# Acid Base Imbalances

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**Objectives**

After completion of this article, the reader should be able to:

Describe the relationship between $H^+$ and $CO_2$
Differentiate between metabolic and respiratory acidosis.
Differentiate between metabolic and respiratory alkalosis.
List common causes of acid-base disturbances.
Recognize the classic signs and symptoms of acid-base disturbances.

## Case Presentation

Unit 809 is dispatched to assist a patient with an altered mental status. Upon arrival the paramedic crew finds a 36 year old male lying in bed. The patient is conscious but disoriented to person and place. The lead paramedic begins her assessment while her partner places the patient on oxygen by mask, takes vital signs, and attaches a cardiac monitor. The patient is unable to provide a history but his wife states that he is an insulin dependant diabetic who did not take his insulin as usual this morning. She also reports that he has been under a great deal of stress lately. He had been complaining of diffuse abdominal pain, thirst and nausea for the previous couple of hours. She just returned from work and called 911 after finding him in his present condition. A physical exam finds no obvious trauma, warm and dry skin which exhibits "tenting" and incontinence. Vital signs are BP 118/76, HR 108 and regular, RR 32 and deep, ECG displays sinus tachycardia without ectopy. A blood sample revealed a glucose level of 500 mg/dL.

## Introduction

The predominant physiological function of the body is maintenance of homeostasis. The biological and chemical processes that are constantly occurring in our bodies depend on having a consistent environment in which to work.  Homeostasis is the body's system for maintaining that consistency. An important and integral goal of homeostasis is acid-base regulation. The chemical reactions within our bodies only function within a narrow pH range. Diseases can effect this range causing a multitude of problems. It is vital that emergency responders understand the mechanisms we use to maintain this balance. This article will describe the mechanisms of acid-base regulation, the disease processes that cause acid-base derangement and what providers can do to treat those derangements.

## Physiology

The body is composed of several systems; each composed of organs made of different types of tissue that are, in turn, composed of individual cells. Each cell needs energy and has its own internal mechanisms for meeting those needs. As cells use nutrients to produce energy, they produce byproducts. Two of these byproducts effecting acid-base balance are carbon dioxide ($CO_2$) and hydrogen ($H^+$).  The key to regulating pH is in regulating hydrogen ion concentration. The levels of hydrogen in the body make a tremendous impact on the ability to maintain homeostasis. Maintenance of these levels is what regulation of acid-base balance is all about. The hydrogen concentration outside of cells is typically $4 \times 10^{-8}$ or 0.00000004 equivalents per liter.[1] Since this is obviously a ridiculously small number that is difficult to deal with, hydrogen concentrations are typically referred to with pH levels. pH levels are inversely proportional to hydrogen concentration which means that as $H^+$ increases, pH decreases and as $H^+$ decreases, pH increases.

| **Condition** | **pH** | **$H^+$** |
|---|---|---|
| Alkalosis | ↑ | ↓ |
| Acidosis | ↓ | ↑ |

A substance that releases an excess of hydrogen ions is an acid while one below normal hydrogen ions is a base or alkaloid. As pH increases, it becomes more alkaloid and as pH decreases it becomes more acidic. If there is an increase in hydrogen concentration the pH falls and if hydrogen concentration decreases, pH rises. The value representative of a neutral pH is 7.0 while the normal pH range in humans is 7.35 in veins and 7.45 in arteries with an average of 7.4.[2] pH values of less than 6.8 or more than 8.0 are fatal. Therefore, the body functions well in a relatively narrow alkaline environment. Maintaining this range is important because, among other problems caused by acid-base imbalance, acute alkalosis can interfere with the body's ability to "offload" oxygen from hemoglobin into tissues leading to cellular hypoxia[3]. The body has three mechanisms for maintaining this narrow range: the bicarbonate buffer system, the respiratory system and the renal system.

**Bicarbonate Buffer System**

The buffer system is the body's first line of defense against acid-base imbalances. It acts almost instantaneously to correct even minute variations in $H^+$ levels. This system is based upon the following equation which really isn't as complicated as it may look:

$$\mathbf{H^+ + HCO_3 \Leftrightarrow H_2CO_3 \Leftrightarrow H_2O + CO_2}$$

As hydrogen ion concentration ($H^+$ ) increases, it binds with bicarbonate ($HCO_3$) which, in the presence of the enzyme carbonic anhydrase, forms carbonic acid ($H_2CO_3$) which, with carbonic anhydrase, immediately breaks down into water and carbon dioxide. Carbonic anhydrase, like all enzymes, helps to activate chemical reactions in the body. Because these elements and enzymes are common in the bloodstream, this reaction occurs almost immediately. As the equation shows, the process moves in two directions. As $H^+$ increases, the equation moves to the right leading to an increase in $CO_2$ and a decrease in available $H^+$. If $CO_2$ were to increase, the equation would move to the left and increase $H^+$ while at the same time decreasing $CO_2$. In this manner, if the cells produce an excess of hydrogen, the buffer system negates the rise by causing an increase in $CO_2$ and keeps the pH within its normal ranges.

Because this is almost instantaneous, it is possible to think of this equation in a simplified form:

$$\mathbf{H^+ \Leftrightarrow CO_2}$$

This means that an increase in $H^+$ leads to an increase in $CO_2$ and a decrease in $H^+$ leads to a decrease in $CO_2$. This simplified equation is very important in the respiratory system's ability to compensate for acid-base imbalance.

**Respiratory System**

If the buffer system isn't able to maintain pH in its normal range, the respiratory system will adjust the frequency and depth of respiration to compensate. In an acidic environment (a low pH and an excess of $H^+$), hyperventilation will "blow off" excess $CO_2$, in effect returning pH to normal. In an alkalotic environment (a high pH and a $H^+$ deficit), *decreasing* the depth and frequency of ventilation will cause the body to retain $CO_2$, thus increasing $H^+$. The respiratory system is amazingly effective in regulating pH. In fact, if you double the respiratory rate from normal, pH will increase by 0.23 from 7.4 to 7.63. On the other hand, a reduction in the respiratory rate by 25% will decrease pH by 0.4 from 7.4 to 7.0. [4]

EMTs are often taught that a disease free individual's drive to breathe comes from an increase in $CO_2$ levels. While this is generally true, it is actually an increase in $H^+$ that causes chemoreceptors to stimulate the respiratory center of the medulla to increase the rate and depth of respiration. In this manner, increases or decreases in acidity set in motion an feedback loop which causes self-correcting behavior. The respiratory system begins to have an effect on pH within a matter of minutes.

**Renal System**

The final line of defense against acid-base imbalance is the renal system. The kidneys are able to selectively change the amount of $H^+$ secreted into urine and therefor passed from the body. If the pH of the solution being filtered in the nephron is acidic, the kidneys increase the amount of $H^+$ secreted into the urine, thereby decreasing the acidity and increasing pH in the blood/body**.** If the pH in the kidneys is alkalotic, the tubules in the nephrons will decrease the amount of $H^+$ secreted, thereby increasing the acidity and lowering pH in the blood/body. While the kidneys are best able to compensate for large variations in pH, their effect is not seen for hours or even days.

**Acid-Base Imbalances**

Acid-Base balance can be askew in one of four ways, metabolic acidosis or alkalosis and respiratory acidosis or alkalosis. The pH can either be high (alkalosis) or low (acidosis). This condition can be caused by a metabolic or respiratory problem. The best way to determine the condition and cause is with laboratory values. These are called ABGs or arterial blood gas reports. While these values are not readily available in the field, knowledge of them can help increase understanding of acid-base disturbances. A simplified and easy way to get a good estimation for the cause of the derangement is by using pH and $CO_2$ values. As previously stated, normal values for pH are 7.35 to 7.45. The normal range for $CO_2$ is 35 to 45 torr. A rule of thumb approach to determining the condition and cause with lab values begins with the pH. If the pH is below 7.35, the condition is acidosis; if it is above 7.45, the condition is alkalosis. The key to determining the cause is to compare the $CO_2$ values to what you would expect from either a respiratory or metabolic cause. For example, you would expect the arterial $CO_2$ levels to be elevated in respiratory acidosis. If the pH level is below 7.35 and the $CO_2$ level is above 45, you have an acidosis likely caused by a respiratory component. If, however, the $CO_2$ levels were normal or low, you would likely have a metabolic acidosis.

The same rule holds true with alkalosis. If the pH is above 7.45 the condition is alkalosis. You would expect a respiratory cause to show a decreased arterial $CO_2$ level. Therefore if the pH is 7.6 and the $CO_2$ is 15, you likely have a respiratory alkalosis, perhaps caused by hyperventilation. On the other hand, if pH was 7.6 and $CO_2$ was 40, it would likely be a metabolic alkalosis.

| | **pH** | **$CO_2$** |
|---|---|---|
| **Metabolic Acidosis** | Low | Normal to low |
| **Metabolic Alkalosis** | High | Normal to high |
| **Respiratory Acidosis** | Low | Low |
| **Respiratory Alkalosis** | High | High |

## Causes of Acid-Base Disturbances

### *Metabolic Acidosis*

Metabolic acidosis is caused by an increase in $H^+$ production. The classic metabolic cause of acidosis is diabetes. Patients who do not produce (or take) sufficient insulin to efficiently transport glucose into cells must rely on other, less efficient, methods of energy production. Acids are byproducts of this inefficient metabolism and cause metabolic acidosis. The body attempts to compensate for this with the respiratory system in a classic pattern known as Kussmaul's Breathing, which is a pattern of deep and rapid respirations. This pattern increases expiration of $CO_2$ and therefor decreases acidosis (increasing pH).  Because it is not able to enter cells in sufficient quantity, glucose accumulates in the bloodstream. As glucose levels continually rise, the kidneys' ability to reabsorb glucose is overwhelmed. Glucose "spills over" into urine and, through osmosis, pulls water with it. This results in dehydration that causes most of the manifestations of diabetic ketoacidosis (DKA). Signs and symptoms of DKA include a gradual onset, warm and dry skin with possible 'tenting" (a sign of dehydration), Kussmaul's breathing and excessive thirst, urination and hunger. Treatment is aimed at rehydration and replacement of insulin.

Other causes of metabolic acidosis include salicylate overdose. Aspirin (acetylsalicylic acid, or ASA) is the most common source of salicylate and can reach toxic levels in adults with as little as 10 gm.[5] Methanol and Ethylene Glycol, commonly found in automotive antifreeze, glass cleaner and Sterno, poisoning may also lead to metabolic acidosis. Treatment for metabolic acidosis is primarily accomplished through increased ventilation.

***Metabolic Alkalosis***

Metabolic alkalosis is caused by a decrease in $H^+$ production, an excess elimination of $H^+$ or an increase of the bicarbonate buffer. A "paramedic-induced" cause of metabolic alkalosis is an overzealous administration of Sodium Bicarbonate. Excessive or prolonged vomiting or excessive diuresis (for example, through inappropriate use of medications such as Furosemide) carries $H^+$ with it, increasing pH and decreasing acidity. Treatment for metabolic alkalosis is aimed at providing the patient with sufficient time to rid itself of excess bicarbonate and increase its $H^+$ concentration.

*Respiratory Acidosis*

Respiratory acidosis is caused by decreased elimination of $CO_2$ secondary to either decreased respiration or inadequate gas exchange.  Narcotic coma, cardiac arrest and COPD are examples of conditions that cause respiratory acidosis. Acidosis occurs due to a build up of $CO_2$ that causes an subsequent increase in $H^+$ concentration and a decrease in pH.

*Respiratory Alkalosis*

Respiratory alkalosis is caused by an increased elimination of $CO_2$ through hyperventilation. This frequently happens during an anxiety or 'panic' attack'. Respiratory alkalosis may also occur as a result of "overcompensation" by overzealous rescuers hyperventilating at 30-40 breaths per minute for conditions resulting in respiratory acidosis.

**Table 1: Common Causes of Acid-Base Disturbances. Adapted from The Merk Manual, Volume 1; 16th Ed.**

| | **Acidosis** | **Alkalosis** |
|---|---|---|
| **Metabolic** | Diabetic Ketoacidosis Excessive Diarrhea<br>Lactic Acidosis 2° to hypoperfusion<br>Salicylate overdose<br>Methanlol or Ethylene Glycol poisoning | Excessive diuresis<br>Vomiting<br>Excessive Sodium<br>Bicarbonate therapy<br>Cushing's Disease |
| **Respiratory** | Respiratory Depression 2° to:<br>Stroke<br>Head or Spinal injury<br>Cardiac or Respiratory Arrest<br>Narcotic Overdose<br>Airway Obstruction<br>COPD<br>Severe asthma | Hyperventilation |

**Presentation**

While the effects of specific conditions will differ, there are general clinical presentations for acidosis and alkalosis. Acidosis typically decreases muscular activity and decreases central nervous system activity. This may cause a decreased level of consciousness, lethargy or coma. Alkalosis generally causes hyperexcitable muscles and nerves[6]. In fact, the excitation can become so severe that some nerves may cause sensations without a stimulus. An example of this is parasthesia or numbness and tingling of extremities. This is a common sensation experienced with hyperventilation. Another sign with hyperventilation is carpopedal spasms or intense muscle contractions of the fingers and thumbs and is another manifestation of hyperexcited muscles. Other signs of alkalosis include respiratory depression or apnea resulting from severe spasms of the diaphragm and intercostal muscles.

**Treatment**

Acid-base disturbances are rarely the primary cause of an illness, rather they are a manifestation of an underlying disease. Therefore, the primary treatment for these disturbances is aimed at correcting the underlying condition. Secondary treatment should be geared towards stabilizing the patient to allow their natural compensatory mechanisms to take effect. The most useful mechanism for this available in the field is ventilation. The respiratory system has a rapid effect on pH levels and it is well suited to correcting acidic conditions, whether from respiratory or metabolic causes. Assisted hyperventilation is indicated for patients with depressed respiratory drive.

Sodium Bicarbonate therapy is controversial at best, especially in the field without laboratory studies. It may be indicated, after reducing $CO_2$ through ventilation, in cases of metabolic acidosis. As with all interventions, you should consult your local protocols before utilizing Sodium Bicarbonate. Sodium Bicarbonate is frequently given to patient's who are hypotensive secondary to an overdose of tricyclic antidepressants (TCA). While it might be natural to assume that this is aimed at treating a resulting acidosis, this isn't the case. Bicarbonate binds with the TCA, thereby reducing the amount of free molecules available to effect the patient.

**Summary**

The paramedic crew correctly identified their patient as experiencing metabolic acidosis secondary to diabetic ketoacidosis. They recognized that their primary treatment for the patient should be rehydration and therefore established a large bore IV of LR at 500 ml/hr. They continued to provide high flow oxygen by mask but did not assist his ventilations as he was already exhibiting Kussmal's Respiration in an attempt to "blow off" excess $CO_2$, reverse the metabolic acidosis and raise his pH. Their paramedic student suggested administering Sodium Bicarbonate, but they correctly informed him that it was not indicated in cases where the respiratory system is attempting to compensate with increased rate and depth. The patient was transported to the local hospital where he was admitted. He received insulin via infusion and was discharged after one day of observation.

**Conclusion**

It is important to have a good understanding of the mechanisms involved with maintenance of acid-base balance and some of the conditions that may lead to a disturbance in this balance. There are three compensatory mechanisms at the body's disposal for regulating pH levels: the bicarbonate buffer system, the respiratory system and the renal system. The bicarbonate buffer system acts almost immediately. The respiratory system effects pH by adjusting $CO_2$ that has a directly proportional relationship with $H^+$ and takes effect within minutes. The renal system has the best ability to make large adjustments in pH by changing the amounts of hydrogen secreted into urine but takes hours to days to have an effect. While the presentation of specific conditions may vary, the treatment of all acid-base disturbances is aimed at treating the underlying cause and stabilizing the patient to allow their bodies time to fully compensate for the disturbance. Assuring effective ventilation is the cornerstone of prehospital care of disturbances in acid-base balance.

## Questions

1. What is the primary aim of homeostasis in relation to acid-base balance?

   A. Maintenance of HCO3 levels
   B. Maintenance of $H^+$ concentration
   C. Maintenance of $CO_2$ levels
   D. Maintenance of O2 levels

2. What is the normal pH range in humans?

   A. 6.25 – 6.35
   B. 6.35 - 6.45
   C. 7.25 – 7.35
   D. 7.35 – 7.45

3. What is the normal range of $CO_2$ levels?

A. 25 – 35
B. 35 – 45
C. 45 – 55
D. 55 – 65

4. Which statement best describes the relationship between pH and acidity?

A. As pH rises, blood becomes more acidic.
B. As pH rises, blood becomes more alkalotic.

5. Which statement best describes the relationship between pH and $H^+$?

A. pH and $H^+$ are directly proportional
B. pH and $H^+$ are indirectly proportional

6. Which pH values are typically considered to be fatal?

A. less than 7.35 and more than 7.45
B. less than 7.25 and more than 7.55
C. less than 7.0 and more than 7.8
D. less than 6.8 and more than 8.0

7. Which compensatory mechanism has the most rapid response to acid-base disturbances?

A. Bicarbonate buffer system
B. Respiratory system
C. Renal system
D. Gastrointestinal system

8. Which compensatory mechanism has the best ability to correct for large acid-base disturbances?

A. Bicarbonate buffer system
B. Respiratory system
C. Renal system
D. Gastrointestinal system

9. Which compensatory mechanism has its effect on acid-base disturbances by affecting $CO_2$ levels?

A. Bicarbonate buffer system
B. Respiratory system
C. Renal system
D. Gastrointestinal system

10. Which statement best describes the relationship between $H^+$ concentration and $CO_2$ levels?

A. as $H^+$ increases, $CO_2$ decreases
B. as $H^+$ decreases, $CO_2$ decreases
C. the relationship is dependant on levels of O2 in the blood
D. there is no relationship between $H^+$ and $CO_2$

11. Which set of values would you expect to see in a patient with metabolic acidosis?

A. increased pH and increased or normal $CO_2$
B. increased pH and decreased or normal $CO_2$
C. decreased pH and increased or normal $CO_2$
D. decreased pH and decreased or normal $CO_2$

12. Which set of values would you expect to see in a patient with metabolic alkalosis?

A. increased pH and increased or normal $CO_2$
B. increased pH and decreased or normal $CO_2$
C. decreased pH and increased or normal $CO_2$
D. decreased pH and decreased or normal $CO_2$

13. Which set of values would you expect to see in a patient with respiratory acidosis?

A. increased pH and increased $CO_2$
B. increased pH and decreased $CO_2$
C. decreased pH and increased $CO_2$
D. decreased pH and decreased $CO_2$

14. Which set of values would you expect to see in a patient with respiratory alkalosis?

A. increased pH and increased $CO_2$
B. increased pH and decreased $CO_2$
C. decreased pH and increased $CO_2$
D. decreased pH and decreased $CO_2$

15. Which of the following conditions is the most likely cause of metabolic acidosis?

A. Diabetic ketoacidosis
B. Hyperventilation
C. Respiratory Depression
D. Excessive Sodium Bicarbonate therapy

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17. Which of the following conditions is the most likely cause of metabolic alkalosis?

A. Diabetic ketoacidosis
B. Hyperventilation
C. Respiratory Depression
D. Excessive Sodium Bicarbonate therapy

18. Which of the following conditions is the most likely cause of respiratory acidosis?

A. Diabetic ketoacidosis
B. Hyperventilation
C. Respiratory Depression
D. Excessive Sodium Bicarbonate therapy

19. Which of the following conditions is the most likely cause of respiratory alkalosis?

A. Diabetic ketoacidosis
B. Hyperventilation
C. Respiratory Depression
D. Excessive Sodium Bicarbonate therapy

20. What is the most effective therapy for reversing acidosis in a patient with exacerbated COPD?

A. Hyperventilation
B. Hypoventilation
C. Sodium Bicarbonate
D. IV Therapy

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[1] Sherwood, L. Human physiology, From Cells to Systems, 2ed, 1993, page 525.
[2] Same as above.
[3] The Merk Manual of Diagnosis and Therapy, 16th Ed.,Volume I, General Medicine, page 880.
[4] Tortora, G., Grabowski, SR., Principles of Anatomy & Physiology, 7th Ed., HarperCollins, 1993, page 914
[5] Mengert, TJ, Eisenberg MS, Copass MK. Emergency Medical Therapy, 4th Ed. 1996, page 951.
[6]