Chapter 24
Water, Electrolyte, and Acid-Base Balance

Water, Electrolyte and Acid-base Balance: An Overview

Water and electrolyte balance

- Water balance
  - The amount of water gained each day equals the amount lost
- Electrolyte balance
  - The ion gain each day equals the ion loss
- Acid-base balance
  - H⁺ gain is offset by their loss

On an average day, we will lose ~500 mg of Na⁺ in urine

Water and Electrolyte Balance
**Fluids - Compartments**

- **Intracellular fluid (ICF)**
  - The cytosol of cells
  - Makes up about two-thirds of the total body water

- **Extracellular fluid (ECF)**
  - Major components include the interstitial fluid, plasma and lymph
  - Minor components include all other extracellular fluids

**Fluids – function and constituents**

- Water losses are normally balanced by gains
  - Eating
  - Drinking
  - Metabolic generation

- Fluid functions
  - Transportation
  - Temperature regulation
  - Lubrication
  - Chemical reactions

- Fluid constituents
  - Water
  - Electrolytes

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**Electrolytes**

**Regulation of fluids and electrolytes**

*Cells and tissues do not directly transport water, so fluid balance actually reflects control of ion concentrations*

- Receptors respond to changes in
  - Plasma volume
  - Osmotic concentrations
- All water moves passively in response to osmotic gradients
  - “water follows salt”
Fluid Movement
“water follows salt”

Fluid shifts

- Water movement between ECF and ICF
  - If ECF becomes **hypertonic** relative to ICF, water moves from ICF to ECF
  - If ECF becomes **hypotonic** relative to ICF, water moves from ECF into cells

Regulation of fluids and electrolytes

- Fluid Deficiency
  - **Volume depletion** (hypovolemia): Water and sodium are lost
    - Hemorrhage, severe burns, chronic vomiting, diarrhea, Addison’s disease (aldosterone hyposecretion)
  - **Dehydration**: more water lost than sodium leading to increased ECF osmolarity (hypertonic)
    - Not drinking, diabetes mellitus, diabetes insipidus (ADH hyposecretion), profuse sweating, diuretic overdose
- Fluid Excess
  - **Volume excess**: Water and sodium are retained
    - Aldosterone hypersecretion, renal failure
  - **Hypotonic hydration** (water intoxication, positive water balance, over hydration): more water than sodium is ingested/retained leading to decreased ECF osmolarity (hypotonic)
    - Drinking plain water to replace fluid loss, ADH hypersecretion

Water AND electrolyte concentration

**Relationship between water and electrolytes, specifically sodium**

- Fluid Deficiency - Dehydration
  - Hypernatremia
  - Na⁺ in the ECF is abnormally high
  - Can lead to circulatory shock
- Fluid Excess - Hypotonic Hydration
  - Hyponatremia
  - Na⁺ concentration in the ECF is reduced
  - Improper hydration can be as deadly as dehydration
74 year old man found unconscious

Fluid, Electrolyte, Acid/Base balance

Regulation of fluids and electrolytes

Nervous system and endocrine system work together

• Nervous system
  • Hypothalamus monitors osmolarity
    • Stimulated by increased osmotic pressure
    • Triggers:
      • Increased thirst
      • Secretion of ADH
  • Baroreceptors monitor pressure
    • blood - heart, carotid arteries
    • CSF – ventricles

• Endocrine System – regulatory hormones

Endocrine Regulatory Hormones

• Fluid Deficiency
  1. Antidiuretic Hormone (ADH)
  2. Aldosterone
  3. Renin
  4. Angiotensin II

• Fluid Excess
  1. Atrial Natriuretic Peptide (ANP)
  2. Brain Natriuretic Peptide (BNP)

Regulatory hormones (fluid deficiency)

1. Antidiuretic hormone (ADH)
   • Made: hypothalamus / posterior pituitary gland
   • Released:
     • ↑ blood osmolarity
     • ↓ blood pressure
   • Stimulates:
     • water conservation (reabsorption in collecting duct)
2. Aldosterone
   - Made: adrenal cortex
   - Released:
     • ↓ blood volume
     • ↓ plasma Na+
     • ↑ plasma K+
     • Angiotensin II
   - Stimulates:
     • Na+ absorption and K+ secretion (kidney tubules)
     \[\text{Uses sodium/potassium pumps}\]

3. Renin
   - Made: juxtaglomerular apparatus
   - Released:
     • Decreased renal blood flow
     • Decreased blood pressure
   - Stimulates: release of angiotensin II

4. Angiotensin II
   - Made: inactive plasma protein converted to active form by enzymes in the lungs and liver
   - Released:
     • ↓ plasma volume
     • renin
   - Stimulates:
     • Thirst
     • Increased peripheral vasoconstriction → increases blood pressure
     • Constricts afferent/efferent arterioles → increases/conserves GFR, ensures filtration even with low BP.
     • Release of aldosterone
     • Release of ADH

Regulatory hormones (fluid excess)

- Natriuretic peptides (ANP and BNP)
  - Made: heart and ventricles
  - Released: stretch receptors respond to increased pressure/volume
  - Stimulate:
    • Decrease thirst
    • Block the release of ADH and aldosterone
    • BNP also blocks EP/NE → peripheral vasodilation
Problems with Electrolyte Balance

- Disturbances
  - Hypo = deficiency
  - Hyper = excess
- Usually result from sodium ion imbalances
- Potassium imbalances are less common, but more dangerous
- Sodium and potassium primary players because
  - Major contributors to osmotic concentrations in ECF and ICF
  - Directly affect functioning of all cells
Sodium balance

- Rate of sodium uptake across digestive tract directly proportional to dietary intake
- Sodium losses occur through urine and perspiration
- Shifts in sodium balance result in expansion or contraction of ECF

Sodium Concentration:
The Homeostatic Regulation of Normal Sodium Ion Concentrations in Body Fluids

Fluid Volume:
The Integration of Fluid Volume Regulation and Sodium Ion Concentrations in Body Fluids

Edema and Na+ Imbalance

Sodium concentration changes lead to fluid volume/pressure changes
Potassium balance

Potassium ion concentrations in ECF are low
- Not as closely regulated as sodium
- Potassium ion secretion at kidneys increases as ECF concentrations rise
- Aldosterone secreted
- Potassium retention at kidneys occurs when pH falls
  - Sodium potassium pumps switch to using H\(^+\) ions instead of K\(^+\)
- **Hypokalemia**: muscle weakness and paralysis
- **Hyperkalemia**: cardiac arrhythmia

### ECF Concentrations of other electrolytes

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>Cause</th>
<th>Symptoms</th>
<th>Cause</th>
<th>Symptoms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Calcium</strong> (4.5 – 5.5 mEq/L)</td>
<td>Increased loss through hypoparathyroidism, decreased dietary intake, increased phosphate levels</td>
<td>Numbness and tingling in fingers; hyperactive reflexes, muscle cramps, tetany, and convulsions; bone fractures, spasms of the laryngeal muscles</td>
<td>Hypocalcemia</td>
<td>Lethargy, weakness, anorexia, nausea, vomiting, polyuria, itching, bone pain, depression, confusion, and coma</td>
</tr>
<tr>
<td><strong>Chloride</strong> (95 – 105 mEq/L)</td>
<td>Increased chloride loss through excessive vomiting, aldosterone deficiency or diuretics; excessive water intake; congestive heart failure</td>
<td>Muscle spasm, metabolic alkalosis, shallow respirations, hypotension; nausea, vomiting, diarrhea; dehydration, excessive urination, muscle cramps, tetany, convulsions; muscle weakness, anorexia, nausea, vomiting, hypotension, and coma</td>
<td>Hyperchloremia</td>
<td>Lethargy, weakness, metabolic acidosis, and rapid, deep breathing</td>
</tr>
<tr>
<td><strong>Magnesium</strong> (1.5 – 2.0 mEq/L)</td>
<td>Increased loss in urine or feces; diuretics, alcoholism, malnutrition and diabetes mellitus</td>
<td>Weakness, irritability, tetany, delirium, convulsions, confusion, anorexia, nausea, vomiting, paresthesia, and cardiac arrhythmias</td>
<td>Hypomagnesemia</td>
<td>Hypotension, muscular weakness or paralysis, nausea, vomiting, and altered mental functioning</td>
</tr>
<tr>
<td><strong>Phosphate</strong> (1.8 – 2.6 mEq/L)</td>
<td>Increased loss in urine, decreased intestinal absorption or increased utilization</td>
<td>Confusion, seizures, muscle pain, paresthesia, and tingling of the fingers; uncoordination, memory loss, and lethargy</td>
<td>Hypophosphatemia</td>
<td>Anorexia, nausea, vomiting, muscular weakness, hyperactive reflexes, tetany, and tachycardia</td>
</tr>
</tbody>
</table>

### Acid-base Balance

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>pH</strong></td>
<td>The negative exponent (negative logarithm) of the hydrogen ion concentration</td>
</tr>
<tr>
<td><strong>Neutral</strong></td>
<td>A solution with a pH of 7; the solution contains equal numbers of hydrogen ions and hydroxide ions</td>
</tr>
<tr>
<td><strong>Acidic</strong></td>
<td>A solution with a pH below 7; in this solution, hydrogen ions predominate</td>
</tr>
<tr>
<td><strong>Basic, or alkaline</strong></td>
<td>A solution with a pH above 7; in this solution, hydroxide ions predominate</td>
</tr>
<tr>
<td><strong>Acid</strong></td>
<td>A substance that dissociates to release hydrogen ions, decreasing pH</td>
</tr>
<tr>
<td><strong>Base</strong></td>
<td>A substance that dissociates to release hydroxide ions or to tie up hydrogen ions, increasing pH</td>
</tr>
<tr>
<td><strong>Salt</strong></td>
<td>An ionic compound consisting of a cation other than hydrogen and an anion other than a hydroxide ion</td>
</tr>
<tr>
<td><strong>Buffer</strong></td>
<td>A substance that tends to oppose changes in the pH of a solution by removing or replacing hydrogen ions; in body fluids, buffers maintain pH within normal limits (7.35–7.45)</td>
</tr>
</tbody>
</table>
• Carbonic acid is most important factor affecting pH of ECF
  – CO₂ reacts with water to form carbonic acid
  – Inverse relationship between pH and concentration of CO₂
• Sulfuric acid and phosphoric acid
  – Generated during catabolism of amino acids
• Organic acids
  – Metabolic byproducts such as lactic acid, ketone bodies

The pH of the ECF remains between 7.35 and 7.45
• Alteration outside these boundaries affects all body systems
  • If plasma levels fall below 7.35 (acidemia), acidosis results
    – CNS shut down: coma, heart failure, peripheral vasodilation (decreased blood pressure), coma
  • If plasma levels rise above 7.45 (alkalemia), alkalosis results
    – Random firing of CNS: spasms, convulsions, coma
Mechanisms of pH control

- Buffers
- Ion exchange with cells
- Compensation
  - modify renal or respiratory function

Mechanisms of pH control - Buffers

- Buffers
  - Bicarbonate
    - intracellular
    - extracellular
  - Phosphate
    - intracellular
  - Proteins
    - intracellular – more
    - some extracellular (plasma proteins)
  - Hemoglobin
    - intracellular

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

\[
\text{PO}_4^{3-} + \text{H}^+ \rightleftharpoons \text{HPO}_4^{2-} + \text{H}^+ \rightleftharpoons \text{H}_2\text{PO}_4^- \\
\]
**Mechanisms of pH control – ion exchanges**

Ion Exchanges: work with intracellular buffering systems to maintain plasma pH

1. **Chloride shift**
   - hemoglobin buffer system
   - $\text{H}^+$ are buffered by hemoglobin
   - $\text{Cl}^-$ swapped for $\text{HCO}_3^-$

2. **Potassium ion exchange**
   - Proteins
   - Phosphate buffer system
     - $\text{H}_2\text{PO}_4^-$ $\leftrightarrow$ $\text{H}^+$ + $\text{HPO}_4^{2-}$
     - $\text{K}^+$ swapped for $\text{H}^+$

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**Maintenance of acid-base balance**

**Compensation:** change system function in response to pH

- Respiratory Compensation
  - Lungs help regulate pH through carbonic acid - bicarbonate buffer system
  - Changing respiratory rates changes $P_{\text{CO}_2}$
  - Acute and chronic
    - Acute ex: lactic acidosis (seizure), alcoholic ketoacidosis
- Renal compensation
  - Kidneys help regulate pH by adjusting secretion and reabsorption of $\text{H}^+$ and bicarbonate
  - Chronic (day or longer)
    - Chronic ex: emphysema
Fluid, Electrolyte, Acid/Base balance

**Respiratory Compensation**

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

- Acidic = too much H⁺
  - Increase respiratory rate
- Basic = too little H⁺
  - Decrease respiratory rate

**Renal Compensation**

**Renal compensation continued**

**Disturbances of Acid-base Balance**
Acid-base balance maintained by

Maintain tight control within range 7.35 – 7.45

- Buffer systems
- Ion exchange
- Compensation
  - Respiration
  - Renal function

Acid-Base Disorders

- Respiratory acid base disorders
  - Result when abnormal respiratory function causes rise or fall in CO₂ in ECF
- Metabolic acid-base disorders
  - Generation of acids
    - lactic acid (anaerobic respiration), ketone bodies (beta oxidation), phosphoric acid (nucleic acid catabolism), fatty acids (lipid catabolism), ...
  - Anything affecting concentration of bicarbonate ions in ECF

Respiratory acidosis

- Results from excessive levels of CO₂ in body fluids
  - Hypoventilation
    - Ex: emphysema, asthma, CNS damage, pneumothorax
  - Cellular ion exchange → increased plasma potassium
  - Renal compensation → increase in plasma bicarbonate

Which conditions are acute and which are chronic?
Fluid, Electrolyte, Acid/Base balance

**Respiratory alkalosis**

- Relatively rare condition
- Associated with hyperventilation
  - Ex: fever, panic attacks, anemia, CNS damage

*Renal compensation → decrease in plasma bicarbonate*

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**Metabolic acidosis**

- Major causes are:
  - Increased production of acids
    - Lactic acid, ketone bodies
  - Ingestion of acidic drugs
    - Aspirin, penicillin, phenobarbital, vit C
  - Bicarbonate loss due to chronic diarrhea or overuse of laxatives
  - Inability to excrete hydrogen ions at kidneys
    - Organ failure, glomerulonephritis, diuretics

*Cellular ion exchange → increased plasma potassium*

*Respiratory compensation → decreased plasma CO2 (decreased bicarbonate)*

*Renal compensation → increased plasma bicarbonate*

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**Anion Gap: distinguish type of metabolic acidosis**

\[
[\text{Na}] + [\text{other cations}] = [\text{Cl}] + [\text{HCO}_3] + [\text{other anions}]
\]

\[
[\text{Na}] - ([\text{Cl}] + [\text{HCO}_3]) = [\text{other anions}] - [\text{other cations}]
\]

= anion gap

= 8-16 mEq/L plasma

- **Increased anion gap** → increased unmeasured anions
  - Most commonly due to **increased acids**
    - Lactic acid, ketoacids, phosphate, sulfate, salicylates, uremia
  - **Normal or decreased anion gap** → decreased unmeasured anions
    - Due to **loss of bases** (bicarbonate), very rare
    - Most commonly diarrhea

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**Metabolic alkalosis**

- Occurs when HCO₃⁻ concentrations become elevated
  - Caused by repeated vomiting

*Respiratory compensation → increased plasma CO2*

*Renal compensation → decreased plasma bicarbonate*
FLUID, ELECTROLYTE AND ACID-BASE DISTURBANCES

High Risk:
• Infants
• Elderly

Homeostasis in Infants
• More body water in ECF
• Rate of fluid intake/output is 7X higher
• Higher metabolic rate
• Produces more metabolic wastes
• Kidneys cannot
  • Concentrate urine
  • Remove excess H³
• Greater water loss
  • Skin (↑ surface area / volume)
  • Lungs (↑ RR)
• Higher K³ and Cl⁻ concentrations

Impaired Homeostasis in the Elderly
• Decreased volume of intracellular fluid
• Decreased total body K³
• Decreased respiratory and renal function
  • Slowing of exhaled CO₂
  • Decreased blood flow and GFR
  • Reduced sensitivity to ADH
• Impaired ability to produce dilute urine

“Reach high, for stars lie hidden in your soul. Dream deep, for every dream precedes the goal.”

Clinical Diagnosis
Clinical Diagnosis

1. Test pH
   - Normal → look at electrolyte imbalance
     - See electrolyte table
   - Abnormal → look at acid base imbalance
     - see next slide
   1. pH
   2. pCO2
   3. Bicarb
   4. Anion gap

Case Studies

Disturbances in Electrolyte Levels

Fluid, Electrolyte, Acid/Base balance
**Case Study #1**

Connie C. was brought to the emergency room by ambulance. She was found unconscious by ski patrol on a triple black diamond run at a local resort. Her only personal possessions were a medical alert bracelet and a small kit containing a glucometer, insulin, and syringe. Attending nurses note a "fruity" smell to her breath. She is slightly obese and her respiratory rate is about 28 breaths/min. A blood and urine analysis was performed and some of the results are listed below:

**Normal Lab Values**

<table>
<thead>
<tr>
<th>Blood Values</th>
<th>Urine Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>pO₂</td>
<td>pH</td>
</tr>
<tr>
<td>104 mmHg</td>
<td>7.45</td>
</tr>
<tr>
<td>pCO₂</td>
<td>Protein</td>
</tr>
<tr>
<td>30 mmHg</td>
<td>&lt; 100 mg/dl</td>
</tr>
<tr>
<td>pH</td>
<td>Protein</td>
</tr>
<tr>
<td>7.25</td>
<td>&lt; 100 mg/dl</td>
</tr>
<tr>
<td>sodium</td>
<td>Protein</td>
</tr>
<tr>
<td>140 mmHg</td>
<td>&lt; 100 mg/dl</td>
</tr>
<tr>
<td>blood glucose</td>
<td>Protein</td>
</tr>
<tr>
<td>35 mg/dl</td>
<td>&lt; 100 mg/dl</td>
</tr>
</tbody>
</table>

**Case Study #1**

**Case Study #2**

Andy R. was rushed to the emergency room after having collapsed in the final "leg" of a marathon, in Los Angeles in August. He is a relatively lean runner who has only been dealing with his chronic respiratory problem this summer. He has been treated for asthma since the age of 11 and has struggled to remain active during the summer months. He has also been treated for type 2 diabetes, which is under control with metformin. He has made several changes to his diet and exercise routine in an attempt to maintain reasonable weight, but he was unable to do so this summer. He has been placed on a urinary catheter and nurses were only able to collect about 20 ml of blood after being placed on a urinary catheter. He informed nurses that he had not urinated in about 5 hours.

**Case Study #3**

Weakness in the legs, abdominal cramping, and an irregular heartbeat. His blood pressure was 150/90 mmHg. He informed nurses that he had not urinated in about 5 hours and after being placed on a urinary catheter nurses were only able to collect about 20 ml of blood. He was rushed to the emergency room after having collapsed in the final "leg" of a marathon, in Los Angeles in August. He is a relatively lean runner who has only been dealing with his chronic respiratory problem this summer. He has been treated for asthma since the age of 11 and has struggled to remain active during the summer months. He has also been treated for type 2 diabetes, which is under control with metformin. He has made several changes to his diet and exercise routine in an attempt to maintain reasonable weight, but he was unable to do so this summer. He has been placed on a urinary catheter and nurses were only able to collect about 20 ml of blood after being placed on a urinary catheter.

For each of the case studies listed above, answer the following questions:

1. List the abnormal symptoms or conditions the patient is exhibiting.
2. List any abnormal lab values the patient has.
3. Explain the cause or each abnormal symptom or condition.
4. Explain the cause of each abnormal lab value.
5. Is the listed abnormal laboratory value or symptom a compensatory or metabolic change?
6. Is it a fluid or electrolyte imbalance? If yes, the type and whether or not compensation is occurring.
7. List the probable etiology (overall cause) behind the person's condition.
8. Identify any abnormal symptoms or conditions the patient is exhibiting.
9. Identify any abnormal lab values the patient has.
10. List the probable etiology (overall cause) behind the person's condition.

**CASE STUDIES**

For each of the case studies listed answer the following questions:

1. Identify any abnormal symptoms or conditions the patient is exhibiting.
2. Identify any abnormal lab values the patient has.
3. Explain the cause of each abnormal symptom or condition.
4. Explain the cause of each abnormal lab value.
5. Is it a fluid or electrolyte imbalance? If yes, the type and whether or not compensation is occurring.
6. Is it a fluid or electrolyte imbalance? If yes, specify whether it is a fluid or electrolyte imbalance and specify which electrolyte is causing the problem.
7. Identify any abnormal symptoms or conditions the patient is exhibiting.
8. Identify any abnormal lab values the patient has.
9. List the probable etiology (overall cause) behind the person's condition.
10. List the abnormal symptoms or conditions the patient is exhibiting.

**CASE STUDIES**

**Case Study #1**

Connie C. was brought to the emergency room by ambulance. She was found unconscious by ski patrol on a triple black diamond run at a local resort. Her only personal possessions were a medical alert bracelet and a small kit containing a glucometer, insulin, and syringe. Attending nurses note a "fruity" smell to her breath. She is slightly obese and her respiratory rate is about 28 breaths/min. A blood and urine analysis was performed and some of the results are listed below:

**Systemic Arterial Blood**

- pO₂: 104 mmHg
- pH: 7.45
- pCO₂: 30 mmHg
- sodium: 140 mEq/l
- bicarbonate: 20 mEq/l
- blood glucose: 35 mg/dl

**Urine**

- protein: trace
- protein: none
- potassium: 6.0 mEq/l
- glucose: none
- ketones: high
- blood glucose: 25 mg/dl
<table>
<thead>
<tr>
<th>1. List the abnormal symptoms or conditions</th>
<th>2. List any abnormal lab values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Explain the cause of each abnormal lab value</td>
<td>4. Explain the cause of each abnormal symptom</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 5. Is this an acid base disorder

- Yes or No
- List what type of acid base disorder
  - Metabolic
  - Respiratory
- Is compensation occurring?
  - Yes or no
  - Respiratory compensation?
  - Renal compensation?
- Is this acute or chronic?

### 6. Is this a fluid-electrolyte imbalance

- Yes or No
- What specific electrolyte is causing the problem?

### 7. List the etiology