The bicarbonate buffer system as the main mechanism for maintaining the acid-base balance of the human body

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Abstract. The article describes modern ideas about the mechanisms of regulation of acid-base balance using a hydrocarbonate buffer system, the basic principles of its operation. The role of the respiratory and urinary systems in maintaining the pH of human blood is analyzed within the framework of changes in the quantitative content of the constituent components of the bicarbonate buffer.

Keywords: bicarbonate ion, hydrogen ion, carbon dioxide, acid-base balance, homeostasis

Introduction

The concentration of hydrogen ions in blood plasma is usually measured in units of pH. The normal range of acid-base balance of the human body is 7.35 - 7.45. [3] When the pH of the blood is shifted to the acidic or alkaline side by only 0.3, it causes severe disturbances in the functioning of the human body, and the shift in pH by more than 0.4 leads to fatal disorders and death. [5] In order to prevent such conditions, the human body needs a buffer system that will quickly equalize the acid-base balance in response to a sharp change in blood pH, and this system must be able to restore its buffer capacity in a timely manner. A bicarbonate buffer system is suitable for these criteria. This article discusses the basic understanding of the bicarbonate buffer system and the mechanisms of its regulation.

Hydrocarbonate buffer system

The main elements of the bicarbonate buffer system are: carbonic acid H2CO3 and base NaHCO3. The combination of carbon dioxide and water under the influence of the enzyme carbonic anhydrase leads to the appearance of a weak carbonic acid, which in turn dissociates into a hydrogen ion and a bicarbonate ion, these interactions are described by the following equation:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+$$ [1]

The NaHCO3 base dissociates into sodium ion and bicarbonate ion:

$$NaHCO3 \rightleftharpoons Na^+ + HCO3^-$$ [1]

Thus, the hydrocarbonate buffer system is described by the following equation:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^- (+ Na^+)$$ [1]

The dissociation constant of carbonic acid is as follows:

$$K = \frac{H^+ * HCO_3^-}{H_2CO_3}$$ [1]

The amount of dissolved carbon dioxide is directly proportional to the number of undissociated carbonic acid molecules, respectively, to determine the amount of hydrogen ions, which determines the pH of the blood, as follows:

$$H^+ = K * \frac{CO_2}{HCO_3^-}$$ [1]

Considering the linear relationship between undissociated carbonic acid molecules and the partial stress of carbon dioxide, which equals: 0.03 of carbon dioxide falls on every millimeter of pCO2. Accordingly, the formula takes the following form:

$$H^+ = K * \frac{0{,}03 * pCO_2}{HCO_3^-}$$ [1]

The concentration of hydrogen ions is usually measured in units of pH

$$pH = pK + log \frac{HCO_3^-}{0{,}03 * pCO_2}$$ [1]

The pK value for the hydrocarbonate buffer system is 6.1, and thus we arrive at the Henderson-Hasselbach equation:

$$pH = 6{,}1 + log \frac{HCO_3^-}{0{,}03 * pCO_2}$$ [1]

The normal content of bicarbonate ion in the human body is 22-26 meq/liter, and pCO2 varies within 35-45 mmHg, however, these indicators may vary depending on gender, ethnicity and area where the person lives. [4]

The pK of the bicarbonate buffer system is early 6.1, and the bicarbonate buffer is most effective when the pK value is equal to the pH value, so at such values the concentration of carbon dioxide and the concentration of bicarbonate ion within the equation of dissociation of carbonic acid are equal to each other.[1] If we take into account the normal pH values of the human body 7.35 - 7.45, then at values the content of bicarbonate ion is 20 times higher than the content of carbon dioxide. The main property that determines the bicarbonate buffer system as the most effective is the rapidity of the bicarbonate buffer, mainly due to the ability of the lungs to quickly remove carbon dioxide, and the kidneys to reabsorb and synthesize bicarbonate ion.

From the Henderson-Hasselbach equation, the basic principles of regulating the bicarbonate buffer system follow: 1. With an increase in the partial voltage of carbon dioxide, the equilibrium shifts to the acidic side and the condition will be called respiratory acidosis in order to equalize the blood pH, turn on renal regulation, which will bring bicarbonate ion into the system, thereby returning the value of acid-base balance to normal values, 2. In the case of a decrease in the partial voltage of carbon dioxide, the equilibrium will shift to the alkaline side, causing respiratory alkalosis, in which case the kidneys will begin to excrete bicarbonate ion. 3. With an increase in the content of bicarbonate ion in the blood, metabolic alkalosis will occur, the respiratory component of the regulation of acid-base balance will turn on, which will retain carbon dioxide, preventing it from being eliminated from the blood. 4. In the case of a decrease in the concentration of bicarbonate ion or the so-called state of metabolic acidosis, an increase in the minute volume of the lungs will occur, which will facilitate the removal of carbon dioxide from the blood.

The role of lung function in maintaining acid-base balance homeostasis

As a result of metabolic processes occurring in the human body, carbon dioxide is formed, which diffuses into the blood, is transferred to the lungs and is released into the atmosphere, normally the partial pressure of carbon dioxide is 40 mmHg, which is equivalent to 1.2 mol of dissolved carbon dioxide.[1]

The respiratory system, as already mentioned, regulates the acid-base balance by changing the partial tension of carbon dioxide by increasing or decreasing the minute ventilation volume, respectively, eliminating or retaining carbon dioxide in the blood plasma. The capacity of this regulation varies over a wide range, so with an increase in minute ventilation of the lungs by 50%, the blood pH will change from 7.4 to 7.63, and a decrease in minute ventilation by 25% will change the pH to 6.95.[1]

The regulation of lung function is controlled according to the principle of negative feedback, so with an increase in the acidity of the blood, chemoreceptors activate the respiratory center, which in turn, through the function of the lungs, increases the volume of minute ventilation. This chain of events leads to a decrease in the partial stress of carbon dioxide and a decrease in blood acidity. The response of the respiratory system to a change in blood pH develops within 3-15 minutes, and the development of the maximum buffer capacity can reach up to 12 hours, and its total role is 1-2 times higher than other buffer systems combined. [1;5]

In the case of metabolic acidosis, minute ventilation of the lungs increases and, if the value of acid-base balance returns to a normal value, then this condition is called compensated metabolic acidosis, if the lungs have not coped with their function, then decompensated metabolic acidosis develops.[5] The opposite situation is also characteristic, in the case of the development of metabolic alkalosis, the respiratory system will decrease the minute volume of ventilation, and if the blood pH returns to the normal value, then compensated metabolic alkalosis occurs, if there is no return to the initial pH value, then decompensated metabolic alkalosis develops.[5] The respiratory system copes worse with a change in pH to the alkaline side, since it performs another important function - saturation of the blood with oxygen, and with a decrease in minute ventilation of the lungs, the respiratory center will give preference to a change in the partial oxygen tension rather than a change in pH.

The regulation of the acid-base balance of the blood by changing the minute volumetric ventilation will not eliminate the main reason for the change in blood pH in the case of metabolic acidosis or alkalosis, but will only save time until other systems are involved in the pH stabilization process.

Renal regulation of the bicarbonate buffer system for normal acid-base balance

The kidneys must be able to maintain normal blood bicarbonate levels through filtration. Every day the kidneys filter about 4320 meq of bicarbonate ion, and at normal pH, all of the filtered bicarbonate ion is reabsorbed back into the blood.[1] Filtration is carried out throughout the tubular system of the nephron, with the exception of the thin segments of the descending and ascending segments of the loop of Henle.[1]

An important function of the kidneys is also that in addition to filtration, it is necessary to synthesize new molecules of the bicarbonate ion. Such processes occur when an excess of acids accumulates in the human body or the pH of the blood decreases. In this case, the synthesis of new molecules of the bicarbonate ion, as well as the excretion of acids, leads to the equalization of the acid-base balance.

Another main function of the kidneys in maintaining homeostasis of acid-base balance is the secretion of hydrogen ions. With normal functioning of the kidneys, the secretion of hydrogen ions per day is approximately 4400 meq.[1]

80 - 90% of the reabsorption of bicarbonate ion occurs in the proximal sections of the baked tubules, 10% of reabsorption occurs in the thick segment of the ascending section of Henle's loop, and 5% is reabsorbed in the distal sections of the renal tubules and collecting ducts. [1;2]

In the proximal part of the renal tubules, as well as in the thick part of the ascending loop of Henle, an equilibrium concentration of hydrogen ions and bicarbonate ion occurs, so 4320 meq/day of bicarbonate ion is filtered into the lumen, into the lumen of these structures, also due to the cotransport system, approximately 4400 meq/day of the hydrogen ion, their excess, in relation to the bicarbonate ion, ensures the removal of non-volatile acids (approximately 80 meq/day).[1] Thus, one hydrogen ion is consumed for each reabsorbed bicarbonate ion. This mechanism for maintaining acid-base balance is provided as follows: with an increase in blood acidity, an excess of hydrogen ions appears, which, in the condition of deficiencies of the bicarbonate ion, is secreted into the urine, and all the bicarbonate ion is reabsorbed into the blood plasma. In the opposite situation, in the case of a lack of hydrogen ions, the entire bicarbonate ion cannot be reabsorbed and, accordingly, is disposed of in the urine.

An important part of the secretion of hydrogen ions takes place in the terminal section of the distal tubules and collecting ducts, which is responsible for acidification or alkalization of urine, in contrast to the proximal tubules and the ascending segment of Henle's loop, where hydrogen ions are in constant interaction with bicarbonate ion. The secretion of hydrogen ions is carried out due to the primary active transport, for each secreted hydrogen ion there is one reabsorbed bicarbonate ion. [1;2]

Conclusion:

Thus, within the framework of maintaining the acid-base balance of the human body, the hydrocarbonate buffer system plays a key role, has a large capacitive potential, and is able to quickly respond to changes in blood pH. The interaction of the respiratory and urinary systems ensures accurate regulation of acid-base balance, through the elimination of carbon dioxide, filtration and secretion of bicarbonate ion.

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