ABG Outline and Background for Carbonic Acid/Bicarbonate Buffer System

Importance of pH

- Normal blood pH is between 7.35 and 7.45.
- Blood pH below 7.35 is known as acidosis.
- Blood pH above 7.45 is known as alkalosis.
- Values less than 6.8 or greater than 7.8 often result in death.
- The body’s pH influences the function of enzymes and thus the speed of cellular reactions, cell permeability, and the integrity of cell structure.

Effect of pH Changes on the Body

- The major effect of acidosis is depression of the central nervous system.
  - When the pH of the blood falls below 7.35, the central nervous system malfunctions, and the individual becomes disoriented and possibly comatose as the condition worsens.

- A major effect of alkalosis is hyperexcitability of the nervous system.
  - When the pH of the blood rises above 7.45, the nervous system can generate impulses without normal stimuli. Peripheral nerves are affected first, resulting in spontaneous nervous stimulation of muscles. Spasms and tetanic contractions and possibly extreme nervousness or convulsions result. Severe alkalosis can cause death as a result of spasms of the respiratory muscles.

Respiratory vs. Metabolic Acidosis/Alkalosis

- Acidosis and alkalosis are categorized by the cause of the condition.
  - Respiratory acidosis or respiratory alkalosis results from abnormalities of the respiratory system.
  - Metabolic acidosis or metabolic alkalosis results from all causes other than abnormal respiratory functions.
  - Although chemical buffers help resist changes in the pH of body fluids, the respiratory system and the Urinary system (kidneys) are the primary systems that regulate the pH of the body fluids. Malfunctions of either the respiratory system or the kidneys can result in acidosis or alkalosis.
Regulation of Acid Base Balance

- **Three regulatory systems** maintain the body’s pH:
  - 1) **Chemical buffers**, 1\textsuperscript{st} line of defense (react in seconds).
  - 2) **Respiratory system (lungs)**, 2\textsuperscript{nd} line of defense (react in minutes).
  - 3) **Renal system (kidneys)**, 3\textsuperscript{rd} line of defense (react in hours to days). Is the most powerful and lasts the longest. “Kidneys don’t kid around!”

Chemical Buffers

- **Chemical Buffers resist changes in pH when an acid or base is added.** They are found in intracellular fluid, interstitial fluid, and blood
  - If an **acidic solution is added**, the buffer will **combine with the extra H}^+ ions to help maintain the pH.
  - If a **basic solution is added**, the buffer will **release H}^+ ions to combine with the base to help maintain the pH.

\[
\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3 \rightleftharpoons \text{H}^+ + \text{HCO}_3^- 
\]

- The body has three main chemical buffer systems:
  1. The **carbonic acid:bicarbonate** buffer system.
  2. The **protein** buffer system (include intracellular proteins and hemoglobin protein)
  3. The **phosphate** buffer system (HPO$_4^{2-}$)

Carbonic Acid:Bicarbonate Buffer System

- Maintains a relatively constant plasma pH of about 7.4 and counteracts any force that would alter this.
- In this system, **carbon dioxide (CO}_2\text{) combines with water (H}_2\text{O to form carbonic acid (H}_2\text{CO}_3\text{), most of which in turn rapidly dissociates to form hydrogen ions (H}^+) and bicarbonate (HCO}_3^-\text{) as shown in the above reaction.**
  - Remember that carbon dioxide is produced as a waste product during **aerobic cellular respiration.**
  - Basically, CO}_2\text{ is not an acid but is acts like an acid because it can combine with water to form carbonic acid, H}^+ acts as an acid, and HCO}_3^- acts as a base.
  - Most bicarbonate is produced by RBCs during the chloride shift. Although H}^+ and HCO}_3^- are created in a 1:1 ratio the **intracellular buffering of H}^+ by hemoglobin** is a major reason the two ions do not appear in the plasma in the same concentration. The HCO}_3^- in the plasma is then available to buffer H}^+ from metabolic sources.
- Any disturbance of the system will be compensated by a shift in the chemical equilibrium by the **law of mass action.**
  - **Example:** If **hydrogen ions are added**, some of those hydrogen ions will associate with bicarbonate, forming carbonic acid and **drive the equilibrium to the left**, resulting in a smaller net increase of acidity than if it was just plain water. The carbonic acid will dissociate into carbon dioxide and water and the respiratory system would increase breathing rate to eliminate the excess CO}_2.
Example: If carbon dioxide is added, the equilibrium will shift to the right. More carbon dioxide will combine with water to form more carbonic acid. The carbonic acid would dissociate and more hydrogen ions and bicarbonate ions will be produced. The production of H+ from CO₂ and H₂O is the single biggest source of acid input under normal conditions.

Note: Acid-base physiology focuses primarily on acids because there are many more acid sources compared to base sources. Many metabolic intermediates and foods are organic acids that ionize and contribute H+ to body fluids. Examples of organic acids include acidic fruits, amino acids, fatty acids, citric acid cycle intermediates, and lactic acid produced by anaerobic respiration. In cases such as diabetes mellitus there is the production of ketoacids. For these reasons, the body uses far more resources removing excess acids (H+).

Respiratory System Acid-Base Regulation

- **The Respiratory System** regulates the amount of carbon dioxide (CO₂) in the blood, which combines with H₂O to form H₂CO₃. Chemoreceptor's in the brain and carotid/aortic bodies sense pH changes and send information to medulla oblongata which varies the rate and depth of breathing to regulate CO₂ levels.
- The partial pressure of arterial CO₂ (PCO₂) reflects the level of unbound CO₂ in the blood.
- Since PCO₂ is regulated by respiration, abnormalities that alter the PCO₂ levels are referred to as **respiratory acidosis** (high PCO₂) and **respiratory alkalosis** (low PCO₂).

Respiratory Acidosis

- Respiratory acidosis (high PCO₂) is caused by hypoventilation and develops when the lungs don’t adequately eliminate CO₂.
  - Respiratory acidosis causes a pH below 7.35 and a PCO₂ above 45 mm Hg. HCO₃⁻ is normal.
  - Hypoventilation can result from:
    - Diseases that affect the lungs (COPD, emphysema, asthma, pulmonary edema, pneumonia, cystic fibrosis),
    - Diseases of the nerves and muscles of the chest that impair the mechanics of breathing (Myasthenia Gravis, Amyotrophic Lateral Sclerosis).
    - Physical trauma such as a broken rib
    - Drugs that slow a patient’s respirations such as sedatives.
Respiratory Acidosis and the Bicarbonate Buffer System

- **Hypoventilation** increases CO$_2$, which by the law of mass action will cause the equilibrium to shift to the **right**. This increases **carbonic acid** (H$_2$CO$_3$) which dissociates and increases H+ ions resulting in a decrease in pH

\[
\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3 \rightarrow \text{H}^+ + \text{HCO}_3^-
\]

- **Kidneys compensate** by secreting more **hydrogen ions in the urine** and **increase reabsorption and production of bicarbonate**, but can take up to 24 hrs to be fully effective.
- **Treatment**: Improve ventilation. May need to administer drugs such as **bronchodilators** to improve breathing and, in severe cases, use **mechanical ventilation**.

Respiratory Alkalosis

- **Respiratory alkalosis** (low PCO$_2$) is caused by **hyperventilation** and develops when the lungs eliminate too much CO$_2$.
  - **Respiratory alkalosis** causes a pH above 7.45 and a PCO$_2$ below 35 mm Hg. HCO$_3^-$ is normal.
- **Hyperventilation** can result from:
  - **Fear and anxiety** (most common cause).
  - **Hypoxemia** (inadequate oxygen levels in blood) caused by pulmonary disease, congestive heart failure, or high altitudes.
  - **Hypermetabolic states** caused by fever, anemia, or thyrotoxicosis.

Respiratory Alkalosis and the Bicarbonate Buffer System

- **Hyperventilation** decreases CO$_2$ levels, which by the law of mass action, will cause the equilibrium to shift to the **left**. This reduces H+ concentrations causing a rise in pH (more alkaline).

\[
\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3 \rightarrow \text{H}^+ + \text{HCO}_3^-
\]

- **Kidneys compensate** by conserving (reabsorb) hydrogen ions and release more **bicarbonate in the urine**. This may take up to 24 hours to be fully effective. Thus, the kidneys are not effective if respiratory alkalosis develops quickly. However, they are very effective if respiratory alkalosis develops slowly. For example, the kidneys are not effective in compensating for respiratory alkalosis that occurs in response to hyperventilation triggered by emotions, which usually begins quickly and subsides within minutes or hours. However if
alkalosis results from staying at a high altitude over a 2 or 3 day period, the kidneys play a significant role in helping to compensate.

- **Treatment:** Goal is to **slow the breathing rate**.
  - If anxiety is the cause, encourage the patient to slow his or her breathing.
  - If pain is causing rapid, shallow breathing, provide pain relief.
  - Breathing into a paper bag allows a patient to rebreathe CO₂, raising the level of CO₂ in the blood.
Overview of Carbonic Acid:Bicarbonate (H$_2$CO$_3$-HCO$_3^-$) Buffer System and Link to Respiratory and Urinary Systems

- **Carbonic Acid:Bicarbonate Buffer System** is considered the most important chemical buffer because it is coupled to the **respiratory system** and **urinary system**.
- **Hypoventilation increases CO$_2$** which by the law of mass action, will increase carbonic acid (H$_2$CO$_3$) and increase H+ ions causing **respiratory acidosis** (lowers pH).
- **Hyperventilation decreases dissolved CO$_2$**, which by the law of mass action, reduces H+ concentrations causing **respiratory alkalosis** (raises pH).
- **Response to respiratory acidosis**: Increased HCO$_3^-$ reabsorption and synthesis (puts base into the blood), and increased H+ secretion into the urine raises blood pH (becomes more alkaline).
- **Response to respiratory alkalosis**: Decreased HCO$_3^-$ reabsorption and synthesis, decreased H+ secretion into the urine lowers blood pH (becomes more acidic).
Metabolic Acidosis

- **Metabolic acidosis** is caused by an increase in acid production or decreased bicarbonate (HCO$_3^-$) levels that are not caused by respiratory problems.
  - Metabolic acidosis causes a HCO$_3^-$ below 22 mEq/L and a pH below 7.35. PaCO$_2$ is normal.
- **Metabolic acidosis** can result from:
  - **Renal disease or failure** resulting in an inability to excrete acids or excess loss of bicarbonate (base) or inability of kidneys to make bicarbonate.
  - **Excess acid production**:
    - **Diabetic ketoacidosis**
    - **Starvation** resulting in increased plasma fatty acids and ketoacidosis
    - **Lactic acidosis** caused by anaerobic metabolism due to poor oxygenated blood perfusion.
    - **Diarrhea** resulting in excess HCO$_3^-$ loss
- **Compensation for metabolic acidosis include**:
  - **Respiratory system**: The reduced pH stimulates the respiratory center, which causes hyperventilation (Kussmaul breathing – deep labored rapid breathing). As carbon dioxide is eliminated at a greater rate there is a shift to the left in the carbonic acid/bicarbonate equilibrium and excess hydrogen ions are eliminated. This counteracts the metabolic acidosis.
  - **Kidneys**: Increase rate of H$^+$ secretion and bicarbonate ion reabsorption. Kidneys can also produce bicarbonate to offset the acidosis. However this may take up to 24 hours to be fully functional.

![Diagram of acid-base balance](image-url)
Metabolic Alkalosis

- **Metabolic alkalosis** is caused by a decrease or loss of metabolic acids or an increase in bicarbonate concentrations that is not caused by respiratory problems.
  - Metabolic alkalosis causes a $\text{HCO}_3^-$ above 26 mEq/L and a pH above 7.45. PaCO2 is normal.

- **Metabolic alkalosis** can result from:
  - Vomiting resulting in loss of stomach acid.
  - H+ loss through the kidneys
  - Excessive ingestion of antacids (increased bicarbonate)
  - Constipation, in which excessive bicarbonate is reabsorbed

- **Compensation for metabolic alkalosis include:**
  - **Respiratory System**: The increased pH inhibits the respiratory center, which causes hypoventilation and increases carbon dioxide accumulates in the blood. Carbon dioxide reacts with water to produce carbonic acid shifting the carbonic acid/bicarbonate equilibrium to the right and the excess hydrogen ions help counter act the metabolic alkalosis
  - **Kidneys** decrease the rate of H+ secretion into the urine and decrease bicarbonate ion reabsorption and production. However this may take up to 24 hours to be maximally effective.

- **Metabolic Acid-Base Imbalances/Compensation**
Arterial Blood Gas (ABG)

- ABG is a diagnostic test used to assess the effectiveness of your patient’s ventilation and acid-base balance.
  - A low partial pressure of oxygen (PO$_2$) suggests that a person is not getting enough oxygen. Normal PO$_2$ values: 80 - 100 mmHg, Normal oxygen saturation values (breathing room air) (SaO$_2$): 94 - 100%
  - Note: PO$_2$ is not the same as SaO$_2$ that you take with the pulse oximeter, also known as the “glow finger”.  
  - Details of PaO$_2$, SaO$_2$, and CaO$_2$ will be presented later

Three results are essential for evaluating acid-base balance:

1) pH: Indicates whether the person is in acidosis or alkalosis but it does not indicate the cause.
2) PCO$_2$: Abnormal values of PCO$_2$ may indicate whether the acidosis/alkalosis is caused by the respiratory system or if the patient is compensating for a metabolic disturbance.
3) HCO$_3$-: Abnormal values of the HCO$_3$- indicate the acidosis/alkalosis is metabolic or if the patient is compensating for a respiratory disturbance.

- Normal values of pH, PCO$_2$, and HCO$_3$-. You will need to memorize these values.
  - pH: 7.35 to 7.45  Average: 7.4
  - PCO$_2$: 35 to 45 mm Hg  Average: 40 mm Hg
  - HCO$_3$-: 22 to 26 mEq/L  Average: 24 mEq/L

Note: PO$_2$ and PCO$_2$ can be written as PaO$_2$ and PaCO$_2$.
The “a” stands for arterial. Since the first word is arterial in ABG often the small “a” is left off.

<table>
<thead>
<tr>
<th>ACID-BASE NORMAL VALUES</th>
<th>ACID</th>
<th>NORMAL</th>
<th>ALKALINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>&lt; 7.35</td>
<td>7.35 – 7.45</td>
<td>&gt; 7.45</td>
</tr>
<tr>
<td>pCO$_2$</td>
<td>&gt; 45</td>
<td>35 – 45</td>
<td>&lt; 35</td>
</tr>
<tr>
<td>HCO$_3$-</td>
<td>&lt; 22</td>
<td>22 – 26</td>
<td>&gt; 26</td>
</tr>
</tbody>
</table>

Fast Facts on Acid-Base Balance

- The more hydrogen ion (H$^+$) in the blood, the lower the pH.
- The less H$^+$ in the blood, the higher the pH.
- When partial pressure of arterial carbon dioxide (PCO$_2$) rises, pH falls.
- When PCO$_2$ falls, pH rises.
- In respiratory acid-base disorders, pH and PCO$_2$ move in opposite directions. Bicarbonate (HCO$_3$-) remains normal until compensation occurs.
- In metabolic acid-base disorders, pH and HCO$_3$- move in the same direction. PCO$_2$ remains normal until compensation occurs.
Arterial Blood Gas Naming

- **ABGs** are identified by **three names**.
  - Example: Uncompensated respiratory acidosis
- **First** we identify the last name.
  - It is an **acidosis**, an **alkalosis**, or is it **normal**?
  - If it is normal we are finished – all is good.
- **Second** we identify the middle name.
  - Is it **respiratory** or **metabolic**?
- **Third**, we identify the first name.
  - Is it **uncompensated**, **partially** or **fully** compensated?

Terms Used In ABG Results

- **Terms used to label abnormal ABG results:**
  - Respiratory Acidosis (uncompensated, partially compensated, compensated)
  - Respiratory Alkalosis (uncompensated, partially compensated, compensated)
  - Metabolic Acidosis (uncompensated, partially compensated, compensated)
  - Metabolic Alkalosis (uncompensated, partially compensated, compensated)

Compensating for imbalances

- Compensation is when the renal and respiratory systems make adjustments to regain acid-base balance.
  - The lungs compensate (respond) to a **metabolic disorder by increasing or decreasing ventilation** and thus the concentration of carbon dioxide.
  - The renal system compensates for a **respiratory disorder by regulating the amount of H+ and HCO₃⁻** that is reabsorbed or secreted producing more acidic or more alkaline urine.
- Partial compensation is when there is a respiratory or metabolic response, but the pH remains abnormal. If the pH returns to normal, the response is called complete compensation.
- Correction occurs when the values for both components of the buffer pair (carbonic acid and bicarbonate) return to normal levels.
Determination of Abnormal ABG Values

- In analyzing ABG results you compare the pH, PCO$_2$, and HCO$_3$- values to the normal values. Will allow you to determine if your patient is normal or in respiratory or metabolic acidosis or alkalosis.
  - For pH anything less than 7.35 is acidic and anything greater than 7.45 is a basic.
  - For PCO$_2$ (NOTE: it is the opposite) anything less than 35 mm Hg is basic and anything greater than 45 mm Hg is acidic.
  - For HCO$_3$- anything less than 22 mEq/L is acidic and anything greater than 26 mEq/L is basic.

Write out the following table to help you understand.

<table>
<thead>
<tr>
<th>Normal Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH: 7.35 to 7.45</td>
</tr>
<tr>
<td>PCO$_2$: 35 to 45 mm Hg</td>
</tr>
<tr>
<td>HCO$_3$-: 22 to 26 mEq/L</td>
</tr>
</tbody>
</table>

TIC-TAC-TOE Method for ABG Analysis

- Tic-Tac-Toe method to determine acid-base balances:
  - The column that the pH is in tells whether the patient has acidosis, alkalosis, or is normal.
  - The position of the PCO$_2$, and HCO$_3$- reveals the origin of any acid-base balance.
  - If the pH and the HCO$_3$- fall in the same column – other than normal, the problem is metabolic.
  - If the pH and the PCO$_2$ fall in the same column – other than normal – the problem is respiratory.
  - To determine compensation we look at the value that didn’t come into alignment with the pH
    - If the value that is not in alignment with the pH is in the normal column, there is no compensation.
    - If the value that is not in alignment with the pH is in the far opposite column, there is partial compensation.
    - If an ABG shows full compensation, the pH will be normal. To determine if it is an acidosis or alkalosis you look at which it is closer to.
- To set up a “tic tac toe” grid, label each “column” as “acid”, “pH”, and “base”. It should look like this:
Practice Problem 1

- ABG results are the following:
  - pH  7.24
  - PCO₂  75 mm Hg
  - HCO₃⁻  28 mEq/L

Analysis of Practice Problem 1

- ABG results are the following: pH 7.24, PCO₂ 75, HCO₃⁻ 28
- Draw your tic tac toe lay out.
- Analyze your pH. Ask yourself is it normal, basic, or acidic? Since the pH is less than 7.35 making it an acid, place it under the acid column.
- Analyze your PCO₂. Ask yourself is it normal, basic, or acidic? Since the PCO₂ is greater than 45 making it an acid, place it under the acid column along with pH. Remember PCO₂ is the opposite and the normal is 35-45.
- Analyze your HCO₃⁻. Ask yourself is it normal, basic, or acidic? Since HCO₃⁻ is greater than 26 making it basic, place it under the base column because the value is considered basic.
- Your tic tac toe lay out should look like this:
- Since your pH is acidic you know that you have acidosis going on but is it respiratory or metabolic acidosis. Since PCO₂ represents respiratory and it is under the acid column with your pH you have respiratory acidosis.
- But is it fully compensated, partially compensated, or uncompensated respiratory acidosis? Look at your HCO₃⁻. Since your HCO₃⁻ is under basic, the kidneys are trying to balance the body’s acidosis by becoming more basic so it is partially compensating. The condition is Partially Compensated Respiratory Acidosis.
- Note: If HCO₃⁻ was under the normal column the kidneys would not be activated to compensate and therefore, it would be considered uncompensated respiratory acidosis.

Practice Problem 2

- ABG results are:
  - pH  7.50
  - PCO₂  36 mm Hg
  - HCO₃⁻  32 mEq/L

Analysis of Practice Problem 2

- Here is what your tic tac toe grid should look like: 
- Analyze your pH. Ask yourself is it normal, basic, or acidic? Since the pH is greater than 7.45 making it a basic, place it under the base column.
- Analyze your PCO₂. Ask yourself is it normal, basic, or acidic? Since the PCO₂ is between 35-45 it is normal, place it under the normal column.
- Analyze your HCO₃⁻. Ask yourself is it normal, basic, or acidic? Since HCO₃⁻ is greater than 26 making it is basic, place it under the base column.
• Since your pH is basic you know you have alkalosis, but is it respiratory or metabolic? Since the \( \text{HCO}_3^- \) (which represents metabolic) is under you basic column with pH, it is a metabolic issue. So your patient is in: **Metabolic Alkalosis**. Now is it fully compensated, partially compensated, or uncompensated metabolic alkalosis? Look at the \( \text{PCO}_2 \)! Since it is under the normal column that means the lungs have NOT tried to help out the body’s system by making increasing the \( \text{PCO}_2 \) levels and making the blood more acidic. So the body is not compensating. **Answer: Uncompensated Metabolic Alkalosis**

**Practice Problem 3**

• Ms. Doe, a 75 year old diabetic, has a long history of non-compliance with her insulin. She was recently admitted to the hospital with the following ABG results:

  • pH  7.26
  • \( \text{PCO}_2 \)  42 mm Hg
  • \( \text{HCO}_3^- \)  17 mEq/L

**Analysis of Practice Problem 3**

• Analysis:
  – Since the pH and the \( \text{HCO}_3^- \) both fall under the ACID column (three in a row), Ms. Doe has Metabolic Acidosis.
  – The \( \text{pCO}_2 \) is normal designating that no respiratory compensation has occurred. Thus Ms. Doe has **Uncompensated Metabolic Acidosis**.

**Practice Problem 4**

• Ms. Doe presented with the following ABGs:

  • pH  7.26
  • \( \text{PCO}_2 \)  32 mm Hg
  • \( \text{HCO}_3^- \)  17 mEq/L

**Analysis of Practice Problem 4**

• Analysis:
  – Because the \( \text{PCO}_2 \) was alkaline instead of normal, it is placed under the alkaline column.
  – This reflects that the respiratory system (\( \text{PCO}_2 \)) has begun to compensate for the metabolic acidosis (\( \text{HCO}_3^- \)) with a resulting respiratory alkalosis. The patient will likely have a high respiratory rate (**Kussmaul breathing** ) as she blows off lots of CO2 to try to raise the pH.
  – Therefore, with these values, Ms. Doe’s diagnosis is now **Partially Compensated Metabolic Acidosis**.
Practice Problem 5
- Mr. Smith presented with the following ABGs:
  - pH 7.49
  - PCO₂ 60 mm Hg
  - HCO₃⁻ 30 mEq/L

Analysis of Practice Problem 5
- Analysis:
  - Because the pH and HCO₃⁻ are alkaline instead of normal, they are placed under the alkaline column.
  - The PCO₂ is in the acidic column which indicates that the respiratory system has begun to compensate for the metabolic alkalosis (HCO₃⁻) with a resulting respiratory acidosis. The patient will likely have a low respiratory rate as they hold onto CO₂ to try to lower the pH.
  - Therefore, with these values, Mr. Smith’s diagnosis is **Partially Compensated Metabolic Alkalosis**.

Practice Problem 6 Full Compensation Example
- Mr. Dalton presented with the following ABGs:
  - pH 7.38
  - PCO₂ 60 mm Hg
  - HCO₃⁻ 27 mEq/L

Analysis of Practice Problem 6
- Analysis:
  - The pH is normal but on the acid side of 7.4 (half-way between 7.35 and 7.45).
  - This problem is considered to the respiratory because between the two, the pH is more on the acidic side, the same side as the PCO₂. HCO₃⁻ is alkaline.
  - This ABG is **fully compensated respiratory acidosis** because the pH is normal and the renal system (metabolic system) is able to compensate by increasing the bicarbonate levels to keep the pH in the normal range.

Practice Problem 7 Full Compensation
- Mr. Dalton presented with the following ABGs:
  - pH 7.36
  - PCO₂ 30 mm Hg
  - HCO₃⁻ 15 mEq/L

Analysis of Practice Problem 7
- Analysis:
  - The pH is normal but on the acid side of 7.4 (half-way between 7.35 and 7.45).
  - This problem is considered to the metabolic because between the two, the pH is more on the acidic side, the same side as the HCO₃⁻. PCO₂ is alkaline.
  - This ABG is **fully compensated metabolic acidosis** because the pH is normal and the respiratory system is able to compensate by decreasing the carbon dioxide level to keep the pH in the normal range.
Additional Practice ABGs
1. pH: 7.32, PCO₂: 21, HCO₃⁻: 21
2. pH: 7.27, PCO₂: 49, HCO₃⁻: 35
3. pH: 7.29, PCO₂: 50, HCO₃⁻: 23
4. pH: 7.61, PCO₂: 44, HCO₃⁻: 37
5. pH: 7.64, PCO₂: 45, HCO₃⁻: 32
6. pH: 7.65, PCO₂: 44, HCO₃⁻: 33
7. pH: 7.71, PCO₂: 55, HCO₃⁻: 28
8. pH: 7.59, PCO₂: 42, HCO₃⁻: 28
9. pH: 7.61, PCO₂: 24, HCO₃⁻: 23
10. pH: 7.33, PCO₂: 27, HCO₃⁻: 15

Additional Practice ABGs showing full compensation
1. pH: 7.36, PCO₂: 30, HCO₃⁻: 15
2. pH: 7.36, PCO₂: 75, HCO₃⁻: 40
3. pH: 7.44, PCO₂: 27, HCO₃⁻: 18
4. pH: 7.43, PCO₂: 49, HCO₃⁻: 31

Video Tutorials: There are four video tutorials on my web site for Arterial Blood Gas (ABG) Tic-Tac-Toe method. Look for the links in the Student Resources section, Anatomy and Physiology, and then Blood Test Information.

Answers to Practice ABGs
1. pH: 7.32, PCO₂: 21, HCO₃⁻: 21 - Partially Compensated Metabolic Acidosis
2. pH: 7.27, PCO₂: 49, HCO₃⁻: 35 - Partially Compensated Respiratory Acidosis
3. pH: 7.29, PCO₂: 50, HCO₃⁻: 23 - Uncompensated Respiratory Acidosis
4. pH: 7.61, PCO₂: 44, HCO₃⁻: 37 - Uncompensated Metabolic Alkalosis
5. pH: 7.64, PCO₂: 45, HCO₃⁻: 32 - Uncompensated Metabolic Alkalosis
6. pH: 7.65, PCO₂: 44, HCO₃⁻: 33 - Uncompensated Metabolic Alkalosis
7. pH: 7.71, PCO₂: 55, HCO₃⁻: 28 - Partially Compensated Metabolic Alkalosis
8. pH: 7.59, PCO₂: 42, HCO₃⁻: 28 - Uncompensated Metabolic Alkalosis
9. pH: 7.61, PCO₂: 24, HCO₃⁻: 23 - Uncompensated Respiratory Alkalosis
10. pH: 7.33, PCO₂: 27, HCO₃⁻: 15 - Partially Compensated Metabolic Acidosis

Answers to Additional Practice ABGs showing full compensation
5. pH: 7.36, PCO₂: 30, HCO₃⁻: 15 – Fully compensated metabolic acidosis
6. pH: 7.36, PCO₂: 75, HCO₃⁻: 40 – Fully compensated respiratory acidosis
7. pH: 7.44, PCO₂: 27, HCO₃⁻: 18 – Fully compensated respiratory alkalosis
8. pH: 7.43, PCO₂: 49, HCO₃⁻: 31 – Fully compensated metabolic alkalosis
Terminology Explained

Arterial Blood Gas (ABG) include the following. Since the first word is arterial in ABG often the small “a” is left off. For example PaO₂ vs. PO₂.

- **Alveolar** partial pressure of oxygen (P\(A_O^2\))
- **Venous** partial pressure of oxygen (P\(v_O^2\))
- **Venous** hemoglobin oxygen saturation (S\(v_O^2\))
- **Arterial** partial pressure of oxygen (P\(a_O^2\))
- **Arterial** hemoglobin oxygen saturation (S\(a_O^2\))
- **Arterial** Oxygen content (C\(a_O^2\))

**OXYGEN PRESSURE: PaO₂.**

- PaO₂, the partial pressure of oxygen in the plasma phase of arterial blood, is registered by an electrode that senses randomly-moving, dissolved oxygen molecules. Oxygen molecules dissolved in plasma (i.e., not bound to hemoglobin) are free to impinge on the measuring oxygen electrode. This "impingement" of free O₂ molecules is reflected as the partial pressure of oxygen; if the sample being tested is arterial blood, then it is the P\(a_O^2\). The amount of dissolved oxygen in the plasma phase -- and hence the PaO₂ -- is determined by alveolar PO₂ and lung architecture only, and is unrelated to anything about hemoglobin.

- Oxygen molecules that pass through the thin alveolar-capillary membrane enter the plasma phase as dissolved (free) molecules; most of these molecules quickly enter the red blood cell and bind with hemoglobin. There is a dynamic equilibrium between the freely dissolved and the hemoglobin-bound oxygen molecules. However, the more dissolved molecules there are (i.e., the greater the PaO₂) the more will bind to available hemoglobin; thus S\(a_O^2\) always depends,
to a large degree, on the concentration of dissolved oxygen molecules (i.e., on the PaO₂).

- Since PaO₂ reflects only free oxygen molecules dissolved in plasma and not those bound to hemoglobin, PaO₂ cannot tell us "how much" oxygen is in the blood; for that you need to know how much oxygen is also bound to hemoglobin, information given by the SaO₂ and hemoglobin content.

- Once bound, oxygen no longer exerts a gas pressure. Thus hemoglobin is like an efficient sponge that soaks up oxygen so more can enter the blood. Hemoglobin continues to soak up oxygen molecules until it becomes saturated with the maximum amount it can hold - an amount that is largely determined by the PaO₂. Of course this whole process is near instantaneous and dynamic; at any given moment a given O₂ molecule could be bound or dissolved. However, depending on the PaO₂ and other factors, a certain percentage of all O₂ molecules will be dissolved and a certain percentage will be bound.

- **OXYGEN SATURATION: SaO₂.**
  - The percentage of all the available heme binding sites saturated with oxygen is the hemoglobin oxygen saturation (in arterial blood, the SaO₂). Note that SaO₂ alone doesn't reveal how much oxygen is in the blood; for that we also need to know the hemoglobin content.
  - An SaO₂ of 97% simply means that of every 100 hemoglobin binding sites, 97 are occupied with an oxygen molecule and the other three are either bound to something else or are unbound.

- Binding sites for oxygen are the heme groups, the Fe²⁺-porphyrin portions of the hemoglobin molecule. There are four heme sites, and hence four oxygen binding sites, per hemoglobin molecule. Heme sites occupied by oxygen molecules are said to be "saturated" with oxygen. Each hemoglobin molecule has four Fe²⁺heme sites for binding oxygen. If there is no interference (as from carbon monoxide, for example), the free O₂ molecules bind to these sites with great affinity. The total percentage of sites actually bound with O₂ is constant for a given set of conditions, and is the "saturation of blood with oxygen". This is called SvO₂ and SaO₂ in the venous and arterial circulations, respectively.
• OXYGEN CONTENT: CaO₂.
  • Tissues need a requisite amount of O₂ molecules for metabolism. Neither the PaO₂ nor the SaO₂ provide information on the number of oxygen molecules, i.e., of how much oxygen is in the blood. (Note that neither PaO₂ nor SaO₂ have units that denote any quantity.)
  • Of the three values used for assessing blood oxygen levels, how much is provided only by the oxygen content, CaO₂ (units ml O₂/dl). This is because CaO₂ is the only value that incorporates the hemoglobin content. Oxygen content can be measured directly or calculated by the oxygen content equation:

\[
CaO₂ = Hb \text{ (gm/dl)} \times 1.34 \text{ ml O}_2/\text{gm Hb} \times SaO₂ + PaO₂ \times (.003 \text{ ml O}_2/\text{mm Hg/dl})
\]

Summary of PaO₂, SaO₂, CaO₂
• PaO₂ is determined by alveolar PO₂ (PAO₂) and the state of the alveolar-capillary interface, not by the amount of hemoglobin available to soak them up. PaO₂, in turn, determines the oxygen saturation of hemoglobin (along with other factors that affect the position of the oxyhemoglobin dissociation curve). The SaO₂, plus the concentration of hemoglobin (15 gm/dl in this example), determine the total amount of oxygen in the blood or CaO₂ (see equation for CaO₂).

Clinical Problem 1
• At 10 a.m. a patient has a PaO₂ of 85 mm Hg, an SaO₂ of 98%, and a hemoglobin of 14 gm/dl. At 10:05 a.m. she suffers a severe hemolytic reaction that suddenly leaves her with a hemoglobin of only 7 gm/dl. Assuming no lung disease occurs from the hemolytic reaction, what will be her new PaO₂, SaO₂, and CaO₂?
  a) PaO₂ unchanged, SaO₂ unchanged, CaO₂ unchanged
  b) PaO₂ unchanged, SaO₂ unchanged, CaO₂ reduced
  c) PaO₂ reduced, SaO₂ unchanged, CaO₂ reduced
  d) PaO₂ reduced, SaO₂ reduced, CaO₂ reduced

Answer: Clinical Problem 1
  b) PaO₂ unchanged, SaO₂ unchanged, CaO₂ reduced.
  • Hemoglobin content is suddenly reduced by half, which will lower CaO₂ by half. However, the PaO₂ and SaO₂ will be unaffected, since their values are independent of the content of hemoglobin present.
  • Neither the amount of hemoglobin, nor the binding characteristics of hemoglobin, should affect the amount of dissolved oxygen, and hence should not affect the PaO₂. Stated another way, the number of dissolved oxygen molecules is independent of the amount of hemoglobin or what is bound to it. To repeat one more time (because it is so important), PaO₂ is not a function of hemoglobin content or of its characteristics, but only of the alveolar PO₂ and the lung architecture (alveolar-capillary interface). This explains why, for example, patients with severe anemia or carbon monoxide poisoning or methemoglobinemia can (and often do) have a normal PaO₂.
**Clinical Problem 2**

- State which of the following situations would be expected to lower PaO$_2$.
  a) anemia.
  b) carbon monoxide toxicity.
  c) an abnormal hemoglobin that holds oxygen with half the affinity of normal hemoglobin.
  d) an abnormal hemoglobin that holds oxygen with twice the affinity of normal hemoglobin.
  e) lung disease with intra-pulmonary shunting.

**Note:** A **pulmonary shunt** is a physiological condition which results when the alveoli of the lungs are perfused with blood as normal, but ventilation (the supply of air) fails to supply the perfused region. A pulmonary shunt often occurs when the alveoli fill with fluid, causing parts of the lung to be unventilated although they are still perfused. An Example would be pulmonary edema and conditions such as pneumonia.

**Answer to Clinical Problem 2.**

- Of the choices given only **answer e)**, lung disease with intra-pulmonary shunting, would be expected to lower PaO$_2$. The other choices represent changes in hemoglobin content and binding and should not (by themselves) lower PaO$_2$.

**Clinical Problem 3**

- Test your understanding by answering the following statements a-h as either True or False.
  a. If the lungs and heart are normal, then PaO$_2$ is affected only by the alveolar PO$_2$. **True**
  b. In a person with normal heart and lungs, anemia should not lower the PaO$_2$. **True**
  c. PaO$_2$ will go up in a patient with hemolysis of red blood cells, as dissolved oxygen is given off when the cells lyse. **False**
  d. As the oxygen dissociation curve shifts to the right, PaO$_2$ rises since less oxygen is bound to hemoglobin. **False**
  e. An anemic patient who receives a blood transfusion should experience a rise in both SaO$_2$ and CaO$_2$. **False. SaO$_2$ not affected but the CaO$_2$ will be increased.**
  f. The PaO$_2$ in a cup of water is zero since there is no blood perfusing the water. **False**
  g. The SaO$_2$ in a cup of water is zero since there is no hemoglobin present. **True**
  h. The CaO$_2$ in a cup of water is zero since there is no hemoglobin present. **False**