Neurobiology

Dr. Nitin Gupta

Department of Biological Sciences and Bioengineering

IIT Kanpur

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Lecture 2.8: Equilibrium potentials of different ions

Hi everyone, welcome to Neurobiology. In the last video we looked at the idea of equilibrium potential of a particular ion. We saw that this is the value of membrane potential at which the electrical gradient and the chemical gradient balance out and therefore there is no net flow of that particular ion. Earlier in this series of videos we have also been developing an electrical representation of a neuronal membrane. So we have represented ion channels as resistors or conductors and we have represented the insulated membrane as a capacitor. And now we will try to add the concept of equilibrium potential into this equivalent representation.

Before I show you may want to think about what that representation might be for equilibrium potential. And we will also try to think about how to take into account the different ions. Do different ions have different equilibrium potentials? And if so then how do we take those into consideration when thinking about the final behavior of the membrane. Let us take another look at the electrical representation of an ion channel.

So say this is a potassium channel embedded in the membrane and here we are looking at one single molecule of potassium channel, one protein molecule. So this is the inner side, this is the outer side and this is the protein molecule through which potassium ions can pass. Now this ion channel can be represented as a resistor and can be quantified in terms of its resistance R_k or its conductance γ_k and γ_k is of course $1/R_k$. So either conductance or resistance can define this channel. And of course we know that potassium ions are more abundant inside compared to the outside.

But for simplicity let us first consider the case where the two concentrations are equal. So there is no concentration gradient. And in that case an equilibrium between electrical and concentration gradient will be reached if the electrical gradient is also zero. Which means that the equilibrium potential for potassium in this case should be zero. We can also get the same thing from using the Nernst equation in which if we plug in the inside concentration and outside concentration to be equal then the ratio is 1 and log of that is zero.

So E_k comes out to be zero in that case. Which means that potassium ions would try to keep the membrane potential or the membrane voltage at zero. And if the membrane potential or voltage is actually at zero then there will be no current through this channel. No ions will be flowing through this ion channel. So if V is zero then the current I will also be zero through this channel.

Now if we change V so let us say we increase the value of V then we are changing the electrical gradient while the concentration gradient still remains zero. So there is a disbalance and when that happens the ions will move in a way so that the two can again come in equilibrium. And the direction of the movement of potassium ions will be such that the voltage can get closer to E_k which is zero in this case. So potassium ions will actually move out so that if the membrane was positively charged inside and positive ions move out so that it can again become neutral. So current I going from inside to outside will be positive.

And if V is negative then the current will also be negative. And if V is large then the current will be small and if V is small then the current will be small. So the amount of current or the magnitude of current is directly proportional to the voltage that is generated inside the neuron. And the exact value of current is basically V/R or we can write V * γ_k which is the same thing 1/R is the conductance. So current is simply γ_k * V which basically corresponds to a line like this and γ_k corresponds to the slope of this IV curve as it is called.

So if you have a larger value of V you will have a larger I which is equal to γ_k times the value of V. Now let's consider what happens when concentration gradient is present. So the concentration inside is higher than the concentration outside for potassium ions. And in this case we know that the equilibrium potential for potassium is negative. So the potassium ions will try to maintain a value of around -75 millivolts inside the neurons.

So E_k is not equal to zero when there is a concentration gradient. And in this case the current through the ion channel will be zero not when the voltage is zero inside the neuron. But when the voltage is equal to E_k so when the membrane potential is same as the equilibrium potential then there is no current through the potassium channels. But if the voltage is different from E_k then there will be a current through the potassium channels and that current will be in a direction so that the voltage can come back towards E_k. We can now redraw the I-V curve and see what it would look like.

So earlier the I-V curve was a line passing through the origin whose slope was the γ_k where γ_k was the conductance of the channel. Now in the presence of concentration gradient when V is zero the current will not be zero in that case because the equilibrium potential is -75. So E_k value is now a negative value and current will be zero at this point not at this point. So this is where current is zero and now if we change the voltage from E_k so if the voltage is higher than E_k then there will be positive current. Current will be flowing out through the membrane and if voltage is more negative than E_k then there will be negative current.

So the line should look something like this. So this is the new I-V curve and the slope of this line still remains γ_k. So the more you deviate from E_k the more current you will have and it depends on the conductance. So if the conductance is large then the current will be larger. If the conductance is low then the current will be lower.

So the line will become less steep if the conductance is smaller. And now we can describe the relationship between I and V with a slightly modified equation. So instead of writing current is equal to V over R or V times conductance now we can write current is equal to conductance times V - E_k. So the current is proportional not directly to V but how different V is from E_k. So it's proportional to the difference between the voltage and the equilibrium potential for potassium ions.

So this is the current through a single ion channel which is equal to the conductance of that ion channel γ_k times the difference in the membrane potential and the equilibrium potential for that ion. And now we can update our electrical representation of this part of the neuronal membrane. So the channel is still represented by the conductance or the resistance so conductance γ_k and this equilibrium potential can be thought of as a battery. So this battery for potassium ions is put in such a way that it is making the inside more negative compared to the outside. So if outside is zero and then the inside will be -75 millivolts.

So if you apply a voltage of -75 here then the voltage at this point becomes zero so there will be no net current through this ion channel. But if this value is different from E_k then there will be some resulting voltage difference here and that voltage difference will derive current through this ion channel. In the previous slide we were looking at a single ion channel molecule but of course the ion channels are not present in single copies there are many many of them embedded within the membrane and we can assume that all of these are identical molecules. So if the conductance of one molecule is γ_k then we can assume that the conductance of the second molecule is also γ_k and the third one is also γ_k. And now if we apply a voltage in the neuron that is different from the equilibrium potential then each of them will conduct current corresponding to the conductance of each of these channels.

And the total current through all these channels taken together will be simply n times the current through a single channel. Or we can also say that the conductance of all these molecules taken together is n times the conductance of a single molecule. So total potassium conductance is the number of potassium channels times the conductance of a single potassium channel. So we can update our equation for current where potassium current now total potassium current is equal to total potassium conductance times V - E_k. So this driving force still remains the difference between the membrane potential and the equilibrium potential.

This quantity does not depend on the number of channels. This only depends on the charge of potassium and the ratio of concentrations inside and outside. So now we can put the battery also in the equivalent circuit for a piece of membrane. Earlier we had the capacitance and the resistance connected in parallel. And now we can add this battery which basically reflects the equilibrium potential of the ion in series with the resistance or the conductance for that ion.

So g_k is the conductance for potassium ions and E_k is the equilibrium potential for potassium ions. And these two are connected in series. Note that the voltage difference between inside and outside whether we look at it through the capacitor in which case this is the membrane potential should be same as the voltage difference between this point and this point. So E_k and voltage drop across the ion channels combined together should be equal to the membrane potential. And if the membrane potential is same as E_k then there is no voltage drop across the ion channels and therefore no net current will be there for potassium.

So the resistance or conductance for potassium and the battery for potassium are in series and this is for one particular ion potassium. Now let's think about how will we incorporate different ions. So let's consider the equilibrium potentials of different ions and because the equilibrium potentials depend on the concentrations inside and outside and the charge of the ion and because these concentrations can be different we can have different values of equilibrium potentials for different ions. So for potassium (K^+) the equilibrium potential is around -75. Now let's see if we can figure out what the equilibrium potential for sodium would be.

So sodium concentration gradients are reversed it is present in lower concentration inside and at a higher concentration outside the neurons and the charge of sodium is same as K^+ it's +1. So can we guess what the equilibrium potential for sodium would be? Well we can get the exact value by plugging in these values in the Nernst equation but even before doing that we can actually figure out whether the equilibrium potential would be positive or a negative value. So for potassium we already know that with this ratio the value is a negative and since here the ratio is in reversed so this will be a positive value. Intuitively also we can think that the concentration gradient will be driving the sodium ions from outside to inside because outside concentration is higher. So for an equilibrium to be reached the electrical gradient should be trying to drive the sodium ions from inside to outside and since sodium is positive sodium ions will be pushed outside only if the inside membrane potential is positive.

So the equilibrium potential for sodium will be a positive value and the exact magnitude turns out to be around 55 millivolts if you plug in these values in the Nernst equation. And what about chloride? So chloride's concentrations are similar to sodium it is lower concentration inside and higher concentration outside and the values are also not very different from sodium but the charge of chloride is -1 instead of sodium which has +1. So the equilibrium potential for chloride will be a negative value and it turns out to be around -60 millivolts if you plug in these values in the Nernst equation and intuitively also we can think that the concentration gradient is trying to push the chloride ions inside so the electrical gradient should be trying to push the ions outside then only an equilibrium can be reached and for chloride ions that are negatively charged that would happen if the inside membrane potential is negative. So now we have the equilibrium potential values for all these ions if the membrane potential is same as any of these values then that particular ion will not have a driving force and will not move but if the membrane potential is different then depending on the magnitude of the difference there will be a driving force on on different ions and these different ions will move through their corresponding channels. So if there is a driving force on chloride then the chloride ions will move through the chloride channels and similarly if there is a driving force on sodium then sodium ions will move through the sodium channels and so on.

So in a real membrane we will have all types of channels embedded sodium channels potassium channels chloride channels and so on and each of them will have their own driving forces depending on the exact membrane potential and the equilibrium potential of that particular ion. So we can represent the ion channels for different ions by the corresponding resistance or conductance and the corresponding battery. So sodiums resistance or conductance and sodiums battery potassiums conductance or resistance and potassiums battery chlorides conductance or resistance and chlorides battery and these are all in parallel. So now we can update the equivalent circuit of a piece of membrane by putting all the ions together and we know that the different channels should go in parallel. So the equivalent circuit becomes something like this.

So you still have the capacitance as before and now you have different paths for different ions. So each ion has its corresponding conductance and the battery. So we now have these three possible paths that the current can take and the capacitor all of them connected in parallel. Now one thing to note here since we know that the membrane potential for sodium is a positive value so we have already shown that here in this symbol where we have shown the positive inside for sodium and for potassium it is negative inside and for chloride it is negative inside and since we have already taken into account the sign of the membrane potential so these E_{Cl}, E_K and E_{Na} values only represent the magnitude in this figure. But if we consider E_{Na}, E_K and E_{Cl} values with their corresponding sign then in that case ideally we should be showing all of these values in the same direction.

So in all of those cases we should show the positive terminal inside and negative terminal outside with the understanding that the value of E includes the sign. But in this figure we have taken the sign out and only left the magnitude to be denoted by these E values. So now we have all the important elements for understanding the membrane potential. So we know that the potassium ions whose equilibrium potential is -75 will try to take the membrane potential to -75 millivolts towards their equilibrium potential. Similarly sodium ions will try to push the membrane potential towards their equilibrium potential +55 millivolts and chloride ions will try to push the membrane potential towards -60 millivolts.

But of course the membrane potential is just one value this is the voltage of the neuron so it cannot be these three different values at the same time. Even though we have these three different factors that are trying to achieve different values but the membrane potential will achieve probably something in between and exactly what that value will be that is what we will try to understand in the next video.