Neurobiology

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Week - 02

Lecture 2.3: Capacitance in neurons

In this series of videos, we have been looking at the electrical properties of neurons. In the last video, we looked at current, voltage, resistance and conductance. And in this video, we will look at capacitance, which is also an important property that determines the functioning of neurons. So, let us see. Capacitance refers to the capacity to store charge. Any electrical element that can store charge can be called a capacitor.

But in the simplest form, a capacitor is formed by two conductive layers that are separated by some insulating material or dielectric. So, here is a schematic. You have one conducting layer here, another conducting layer here, and these two are separated by an insulating material. And if you connect this capacitor to a source of voltage like a battery, then charge can flow through the capacitor.

So, basically the battery would like to move the current from its positive terminal towards its negative terminal. And if you have a capacitor in the circuit, so current is basically the movement of charged particles and we can, for the sake of simplicity, we can assume that positive charged particles are moving in this direction. So, these positively charged particles will come and collect at this terminal of the capacitor. Of course, nothing can flow through the dielectric or the insulator. But whatever is the amount of current flowing in this direction, the same amount of current must be coming back.

So, if X number of positively charged particles have collected on this plate, the same number X of positively charged particles must leave this plate and move in this direction. In effect, we get a negative charge on this plate with the same amount as the positive charge on this plate. And the capacitance is typically denoted by the symbol C and C is equal to Q over V, where Q stands for charge, V stands for voltage and C stands for capacitance. And what this formula tells us is that if the capacitance is large, then you will be able to accumulate more charge on the capacitor per unit voltage. So, if you have a large capacitor, then more current will be able to flow and more charge will get accumulated on this capacitor before it stops.

The unit for capacitance is called farad and 1 farad is equal to 1 coulomb of charge per unit voltage. But the capacitance values that we encounter in neuronal membranes are actually much smaller. We typically deal with capacitance values that are on the order of picofarads or 10^{-12} farads. Also, one thing I should point out, a capacitor is typically denoted by the symbol of two parallel lines drawn perpendicular to the flow of current. And this basically represents two conducting plates separated by some insulating material.

The previous slide, we had developed an analogy between current flow in an electrical circuit and water flow. In that analogy, we saw that pressure difference in the case of water can be compared to voltage in the case of electrical circuits and water flow itself can be compared to the flow of current and amount of water that has flown can be compared to the amount of charge that has flown in the electrical circuit. In this analogy, an aeropipe can be compared to a resistor. Now let's think about what would be the equivalent of a capacitor in the case of this water flow analogy. Before I show you the answer, maybe you can pause your video and see if you can guess what the analogy would be.

Okay, so now let me show you the one example in which a capacitor can be made in the case of water flow. So, imagine a cylindrical pipe and in the middle of the pipe, we put a patch of a rubber membrane inside the pipe and it is touching the inner surface of the pipe on all sides and it is sealed so that no water can pass from one side of the membrane to the other. Now in this case, if you apply a pressure difference to this water pipe so that you have higher pressure on this side and lower pressure on the left side, then you can imagine water will try to move from right to left and it will stretch the membrane. And the ability of this membrane to stretch and accumulate water can be called as the capacitance of this membrane. Now let us compare this membrane with the electrical capacitance.

And we can see that there are several similarities in their behavior. So, one obvious thing is that if you apply some pressure difference, current can flow. So, in the case of pipe, if you apply a pressure difference in water, water will flow through this pipe. Even though there is no water molecule that is actually crossing this membrane. Similarly, in the case of electrical circuit, when you have this capacitor and you apply a voltage here, you can have current moving through the circuit even though no charged molecules actually cross this insulator.

But you could still have positive charge moving in this direction and positive charge moving in this direction. And as the charge moves and as water molecules move in this case, you get water molecules accumulated on the membrane and similarly you get charge accumulated on this capacitor. So, you get positive charge accumulated here and negative charge accumulated here. And as this charge accumulation keeps on happening, the membrane keeps on stretching more and the more it stretches, the more opposite pressure it would apply on the water molecules. So, as it stretches more and more, the opposing pressure that it is creating will keep on increasing and at some point this opposite pressure will become equal to the original pressure difference that was applied.

And when that happens, the flow of water will stop. It will keep on decreasing gradually and at some point it will stop. Similarly, here as charge is getting accumulated on the capacitor, it also generates an opposing voltage and that opposing voltage reduces the amount of current that is flowing over time. And at some point this opposing voltage becomes equal to the original voltage and at that point the current flow stops. So, that is the point when you have maximum charge stored on the capacitor.

And the amount of charge that is stored at that point depends on the capacitance of the capacitor. So, if you have a larger capacitance, then you will have more charge accumulated for the same amount of voltage. And if you have less capacitance, then you will have less amount of charge accumulated. Similarly, here if you have a very flexible, stretchy membrane, then you will have more water accumulated for the same initial pressure difference. Whereas if you have a tight membrane, then you will have lesser amount of water accumulated.

So, this ability to store water or ability to store charge is the capacitance of the corresponding element. So, now let us look at our neuronal membrane again. So, we are looking at a small piece of membrane and as you recall already that the membrane is made of lipid bilayer. So, you have the polar heads of these lipid molecules facing outside and inside and in the middle we have these hydrophobic tails. And this hydrophobic region in the middle does not allow charge to pass through, so it acts as an insulator.

Whereas these polar heads are more friendly to charge, so charge, positive charge or negative charge can accumulate along these layers. So, this arrangement functions like two conducting layers separated by an insulator, so it acts like a capacitor. And because this capacitor is in parallel to ion channels which function like resistors or conductors, we can update our electrical diagram of the neuronal membrane by adding capacitance. So, this capacitance is in parallel to the resistance of the ion channels. Now, let us think about how do these properties depend on the surface area.

So, if you have a larger membrane, how will these values of Rm and Cm, membrane resistance and membrane capacitance would change? You might recall from your basic physics classes that the resistance is inversely proportional to the cross section area of any conducting medium. So, if you have a thin copper wire, then it will offer more resistance to the flow of current and if you have a thick wire, then it will allow the current to pass through more easily. So, as the area increases, the resistance decreases. In the case of neuronal membranes, we can also intuitively understand it in this way that the resistance or the conductance is actually provided by the ion channels. And if you have a larger area, then you will have more ion channels in that piece of membrane.

So, you will have more conductance. So, more area means more conductance and less resistance. So, resistance is inversely proportional to the surface area. Now, let us see how the capacitance would depend on the surface area. So, we can imagine that if the surface area is large, then there will be more area for accumulating the charge.

So, the capacitance will increase with the surface area. And sometimes we can consider that the membrane, the neuronal membrane is uniform throughout and in that case, we can talk of the resistance per unit area and capacitance per unit area. So, Rm and Cm values can refer to the capacitance and resistance values per unit area of the membrane. Thank you.