ACID-BASE BALANCE

The body must regulate the H^+ concentration of body fluids. Concentration of H^+ ($[H^+]$) is measured as pH. A pH of 7 is neutral, meaning that $[H^+] = [OH^-]$ (recall that $H_2O \Leftrightarrow H^+ + OH^-$). A pH below 7 is acidic, while a pH above 7 is basic. The pH of arterial blood is normally 7.45, and that of the venous blood is normally 7.35. Outside of the normal range of pH, enzymes cannot function properly and function of excitable cells is disrupted. In the body, a pH below 7.35 is considered acidotic, while a pH above 7.45 is alkalotic. Death occurs at a pH of less than 6.8 or more than 8.0.

The clinical effects of acidosis include depression of the CNS, disorientation (less severe cases), coma, and death. Because the kidneys, in an attempt to rid the body of the excess H^+, must secrete less K^+, an excess of K^+ accumulates (hyperkalemia). The main impact of hyperkalemia is overexcitability of the heart, leading to potentially fatal arrhythmias.

The clinical effects of alkalosis include overexcitability of the nervous system. Usually the PNS is affected first, and "pins and needles" sensations are felt. Muscle twitches and even severe muscle spasms can occur due to overexcitable motor neurons, resulting in death when the respiratory muscles are affected. When the CNS is affected, convulsions may occur. Less severe cases result in extreme nervousness. Hypokalemia can result as the kidneys attempt to compensate for alkalosis, leading primarily to weakness of smooth and skeletal muscle.

H^+ is constantly being added to the body because of metabolic activities (very little is in food). The major source is carbonic acid ($CO_2 + H_2O \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3^-$). Other sources are inorganic acids (sulfuric acid and phosphoric acid) produced as by-products of protein metabolism. Also, intermediary metabolism results in the production of organic acids such as fatty acids and lactic acid.

The body has three major defense systems to guard against changes in pH. These are the chemical buffer systems, the respiratory mechanism, and the renal mechanism.

Chemical Buffer Systems

A chemical buffer system is a mixture of chemicals that resists changes in pH. Chemical buffer systems can work in fractions of a second to maintain normal pH levels. These systems work by using weak acids and bases. An acid is a substance that releases H^+, and a base is a substance that can bind H^+. Both acids and bases can be weak or strong. A weak acid only dissociates slightly, releasing relatively little H^+, while a strong acid dissociates almost completely.

H_2CO_3:HCO_3^- buffer pair

In the equation ($CO_2 + H_2O \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3^-$), carbonic acid is the weak acid, and bicarbonate is the weak base. If H^+ is added to a solution containing this buffer system, the reaction will shift to the left, taking up the excess H^+. If H^+ is removed from solution, the reaction will shift to the right, producing more H^+ to replace it. This is the most important buffer system in the ECF. It is important to realize, however, that this buffer system cannot buffer itself, meaning that it can only buffer H^+ coming from a non-H_2CO_3 source.

Protein buffer system

Proteins can both give up and take up H^+. This is the most important buffering system in the ICF, and is of minor importance in the ECF.

Hemoglobin buffer system

Hemoglobin takes up the H^+ generated from CO_2 during its transport in the blood.

Phosphate buffer system

This system is important in buffering the urine and the ICF: $NaH_2PO_4 + Na^+ \Leftrightarrow Na_2HPO_4 + H^+$

Respiratory Mechanism

When arterial pH decreases, the respiratory system is stimulated to increase pulmonary ventilation, blowing off CO_2 and removing acid from the body. When arterial pH increases, pulmonary ventilation decreases, allowing CO_2 to accumulate and form more H^+. This respiratory mechanism works within minutes.

Renal Mechanism

The renal mechanism is the most powerful regulator of acid-base balance, and functions over the long term (hours to days). The chemical buffer systems are overwhelmed by large changes in pH, and respiratory mechanisms cannot compensate 100% for changes in pH. Ultimately, the kidneys must act to maintain pH of body fluids. When pH level in the body decreases, the kidneys both secrete H^+ and reabsorb HCO_3^-. When pH rises, the kidneys can excrete HCO_3^- instead of reabsorbing it, and decrease secretion of H^+. It is important that the filtrate/urine itself be buffered, because H^+ can only be secreted until the urine/filtrate has 800 times more H^+ than plasma (active transport mechanisms cannot transport H^+ up a gradient steeper than this). The urine is buffered by the phosphate buffer system, and, more importantly, by ammonia that is secreted by the tubule cells. When pH of body fluids decreases, more ammonia is secreted. The ammonia combines with H^+ to form ammonium ion: $NH_3 + H^+ \Leftrightarrow NH_4^+$

Acid-Base Disturbances

Both acidosis and alkalosis can originate from respiratory or metabolic problems. Disturbances of respiratory origin are compensated for by chemical buffer systems and the kidneys, while disturbances of metabolic origin are compensated for by chemical buffers, respiratory, and renal mechanisms. Below are some of the causes of acid-base disturbances. See Table 15-9 in your text for a comparison of pH, $[CO_2]$, and $[HCO_3^-]$ in both compensated and uncompensated disturbances.

Respiratory acidosis - caused by hypoventilation due to: lung disease, depression of respiratory center from drugs or disease, nerve or muscle disorders, breath holding.

Respiratory alkalosis - caused by hyperventilation due to fever, anxiety, or aspirin poisoning. It is a normal physiological response at high altitudes.

Metabolic acidosis - caused by excessive loss of bicarbonate rich fluids (as in severe diarrhea), accumulation of non-carbonic acids (as in ketosis occurring due to diabetes mellitus, or lactic acid production during strenuous exercise), or renal failure (kidneys cannot excrete H^+). This is the most common acid-base disorder.

Metabolic alkalosis - caused by a decrease in non-carbonic acids (as in vomiting) or ingestion of alkaline drugs (like baking soda: $NaHCO_3$). Note that if "deep" vomiting results in loss of duodenal contents, HCO_3^- is lost, leading to acidosis.