Electrolyte and Water Control Mechanisms

From Electrolyte & Water Balance in Calves
Developed by Rob Costello, Technical Specialist

This section describes how individual cells, the kidneys and the lungs regulate the body's electrolytes and water. The kidneys and lungs regulate the chemical composition of blood, providing primary control over electrolytes and water in body fluids. A discussion of acid-base balance describes how the concerted efforts of the kidneys and lungs help maintain an electrically neutral environment.

This elementary exploration of the physical chemistry of biological solutions is the most technical in this publication. Although an understanding of this material is not required before reading the remaining sections, these discussions provide a better understanding of electrolyte and water balance, dehydration, and electrolyte formulation.

Individual cells work in conjunction with the kidneys and lungs to regulate and maintain normal water and electrolyte balance within the body. The kidneys have the largest responsibility for maintaining blood chemistry, and in concert with the lungs are responsible for regulating the acid-base balance within the blood. These processes involve both electrolytes and water.

Figure 6 shows the typical chemical composition of body fluids. Extracellular fluid makes up about 40% of the body's water and includes the fluid in blood and the space between cells, called the interstitial space. The remaining 60% is intracellular fluid, residing inside of cells. Extracellular fluid provides all of the nutrients, oxygen, waste removal, pH and temperature control for the cell. Cells simply react to conditions in the extracellular fluid.

Chemical Composition Of Extracellular & Intracellular Fluids

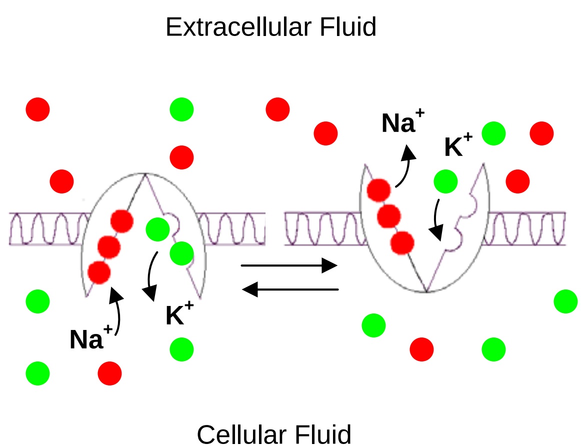
		Extracellular Fluid	Intracellular Fluid
Strong Ions	Na^-	140 mEq/l	10 mEq/l
	K^+	3 mEq/l	150 mEq/l
	$Ca^{?}$	1 mEq/l	< 1 mEq/l
	$Mg^{?}$	2 mEq/l	10 mEq/l
	Cl^-	103 mEq/l	4 mEq/l
	Other Strong Ions	1 mEq/l	35 mEq/l
Strong Ion Difference [SID]*		37	131
	HCO_3^-	28 mEq/l	12 mEq/l
	Phosphates	4 mEq/l	75 mEq/l
	SO_4	1 mEq/l	2 mEq/l
	Glucose	90 mg %	0 - 2 mg %
	Amino Acids	30 mg %	200 mg %
	Cholesterol, Phospholipids, Neutral fat	0.5 mg %	2 - 95 mg%
	PO_2	35 mmHg	20 mmHg
	PCO_2	46 mmHg	50 mmHg
	pH	7.4	7.0

*[SID] = [Na+]+[K+]+[Ca+]+[Mg2+]-[Cl-]-[other strong anions]
[ ] means: concentration of

Figure 6.

Cells. Sodium (Na^+) is the major ion, or electrolyte, outside of the cell. Potassium (K^+) is the major ion inside the cell. Since cell membranes are permeable to Na^+, it diffuses into the cell where its concentration is lower. To maintain the low intracellular Na^+ concentration, the cell quickly pumps Na^+ back into the extracellular fluid. Sodium pumps located in the cell membrane pump Na^+ out of and K^+ into the cell, maintaining normal osmotic gradients.

Figure 7. Sodium Pump



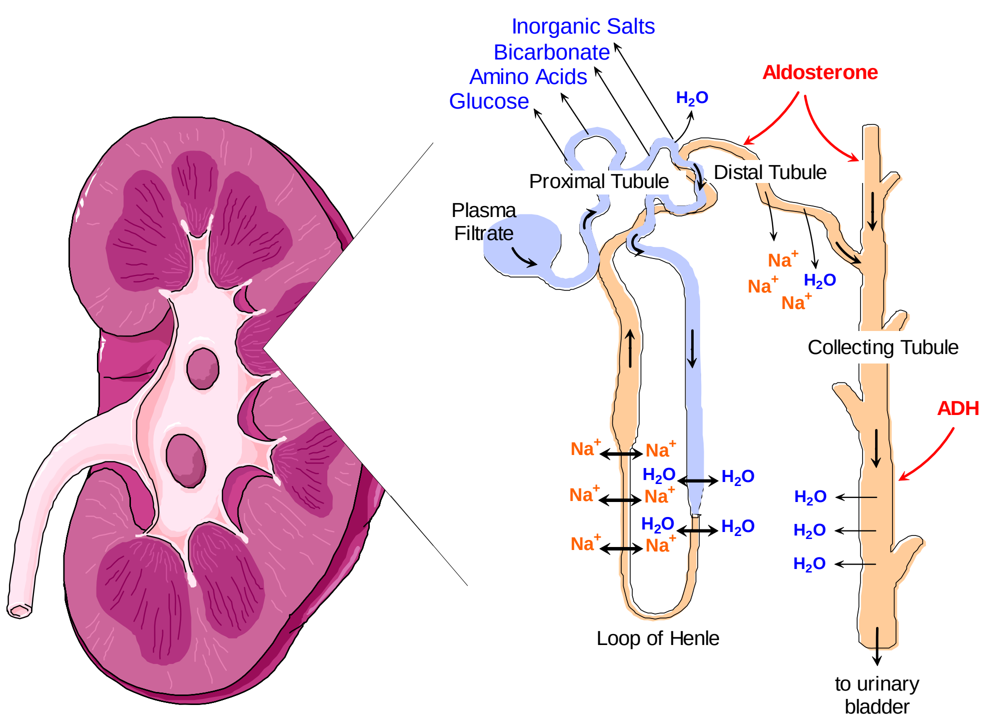
Kidneys. The kidneys filter the blood to remove harmful metabolic acids and wastes and reabsorb those substances the body needs. They help control plasma ion concentration and maintain pH by removing strong ions such as Na^+ and Cl^- from plasma into urine. By removing more Na^+ than Cl^-, for example, the kidneys lower the plasma Strong Ion Difference [SID]. SID is simply the difference between the concentrations of positive and negative strong ions. Refer to Figure 6. As Na^+ is removed, the number of positive ions decreases causing a relative increase in the concentration of negative ions. To offset the increase of negative charges created by Na^+ removal, the concentration of hydrogen ions, $[H^+]$, increases. As $[H^+]$ increases, pH decreases, making plasma more acidic. On the other hand, removing more Cl^- than Na^+ raises plasma [SID], which lowers $[H^+]$ and raises pH. The concept of electrical neutrality is discussed later in this section.

The kidneys also control blood volume by regulating the amount of water in extracellular fluid. Figure 8. Two hormones, aldosterone and antidiuretic hormone (ADH) help the kidneys control the fluid volume of blood. When water is lost from the body, blood volume decreases. This leads to increased production of aldosterone and

Figure 8. Kidney tubules

The kidneys contain a vast blood filtering system. Blood cells and proteins are removed, creating a plasma filtrate that passes into the tubules. Glucose, amino acids, bicarbonate and inorganic salts are removed in the proximal tubule. As these solutes are removed from the filtrate, water follows them out of the proximal tubule by osmosis.

Sodium is removed from the filtrate in the Loop of Henle, creating a strong osmotic gradient that draws water out of the tubule. Water can also be removed in the distal and collecting tubules. When additional water needs to be conserved, aldosterone is released, causing increased Na^+ removal from the distal tubule, which draws out additional water. Antidiuretic hormone (ADH) is released, causing increased permeability of the distal and collecting tubules to water. As a result, urinary output is reduced, conserving more water.



ADH. Elevated aldosterone increases Na+ pump activity in the kidney tubules. As a result, more Na^+ is removed from the distal tubules and concentrated within the kidney rather than being excreted. This high concentration of Na^+ in kidney tissue creates an osmotic gradient that pulls water out of the tubules. Elevated ADH works in conjunction with aldosterone by increasing the permeability of the tubules to water, allowing water to follow Na^+ out of the tubules, thereby reducing urinary water loss.

Lungs. The lungs play an important role in regulating plasma CO_2 and pH. Since CO_2 is a gas, the term partial pressure, PCO_2, is used to describe its concentration in liquids. Changes in respiration rate relate to changes in the partial pressure of CO_2. For example, CO_2 is produced during exercise and is removed from muscle tissue by the blood, increasing PCO_2. To quickly rid the blood of excess CO_2, respiration rate increases. In this process, CO_2 from the muscle combines with water to form carbonic acid in the blood, which then dissociates to H^+ and bicarbonate ions (HCO_3^-). Bicarbonate is the primary storage and transportation form of CO_2 in plasma. In the lungs, this process is reversed with CO_2 and water being exhaled. Figure 9.

As the rate of CO_2 production increases, PCO_2, [HCO_3^-] and respiration rate increase. If CO_2 production outstrips the lungs' ability to convert HCO_3^- to water and CO_2, plasma [HCO_3^-] will continue to rise. Plasma [H^+] will also rise, offsetting the associated negative charges, causing plasma pH to decrease.

Acidosis = $\uparrow PCO_2$, $\uparrow HCO_3^-$, $\downarrow$pH

Alkalosis = $\downarrow PCO_2$, $\downarrow HCO_3^-$, $\uparrow$pH

Acid - Base Balance. By regulating blood chemistry, the kidneys and lungs maintain an electrically neutral environment. The processes involved in maintaining electroneutrality are referred to as acid-base balance. The power of the lungs to excrete large quantities of carbon dioxide enables them to compensate rapidly, while the smaller capacity of the kidneys corresponds to a relatively slower rate of compensation through metabolic means. Both must work in concert to maintain an acid-base balance.

Metabolic Regulation. Strong ions are fully dissociated from each other in aqueous solutions such as plasma, and form charged water complexes. For example, Na^+ and Cl^- do not associate with each other to form NaCl in plasma. Instead, Na^+ associates with the O^- component of water while Cl^- associates with the H^+ component. Figure 10.

Figure 10. Charged Water Complexes

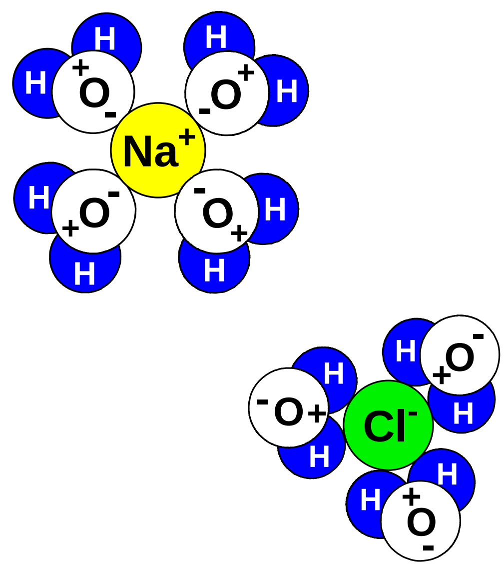
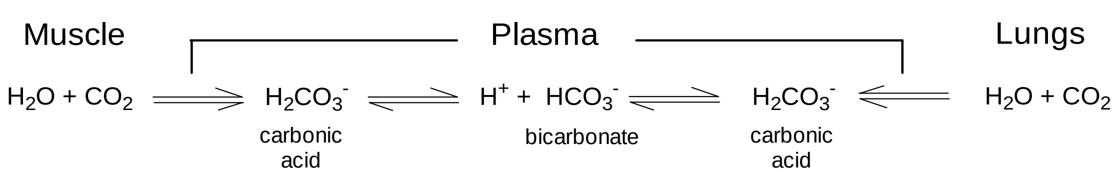
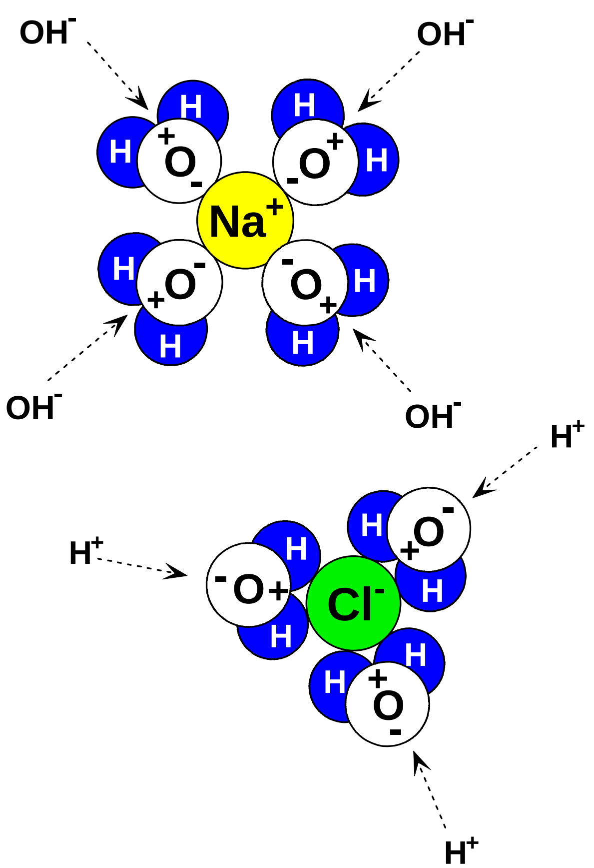


Figure 9. Plasma Carbon Dioxide Transport



The orientation of water molecules to a strong ion counterbalances and isolates the ion's charge, and exposes either the positive or negative portion of the water molecules. Charged water complexes of Na^+ have an overall positive charge that attracts OH^-, while negative charges associated with Cl^- water complexes attract H^+. Figure 11.

Figure 11.



H^+ are talked about as if they are separate entities that can be physically grabbed and moved. This approach is a conventional way of explaining H^+ activity, but somewhat misrepresents their actual nature. For example, the attractive force between water molecules is such that hydrogen ions of one water molecule are strongly drawn to the oxygen of another. As a result, hydrogen ions readily "jump" to adjacent water molecules causing water to dissociate, forming hydronium ions (H_3O^+) and hydroxyl ions (OH).

In acidic solutions, $[H_3O^+] > [OH^-]$, while $[OH^-] > [H_3O^+]$ in basic solutions. Although $[H_3O^+]$ may better represent the hydrogen ion status of biological solutions than $[H^+]$, the term $[H^+]$ is more commonly used and is the terminology used in this text.

By selective removal of Na^+ or Cl^-, the kidneys adjust the relative proportion of H^+ to OH^- in plasma. As Na^+ is removed, the amount of OH^- required to offset positive charged water complexes decreases. Consequently, the amount of OH^- in the solution decreases. As OH^- decreases, the relative amount of H^+ increases, bringing about a reduction in pH. On the other hand, removal of negative charged water complexes reduces the amount of H^+ needed in the solution to offset negative charges. As the relative amount of OH^- increases, the solution becomes more basic and pH rises. These processes are summarized below.

Figure 12.

Kidney Action to Maintain Electroneutrality

$\downarrow Na^+, \downarrow [OH^-], \uparrow [H^+], \downarrow pH$

$\downarrow Cl^-, \downarrow [H^+], \uparrow [OH^-], \uparrow pH$

In a nutshell, that's how the kidneys help maintain electrical neutrality. Obviously there has to be some biological reason for the kidney to remove Na^+ or Cl^-.

Respiratory Regulation. Since bicarbonate (HCO_3^-) is the plasma transport form of CO_2, its regulation falls under the jurisdiction of the lungs, not the kidneys. As previously discussed, the lungs quickly adjust the partial pressure of carbon dioxide in plasma (PCO_2) by either increasing or decreasing respiration rate. As a result, plasma bicarbonate either decreases or increases.

Combined Effect of Respiratory & Metabolic Regulation. Although the lungs and the kidneys have their own regulatory processes, they work together to maintain the electrical neutrality of plasma. As an example, consider a baby calf that is undergoing the common summertime problem of heat stress. In an attempt to get rid of extra heat, the calf's respiration rate increases. Although rapid breathing rids the body of some excess heat, it also causes a loss of CO_2, which lowers plasma PCO_2. This lowers [HCO3-] and reduces the associated [H+] required to offset the negative charges associated with bicarbonate. As plasma $[H^+]$ decreases, the relative $[OH^-]$ increases, causing plasma to become more alkaline. Plasma pH rises. This situation is generally referred to as respiratory alkalosis. Figure 13 summarizes the changes that occur in the calf as a result of increased respiration rate due to heat stress.

Figure 13.

Effect of Increased Respiration Rate In Response To Heat Stress

$\downarrow CO_2$, $\downarrow PCO_2$, $\downarrow HCO_3^-$, $\downarrow [H^+]$, $\uparrow [OH^-]$, $\uparrow$pH

To compensate, the kidneys remove Na^+. As Na^+ is removed, the $[OH^-]$ required to offset the positive charge of sodium is reduced. This reduction in plasma $[OH^-]$ increases the relative $[H^+]$, bringing plasma pH down to normal. Figure 14 summarizes the kidney response to the calf's respiratory alkalosis caused by heat stress.

Figure 14.

Kidney Metabolic Response To Respiratory Alkalosis

$\downarrow Na^+$, $\downarrow [OH^-]$, $\uparrow [H^+]$, $\downarrow$pH

Through their combined actions the lungs and kidneys may have averted a couple of potentially life-threatening situations. Nevertheless, the calf has lost body water during the heat stress and the removal of Na^+ has lowered the plasma [SID] below normal in order to maintain electrical neutrality. Oral electrolyte therapy is an obvious remedy for both the water and electrolyte loss. If administered early enough, the electrolyte treatment could avert or at least lessen the heat stress and resulting physiological changes in the calf.

pH. The pH of intracellular fluid is about 7.0 and about 7.4 for extracellular fluid. At normal body temperature, the pH of a solution is 6.8. Therefore, body fluids are actually maintained at a slightly alkaline pH. The pH range of physiological solutions is small, with a pH change of 1.0 being fatal.

Ion movements in body fluids cause changes in pH, making it a dependant variable. As demonstrated above, significant changes can occur in plasma chemistry that result in virtually no change in pH. Furthermore, equal changes in $[H^+]$ and $[OH^-]$ in physiological solutions do not bring about equal changes in pH. To summarize, a change in pH indicates a problem. It does not, however, indicate what is causing the problem or what needs to be corrected. pH is not a very sensitive measure for evaluating the acid-base status or changes in status of body fluids.

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