Introduction to Complex Biological Systems
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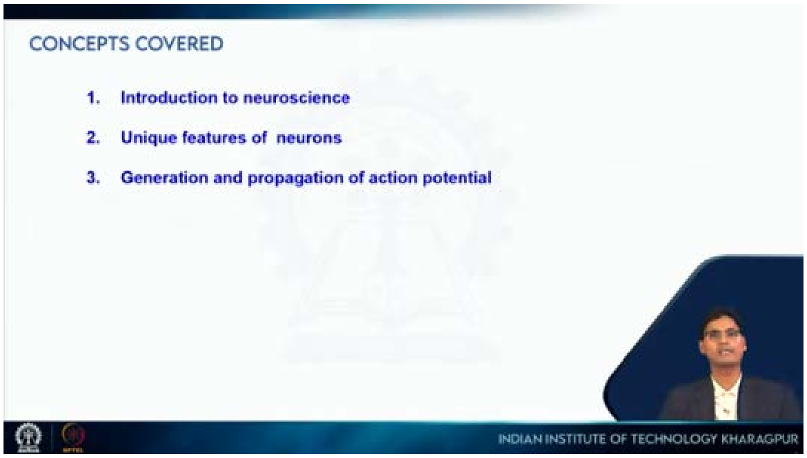
Lecture 30
Introduction to Neuron and the action potential

Hello everyone, today I am going to discuss our brain neurons and the action potential. So, this is the last topic of module 6, and here I will be covering unique features of neurons and the generation and propagation of action potential. So, neurons are present in our body, and they play a very important role. Particularly, neurons are very specialized cells.



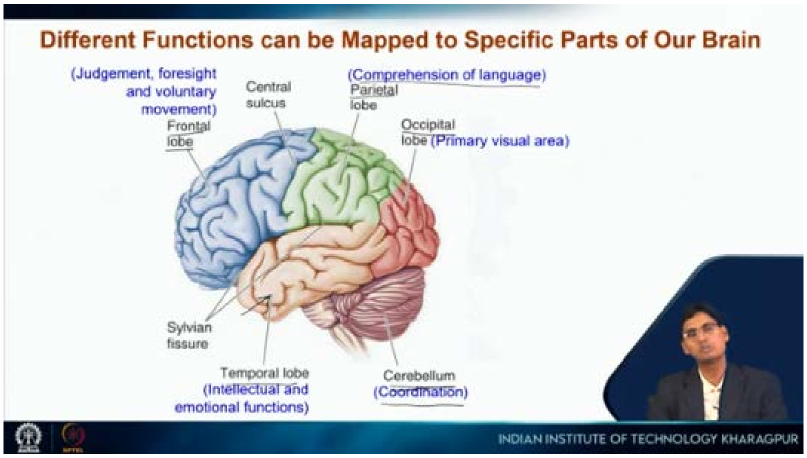
In the last three or four lectures, I discussed many different types of cells, but I never talked about neurons, particularly cells present in huge numbers in our brain as well as throughout our body. So, if you see, our brain is a very complex machine, a complex organ you can say, also part of our body. So, a long time ago, Ramon Cajal, he particularly mentioned that the brain is a world consisting of a number of unexplored continents and great stretches of unknown territory. As you can see, he even received the Nobel Prize in 1906 in physiology and medicine, and he is considered the founder of modern neuroscience. So, I would say more than 100 years have gone by, and a lot of understanding and improvements have happened in the field. But still, today, the brain is very much unknown to us. A lot of things are known, but we cannot explain them properly.

But today I will just introduce some basic concepts about our neuronal cells and how a nerve impulse is generated and propagated. So, here if you see, our brain is the most sophisticated computational machine, whatever you can think about some complex equipment or complex machine, but I would say it is the most sophisticated and it can change its own components. So, own components mean I would say the configuration of neurons itself, its connections, and rewiring itself into a new configuration as required for a new function, this is tremendously important for our day-to-day life also. So now let's see different parts of our brain. So if you see different positions in our brain, there are different functions that can be mapped to specific parts in the brain. So, we can even map different types of functions here in different locations, but mostly I am trying to say that in this brain, if you see, this part is called the cerebellum.

This is present just at the back of the brain and then this is the occipital lobe, parietal lobe, and this is the frontal lobe, just at our head part here, the frontal part, and this is the temporal lobe. So, this image is from one side. So, as you can see, whatever this temporal lobe you can see, if this is temporal, then you have the other side here also. So, anyway, but if we can map their functions, we will be saying they have some kind of specialized function. Somehow those portions of the brain are particularly doing this kind of function.

For example, coordination, which is mostly happening in the cerebellum region. Similarly, I would say, this is the parietal lobe, and here, comprehension of language. So, this is also happening in this region. And the frontal lobe, as you can see, judgment, foresight, and voluntary movement are very important aspects and if you see the temporal lobe here, the major functions are intellectual and emotional functions.

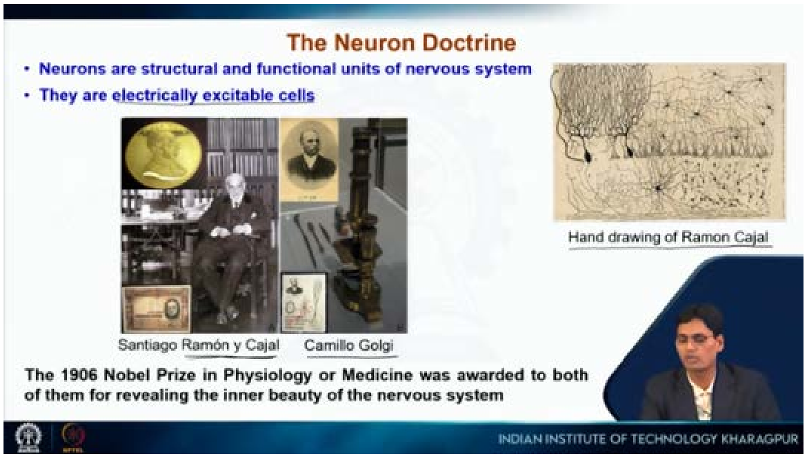
So, as a result of that, although it is filled up with many different types of cells, particularly mostly a lot of neurons, somehow their functions are being segregated in different locations in our brain. Now, as I am saying that neurons are the major cells, they are the cells of our nervous system, our neuronal system. So, here I am going to discuss the neuron doctrine. So, neurons are the structural and functional units of our nervous system, and most importantly, they are electrically excitable cells. So, I am going to discuss more about this later.



Now, here you can see I am just particularly showing you two very great scientists here, Ramon Cajal and Camillo Golgi. Both of them received the Nobel Prize in 1906 in Physiology and Medicine for their work regarding our nervous system. So, what happened is, Camillo Golgi discovered some kind of dye, some kind of staining reagent that is called Golgi stain, and during that time, Golgi stain was used to stain neuronal tissue, for example, brain tissue, and then they were trying to visualize what is present inside our brain, and from that kind of experiment, Camillo Golgi concluded that in our brain we have thread-like cells, but those cells are connected to each other. Again, I am repeating this because it is very important that we have very thread-like cells, a lot of cells, but they are connected to each other.

On the contrary, if you see Ramon Cajal, he also used the same stain, the Golgi stain, which was discovered by Golgi, but he concluded no, those cells are thread-like cells, but somehow they are not directly connected. There is some kind of gap in between those cells and he also drew and this is a kind of hand drawing by Ramon Cajal.

He is mentioning that this is the cell. So, they have a lot of branches, and this is particularly the cell body, but those cells are not directly connected. Today we know that neuronal cells are not directly connected to blood vessels; rather, they have some kind of gap between two cells. So now, if you see just one neuron here, I would say the function of a neuron depends on its elongated structure. So, if you see here, we are showing one neuronal cell, and particularly this portion here is the cell body.

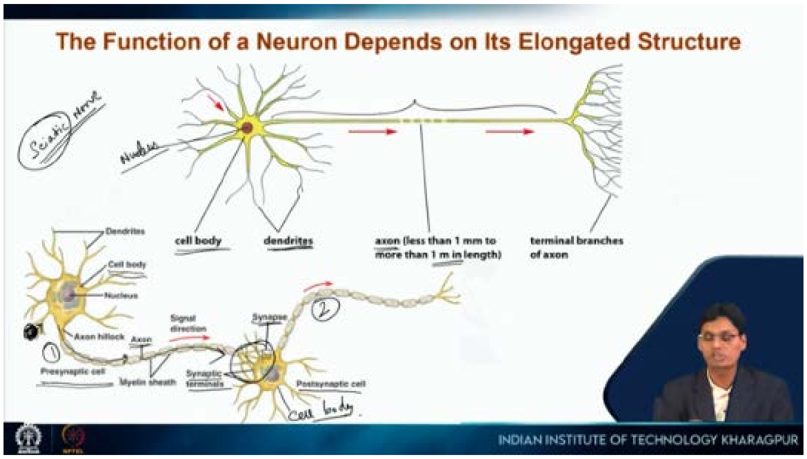


So, here you can see the nucleus. So, this is our nucleus present in this cell, and then all other cell organelles are also present, just like in other cells. Then we have dendrites, which are spine-like projections, and they have a lot of branches. This is the very long portion of a neuronal cell, called the axon. Interestingly, this axon can sometimes be 1 meter in length. See, 1 meter and it can be less than 1 millimeter to 1 meter in length so the size varies a lot, actually. So, particularly, if I mentioned here some nerve cells, like the longest nerve cell in the human body, is the sciatic nerve. Sciatic nerve. So, this starts from our lower back, and it goes through our leg towards the back side. It is a very long nerve, and sometimes you might have heard of sciatic pain. So, some kind of compression, some kind of pinch related to an injury in this neuron, might give you a lot of pain. That is called sciatic pain.

So, this nerve is called the sciatic nerve. But anyway, what I am trying to say here is that the length of these nerve cells varies a lot, and that is the major point. Now, if you see all nerves are not that big but the point is, whatever decision-making is happening, it is in our brain. I already mentioned the brain. So, even if you pinch here, for example, in the finger then quickly we can understand that and this is not always true that a single nerve directly carries this information to our brain. I would say in most cases multiple neuronal cells are connected to each other. Although they are not physically connected, somehow they are connected; they can take the information from the particular site to our brain. So, now, intentionally, I am showing you two neuronal cells. So, this is the first cell, and this is the second cell, for example and then you can see this is the cell body and axon here, and this is another cell here. So, we say that this is also a cell body and here this is the synapse. So, synapse means the connection between these two neurons. So, as you can see in the first neuron.

So, these are the synaptic terminals. At the end of an axon, you have some branches that are synaptic terminals, and that is somehow making some connection with the dendrites of the next neuron. The next neuron after the synaptic junction, we say that is the postsynaptic cell, just to refer to it, and the previous cell should be, in this case, the cell number one, whatever I mentioned, that should be the presynaptic cell. Some event is happening here, and this neuron receives this signal, and it is flowing like this.

This synaptic junction or the synapse will go into the next neuron. So, that is why we are saying this is the presynaptic. So, before the synapse, and this is the postsynaptic cell, and this way the information will flow, but the point is how the information will flow, that is the major question which I am going to discuss today. So, now, but already I mentioned that these cells are electrically excitable cells. Now, I am going to mostly discuss the electrical activity of neurons, particularly the nerve impulse or action potential.



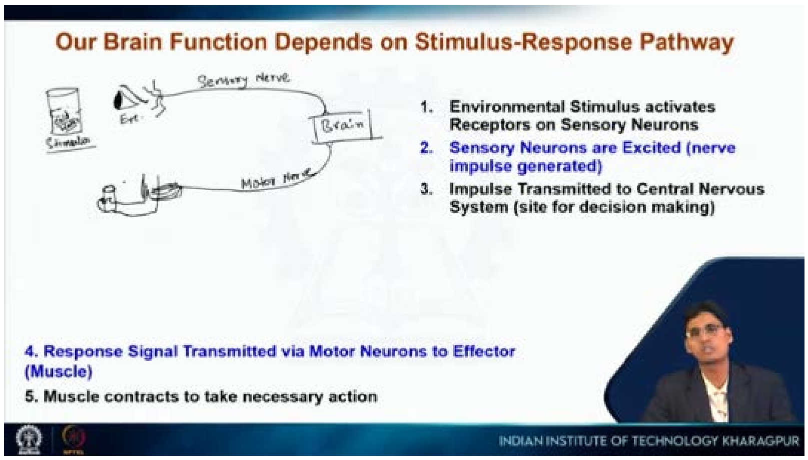
So if you see that our brain function depends on the stimulus-response pathway. So, if I try to explain to you that environmental stimulus activates receptors present on sensory neurons so the sensory neurons and the motor neurons. We can largely classify them. Sensory neurons mean the neurons that are taking some kind of changes in something.

So, that takes the information from there and then it sends it to the brain, and the brain will make some kind of decision, and we have to execute the function. The function will be executed by the motor neuron, so that way, if I try to draw it in a simple way, it will be much clearer to us. So here, for example, if I mention here this is just to imagine that we have a glass of water. So, this is cold water during a hot summer day and now I would say this cold water is now a stimulus and whenever we will see the cold water.

So this is just a cartoon diagram, just imagine this is our eye. So, this is our eye. So, here inside our eye, we have a lot of photoreceptors and nerve cells also present. So the photoreceptors present here will somehow catch this information. So what will happen? So this is, say, a nerve cell, for example. and here this nerve. I will say that this is a sensory nerve that I already mentioned, which is checking this stimulus-like information.

So somehow it is sending this information to our brain, the central nervous system. The brain will now make some decisions, and that decision will be carried forward. It will be going like this again in order to make some kind of function. So, this is motor nerve. Now maybe this motor nerve is going to something like this, just a cartoon diagram.

So, I would say this is the water bottles. So, here muscles are there, and this is coming here. So, as a result of that, the motor nerve finally helps our muscle cells to contract, and then we are taking the glass of water and we can drink that water also. So, as a result of that I was trying to explain to you how a stimulus can help. Here in this case of a photoreceptor, I mentioned it can be different types of other stimuli. It can be sometimes a smell, some chemical present in some food, it can be many other things.



So, in summary, if you see that environmental stimulus activates receptors present in our sensory neurons, then sensory neurons will be excited. As a result of that, the nerve impulse will be generated. So, that is the action potential will be generated. I am going to discuss it in the next slide. This impulse will be transmitted to our brain, and some kind of decision will be formed, and finally, the response signal will be transmitted via our motor neurons to the effectors. So, in this case, for example some muscle, and then the muscle will contract to take the necessary action, what I mentioned in this case is that we might drink the water. That's all.

Now, if you see here how this nerve impulse is generated. So, that is very important in today's lecture. So, let us see. So, again, I am drawing a small cell here. So, if you see, this is our nerve cell, just a cartoon diagram, sorry.

So, this is our cell body, and this is the axon. This is the nucleus present in the cell body. So, this is a nerve cell. So, now if you look into this, why I drew this is that I am just trying to zoom in on this portion. Here, this portion. So, as a result of that, I would say this is the outside.

So, this is the extracellular fluid in this portion, and this is the cytosol. This is the part of the neuronal cell, this portion. So, what is resting membrane potential? This is not just true for neurons, but this is also true for some other electrically excitable cells, like muscle cells. An electrical potential difference across the cell membrane always exists in neurons. Particularly, neurons have a resting membrane potential around -60 to -70 millivolts. So, how is it maintained?

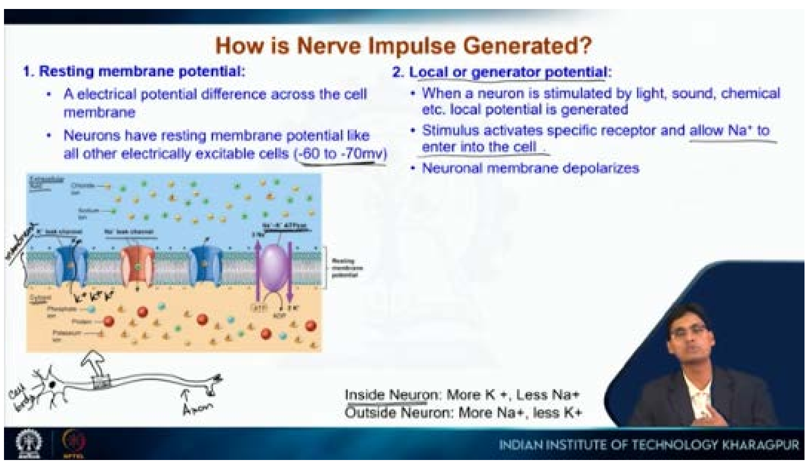
So, if you see here, briefly, if I say that inside the neuron, we have more potassium ions and less sodium and outside the neuron, we have more sodium ions and fewer potassium ions so just the opposite not only that we also have chloride ions and other negative ions, but for this explanation, we are not going to discuss too much about those things. Very briefly, I am going to discuss action potential, and that is what I am trying to explain here. So you have more sodium ions on the outside and fewer sodium ions on the inside when it is in its resting stage, during the resting membrane potential.

So what will happen on the membrane? So, this is the membrane. Now if you see here, we have some leak channels; those are potassium leak channel and the sodium leak channel. Since potassium is more inside, we have a lot of potassium ions inside. So, as a result of that, potassium will go through this leak channel, as you can see.

Similarly, sodium ions will come from outside to inside through the sodium leak channel. But in order to maintain this potential of -60 to -70 millivolts the inside is a little bit more negative compared to the outside. So, now you will see that the sodium-potassium pump is continuously working, and a lot of energy is being used by this pump to maintain this particular potential here. So, as you can see, sodium is going out, and potassium is again coming back to the cell.

So, as a result of that, you need to spend some energy because you are doing this against the gradient. So, outside we have more sodium, but here through this pump, you are actually sending sodium out. So, you need some kind of energy also, but this is very important to maintain this kind of potential difference across the membrane in neuronal cells. Now, what happened during the generation of action potential, the local or generator potential?

So, when a neuron is stimulated by light, sound, chemicals etc., for example, in the previous example, I told that we saw some water present in a glass full of water. So, photoreceptors actually catch that information. So, as a result of that light, sound, chemical, or some mechanical disturbances, all those things can generate some local potential and then that stimulus activates specific receptors and allows sodium ions to enter inside the cell. So, this receptor is not this leak channel; what I am trying to say is that because of this stimulus, it will activate some kind of sodium pump and that will actually help sodium to come inside. Then what will happen? I just mentioned during the resting stage, the resting membrane potential, that means sodium is more outside, potassium is more inside, but overall, inside is more negative, and this is how much -60 to -70 millivolts. Now, because of this, that sodium ion will come inside the cell, and the neuronal membrane will depolarize. So, slowly, it will go into the positive direction, and finally, it will depolarize.



So that part we will learn here. These are the different types of receptors as I already mentioned here. Now if you see the generation of action potential, how it actually happens, I just mentioned a little bit, and now, what is action potential? The action potential is a brief reversal of membrane potential. So, whatever I mentioned, that -60 to -70, but it will go into the positive side for some time. So, for a brief reversal of membrane potential difference of a neuron, it produces a nerve impulse in the neuron, and then that impulse should be propagated across the neuron. Now, if you see here, a stimulus from a sensory cell or another neuron depolarizes toward the threshold potential.

So, let me explain that. So, this is a very important slide. So, something like this on the x-axis, I am putting time here and on the y-axis, this is millivolts. Now, I am just putting some lines so that it will be easy for me to explain this.

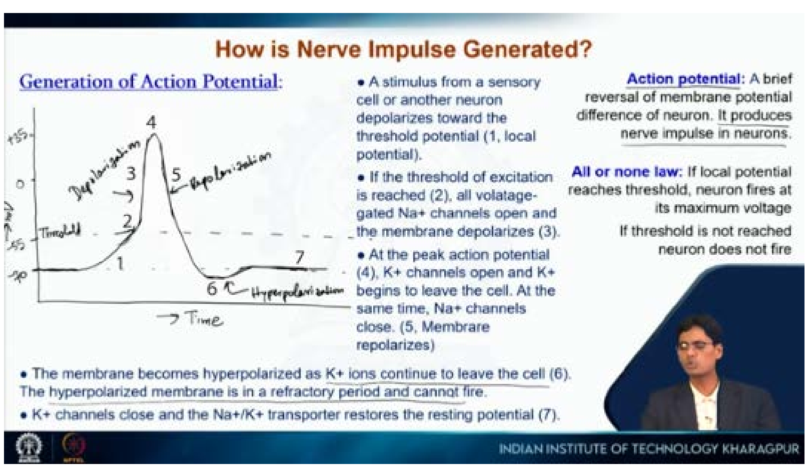
So, if I say this is -70 millivolts and this is -55 millivolts, and here it is 0 millivolts, and somewhere here it is +35 millivolts. Now, during the resting potential, it is something like this, like -70 millivolts, as I already mentioned, -55 to -70 millivolts. Now, what will happen because of some stimulus? It will go like this and this is the threshold level. So, when the potential difference is -55 millivolts, then you will see that it is going very quickly like this and then dropping like this. So, it will go up to +35 millivolts. So, although it looks like it is going, let me correct it a little bit. So, it will go approximately. So, as you can see here, this is the threshold point, and now here depolarization is happening, as you can see that the millivolts are going above 0 millivolts, and here it is maximum at +35 millivolts and this here, number 5, is the repolarization. That means, during that time again the polarization is changing. So, this is repolarization, and this is depolarization and finally, you will see that this is again coming below -70 millivolts. So, this is below -70 millivolts. This stage is called hyperpolarization. This will be for a very short period of time.

So, during that time, again, this same cell will not be excited, and quickly it will return to the resting potential level. This is 7. So, as a result of that, if we start from here, 1, 2 is the threshold, 3 is depolarization, 4 is the maximum level it reaches, then 5 is repolarization, and 6 is hyperpolarization, and 7 is again restoring the resting membrane potential. So, now if you see whatever I drew step by step, everything written here, you can just go through it. A stimulus from a sensory cell or another neuron depolarizes towards the threshold point.

So if the threshold of excitation is reached, this is 2, the second level I marked here. All voltage-gated sodium channels are open, and the membrane depolarizes. So sodium is coming inside the cell, and the membrane is depolarized. Then, at the peak of the action potential, which is marked by number 4 here, during that time, the K^+ channels will also open, and the K^+ ions begin to leave the cell. At the same time, the sodium channels will also close. So, as a result of that, if the sodium channels are closed, sodium is not coming inside anymore, but potassium is going outside the cell. Then what will happen?

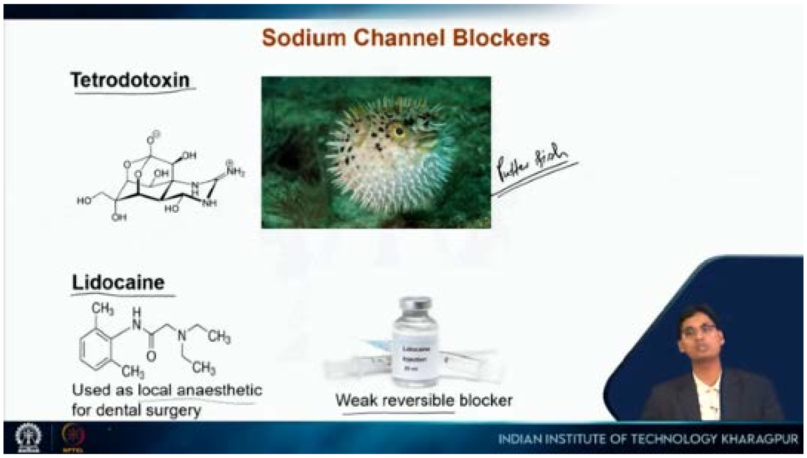
Then again, the membrane will be repolarized again, and it will come down, but the thing is that If the potassium ions leave a little bit more, then it will be hyperpolarized, which is actually happening. As you can see, the membrane becomes hyperpolarized as K^+ ions continue to leave the cell, and the hyperpolarized membrane is in a refractory period and cannot fire, so it needs to wait for a little bit of time and then, the K^+ channels close, and the sodium-potassium channels, as I discussed, will again restore the membrane potential to the resting membrane potential of -70 millivolts. So, this way, some kind of electrical activity is happening. This is called an action potential, this spike. Now, this will migrate to the neurons because, as I mentioned, neurons are very long.

In addition to that, for a long neuron, it has some kind of insulator, which is called myelin sheath. So, the myelin sheath actually covers the neuronal axon in such a way that the signal will not be lost easily. So, it can go very fast, very rapidly. So, that way, neurons help to propagate this nerve impulse or action potential through the neuron, and it can also be sent to the next neuron. So, here, one important thing should be mentioned about the all-or-none law, which means if the local potential reaches the threshold here, then the neuron fires at its maximum voltage, but if the threshold is not reached, the neuron does not fire, okay. So, that means this is the all-or-none law and now, the sodium channels are very important.



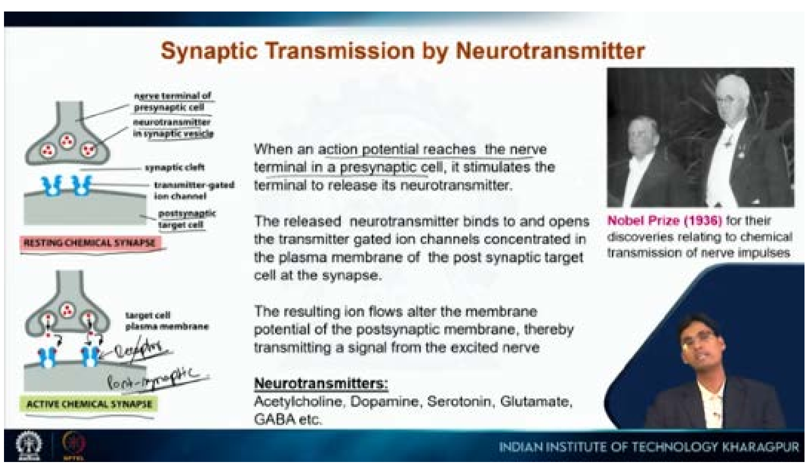
So, there are some chemicals, as you can see here, like tetrodotoxin. So, this is naturally found in some, mostly in marine organisms, for example, this is a puffer fish and it is also available in some octopuses and sometimes in some jellyfish. So, they have this kind of toxin, which is a very potent neurotoxic agent, and it blocks sodium channels. So, as a result of that, it is creating a lot of problems as it is a kind of poison and lidocaine, this is a weak reversible blocker of the sodium channel, which we use as a local anesthetic for dental surgery.

So, this is only for a few minutes to a few hours. It will be in effect, and then after that, everything will be fine because it is a reversible blocker of the sodium channel. Now, this is the last thing to discuss. Whatever I mentioned, that this action potential, this electrical activity, is going through the action, for example to the nerve cell, but nerve cells are now somehow not continuous; they have some gaps in between, as I mentioned at the beginning. So, as a result of that, if you see that synaptic transmission by neurotransmitters, that means, at the end of a neuron, at the end of an action, particularly, some neurotransmitters will be secreted from that action end, and that neurotransmitter will bind to the next neuron, or the postsynaptic neuron, and that neurotransmitter will again open some channels, and that will create or generate some action potential again in the next neuron. So that way it will be carried forward to our brain. So, this is the idea.



So, here is the resting chemical synapse. So, why is it a chemical synapse, because in this case the chemical activity actually leads to the transfer of this thing from one neuron to the next neuron so here is the nerve terminal of the presynaptic cell, and the neurotransmitters are some kind of chemical, and they are present in some synaptic vesicles at the terminal of this action. In the case of an active chemical synapse, these neurotransmitters will be coming out at the synapse. They are coming out from the cell, and then they will bind to these receptors present in the postsynaptic neuron, and as a result of that, again, action potential will be generated. So, I should also mention that during this transfer of information chemically, calcium ions also play a major role. These are the steps that the action potential reaches the nerve terminal in a presynaptic cell, and it stimulates the terminal to release its neurotransmitter. And then the released neurotransmitter binds to and opens the transmitter-gated ion channel. Whatever I told you, this is a receptor, which is nothing but some ion channel, but transmitter-gated, this depends on the neurotransmitter itself. So, transmitter-gated ion channels are concentrated in the plasma membrane of these postsynaptic target cells.

So, here, this is the postsynaptic cell and then the next step is the resulting ion flow alters the membrane potential of the postsynaptic membrane, thereby transmitting a signal from the excited nerve. These are the common neurotransmitters you can see: acetylcholine, dopamine, serotonin, glutamate. Those are very common neurotransmitters. So you can understand that this electrical activity as well as this chemical activity that are happening at the synapse, both are very important to carry forward the neuronal signal to our brain and from the brain back as well.



That is all. So, you can follow this textbook, Molecular Biology of the Cell by Alberts, and thank you.

REFERENCES

1. Molecular Biology of the Cell by Alberts et al., Sixth Edition (Garland Science)