Changes of membrane potential demonstrated by changes in solution color

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Submitted 25 June 2009; accepted in final form 29 July 2009

Since membrane potential regulates the activity of nerves, muscle, and endocrine cells, and many drugs alter the membrane potential, an understanding of the general concepts for the regulation of membrane potential is important. Yet, membrane potentials and ion gradients are often tough areas for students to understand. Analogies can be helpful; for example, Cardozo (2) recently provided a spring analogy for membrane potential. However, in my experience, part of the difficulty probably relates to an adverse reaction to physics and math terms; another part of the problem is just the new technical terms that make it difficult for the students to decipher the concepts. For some of these students, springs may not be enough of an improvement. I have found that a qualitative understanding is facilitated by providing a demonstration and a series of analogies. These analogies will quickly help the students understand the different ways in which a cell can be depolarized (opening Na\(^{+}\) channels or closing K\(^{+}\) channels) and hyperpolarized (opening additional K\(^{+}\) channels or closing Na\(^{+}\) channels).

The analogy is to consider the color of solution in a clear bucket as representing the membrane potential. Two carboys, one filled with blue solution and one with red solution, have tubes that lead to the bucket. The blue solution represents the K\(^{+}\) gradient, and the red solution represents the Na\(^{+}\) gradient. The rate of flow of fluid, governed by the valve, reflects the conductance. For most cells, the resting potential is pretty close to the K\(^{+}\) equilibrium potential, so the flow from the blue solution into the bucket is much greater than that from the red solution and the bucket is slightly purple—but mostly blue. I then ask the class how I can depolarize the bucket, that is, how can I make the solution more purple (or even red). They all immediately see that opening up the valve from the third carboy (Cl\(^{-}\) gradient) will do it. Then, I ask “what other way is there?” After a few moments of thought, they realize that closing K\(^{+}\) channels (reducing the flow from the blue solution) also works, which is how pancreatic β-cells depolarize.

One can extend the analogy to cover Cl\(^{-}\) channels. It is probably worthwhile to remind the students that this analogy is just an approximation and not to overinterpret this color analogy. To extend the analogy, a third carboy (the Cl\(^{-}\) gradient) is introduced; it can be merely a virtual carboy because the students can quickly pick this up after having seen the original demonstration. It is important to stress at this point that the Cl\(^{-}\) gradient differs in each cell, and so the color of this third carboy is cell dependent. For skeletal muscle cells, it is the same color purple as the resting membrane potential (which is mostly blue and a bit of red). At this point, one may want to talk about fainting goats (1), including showing a short YouTube video. These goats have reduced Cl\(^{-}\) channel activity in their muscle cells, and thus the muscle membrane potential is less stable. In wild-type goat muscle cells, the valve is substantially open. This does not change the color of the solution in the bucket. But, the class will quickly realize that one has to really open the red carboy valve (Na\(^{+}\) channels) to get the bucket solution to change color. However, in the fainting goats, the valve from the third carboy (Cl\(^{-}\) channels) is almost closed, and so a small change in Na\(^{+}\) conductance can drastically change the color of the bucket solution.

In other cells, the Cl\(^{-}\) gradient can be either more blue than the resting purple membrane potential or more red. Thus, when the Cl\(^{-}\) channel opens, the direction of the change of membrane potential (more blue, more hyperpolarized; more red, more depolarized) depends on the color of the Cl\(^{-}\) gradient.

One can even push the analogy further and talk about cells or conditions where the Na\(^{+}\) and K\(^{+}\) gradients change. A smaller K\(^{+}\) gradient can be represented by a lighter blue solution in the bucket. This means that, even when the valves on the Na\(^{+}\) and K\(^{+}\) carboys are not changed, the resting potential is more reddish than when the K\(^{+}\) gradient was larger (the carboy had a darker blue solution).

For classes that are resistant to quantitation, one can point out that talking about how red or blue the purple solution is can be quantitated. One could actually put up a color scale from blue [−90 mV (K\(^{+}\) equilibrium potential)] to slightly purple (−60 mV) to purple (0 mV) to reddish purple (+30 mV) to red [+60 mV (Na\(^{+}\) equilibrium potential)]. This would fit particularly well in classes that study Ca\(^{2+}\) levels in cells using fluorescent dyes or other measurements that are presented using a pseudocolor approach.

In summary, the difficulty that some students have in understanding what maneuvers change membrane potential is that they can’t relate the terms to their everyday world picture, not necessarily that the students find the concepts difficult. The use of colored solutions and changes of flow and degree of color provides a real-world example so that they can quickly grasp the concepts.

REFERENCES