ILLUMINATIONS

The Old West analogy for acid-base buffering

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INTRODUCTION

Understanding the concept of buffering is essential for understanding acid-base physiology. In simple terms, a buffer is a mixture of a weak acid and its conjugate base (e.g., carbonic acid and bicarbonate), or a mixture of a weak base and its conjugate acid (e.g., ammonia and ammonium), that, when present in a solution, resists changes in the pH of that solution. The way buffers work is also relatively simple: when a strong acid (e.g., hydrochloric acid) is added to the solution, the protons that come with the strong acid will combine with the weak base (e.g., bicarbonate) to yield the weak acid (e.g., carbonic acid). Most free protons that come with the strong acid will thus be “sequestered” in the weak acid, and, since they will not remain as free protons, they will not contribute to (i.e., change) the pH of the solution. Two conditions have to be met for this to happen: First, there has to be sufficient buffer in the solution to bind the added protons, and that is why buffer concentration matters. Second, the starting pH of the solution has to permit both forms of the buffer (e.g., weak acid and conjugate base) to coexist in the solution, which happens when the pK of the buffer is relatively close to the pH of the solution (with maximal buffering capacity for that individual buffer occurring when pK = pH), and that is why buffer pK matters.

It is reasonable to assume that virtually all medical students who are taught the concepts outlined above, when given concrete physiological context and adequate time for study, will gain a good understanding of how buffering works. However, the pressures of preclinical medical education often do not allow for detailed explanation of such basic concepts, or for appropriate study time dedicated to understanding them. Furthermore, medical students are generally expected to already possess this knowledge from undergraduate course work. However, in the author’s experience, many students memorize facts about buffering without gaining a true understanding of their underlying logic.

Description of the analogy. To facilitate students’ rapid understanding of buffering, the author developed an analogy that has received high praise in both formal anonymous evaluations of the “Introduction to Acid-Base Physiology” lecture for first-year medical students and in informal student feedback. The analogy makes use of common knowledge of the Old American West, as depicted in numerous Western movies that are part of popular culture both in the U.S. and abroad, but without resorting to any representation that may be perceived as culturally insensitive. Because of its simple premise, the analogy could also be modified and adapted outside the United States to better suit local culture and history.

As shown in Fig. 1, let us imagine that protons are outlaws, and the body is a town in the Old West (the entire body is used here for simplicity, but the context in which the analogy is delivered implies that it refers to body fluid compartments). Similar to the constant inflow of protons from diet and metabolism with which the body has to deal, there is a constant inflow of outlaws in our Old Western town (Fig. 1A). If the town has no mechanisms in place for defense against the outlaws, it is going to be overrun.

Luckily, the town has deputies who arrest the outlaws and place them in jail. So, an outlaw, which is a proton, comes into town, is arrested by a deputy, such as, for instance, hydrogen phosphate, and is placed in jail, which, in this example, is dihydrogen phosphate (Fig. 1B). Of course, the jail cell here is a metaphor, not meant to imply that the proton is sequestered in a fixed physical location in the body: it is more like jail wagons, that still circulate through town. The point is that the outlaw can no longer wreak havoc while in jail, but he is still in town, and a deputy is busy guarding him. The deputies and jail cells in this example are the buffer pair.

Even though it is just one deputy who makes the actual arrest, it is obvious that the more deputies the town has, the more rapidly each outlaw will be captured. This is why buffer concentration matters. It is also quite obvious that, if the town could only have deputies, but no jail cells, or only jail cells, but no deputies, this would not work. The town must afford to have a relatively balanced number of deputies and jail cells, and this is what buffer pK determines.

Finally, there is regular train service from our Western town to a nearby federal fort, and the train carries the captured outlaws to federal prison (Fig. 1C). This represents proton excretion. Although not depicted in Fig. 1, the train also has guards who make sure the outlaws do not escape, and these are the urinary buffers.

Conclusions, limitations, and use in context. In summary, the key goals of the Old West analogy for acid-base buffering are to help students gain a rapid and intuitive understanding of the role of buffers, and of the principal factors that define a good buffer (i.e., pK and concentration). Based on the author’s experience with student questions, informal feedback, and formal evaluation of teaching, the analogy excels at achieving these goals, while not appearing to cause any inadvertent confusion or misunderstanding.

However, like any science analogy, the one presented here has important limitations and should not be overextended.
analogy is not intended to represent whole body acid-base physiology, because it does not include depictions of volatile acid handling, new bicarbonate generation, the concept of open versus closed buffer systems, and the distinction between ammonium and nonammonium urinary buffers. In addition, it does not directly address the fact that physiological acid buffering involves the simultaneous action of multiple buffers, with different pK values and concentrations (although the analogy is used to help students understand why these characteristics matter).

Finally, the context in which this analogy is delivered to students is critically important to enhance understanding and avoid potential confusion. For instance, one could start by discussing the physiological importance of buffers, defining the chemical concepts of buffer pair and pK, and explaining the Henderson-Hasselbalch equation (including concrete examples of what happens to the relative concentrations of the components of a buffer pair when pH = pK, pH = pK + 1, pH = pK – 1, etc.). The notion that multiple buffers with different pK values coexist physiologically in an equilibrium that is dependent on the pH of the solution (the isohydric principle) could then be introduced, still making use of the Henderson-Hasselbalch equation. Only after this theoretical introduction could the analogy presented in this article be used to help clarify and reinforce the concept of pK and to help students intuitively understand why both pK and buffer concentration are important. After this discussion, the students would be ready to learn about the major buffers in extracellular and intracellular fluid compartments, and the roles they play in buffering fixed and volatile acid. The analogy would not be revisited during later presentation of respiratory and renal regulation of acid-base balance, but students’ understanding of these processes would greatly benefit from their prior understanding of buffering.

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