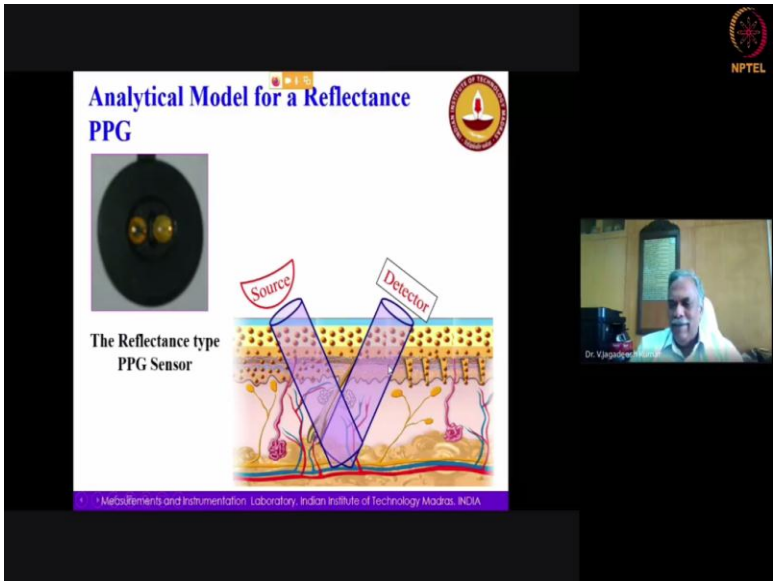

Now, if I put the source and the detector on one, source on one side, detector on another side, this is a cylinder that comes out. So, this is the V shaped cylinder now made horizontal and I have input light at a particular wavelength and I have the output that is going to the detector.

Now how do I look at it? I take a small disk in this path of light, I will again repeat this is not a cylindrical part, it is only an approximation, but we will see that approximation holds good.

So, they discuss an area A it has all the cells depending upon where the disc is, if the disk is here it will be only epidermis cells, if the disk is somewhere here it will be only dermis or what skin cells and if it is slightly inside it will tissue venous blood and arterial blood and so on. So, the I take the thickness of the disc as dl and input intensity is il and the attenuation as dil. This is for making a model.

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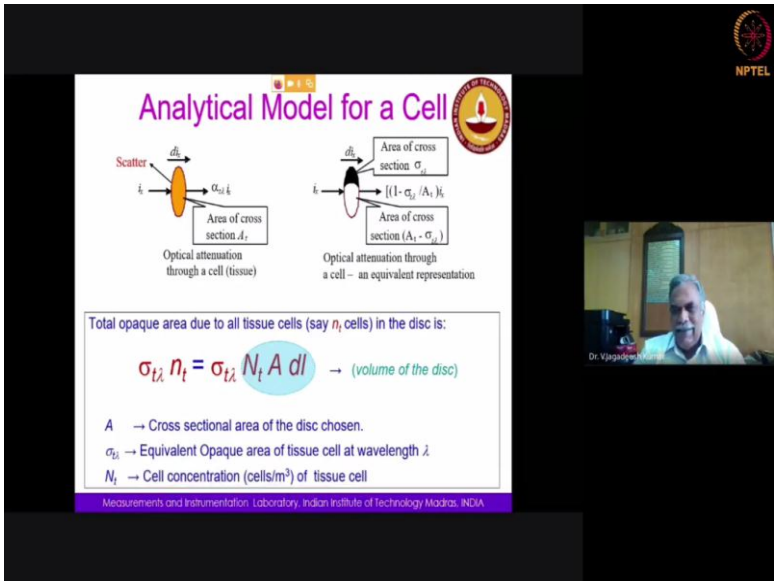

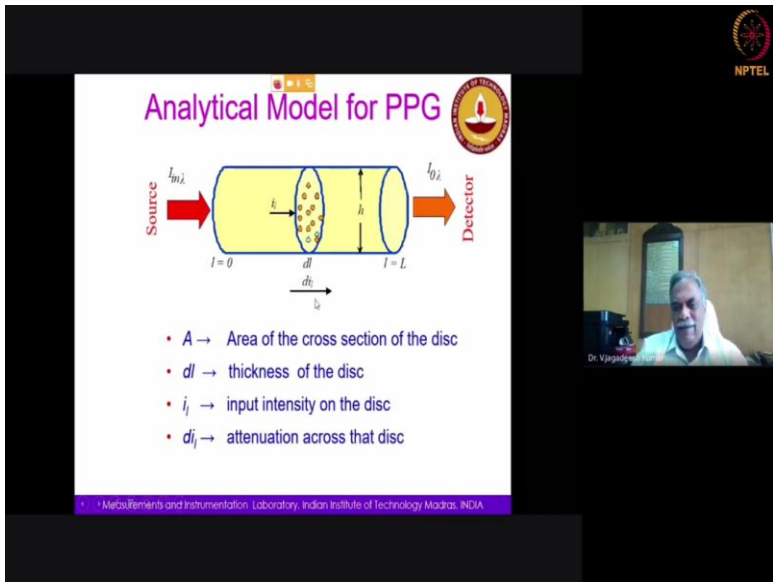

So, for example, I take one cell let us say a tissue cell. Those of you who are non-vegetarian will immediately understand the tissue looks brown. So, that is why I colored the cell as brown. So, I have some input intensity ix I get some output intensity ik, some gets absorbed, some gets reflected or scattered. Now, I have to find out the attenuation due to the blood. Believe me, we tried to model this, it is really, really very complex and not possible to model.

One day when I was discussing with Leo I told him, Leo we are not interested in all the things that are going on in the optical world, I want to model what is input and what is output. So I have 100 candela, I am giving here, I am getting let us say 80 candela which means, I can put this tissue as 80 percent opaque, 20 percent opaque and 80 percent transparent. So, if I give 100 candela I will get 80 candela.

Of course, it is wave length dependent at a particular wavelength whatever is the attenuation, I do not say I do not have to really worry about what is scattered and what is transmitted what is absorbed, I make this top down approach. This binary equivalence of the absorption of the cell is really nice, because you can now model everything, I can now say the opaque area is this sigma tissue lambda into number of cells in the disk.

What is the number of cells? The concentration of the cells in that area, the area of the disk and dl A into dl disc volume of the disk and A is the cross sectional area, sigma is equivalent opaque area and cell concentration. Now, we come back I know how to model this, now I will have to take the total opaque area in the disk.

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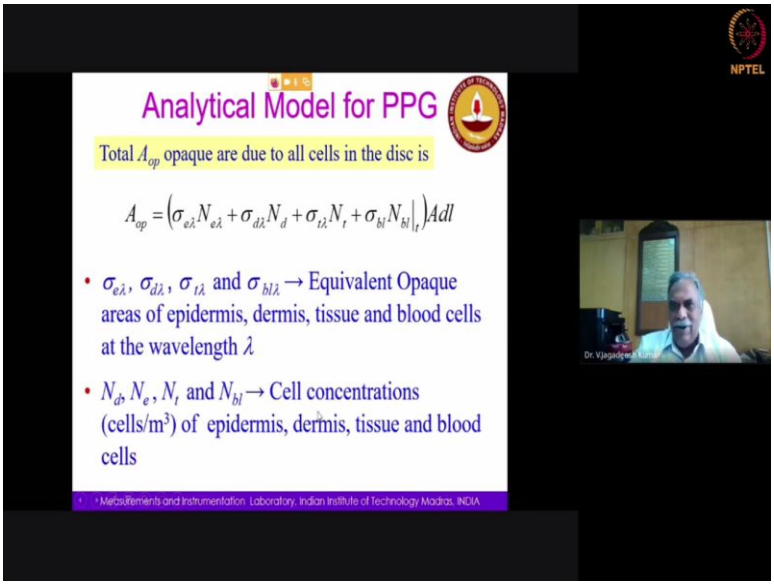

So, I can now add all the parameters the total opaque area in the disk is if epidermis is present is concentration and the volume of the disk; if dermis is present is concentration and volume of disk. So, like that I can put. And if you see all these I have not put any this thing here I put subscript t, because blood varies as time varies, blood flows, that is a dynamic property. So, that is why this is only this is the only parameter that where is with respect to the time in the window of measurement. Of course, epidermis, dermis, tissue, varies but varies over a day or a week or a month, not in the small few seconds I measured. So, here again I these are the opaque areas and these are the concentrations.

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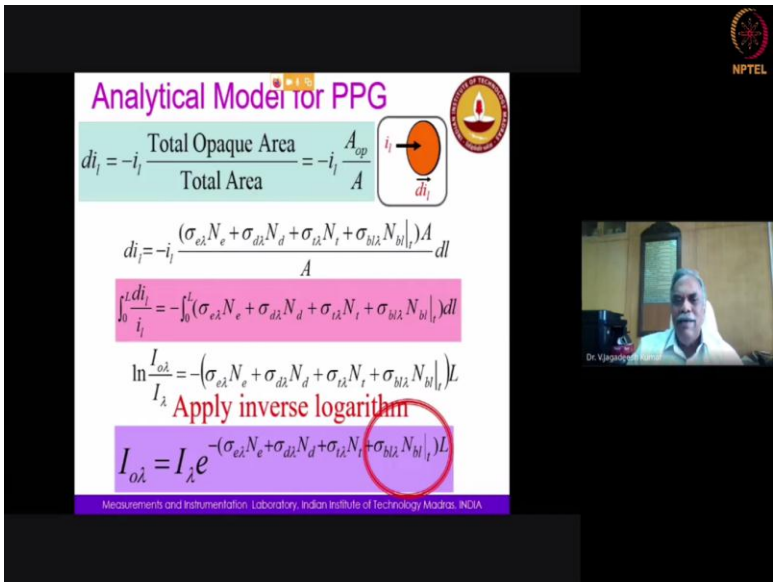

So, if I do that, now, I come to the analytical model, the attenuation across the disk is the input intensity i into Total Opaque Area by Total Area, that is very clear. And why did I put a minus sign, because attenuation it is reducing. So di by dt would be negative. Now I can write this equation for di and bring the i on this side and integrate this disk from 0 to full. What is 0 to full? 0 is at the source, l is at the detector. So if I keep moving the desk, step by step through from the source to the detector I get the complete attenuation.

So if I do this mathematically, I get the equation as I lambda by lambda into all this, do not be intimidated by all these numbers. We will see later, many of these things we will throw out, we do not need them what, what we need is only blood the rest we do not want it. So, if I now take ln inverse and take the I lambda on the other side, I get I naught lambda, this is the detected light on the photo diode, which is my photoplethysmogram is input intensity of light into e power minus all this. This looks exactly like the Beer Lambert's law for attenuation of light in a solution. It is its nature, so everything works the same.

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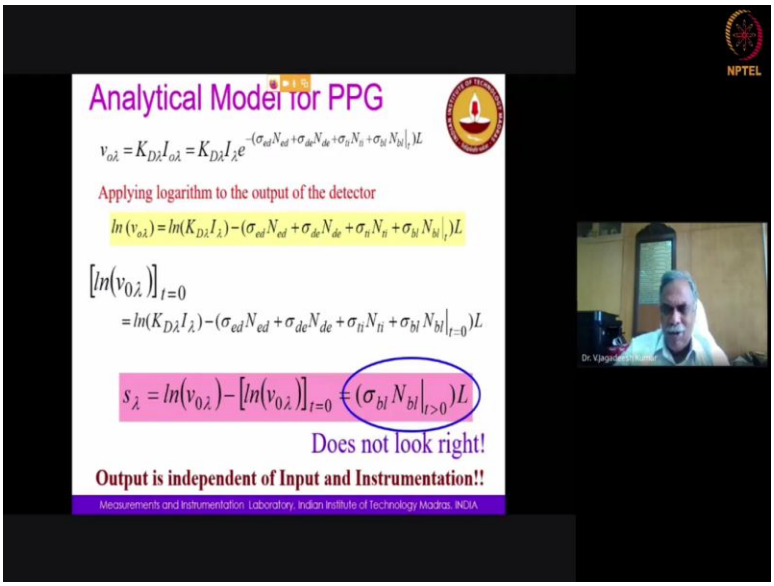

Now, if I now put a diode and detect this light, the output from the diode or diode detector circuit v naught lambda will be sensitivity of the diode into the intensity of the diode that is intensity of the light that falls on the diode. So, I simply multiply this now, if I take the logarithm at the output of the detector, that is this is the output from the photodiode I take ln I get this equation.

Now, what I do is I take v naught, ln v naught lambda t equal to 0 and subtract it from the future ln v naught lambda. So, I take the signal which is s lambda is ln v naught lambda minus ln v naught lambda t equal to 0. When I say t equal to 0 at whatever point I am doing the experiment, and I see that I get only this. The moment I looked at this, the first thing that came to my mind I told Leo, Leo this is wrong. I do not accept all the work that you have done has gone to dogs.

So, can anyone tell me why I said this? Because this is my output signal s lambda. But where is my input intensity? i lambda it is not there, where is my diode sensitivity KD lambda it is not there. So, it looks like I am getting a signal which is independent of my instrumentation, I can have a diode giving 1000 candela or 10,000 candela I will get the signal, I can have a detector with a gain of 10 100,000, 100,000 I will still get the signal.

So it becomes independent of input an instrumentation which is not really right. So, I myself and Leo, we sat together we went backwards, forwards find, to find out whether we are making a mistake somewhere in the derivation. Then after three months, I said I mean whether we are doing something really stupid, or this is really right. In fact, Leo quipped, sir, if you look at the

Sherlock Holmes novels, Sherlock Holmes always says, If you remove all the impossibilities, whatever remains however impossible, must be the truth. So, he said maybe it is correct, then I said, we will test it. How do you test it?

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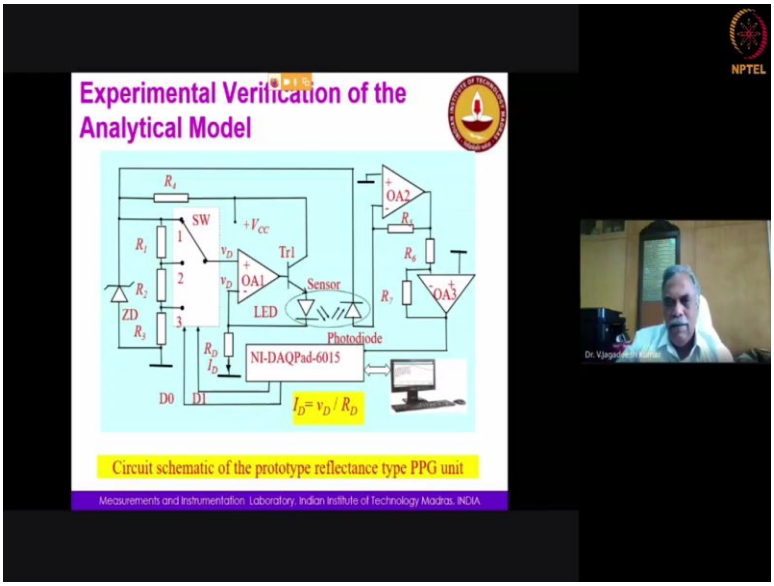

You make an experiment. So, this is a sensor, which has a diode and photo detector and this is a photo detector signal conditioning circuit. So one current to photocurrent to voltage amplifier and another amplifier and we put a data acquisition system and what we did was we vary the intensity of the diode by changing the current if I put the switch here, I will get a full 0 diode voltage here and the current here ID will be 0 diode voltage over VD by RD. If I put a switch here, it will be part of the 0 diode voltage. So, this VD decreases this VD decreases ID again will be VD by RD decreases. So three possible currents. And we made an experiment the.

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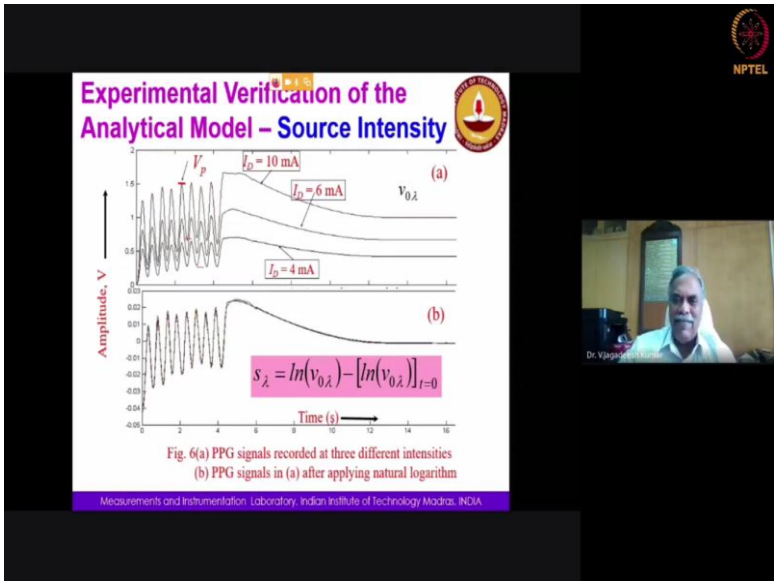

So this is the result of the experiment. Of course, if I take the actual signal that is coming from the photodiode. When I have 4 milli amperes, I see that the signal is low. If I have 6 milli amperes it is slightly higher amplitude and this is the highest amplitude. Now, from these three, if I calculate S lambda as ln of v lambda minus ln v lambda t equals 0, I see that all are the same, which means they are giving me only the blood variation in the sensor.

The sensor output, which is responsible for from the blood alone is. So, the now I can do all sorts of measurements on the blood on the blood flow, because I have a signal which is only proportional to blood flow, the skin color of the patient is immaterial. Even instrumentation is immaterial, I can give a gain of 100, I can give a gain of 50, I can have a diode which gives me 100 candela, I can have a diode which gives me 300 candela does not matter, I will get my signal, which is only proportional to blood.

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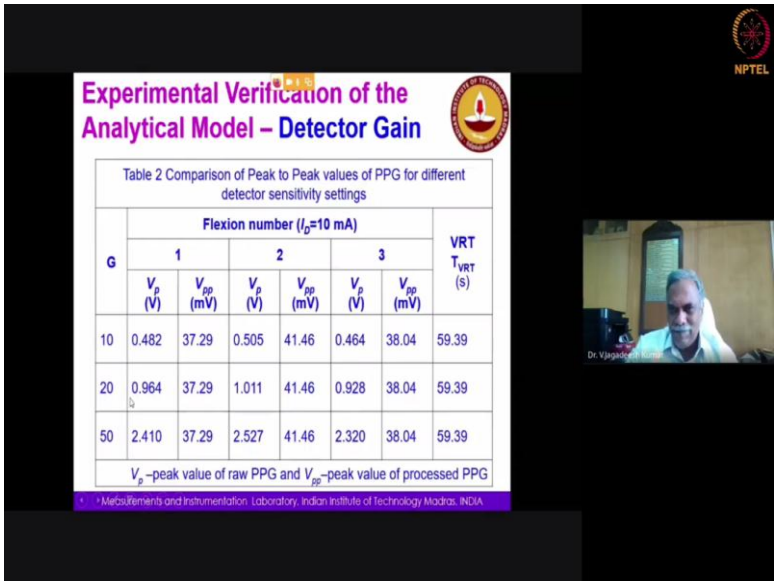

So, we went ahead and tested, again if you see this the gain of the instrumentation amplifier, and we saw that the measurement on the blood is exactly the same even if I increase the gain by 10 times, 5 times. This is a gain of the second amplifier in the circuit.

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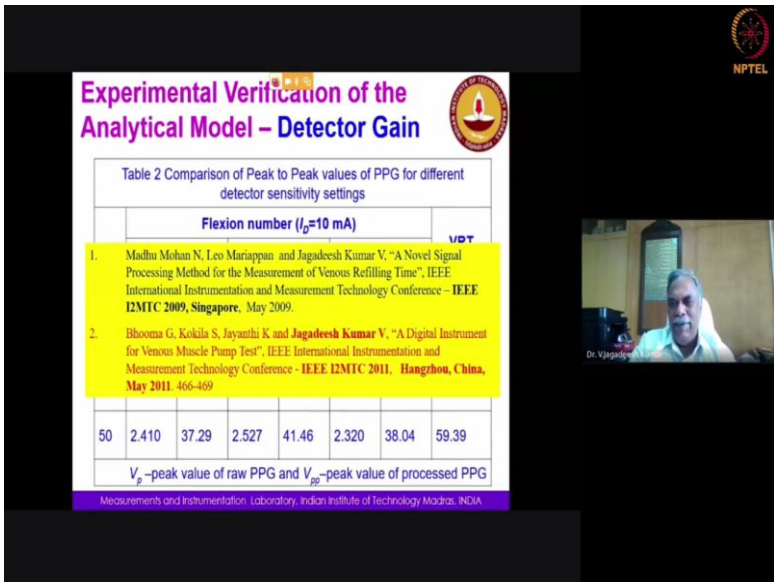

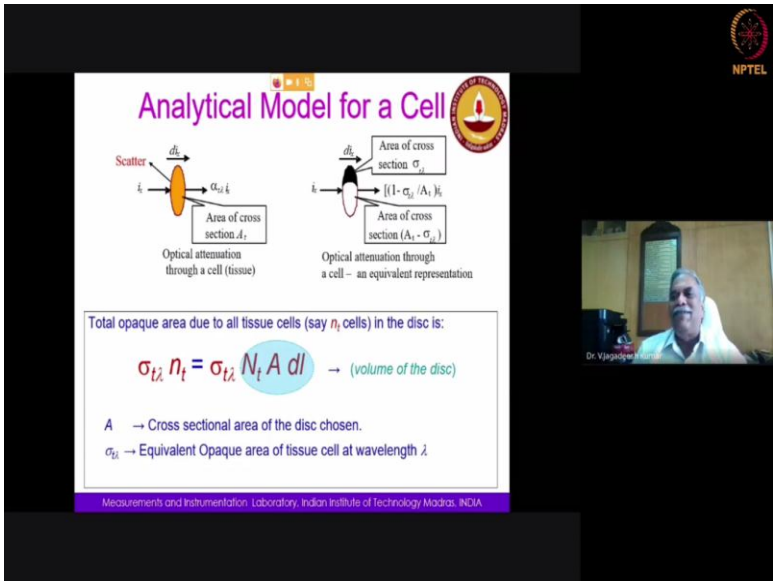

So, obviously, what do you do you publish your work, you also took a patent. I will talk about the patent a little later. And the first paper was IEEE, I2MTC Singapore in 2009. And the second paper was another paper by another set of students who built an instrument in another I2MTC.

Professor Balaji Srinivasan: Shall we take a few questions? There have been some questions in the chat box.

Professor V Jagadeesh Kumar: Can you read it? Because my screen cannot

Professor Balaji Srinivasan: I will read it out. Just wanted to know that I am interrupting. So, so the first question is about the venous flow measurements that you mentioned early on, when somebody is like tapping their foot. And then you have, so what are the typical timescales involved? What sort of bandwidth do you need to capture those sort of signals?

Professor V Jagadeesh Kumar: This are very slow varying. You tap at the rate of about 1, every 2 seconds or so. I can actually tap and show the like that. So you just raise your foot, tap again. And you have to do 8 to 10 it really does not matter as long as it is greater than 8. It is immaterial how many times you tap, it (()) (32:51).

When you stop, t takes about, if you are a healthy person, the venous refilling time is roughly about 50 seconds, quitter than 50 seconds. And if you have a problem, then it will be less than 30 seconds. If you if your VRT is less than 30 seconds, you have a problem. So 30 to 60 is gray area, the doctor has to do something else to test you. Next question.

Professor Balaji Srinivasan: I suppose we have not discussed noise so much. But in terms of mitigation of noise, I suppose you would use a low pass filter or maybe do some even do some runtime averaging to make sure your signal to noise ratio is good?

Professor V Jagadeesh Kumar: The basic thing is the for the venous refilling time noise is not a problem. The signal that you get is very high, hundreds of milli volts from the diode itself. So when we go to the pulse oximetry, that is where the noise comes in. You have to do a lot of filtering. Here, we did not use any filter.

Professor Balaji Srinivasan: No problem. So the other question is, you talked about two different configurations, one was actually reflecting or a scattering configuration. The other one was actually a transmission type configuration, like the model that you mentioned was more like a transmission.

Professor V Jagadeesh Kumar: No, no I will go back to that and this is the one. So if you look at it, I have to model input output. Some light it is given and some light is coming out. But what actually happens is some light gets absorbed, some gets scattered, some goes through. And I have to take all these characteristics into account and make a model which is very complex.

We tried all sorts of modeling techniques, including The Monte Carlo method, but you do not get anywhere. It is so complex. But on the other hand, if I really look at it what I am interested in, I am getting a light input, I am getting a light output. I put a black box in between. I just assume I am giving a light of weight a 100 candela, I am getting 80 candela, 20 is eaten away by the black box.

Professor Balaji Srinivasan: So it does not matter whether it is a transmission configuration or?

Professor V Jagadeesh Kumar: I do not care what happens inside. It is a very top down, input output model and it works. So many times, that is what I keep telling students, simple things are the best things. Of course we analyze complex, this process is really complex. But the method that we used is totally simple.

Professor Balaji Srinivasan: So one more question sir. You talked about adjusting the intensity for the different colors of skin and so on. So the question is, how do we generalize this equipment for any person?

Professor V Jagadeesh Kumar: No, no, that was the old method, which was pre 90. And today, of course, we do not use that. We still use that to optimize the instrumentation. But the moment you use the model, as I told you the nothing matters. I can have a I can change the diode with different sensitivity, my system will still work.

Professor Balaji Srinivasan: Yes, yes. Yes. And related questions also about the arterial valves and the venous valves?

Professor V Jagadeesh Kumar: There is no valve in the artery, because the pressure will go high. Only (()) (37:06) valves in the veins. I am really sorry, I am not a one to one in the class, otherwise, I suffer from varicose veins, I could have shown them my foot. I showed them the bulging of my veins. In fact, I cannot stand in a place for more than three minutes, I will faint. Because I have to keep moving for my venous blood to go up.

Professor Balaji Srinivasan: But in general, any extra absorption beyond whatever you have shown and they will all get canceled anyway, because of that reference measurement, it is very important. And that brings up the question. So you mentioned t equal to 0, so t equal to 0 should hopefully be a measurement where the blood absorption is relatively lower, so that you can actually zone in on the blood absorption component itself?

Professor V Jagadeesh Kumar: The basic thing is, at infrared blood absorbs almost everything. So it looks like a black. Only 15 percent of the light that goes into blood comes out an infrared. And so it looks like a black line against a white background.

Professor Balaji Srinivasan: So you would use basically one of those things, what are the points where there is very little absorption and then use that to basically…

Professor V Jagadeesh Kumar: We can do this any part of the body, all our skin it look, behaves exactly the same. Whether it is my forehead or my forearm. Yes, it behaves exactly the same.

Professor Balaji Srinivasan: Understood. And one last question. You gave us a teaser, basically, about this glucose measurement and you talked about a third wave length, maybe you will come back to it?

Professor V Jagadeesh Kumar: No. I had…

Professor Balaji Srinivasan: (()) (39:11) wavelength. What is it?

Professor V Jagadeesh Kumar: No, no I am not going to talk about it. But it is possible. The thing is, glucose also has its absorption. So you put absorption frequency light and there are problems, the light wavelength that is sensitive to glucose, it is not very nice to use those wave lengths, you may end up triggering a cancer, skin cancer on the patient. So there is a lot of problems. But in theory, you can do that. There are practical difficulties.

As I said, there is a very big group in Cambridge working on that, in fact they invited me there to brainstorm with them. I could not get, get out of the problems. As on today it looks that we cannot solve problems. But it is in my opinion there is no problem which can be left unsolved. You can crack it someday, maybe.

Professor Balaji Srinivasan: So far, so far you have talked about single wavelength only?

Professor V Jagadeesh Kumar: Single wavelength.

Professor Balaji Srinivasan: I think you will go on to maybe two wavelengths?

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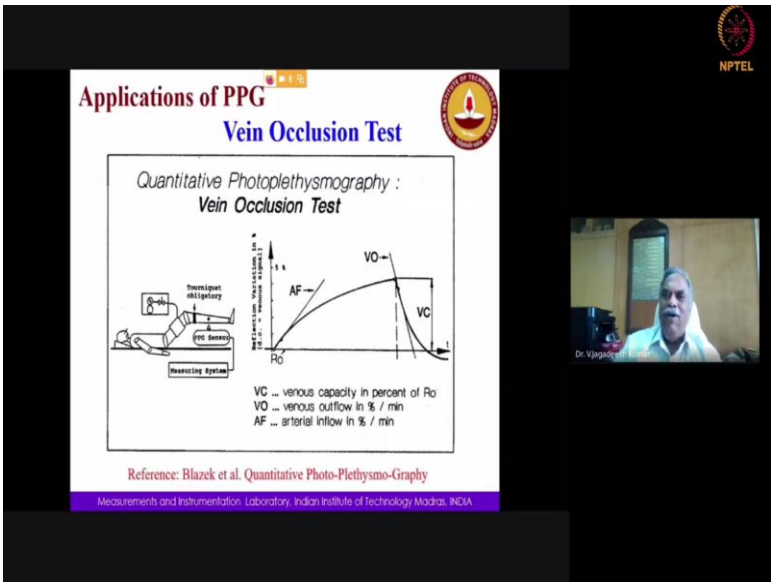

Professor V Jagadeesh Kumar: Yeah. Quickly. So a single wavelength, we can do vein occlusion test. I am not going to details in this because this has nothing to do with optical sensors.

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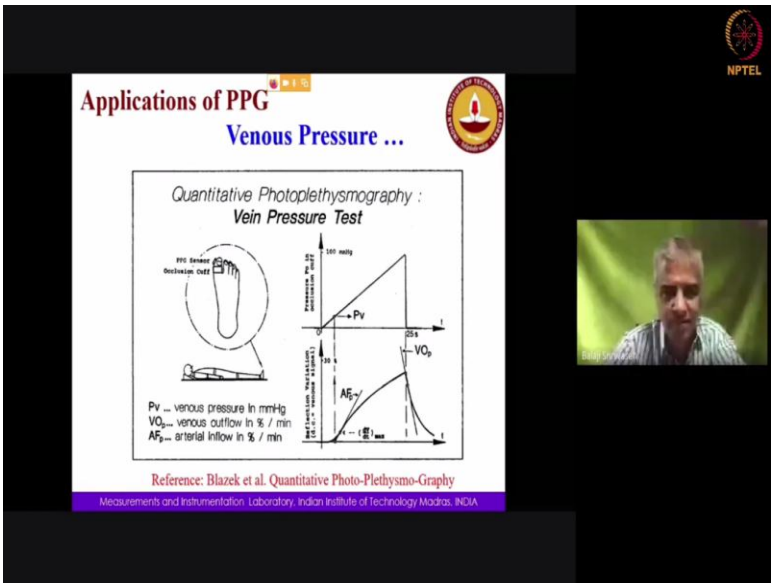

You can actually measure vein venous pressure

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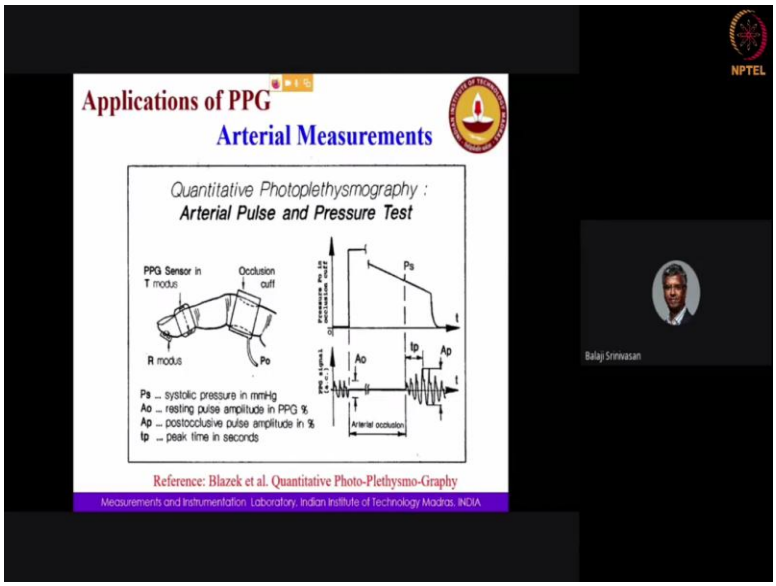

Then you can measure Arterial Pressure.

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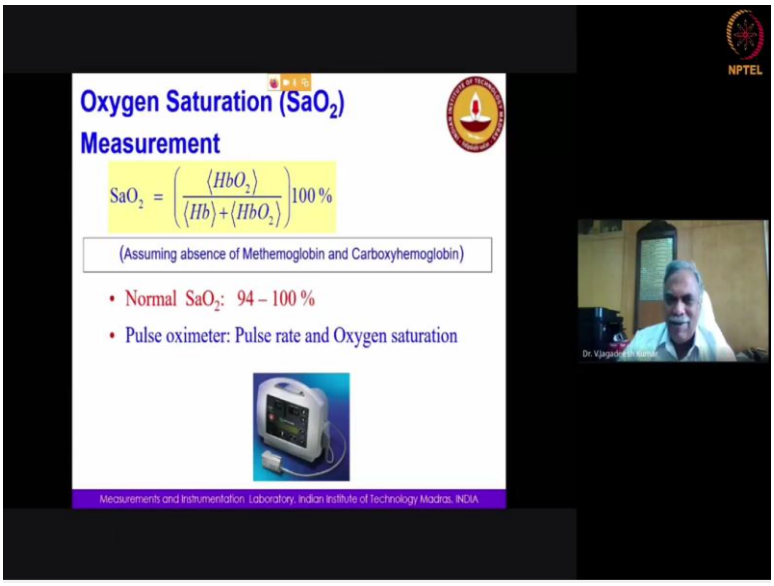

Now, if we come to the oxygen saturation with two wavelengths, we can measure oxygen saturation. What is oxygen saturation? The arterial blood contains hemoglobin with oxygen. Of course, for various reasons, this oxygen level can go low. For example, if you are ill, then the hemoglobin content itself gets reduced and your oxygen rate gets reduced. Or if you are ill, some of the hemoglobin may be killed, we call this as Methemoglobin and or if you absorb carbon monoxide of course, again, carbon monoxide kills the hemoglobin from carrying oxygen. So we put the oxygen saturation as amount of hemoglobin in arterial blood that is carrying oxygen and amount of total hemoglobin as a percentage. So I do not know because of this virus, this pulse oximetry has become very popular.

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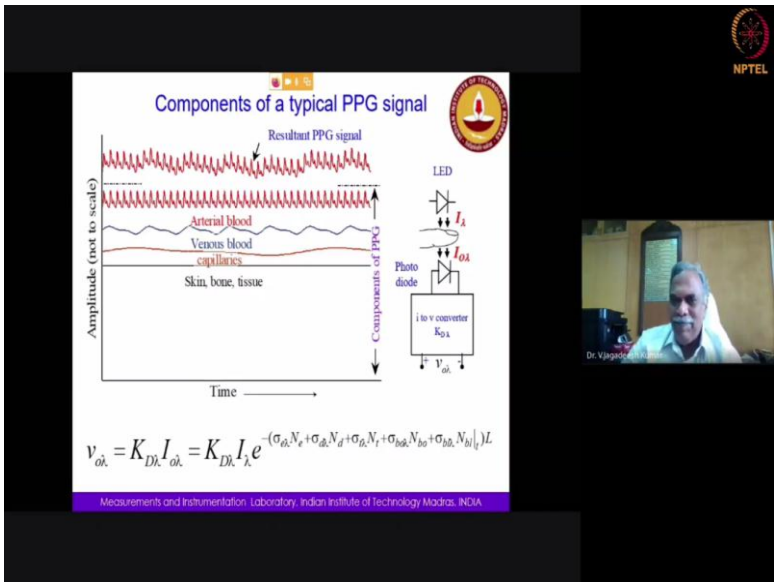

How is it done? Again, you have just one led one photodiode that is the photo sensor. My entire work I have used only one optical sensor that is photodiode. So, you send light and receive light, we have already seen this you have already seen this equation.

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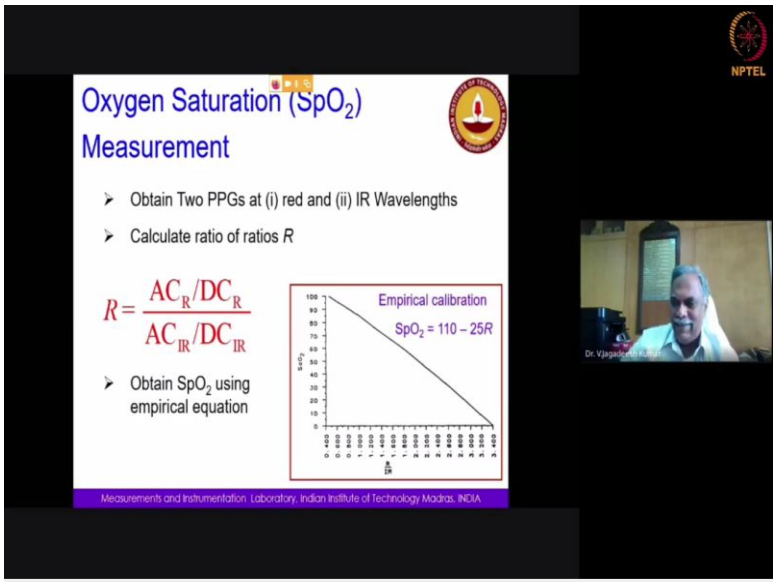

So, what do you do this was again typical, you take the red wavelength, find out the pulse magnitude divided by the DC that comes out, again take infrared wavelength and plot this against pulse oxygen saturation, this is 1974 or 76. I am not sure, this equation is actually from

Japanese researcher. So, most of the pulse oximeters that you buy today use this calibration especially cheap one. So you simply take this ratio of ratios and calculate the oxygen saturation.

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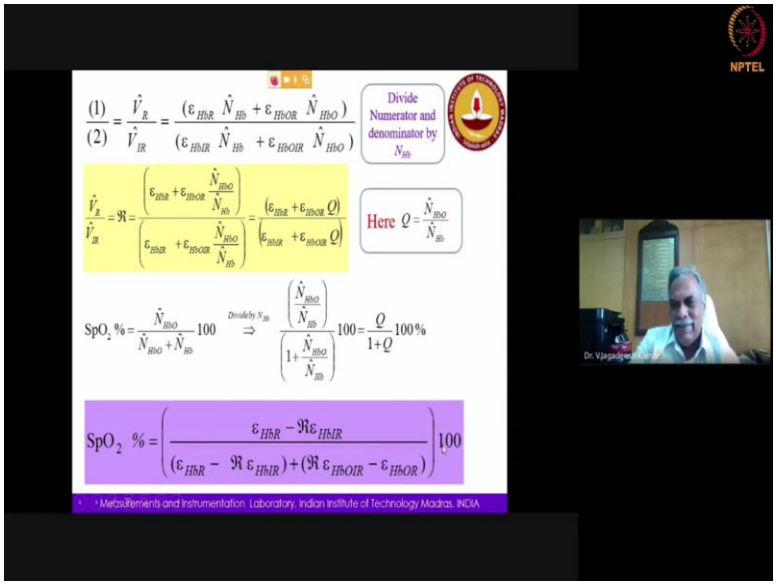

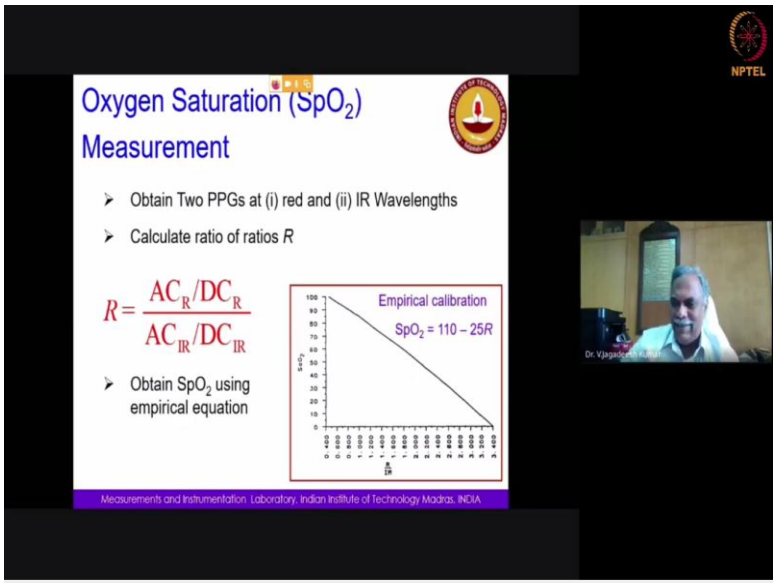

So here, what we did was we again have this model, we now look at the blood and the I skip this this is not enough. So, if I look at the infrared PPG value, I see that it is hemoglobin concentration and oxygenated hemoglobin concentration. Again I take the infrared hemoglobin concentration oxygen, I just divide the detected voltage at a red wavelength, detected voltage at infrared wavelength and I can easily calculate the oxygen saturation like this. The advantage of

this method or the this, this particular method is that it is not empirical it is it comes out of the patient itself and these are all constants. Where R is the one that I measured this R is the one.

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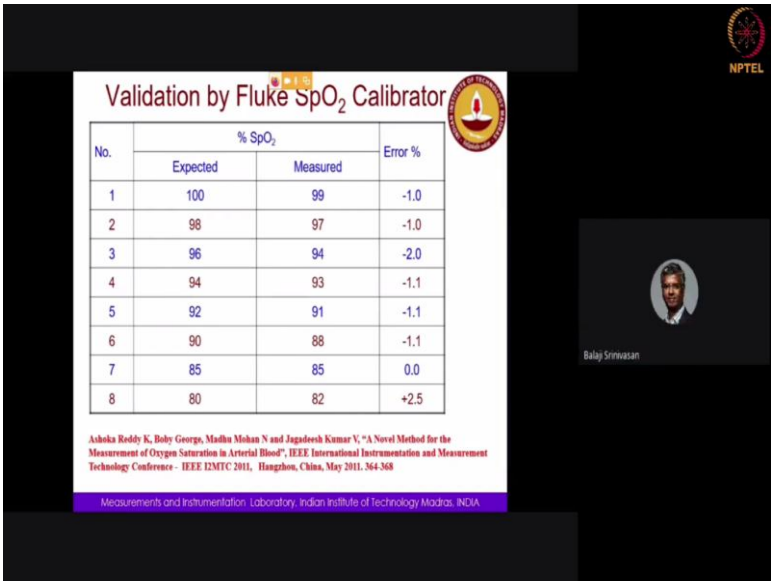

So we again tested this and you calibrate everything. How much time we have? We are almost through.

Professor Balaji Srinivasan: Another 5 10 minutes is fine, sir.

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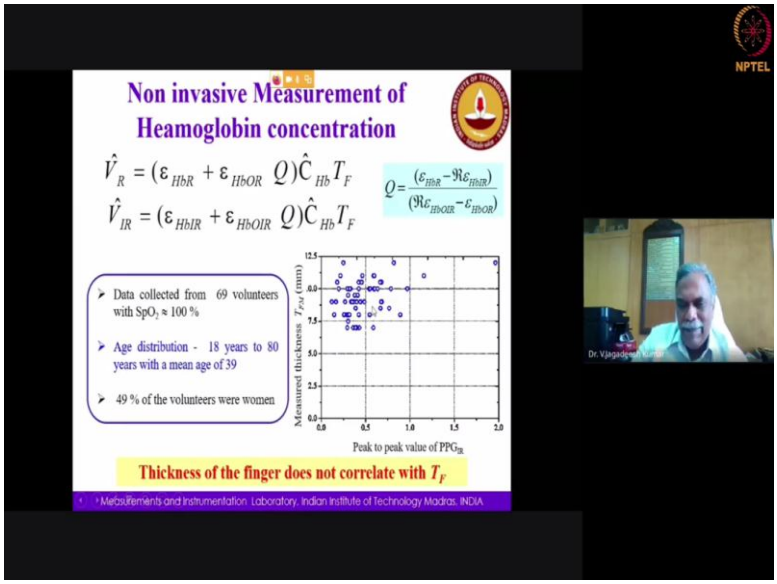

Professor V Jagadeesh Kumar: So I will simply go through it. So if you look at this, this equation says the rate amplitude is the extinction coefficient of hemoglobin at rate, extinction coefficient of oxygenated hemoglobin at rate into the ratio of hemoglobin to oxygen hemoglobin, concentration of hemoglobin and of course, the path length. The TF is the path length. So we thought if I do this, I can measure this concentration of hemoglobin.

So to get concentration of hemoglobin, I should know what is TF in this equation? So we made measurements, we measured the finger thickness, because you put the sensor on the finger, one side LED, one side photodiode. So the thickness we thought would give us this TF. But it does not happen. If you look at it, it is all over the place, this is with respect to peak to peak (()) (45:49) and the thickness that we actually measured on patients. So, then we went back.

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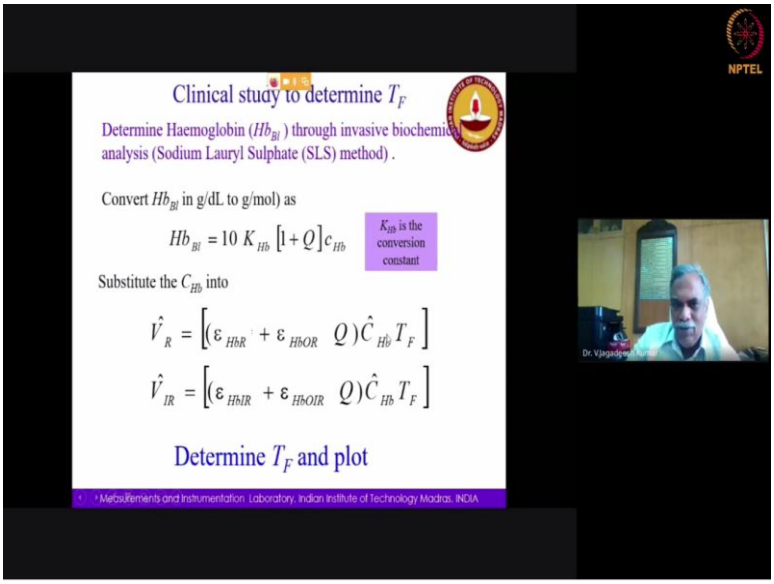

This is again the same equation, the same equation, and so why not plot these equations as such, and see whether I can get the TF.

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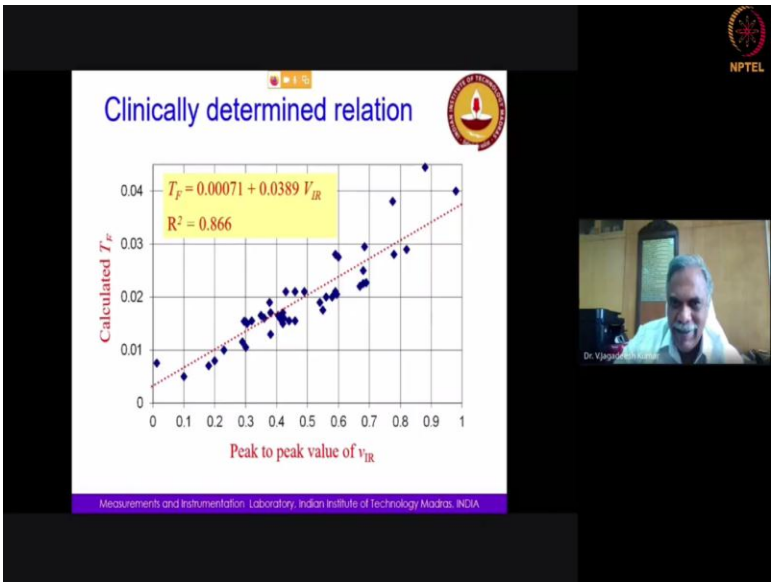

So, we did that plotted sort of, we got a linear, those of you who work in the curve fitting, you will know this is the straight line fitting for this data. And this is called regression analysis R square. If it fits exactly, it must be 1. But I got 0.866, which is about 15 percent error. So not really good, you can have a measurement method, especially in biomedical engineering with 15 percent error. And this was done by Albina. So after about struggling for a week, I told Albina, segregate the data as male and female and do the same thing.

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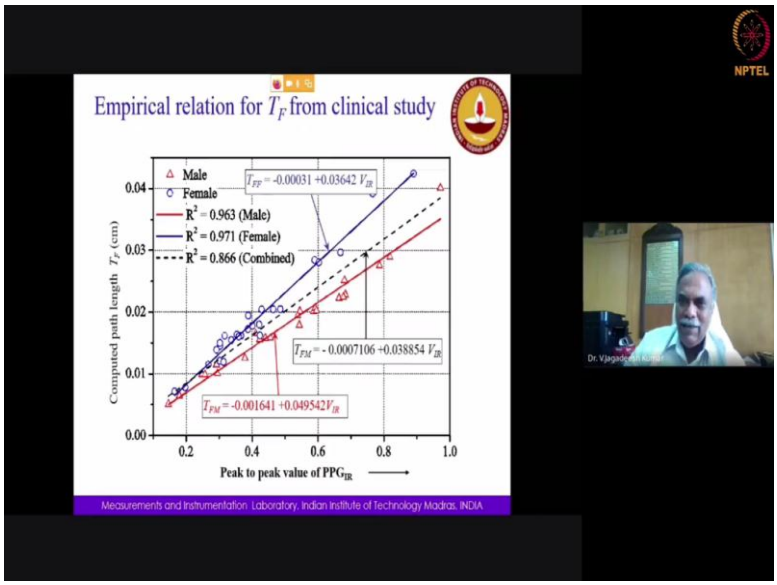

So when she did that, we hit a jackpot. If you look at for the male and female segregation, it is 0.963 it should be 1. But it is very close to 1, 0.963 is only 4 percent. Here, it is only 3 percent. So, you use two sets of equations to measure for males and females, then you actually get hemoglobin measurement. So this is actually what the patent that I sold Balaji.

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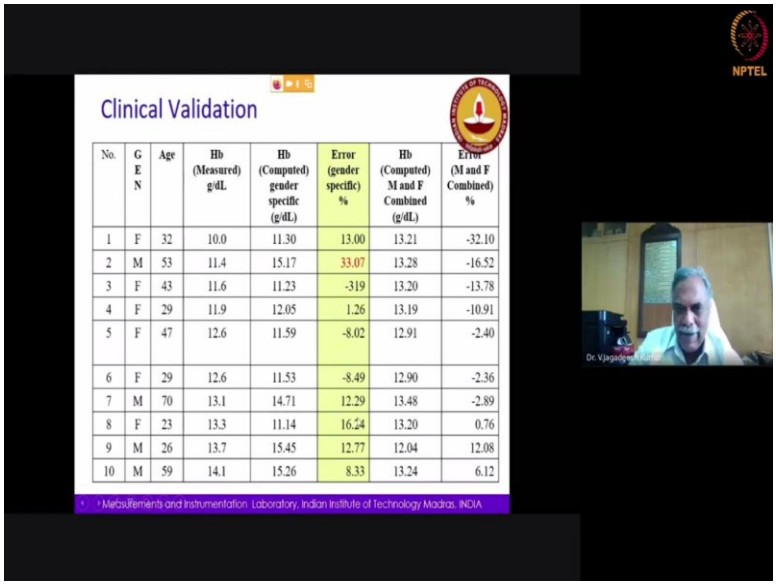

No.	G E N	Age	Hb (Measured) g/dL	Hb (Computed) gender specific (g/dL)	Error (gender specific) %	Hb (Computed) M and F Combined (g/dL)	Error (M and F Combined) %
1	F	32	10.0	11.30	13.00	13.21	-32.10
2	M	53	11.4	15.17	33.07	13.28	-16.52
3	F	43	11.6	11.23	-319	13.20	-13.78
4	F	29	11.9	12.05	1.26	13.19	-10.91
5	F	47	12.6	11.59	-8.02	12.91	-2.40
6	F	29	12.6	11.53	-8.49	12.90	-2.36
7	M	70	13.1	14.71	12.29	13.48	-2.89
8	F	23	13.3	11.14	16.24	13.20	0.76
9	M	26	13.7	15.45	12.77	12.04	12.08
10	M	59	14.1	15.26	8.33	13.24	6.12

So you can make hemoglobin measurement, of course, we went and made the test. So this is the kind of error that you get compared to the present method.

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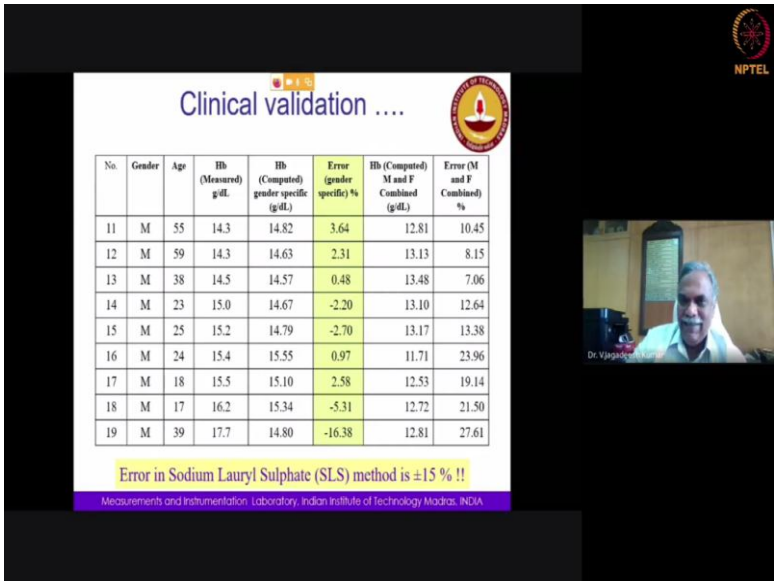

No.	Gender	Age	Hb (Measured) g/dL	Hb (Computed) gender specific (g/dL)	Error (gender specific) %	Hb (Computed) M and F Combined (g/dL)	Error (M and F Combined) %
11	M	55	14.3	14.82	3.64	12.81	10.45
12	M	59	14.3	14.63	2.31	13.13	8.15
13	M	38	14.5	14.57	0.48	13.48	7.06
14	M	23	15.0	14.67	-2.20	13.10	12.64
15	M	25	15.2	14.79	-2.70	13.17	13.38
16	M	24	15.4	15.55	0.97	11.71	23.96
17	M	18	15.5	15.10	2.58	12.53	19.14
18	M	17	16.2	15.34	-5.31	12.72	21.50
19	M	39	17.7	14.80	-16.38	12.81	27.61

But to our horror, if you go to the laboratory and test it today, they use what is known as the SLS method, Sodium Lauryl Sulfate method that itself has an error of 15 percent. So ours is only 4 percent or 5 percent, which is much better.

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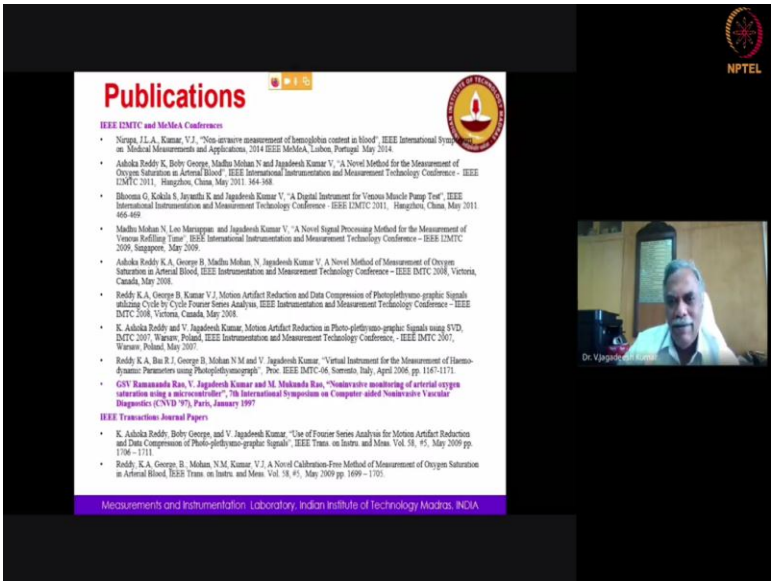

Now, the entire work I have given you the set of publications. So, the most recent is on the top and the oldest is at the bottom. And you can see there are over one journal paper is missing, I will give you Balaji three journal papers and large number of conference papers. And as he already said, Ashoka Reddy has done his PhD Madhu Mohan and Nirupa did her MS.

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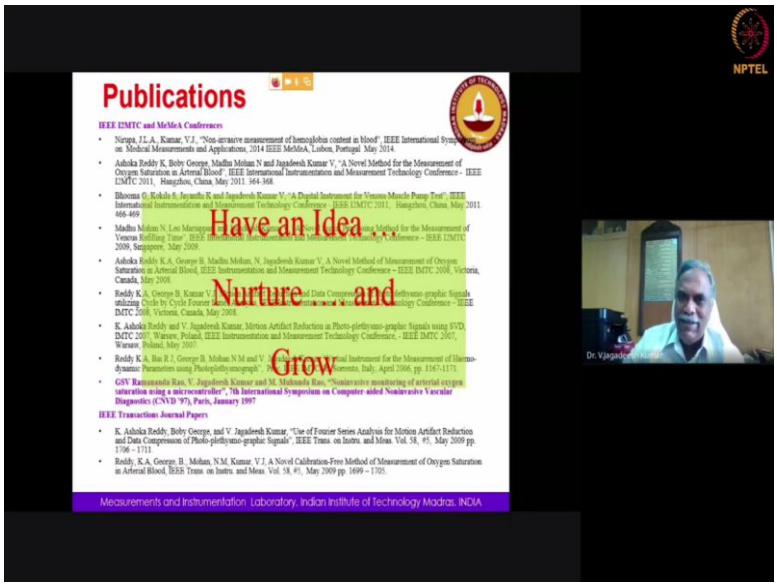

So the thing is; have an idea, I mean, it started with 1995 with just one photodiode and one LED. And that has really potential, all you have to do is think how I can think refine, think how I can get a better method I can solve problems that is in the existing method. Keep on doing that. You would definitely grow.

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I know the second part I have rushed through. But basically there is really not a big deal. Once you have understood the Venous Refilling Time, it is exactly the same but for two wave lengths, that is all.

Professor Balaji Srinivasan: Yes. First of all I thank you for this nice presentation that you have. There are a few more questions. So I will actually read it out.

Professor V Jagadeesh Kumar: Read the questions sir, I am only my screen, I am not able to see anything else.

Professor Balaji Srinivasan: Sure no problem. So the question is about the what is the normal frequency of operation for the Pulse-oximeter?

Professor V Jagadeesh Kumar: Actually our heart rate is anywhere between slightly less than 1 hertz, athletes will have something like 0.8 hertz 45 beats per minute and normal young people will have 60 beats per minute. So 1 hertz frequency and old people will have about double 120 hertz. You might think it is not a sine wave, it has a kink you see there is a dichromatic match because of the pulse rated flow of blood in the arteries, that is deflection. And if you want to do that, you need to go up to about 28th harmonics. So, typically 20 hertz is good enough. But what we do is we go up to 40 hertz, So, most of my instrumentation the bandwidth is kept at 40 hertz.

Professor Balaji Srinivasan: Of course, when we do at low frequencies, the 1 over F noise is a problem, right sir? So, how do you deal with that in your case?

Professor V Jagadeesh Kumar: No, in the method if you see I have a photo detector output and immediately I apply logarithm. The moment I apply logarithm, I hope I am in a class I can go to the board and show you synthetic examples. I the moment I apply natural logarithm on my signal the noise gets attenuated like anything. Because if you take a random signal and apply e power x, e power minus x, then it simply vanishes out.

And there is a secondary benefit, if you look at all my signals, DC is 90 percent because most of the signal comes from a skin or my tissue or my bones if I put it across the finger, there is a soft bone inside, 90 percent of signal is DC. So that gets really attenuated to a very small amount. And my contrast between what I am interested which is the pulse rating signal and what I am not interested, which is DC, enhanced by e power inverse. So now my signal becomes instead of 10 90 becomes 90 10. So, noise was not at all a problem in PPG.

Professor Balaji Srinivasan: So of course, when we talk about general instrumentation, if we really want to push it to the limits, you could possibly use a locking detection as, as people have

people explored that option of going out to basically modulating your source and at a higher frequency and then locking to that and then that can really take you to the, although you, as you mentioned noise may not be as much of a problem, but you really want to keep it down, you could potentially go to that extreme?

Professor V Jagadeesh Kumar: I have not seen a single work on using that. Mainly because in the normal instrumentation itself, you get really very good signal. The output from the photodiode would be 10s of milliwatts, not milliwatts. So it will be above the noise floor of the instrumentation and you do not have any problems.

Professor Balaji Srinivasan: The two techniques that you mentioned sir for pulse oximetry, actually, that is a personal question from my side. Actually, I did not quite appreciate the difference between the both of them use two wavelengths…

Professor V Jagadeesh Kumar: Both of them use two wavelengths, one uses an empirical equation. One use the actual equation through modeling. Second on is a little more complicated to compute. So, you will see that only inexpensive instruments.

Professor Balaji Srinivasan: And calibration is a big issue in a lot of these instruments, right sir?

Professor V Jagadeesh Kumar: You know, because you make ratio metric measurement and your empirically equation is automatically calibrated.

Professor Balaji Srinivasan: So when you talk about SPO2 versus that ratio, that curve was, I suppose, the first method there was the empirical that you are mentioning…

Professor V Jagadeesh Kumar: Yeah. See what, what happened was the initially when the Japanese made the first instrument available, because there instrument was not as cute as the one that you use today. There are several other groups, especially Philip signed the one, Hewlett Packard, Hewlett Packard, had a long presence, Dell car, all these made their own testing. So in fact, what they do is they take volunteers, ask them to take a reduced amount of oxygen.

So they actually lower their blood oxygen and take the red and infrared PPG measurements. And there is a gold standard, I forgot to tell you the gold standard. Gold standard is called the Blood Gas Analyzer, BGA, which actually tells how much of oxygen is there, how much of carbon dioxide is there. But to do that you are to puncture an artery. Take about three CC of blood.

which is very dangerous. So the initial calibration getting that equation 110 minus 25 R as well as my equation, we have to do those test. So, that is (()) (56:12) validation that is done only by the certified laboratory.

Professor Balaji Srinivasan: So what is an accept acceptable error in the oxygen saturation? I suppose you are working in a very small range, I mean, if it is less than 98, on your…

Professor V Jagadeesh Kumar: Balaji one good thing about our physiology, in fact, there is nothing like precisely, see earlier they used to say 110 milligram of per deciliter of glucose is necessary. Now, they say no, no, no, up to 90 is also okay. (()) (57:00) oxygen saturation. Earlier, there was a very big debate, saying that you should have 95 and above.

Professor Balaji Srinivasan: That is what I heard.

Professor V Jagadeesh Kumar: And then when they went and measured people in Himalayas, they are all surviving with 85. Your body gets adapting

Professor Balaji Srinivasan: People, body adapts.

Professor V Jagadeesh Kumar: And, I mean, they are much better than us in terms of Himalayas atmosphere. But in fact…

Professor Balaji Srinivasan: (()) (57:30) measurement scale is actually, the useful scale that you design the instrument for is only that 20-25 percent?

Professor V Jagadeesh Kumar: 80 to 100 percent. Because if it is less than 80, you will see your brain needs, again, this is another information, our body is really, really complex and sometimes you do not realize. My brain weighs only 1 kilogram, but it takes 60 percent of the oxygen I generate through my lungs, 40, 40 percent goes to the other parts of the 84 kg of my. Brain needs lot of oxygen and if the oxygen level reduces below 85 percent 80 percent, you will faint. No one in the world so far today has survived at 80 percent. You will be in then ICU if you are a (()) (58:26).

Professor Balaji Srinivasan: Of course, we do hear about those cases more often these days than normal.

Professor V Jagadeesh Kumar: More than percentage, the actual thing is, it is anywhere between 9 milligram per deciliter to 13 milligram per deciliter. If amount of oxygen is less than 9 milligram per deciliter in your blood, your brain will shut down. There is a mechanism. It is not that you die, your brain will shut down and you can revive if you do very quickly, otherwise, you will go into coma.

Professor Balaji Srinivasan: Last question from my side and then I will look for some other questions if there are from the students; the ADC sir that that you use for these applications, what is the level of precision that is required there? How many units…

Professor V Jagadeesh Kumar: Initially, I used 12 bit then graduated to 16 bit, and today I use 23 bit.

Professor Balaji Srinivasan: Wow. Really

Professor V Jagadeesh Kumar: Frequency is low, you cannot bet at 23 bit, ADC will (()) (59:29)

Professor Balaji Srinivasan: You were saying that 23 minutes because from what you mentioned that the noise being so low that…

Professor V Jagadeesh Kumar: No, no, I can show you the data. I will send you the data. 23 bit ADC each bit counts. That is what I do is I remove all the unwanted noise at the beginning itself by applying logarithm. As I told, I do not have noise in the initial output. The advantage of a 23 bit I mean you really do not need 23 bit, 16 bit is more than adequate, much more than adequate 12 bit itself is good.

But 23 bit, we simply use because today you get a 23 bit 2 kilo samples per second, you see you really do not need that large samples per second. That is 23 bit 2 kilo samples per second is only 300 rupees. So you are not using, whereas 16 bit whether you go to analog devices or textures instruments is still about 4000-4500 rupees. Thanks to all this cheap pulse oximeters, the 2 kilo samples per second ADC, 23 bit has really dropped down in price.

Professor Balaji Srinivasan: I did not, I did not know it was so cheap, actually.

Professor V Jagadeesh Kumar: It is very cheap.

Professor Balaji Srinivasan: Thanks for the information. I am just pausing to see if there are any questions, guys, if you have a question you can ask now. Otherwise, of course, we can ask Professor VJK, separately offline as well. So with that, let me close this session sir. Thank you very much, once again, for sharing your wide deep experience in medical instrumentation.

Professor V Jagadeesh Kumar: I of course, this is an optical sensors course. But you can see with a very simple photodiode you can do so much. You will see that the optical sensors have really, really a very large application potential.

Professor Balaji Srinivasan: Great. Thank you. Thank you, sir, Thanks for your time today.

Professor V Jagadeesh Kumar: See you all.