Chapter 13

Acid-Base Balance
Objectives

- Describe how the lungs and kidneys regulate volatile and fixed acids.

- Describe how an acid’s equilibrium constant is related to its ionization and strength.

- State what constitutes open and closed buffer systems.

- Explain why open and closed buffer systems differ in their ability to buffer fixed and volatile acids.

- Explain how to use the Henderson-Hasselbalch equation in hypothetical clinical situations.
Objectives (cont.)

- Describe how the kidneys and lungs compensate for each other when the function of one is abnormal.

- Explain how renal absorption and excretion of electrolytes affect acid-base balance.

- Classify and interpret arterial blood acid-base results.

- Explain how to use arterial acid-base information to decide on a clinical course of action.
Objectives (cont.)

- Explain why acute changes in the blood’s carbon dioxide level affect the blood’s bicarbonate ion concentration.

- Calculate the anion gap and use it to determine the cause of metabolic acidosis.

- Describe how standard bicarbonate and base excess measurements are used to identify the nonrespiratory component of acid-base imbalances.

- State how Stewart’s strong ion difference approach to acid-base regulation differs from the Henderson-Hasselbalch approach.
Hydrogen Ion Regulation in Body Fluids

- Acid-base balance is what keeps [H+] in normal range.
  - For best results, keeps pH 7.35–7.45.

- Tissue metabolism produces massive amounts of CO₂, which is hydrolyzed into the volatile acid H₂CO₃.
  \[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3 \rightarrow \text{H}^+ + \text{HCO}_3^- \]

  - Rx is catalyzed in RBCs by carbonic anhydrase.
  - Lungs eliminate CO₂, the falling CO₂ reverses Rx.

Ventilation

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

\[ \text{HHb} \rightarrow \text{H}^+ + \text{HCO}_3^- \]
Hydrogen Ion Regulation in Body Fluids (cont.)

Buffer solution characteristics

- A solution that resists changes in pH when an acid or a base is added
- Composed of a weak acid and its conjugate base
  - i.e., carbonic acid/bicarbonate, which in blood exists in reversible combination as NaHCO$_3$ and H$_2$CO$_3$
  - Add strong acid HCl + NaHCO$_3$ → NaCl + H$_2$CO$_3$, and it is buffered with only a small acidic pH change.
  - Add base NaOH + H$_2$CO$_3$ → NaHCO$_3$ + H$_2$O, and it is buffered with only a slight alkaline pH change.
Hydrogen Ion Regulation in Body Fluids (cont.)

Bicarbonate and nonbicarbonate buffer systems

- Bicarbonate: composed of $\text{HCO}_3^-$ and $\text{H}_2\text{CO}_3$
  - Open system as $\text{H}_2\text{CO}_3$ is hydrolyzed to $\text{CO}_2$.
  - Ventilation continuously removes $\text{CO}_2$ preventing equilibration driving reaction to right

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

- Removes vast amounts of acid from body per day
Hydrogen Ion Regulation in Body Fluids (cont.)

Bicarbonate and nonbicarbonate buffer systems (cont.)

- Nonbicarbonate: composed of phosphate and proteins
  - Closed system as no gas to remove acid by ventilation
  - $H_{buf}/buf^-$ represents acid and conjugate base.
    - $H^+ + buf^- \leftrightarrow H_{buf}$ reach equilibrium, buffering stops
  - Both systems are important to buffering fixed and volatile acids.
Buffer Systems

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

\[ \text{Blood [H}^+\text{]} \]

\[ \text{H Buf} \leftrightarrow \text{Buf}^- + \text{H}^+ \]

(Modified from Beachey W: Respiratory care anatomy and physiology: foundations for clinical practice, ed 2, St Louis, 2007, Mosby.)
pH of a Buffer System: Henderson-Hasselbalch Equation

- Describes $[H^+]$ as the ratio of $[H_2CO_3]/[HCO_3^-]$

\[
pH = 6.1 + \log \frac{[HCO_3^-]}{(PaCO_2 \times 0.03)}
\]

- pH is logarithmic expression of $[H^+]$.
- 6.1 is the log of the $H_2CO_3$ equilibrium constant.
- $(PaCO_2 \times 0.03)$ is in equilibrium with and directly proportional to blood $[H_2CO_3]$.

- Blood gas analyzers measure pH and PaCO$_2$; then use the H-H equation to calculate HCO$_3^-$.
Hydrogen Ion Regulation in Body Fluids (cont.)

Bicarbonate buffer system

- HCO₃⁻ can continue to buffer fixed acid H⁺ as long as ventilation is adequate to exhale the volatile acid CO₂.

\[
\text{Ventilation} \\
\uparrow \\
H^+ + HCO_3^- \rightarrow H_2CO_3 \rightarrow H_2O + CO_2
\]

Fixed acid

- HCO₃⁻ cannot buffer H₂CO₃ (volatile) acid
  - In hypoventilation, H₂CO₃ accumulates; only the nonbicarbonate system can serve as a buffer.
Hydrogen Ion Regulation in Body Fluids (cont.)

Nonbicarbonate buffer system

- **Hb** is the most important buffer in this system as it is most abundant.

- Can buffer any fixed or volatile acid

- As closed system, products of buffering accumulate and buffering may slow or stop \( (H^+ + \text{Buf}^- \leftrightarrow \text{HBuf}) \).

- **HCO_3^-** and **buf^-** exist in same blood system so

\[
\begin{align*}
H^+ + HCO_3^- & \rightarrow H_2CO_3 \\
H_2CO_3 & \rightarrow H_2O + CO_2
\end{align*}
\]

**Fixed acid** \( \rightarrow H^+ + \text{Buf}^- \leftrightarrow \text{HBuf} \)

Ventilation
Acid Excretion

• Buffers are a temporary measure; if acids were not excreted, life-threatening acidosis would follow.

• Lungs
  - Excrete CO$_2$, which is in equilibrium with H$_2$CO$_3$
  - Crucial as body produces huge amounts of CO$_2$ during aerobic metabolism (CO$_2$ + H$_2$O → H$_2$CO$_3$)
  - In addition, through HCO$_3^-$ eliminate fixed acids indirectly as the byproducts are CO$_2$ and H$_2$O
  - Remove ~24,000 mmol/L CO$_2$ removed daily
Acid Excretion (cont.)

- **Kidneys**
  - Physically remove H\(^+\) from body
  - Excrete <100 mEq fixed acid per day
  - Also control excretion or retention of HCO\(_3^-\)
  - If blood is acidic, then more H\(^+\) are excreted and all the HCO\(_3^-\) is retained, vice versa
  - While lungs can alter [CO\(_2\)] in seconds, the kidneys require hours to days change HCO\(_3^-\) and affect pH.
Acid Excretion (cont.)

Basic kidney function

- Renal glomerulus filters the blood by passing water, electrolytes, and nonproteins through semipermeable membrane.
  - Filtrate is modified as it flows through renal tubules

- HCO₃⁻ is filtered through membrane, while CO₂ diffuses into tubule cell, where it is hydrolyzed into H⁺, which is secreted into renal tubule.
  - H⁺ secretion increases in the face of acidosis.
    - i.e. hypoventilation or ketoacidosis increase secretion.
Acid Excretion (cont.)

Basic kidney function (cont.)

- Reabsorption of HCO$_3^-$
  - For every H$^+$ secreted, an HCO$_3^-$ is reabsorbed.
  - They react in the filtrate, forming H$_2$CO$_3$ which dissociates into H$_2$O and CO$_2$.
  - CO$_2$ immediately diffuses into cell, is hydrolyzed and H$^+$ is secreted into filtrate, HCO$_3^-$ diffuses into blood.
  - Thus, HCO$_3^-$ has effectively been moved from the filtrate to the blood in exchange for H$^+$.
  - If there is excess HCO$_3^-$ that does not react with H$^+$, it will be excreted in urine.
Acid Excretion (cont.)
Acid Excretion (cont.)

Basic kidney function (cont.)

- Role of urinary buffers in excretion of excess $H^+$
  - Once $H^+$ has reacted with all the available $HCO_3^-$, the excess reacts with phosphate and ammonia.
  - If all urinary buffers are consumed, further $H^+$ filtration ends when pH falls to 4.5.
  - Activation of ammonia buffer system enhances $Cl^-$ loss and $HCO_3^-$ gain.
Acid-Base Disturbances

Normal acid-base balance

- Kidneys maintain HCO$_3^\text{-}$ of ~24 mEq/L.
- Lungs maintain CO$_2$ of ~40 mm Hg.
- These produce a pH of ~7.40 (H-H equation).
  \[
  \text{pH} = 6.1 + \log \left( \frac{24}{40 \times 0.03} \right) \rightarrow \text{pH} = 7.40
  \]
- Note pH determined by ratio of HCO$_3^\text{-}$ to dissolved CO$_2$
  - Ratio of 20:1 will provide normal pH (7.40).
  - An increased ratio results in alkalemia, while a decreased ratio results in acidemia
Primary respiratory disturbances

- As $\text{PaCO}_2$ is controlled by the lung, changes in pH caused $\text{PaCO}_2$ are considered respiratory disturbances

  - Hyperventilation lowers $\text{PaCO}_2$, which raises pH, so is referred to as respiratory alkalosis.
  - Hypoventilation ($\uparrow \text{PaCO}_2$) decreases the pH, so is called respiratory acidosis.
Primary metabolic disturbances

- These disturbances involve a gain or loss of fixed acids or HCO$_3^-$.
- Both will appear as changes in HCO$_3^-$ as changes in fixed acids will alter the amount of HCO$_3^-$ used in buffering.
Acid-Base Disturbances (cont.)

Primary metabolic disturbances (cont.)
- A decrease in $\text{HCO}_3^-$ results in a metabolic acidosis.
- An increase in $\text{HCO}_3^-$ results in metabolic alkalosis.

Compensation: Restoring pH to normal
- Any primary disturbance immediately triggers a compensatory response.
  - Any respiratory disorder will be compensated for by the kidneys (process takes hours to days).
  - Any metabolic disorder will be compensated for by the lungs (rapid process, occurs within minutes).
Acid-Base Disturbances (cont.)

Compensation: Restoring pH to normal (cont.)

- Respiratory acidosis (hypoventilation)
  - Renal retention $\text{HCO}_3^-$ raises pH toward normal

- Respiratory alkalosis
  - Renal elimination $\text{HCO}_3^-$ lowers pH toward normal

- Metabolic acidosis
  - Hyperventilation $\downarrow\text{CO}_2$, raising pH toward normal

- Metabolic alkalosis
  - Hypoventilation $\uparrow\text{CO}_2$, lowering pH toward normal
Acid-Base Disturbances (cont.)

The CO₂ hydration reaction’s effect on [HCO₃⁻]

- A large portion of CO₂ is transported as HCO₃⁻.

- As CO₂ increases, it also increases HCO₃⁻.

- In general, the effect is an increase of ~1 mEq/L HCO₃⁻ for every 10 mm Hg increase in PaCO₂.
  - An increase in CO₂ of 30 would increase HCO₃⁻ by ~3 mEq/L.
Clinical Acid-Base States

Box 13-2

Systematic Acid-Base Classification

- Inspect the pH (acidemia, alkalemia, or normal).
- Inspect the PaCO₂ (respiratory component). Can it explain the pH?
- Inspect the HCO₃⁻ (metabolic component). Can it explain the pH?
- Check for compensation. Did the noncausative component respond appropriately?

Clinical Acid-Base States (cont.)

Respiratory acidosis (alveolar hypoventilation)

- Any process that raises $\text{PaCO}_2 > 45 \text{ mm Hg}$ and lowers pH below 7.35
  - Increased $\text{PaCO}_2$ produces more carbonic acid.

- Causes
  - Anything that results in a $\dot{V}_A$ that fails to eliminate $\text{CO}_2$ equal to $\dot{V}_{\text{CO}_2}$
Clinical Acid-Base States (cont.)

Box 13-3

Common Causes of Respiratory Acidosis

NORMAL LUNGS

CENTRAL NERVOUS SYSTEM DEPRESSION
Anesthesia
Sedative drugs
Narcotic analgesics

NEUROMUSCULAR DISEASE
Poliomyelitis
Myasthenia gravis
Guillain-Barré syndrome

TRAUMA
Spinal cord
Brain
Chest wall
Severe restrictive disorders
Obesity (Pickwickian syndrome)
Kyphoscoliosis

ABNORMAL LUNGS
Chronic obstructive pulmonary disease
Acute airway obstruction (late phase)
Clinical Acid-Base States (cont.)

Respiratory acidosis (cont.)

- Compensation is by renal reabsorption of $\text{HCO}_3^-$.
  - Partial compensation: pH improved but not normal
  - Full compensation: pH restored to normal

- Correction (goal is to improve $\dot{V}_A$)
  - May include
    - Improved bronchial hygiene and lung expansion
    - Intubation and mechanical ventilation
  - If chronic condition with renal compensation, lowering $\text{PaCO}_2$ may be detrimental for patient.
Clinical Acid-Base States (cont.)

Respiratory alkalosis (alveolar hyperventilation)
- Process that lowers arterial PaCO$_2$ decreases carbonic acid, thus increasing pH.

- Causes (see Box 13-4)
  - Any process that increases $V_A$ so that CO$_2$ is eliminated at a rate higher than $VCO_2$.
  - Most common cause is hypoxemia.
  - Anxiety, fever, pain

- Clinical signs: early paresthesia; if severe, may have hyperactive reflexes, tetanic convulsions, dizziness
Clinical Acid-Base States (cont.)

Respiratory alkalosis (cont.)

- Compensation is by renal excretion of \( \text{HCO}_3^- \).
  - Partial compensation returns pH toward normal.
  - Full compensation returns pH to high normal range.

- Correction
  - Involves removing stimulus for hyperventilation
    - i.e., hypoxemia: give oxygen therapy
Alveolar hyperventilation superimposed on compensated respiratory acidosis (chronic ventilatory failure)

- Typical ABG for chronic ventilatory failure:
  - pH 7.38, PaCO$_2$ 58 mm Hg, HCO$_3^-$ 33 mEq/L
  - Severe hypoxia stimulates increased $V_A$, which lowers PaCO$_2$, potentially raising pH on alkalotic side
    - i.e. pH 7.44, PaCO$_2$ 50 mm Hg, HCO$_3^-$ 33 mEq/L
  - This appears to be compensated metabolic acidosis.
  - Only medical history and knowledge of situation allow correct interpretation of this ABG.
Clinical Acid-Base States (cont.)

Metabolic acidosis

- Low $\text{HCO}_3^-$, with a low pH

Causes

- Increased fixed acid accumulation
  - Lactic acidosis in anaerobic metabolism

- Excessive loss of $\text{HCO}_3^-$
  - Diarrhea

- Anion gap can help identify which of the above is the cause.
Clinical Acid-Base States (cont.)

Increased anion gap metabolic acidosis

- Normal anion gap is 9 to 14 mEq/L.
- As fixed acids increase, they dissociate and the $H^+$ binds with $HCO_3^-$, leaving the unmeasured anion behind.
  - Thus increased anion gap

Normal anion gap metabolic acidosis

- $HCO_3^-$ loss does not cause an increased gap.
  - As $HCO_3^-$ is lost, it is offset by a gain in $Cl^-$.  
  - Also called hyperchloremic acidosis
Clinical Acid-Base States (cont.)

Compensation for metabolic acidosis

- Hyperventilation is the main compensatory mechanism.
  - Acidosis activates CNS receptors, signaling the need to increase $V_E$

- Compensation happens very quickly.
  - Lack of compensation implies a ventilatory defect.

- Symptoms
  - Patients often complain of dyspnea due to hyperpnea.
  - Kussmaul’s respiration seen with ketoacidosis.
  - Neurologic response may range from lethargy to coma.
Clinical Acid-Base States (cont.)

Medical intervention to correct metabolic acidosis

- If pH is >7.2, no correction is required.
  - Hyperventilation usually brings it above this level.

- pH below 7.2 can cause serious cardiac arrhythmias.
  - In severe acidosis, treat with IV NaHCO$_3$.
Clinical Acid-Base States (cont.)

Metabolic alkalosis

- Increased $[\text{HCO}_3^-]$, with an elevated pH

- Causes
  - Due to increased buffer base or loss of fixed acids
  - Loss of fixed acids occurs during vomiting (HCl)
  - Often, it is iatrogenic due to diuretic use or gastric drainage.
Clinical Acid-Base States (cont.)

Metabolic alkalosis

● Compensation
  ➢ Hypoventilation, despite ensuing hypoxemia
  ➢ Metabolic alkalosis blunts hypoxemic stimulation of ventilation.
    • $\text{PaO}_2$ as low as 50 mm Hg with continued compensation

● Correction
  ➢ Restore normal fluid volume, $K^+$, and $Cl^-$ levels
  ➢ In severe alkalosis, may give dilute HCl in central line
Clinical Acid-Base States (cont.)

Metabolic acid-base indicators

- Standard bicarbonate
  - Attempts to eliminate the influence of CO$_2$ on HCO$_3^-$
  - In the blood gas machine the plasma [HCO$_3^-$] is measured after equilibration to PaCO$_2$ 40 mm Hg
  - Flawed process as it cannot mimic in vivo conditions.
Mixed acid-base states

- Primary respiratory and primary metabolic disorders that occur simultaneously
  - i.e., pH 7.62, PaCO$_2$ 32, HCO$_3^-$ 29
  - High pH caused by a low PaCO$_2$ and high HCO$_3^-$
    - so it is a combined alkalosis
  - Compensation is not possible.