Red State or Blue State Depends on the Ventilation Rate: A Respiratory Acid Base "Shock and Awe" Demonstration

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Abstract
This article describes a simple and inexpensive "shock and awe" classroom demonstration for understanding the importance of carbon dioxide (CO_2) in acid-base regulation. Before class, a solution was prepared by adding sodium bicarbonate and universal indicator solution to a sample of distilled water contained in a standard plastic water bottle. Upon arriving to class, the students observed the blue-violet solution and were told that the solution could be considered a surrogate for the arterial blood. At this point, a small piece of solid CO_2 (dry ice) was dropped into the bottle and a balloon, filled with confetti, was placed over the opening of the bottle. As expected, the solution rapidly turned bright pink/red as the solid CO_2 underwent sublimation and filled the balloon. At this point the balloon was "popped", making a loud noise and flying confetti about the room contributing to the "shock and awe" appeal. Furthermore, CO_2 was released simulating ventilation. To simulate hyperventilation, a piece of tubing connected to a hand bicycle pump was inserted into the bottle and air was pumped into the solution. As expected, the solution slowly changed from red to orange to yellow to green and finally approached blue as CO_2 was forced out of the solution. This straightforward and easy to perform demonstration provoked intense interest and provided a memorable learning experience by attracting and sustaining attention and increasing students' motivation to focus on the material. https://doi.org/10.21692/haps.2020.001

Key words: hyperventilation, hypoventilation, sublimation, carbon dioxide

Introduction

All the classroom is a stage…
and all the teachers and students
merely players
(apologies to William Shakespeare,
April 26, 1564 – April 23, 1616)

Teaching is not just about content; it is also about being a performer and entertainer. The content must do more than educate; it must also entertain, because teaching is a performance art and every presentation is a performance (Curran-Everett 2019). In the classroom, the teacher has the responsibility to communicate as well as engage and entertain (Savage et al. 2017). In this context, "shock and awe" classroom demonstrations engage and entertain by attracting and sustaining attention and increasing students' motivation to focus on class material, all of which aid in the learning process. Specifically, the spectacle and inherent drama of "shock and awe" classroom demonstrations offer emotionally engaging scientific theatre. Emotionally engaging scientific theatre stimulates significant student interest and exploits our primitive power of curiosity (Lujan and DiCarlo 2016; 2018; Lujan et al. 2019). To this end, we used a "shock and awe" classroom demonstration to create scientific theatre for understanding respiratory acidosis.

Background
Carbon dioxide (CO_2), in its normal range from a partial pressure of 38 to 42 mm Hg, plays important physiological roles. CO_2 regulates the pH of blood, stimulates breathing, and influences the affinity hemoglobin has for oxygen (O_2). Accordingly, variations in CO_2 levels are highly regulated and can cause disturbances if normal levels are not maintained. For example, by exhaling more CO_2 or less CO_2, the body can change the concentration of CO_2 in body fluid, and thereby regulate the pH of body fluid. During hypoventilation the rate of removal of CO_2 from the blood is decreased and shifts the hydration equation to the right. That is, when CO_2 dissolves in water, it forms a weak acid known as carbonic acid, H_2CO_3. H_2CO_3 can quickly dissociate into a hydrogen ion (H^+) and bicarbonate ion (HCO_3^-). The increase in the H^+ concentration causes the pH to decrease. Some of the H^+ produced when CO_2 acidifies the blood is buffered instantly by buffering systems found in bone, hemoglobin, and amino acids. The kidney subsequently produces "new HCO_3^-" that compensates for the increased [H^+] (Figure 1).

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In contrast, during hyperventilation the rate of removal of CO_2 from the blood is increased and shifts the hydration equation to the left. This leads to a decrease in the H^+ concentration and causes the pH to increase. Some H^+ is released from the bone, hemoglobin, and amino acids while the kidney eliminates HCO_3^- that compensates for the decreased [H^+] (Figure 2).

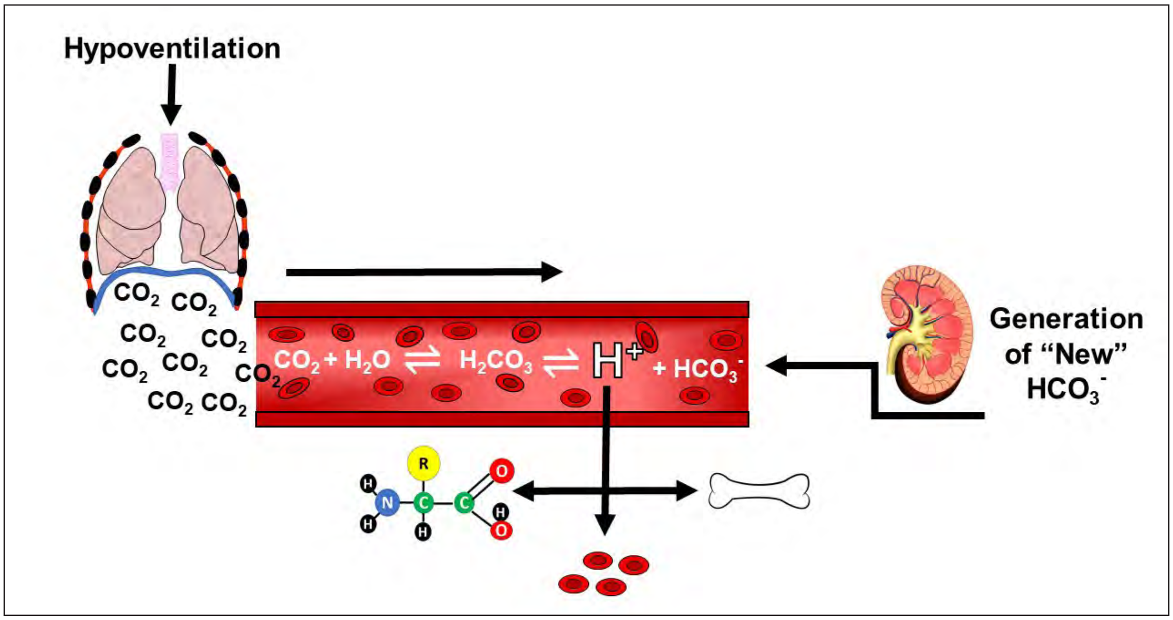

Figure 1. *Hypoventilation leads to an increased concentration of CO_2, which results in an increased H^+ concentration. The increased H^+ concentration results in decreased pH. Some of the H^+ produced when CO_2 acidifies the blood is buffered instantly by bone, hemoglobin, amino acids. The kidney produces "new HCO_3^-" which compensates for the increased [H^+].*

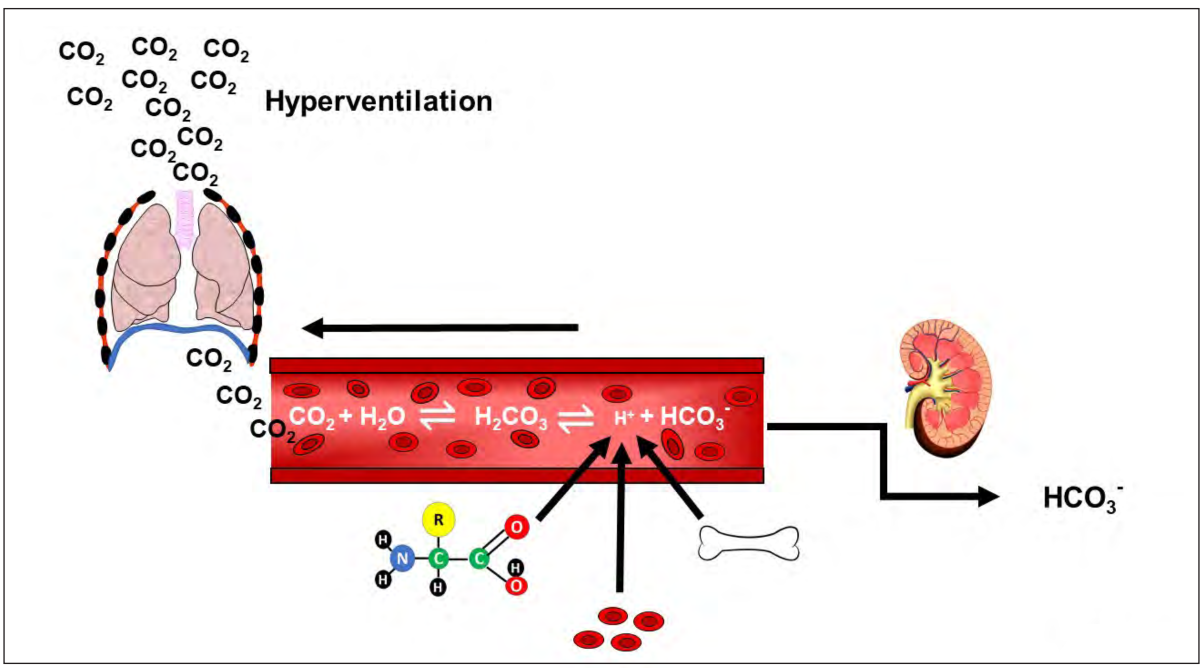

Figure 2. *Hyperventilation leads to a decreased concentration of CO_2, which results in a decreased H^+ concentration. The decreased H^+ concentration results in an increased pH. To compensate for the decreased H^+ concentration, some H^+ is released from the bone, hemoglobin, and amino acids while the kidney eliminates HCO_3^-.*

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Volatile acids

To help students understand the importance of CO_2 in acid-base regulation we begin with a discussion of volatile acids. Students are told that acid produced from CO_2 is called a volatile acid, because CO_2 is a gas that can be exhaled by the lungs. In fact, CO_2 is a colorless gas that comprises approximately 0.04% of Earth's atmosphere. In the human body, CO_2 is formed from the metabolism of carbohydrates, fats, and amino acids, in a process known as cellular respiration. The normal, resting CO_2 production is about 200 mL (8.9 mmol/per minute). This much CO_2 would yield 8.9 mmol of H^+ per minute. That is 12,800 mmol of H^+ per day. This rate of H^+ production, if it remained in body fluid as free H^+, would be fatal in minutes. However, a healthy respiratory system readily exhales this CO_2 as fast as it is produced so no net load of volatile acid accumulates in the body. All the other acids in the body (not produced from CO_2) are called non-volatile acids, non-carbonic acids, non-respiratory acids, metabolic acids, or fixed acids. Several metabolic processes produce fixed acids, and therefore increase the concentration of H^+ ($[H^+]$). Fixed acids are produced due to incomplete metabolism of carbohydrates (e.g. lactate), fats (e.g. ketones) and protein (e.g. sulphate, phosphate). Other metabolic processes produce bases and therefore consume H^+.

In this context, students, even advanced students, are often surprised to learn that nearly all the weight lost, for example with dieting, is exhaled by the lungs. As noted above, metabolism of fat produces carbon dioxide and water and we exhale the carbon dioxide and the water is lost as urine or sweat. In fact, metabolism of 4.5 kilograms (10 pounds) of fat results in 3.8 kilograms (8.4 pounds) being exhaled from the lungs and the remaining 0.7 kilograms (1.6 pounds) lost in the urine or sweat. Thus, nearly all the weight we lose is exhaled by the lungs (Meerman and Brown 2014).

The Demonstration

"No written word, no spoken plea can teach our youth what they should be; nor all the books on all the shelves --it's what the teachers are themselves."
Anonymous, quoted by John Wooden

To demonstrate the importance of CO_2 in acid-base regulation and model the scientific inquiry process, we created scientific theatre by presenting a "shock and awe" demonstration (Lujan and DiCarlo 2016; Lujan et al. 2019). Before class, we prepared a solution by adding 1 mL of universal indicator solution to a sample of distilled water contained in a standard plastic water bottle. The solution immediately displayed a yellow color, with a pH around 5.5. Tap water may be used; however, the color of the solution will be yellow or green/blue, depending on the acidity of the water. Next, 0.1 grams of sodium bicarbonate was added to the solution. The color of the solution turned blue-violet (Figure 3, Panel A). We also obtained a few small pieces of dry ice. Dry ice is the solid form of carbon dioxide.

Figure 3. *The blue-violet solution (Panel A) was considered a surrogate for the arterial blood. A small piece of dry ice was dropped into the bottle and a 10-inch balloon, filled with confetti, was placed over the opening of the bottle (Panel B). The solution immediately turned bright pink/red and the balloon expanded as it filled with carbon dioxide (Panel B). To simulate respiratory compensation, the balloon was "popped" releasing the confetti and CO_2 (Figure 3, Panel C). Popping the balloon simulated ventilation. Finally, a catheter connected to a hand bicycle pump was inserted into the bottle and air was pumped into the solution. As expected, the solution slowly changed from red to green and eventually back to towards blue (Panel D).*

Upon arriving to class, the students observed the blue-violet solution and were told that the solution could be considered a surrogate for the arterial blood (Figure 3, Panel A). At this point, a small piece of solid CO_2 (dry ice) was dropped into the bottle and a balloon, filled with confetti (Lujan et al. 2019), was placed over the opening of the bottle (Figure 3, Panel B). As expected, the solution rapidly turned bright pink/red as the solid CO_2 underwent sublimation and filled the balloon. Sublimation is a chemical process where a solid converts into a gas without going through a liquid stage.

The solution turned pink/red because as the CO_2 dissolved in water, it formed a weak acid known as carbonic acid, H_2CO_3. H_2CO_3 dissociated into a hydrogen ion and bicarbonate ion. The addition of hydrogen reduced the pH [pH= negative log (activity H^+)]. Ion activity is also known as the effective ion concentration. Solutions with a high effective concentration of hydrogen ions have a low pH and solutions with a low effective concentration of hydrogen ions have a high pH. The balloon expansion (Figure 3, Panel B) represents CO_2 retention as occurs with hypoventilation (Figure 1).

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At this point the balloon was "popped", making a loud noise and flying confetti about the room contributing to the "shock and awe" appeal (Figure 3, Panel C) (Lujan and DiCarlo 2016; Lujan et al. 2019). Furthermore, CO_2 was released, simulating ventilation. To simulate hyperventilation, a piece of tubing connected to a hand bicycle pump was inserted into the bottle and air was pumped into the solution. As expected, the solution slowly changed from red to orange to yellow to green and finally approached blue as CO_2 was forced out of the solution (Figure 3, Panel D). Specifically, by pumping air with nearly no CO_2 into the bottle, the solution was mixed and exposed to the air. By creating a large surface area, the CO_2 diffused from the water into the lower- CO_2 air.

This simple, easy to perform demonstration provoked intense interest and provided a memorable learning experience because teaching is theatre. When we teach, we are acting. Our best "performance" occurs when we tap into our authentic emotions and connect with our students. When this happens, our students will be moved, and somehow changed intellectually and emotionally. Thus, the success of this demonstration may be attributable, in part, to a powerful emotional connection. All humans share basic emotions. When we experience emotion in our lives, we tend to remember the experience. In fact, the more emotional impact an experience has, the more intensely we remember its details and the more likely it will be stored in long-term memory (Lujan and DiCarlo 2016; 2018; Lujan et al. 2019). Accordingly, maybe we all should consider Amy Farrah Fowler's (fictional character in *The Big Bang Theory*, portrayed by Mayim Bialik) advice to Sheldon Lee Cooper (fictional character in *The Big Bang Theory*, portrayed by Jim Parsons) regarding improving his teaching (https://bigbangtrans.wordpress.com/series-4-episode-14-the-thespian-catalyst/):

Amy: Perhaps you should consider taking acting lessons.

Sheldon: Acting lessons. Interesting.
It might help if I could act as though I care about
my students and whether or not they learn.

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