Neurobiology

Dr. Nitin Gupta

Department of Biological Sciences and Bioengineering

IIT Kanpur

Week - 02

Lecture 2.7: Equilibrium potential

Hi everyone, welcome to Neurobiology. We have been looking at membrane potential and various membrane properties in last few videos. And we have always been saying that the membrane potential is usually around -65 or -70 millivolts. So, let us now try to understand where this number comes from. In the very first video in this series, we looked at two driving forces on the ions. And these driving forces are actually what result in the value of the membrane potential.

So, these driving forces were chemical gradient and electrical gradient. Now, let us try to understand how these two gradients work together and determine the membrane potential. Let us start by looking at the concentration gradient. And these gradients are going to be different for different ions.

So, let us look at potassium ions in particular, K^+. We know that these potassium ions are more abundant inside compared to outside. So, we have a bunch of K^+ ions here and fewer K^+ ions on the extracellular side. And by the concentration gradient, these ions would like to move outside. So, if we open an ion channel here that allows potassium ions to move, then these ions would move out.

And we can actually calculate how much energy will be released as these potassium ions move out. So, because these ions are moving along their concentration gradient, moving out would be an energetically favorable reaction. So, energy should be released. And the amount of energy released will depend on the ratio of potassium ions here to the ratio of potassium ions here. So, what is the concentration here and what is the concentration here, outside.

And the exact relationship is given by this formula. So, energy released per mole of potassium ions moving out is equal to RT $\ln(K_i/K_o)$, where R is the gas constant, T is the absolute temperature in kelvins, ln is the natural logarithm, K_i is the concentration of potassium ions inside and K_o is the concentration of potassium ions outside. So, if this ratio is more than 1, the concentration inside is higher, then this term is positive. So, energy positive energy is being released when the potassium ions move out. And if concentration inside were less, then the energy released would be negative.

So, that means energy would be consumed. The second gradient is the electrical gradient. And this gradient is present because the total charge is outside and total charges inside are different. So, typically there is more negative charge inside and the inside membrane potential relative to outside is negative. So, if we denote outside as 0 or reference, then inside membrane potential E would be a negative value -65 or -70 millivolts.

And because potassium ions are positively charged, they will be attracted towards the negative potential. So, although the concentration gradient was driving the potassiums from inside to outside, the electrical gradient will try to bring the potassium ions inside. If you open an ion channel that allows potassium ions to flow, then according to the electrical gradient, the potassium ions would like to move in and this movement towards inside would be energetically favorable. And we can again quantify the energy that would be released per mole of potassium ions if they move in. This energy is given by -z E F, where z is the charge on potassium ions, which is +1.

E is the membrane potential, which is -65 or -70 or whatever value is present in the neuron. And F is the Faraday's constant. So, because E is negative and there is this negative sign, so this quantity becomes positive. So, positive energy is being released when potassium ions move in. And we can also write the energy released per mole for the outward movement that would be just the inverse of this.

So, it will be +z E F. So, this is the energy released per mole if potassium ions move out. So, now we have the terms for energy released per mole of potassium ions when they move out according to electrical gradient. And on the previous slide, we saw energy released per mole if they move out according to concentration gradient. An equilibrium will be reached when the total energy released by both the gradients is zero.

So, if the potassium ions are moving out, but the total energy released by the chemical gradient is let us say positive and the energy released by the electrical gradient is negative. And if they are equal in magnitude and they cancel out, then there will be no net driving force on the potassium ions. So, we can write the energy released by the electrical gradient z E F plus the energy released by the chemical gradient RT ln ratio of concentrations is equal to zero. If this condition is met, then the potassium ions will be at equilibrium and they will not move. We can rearrange the terms and derive what the value of E will be at that point.

$$zEF + RT \ln \left(\frac{K_i}{K_o} \right) = 0$$

So, if we move the terms, we get RT ln Ki over Ko on this side with a minus sign. And since there is a minus sign, we can take the minus sign inside logarithm and it becomes the outside can come in the numerator and inside can come in the denominator. And z and F go in the take on the other side. So, they also come in the denominator here. So, the equation becomes the equilibrium potential Ex is equal to RT over z F log concentration outside over concentration inside.

$$E_x = \frac{RT}{zF} \ln \frac{[X]_o}{[X]_i}$$

And this equation is valid for any ion not just potassium. If we use this equation for sodium, then we can put the concentrations of sodium here, sodium outside over sodium inside and the charge of sodium, we can get the equilibrium potential for sodium and similarly any other ion. So, this is known as the Nernst equation because it was derived by Walter Nernst in 1888. And although we have been looking at this equation in the context of neurons, it is also applicable for any other cell or in any situation where chemical gradient and electrical gradients are balanced for any kind of ion. And in this equation R again is the gas constant which is equal to 8.314 in the SI units. T is the absolute temperature in kelvins. F is the Faraday constant which is approximately 100,000 in SI units. And z is a dimensionless quantity which indicates the valence of the ion. So, it is 1 for K, +2 for calcium, -1 for chloride and so on, +1 for sodium. And $[X]_o$ and $[X]_i$ are the concentrations of the ions outside and inside.

And what matters is the ratio. So, if both the concentrations are multiplied by 2, it will not change the equilibrium potential. And this value that we get, value of the potential that we get here is the equilibrium potential and it is also sometimes called the reversal potential or the Nernst potential of the particular ion X that we are looking at. So, for potassium we will get a particular value if we put in the concentrations of potassium and the charge of potassium. And we might get a different value for sodium and a different value for chloride.

So, each ion may have its own particular equilibrium potential. So, this is the Nernst equation again and if we are applying it at room temperature approximately 25 degrees Celsius or 298 kelvins, then we can plug in 298 here and R and F are constants and plugging those values in, this factor RT over F becomes 25 millivolts. And further replacing natural log by log base 10, this equation can be rewritten as 58 millivolts over z which is the valence of the ion, log ratio of concentrations outside over inside. So, we just need to know the concentration ratio and the charge or the valence of the ion and we can easily calculate the equilibrium potential at room temperature for that ion using this shortcut. So, now that we have the formula for calculating the equilibrium potential, let us try this out for calculating the equilibrium potential for potassium ions in the squid giant axon.

So, here are the concentrations of the potassium ions again. It is 400 millimolar inside the neurons in the cytoplasm and 20 millimolars outside in the extracellular space. And we just need to know the ratio of these two values. So, we plug that in, in this formula 58 millivolts over z, z is +1 for potassium, log concentration outside over concentration inside and this turns out to be -75 millivolts. So, the equilibrium potential for potassium ions in the squid giant axon at room temperature is -75 millivolts.

So, this is the value of the membrane potential at which the electrical gradient and chemical gradients for potassium ions will be balanced out and there will be no net driving force on the potassium ions if the membrane potential is equal to -75. So, we saw that potassium ions equilibrium potential is -75 millivolt and if the membrane potential is equal to that value, then there is no net movement of potassium ions because the two gradients electrical gradient and chemical gradient balance out. Now let us consider what would happen if the membrane potential is lower than -75. So, say it is -80 millivolts or -90 millivolts. In that case, the chemical gradient for the potassium ions to move out remains the same, but the electrical gradient that is trying to bring the potassium ions inside becomes stronger because now the membrane is even more negative.

So, there is a bigger electrical driving force trying to bring the potassium ions inside. And so, the net movement of potassium ions will be towards inside and as potassium ions come in, as these positively charged ions come in, the membrane will become less negative. So, from -80 it will start coming back towards -75 and after some time it will have reached -75 millivolts. So, basically the potassium ions try to bring the membrane potential towards -75 if the membrane potential goes below this value. Similarly, if the membrane potential is above -75, so let us say it is -60 or -20 millivolts.

In that case, the chemical gradient still remains the same, but the electrical gradient that was bringing the potassium ions in becomes weaker and so the net movement of potassium ions is now from inside to outside. And as potassium ions move out, the membrane will start becoming more negative. So, from -20 it will start coming towards -30, -40, -50 and eventually it will reach -75 millivolts again. So, this is the value that the potassium ions try to achieve. If the membrane potential is above it or below it, in both the cases, the potassium ions move in such a way that the membrane potential can return to -75.

So, this equilibrium potential reflects the value of membrane potential which the ions try to achieve and different ions will try to achieve different values of the equilibrium potential.