Fluids, Electrolytes
and Acid-Base Balance

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Objectives

- Define normal ranges of electrolytes
- Compare/contrast intracellular, extracellular, and intravascular volumes
- Outline methods of determining fluid and acid/base balance
- Describe the clinical manifestations of various electrolyte imbalances.
Normal Plasma Ranges of Electrolytes

- **Cations**
  - Sodium
  - Potassium
  - Calcium
  - Magnesium

- **Anions**
  - Chloride
  - Bicarbonate
  - Phosphate
  - Sulfate
  - Organic Acids (Lactate)
  - Total Protein

- **Concentration**
  - Sodium: 135-145 mEq/L
  - Potassium: 3.5-5.0 mEq/L
  - Calcium: 8.0-10.5 mEq/L
  - Magnesium: 1.5-2.5 mEq/L
  - Chloride: 95-105 mEq/L
  - Bicarbonate: 24-30 mEq/L
  - Phosphate: 2.5-4.5 mEq/L
  - Sulfate: 1.0 mEq/L
  - Organic Acids (Lactate): 2.0 mEq/L
  - Total Protein: 6.0-8.4 mEq/L
Normal Ranges of Electrolytes

- **Sodium (Na⁺)**
  - Range 135 - 145 mEq/L in serum
  - Total body volume estimated at 40 mEq/kg
  - 1/3 fixed to bone, 2/3 extracellular and available for trans-membrane exchange
  - Normal daily requirement 1-2 mEq/kg/day
  - Chief extracellular cation
Normal Ranges of Electrolytes

- **Potassium (K⁺)**
  - Range 3.5 - 5.0 mEq/L in serum
  - Total body volume estimated at 50 mEq/kg
  - 98% intracellular
    - Concentration of 150 mEq/L
    - Extracellular concentration of 70 mEq/L
  - Normal daily requirement 0.5 – 0.8 mEq/kg/day
  - Chief intracellular cation
Normal Ranges of Electrolytes

- **Intracellular v Extracellular**
  - Electrolyte composition is different
    - Intracellular: $K^+$, $Mg^+$, $PO_4^-$, $SO_4^-$, and proteins
    - Extracellular: $Na^+$, $Ca^+$, $Mg^+$, $Cl^-$, $HCO_3^-$ and lactate
  - Compositions of ions are maintained
    - selective permeability of cell membranes
    - active ion pumps
  - Movement of water is passive
    - colloid osmotic gradients intravascular v interstitial spaces (extracellularly)
    - osmolar gradients intracellularly v extracellularly
Fluid Balance

- **Calculation of Osmolarity**
  - \( \text{Osm} = 2 \times [\text{Na}_s] + [\text{glu} / 18] + [\text{BUN} / 2.8] \)
  - Normal osmolarity is 280-300 mOsm/L

- **Na\(^+\) resorption and excretion are the driving forces for osmolarity**

- **Calculating TBW deficit**
  - \( \text{TBWD males} = [(140 – S\text{Na}^+) \times 0.6 \times \text{IBW (kg)}]/140 \)
  - \( \text{TBWD females} = [(140 – S\text{Na}^+) \times 0.5 \times \text{IBW (kg)}]/140 \)
Fluid Balance

- Here’s a trick
  - For every 3.5 mEq the Na$^+$ is over 140, there is an estimated free water deficit of 1 L.
Normal Physiology

- **Total body water**
  - 60% IBW of males
  - 50-55% IBW of females
    - directly related to muscle mass (70% water)
    - inversely related to fat content (10% water)
    - This is why witches float

- **Compartments**
  - Intracellular
  - Extracellular
  - Interstitial
Body Fluid Compartments

- 2/3 (65%) of TBW is intracellular (ICF)
- 1/3 extracellular water
  - 25 % interstitial fluid (ISF)
  - 5- 8 % in plasma (IVF intravascular fluid)
  - 1- 2 % in transcellular fluids – CSF, intraocular fluids, serous membranes, and in GI, respiratory and urinary tracts (third space)
Normal Physiology

- Intravascular water: 8%
- Interstitial water: 25%
- Intracellular water: 67%
Normal Physiology

- Two main compartments

  - Intracellular
    - 2/3 of TBW
    - 40% body weight
  - Extracellular
    - Intravascular and Interstitial compartments
      - 1/3 of TBW
      - 20% body weight
Total body water

Intracellular fluid (63%)

Membranes of body cells

Interstitial fluid
Plasma
Lymph
Transcellular fluid
Extracellular fluid (37%)
Fluid compartments are separated by membranes that are freely permeable to water.

Movement of fluids due to:

- hydrostatic pressure
- osmotic pressure

- Capillary filtration (hydrostatic) pressure
- Capillary colloid osmotic pressure
- Interstitial hydrostatic pressure
- Tissue colloid osmotic pressure
Cell in Isotonic Solution
Cell in a hypertonic solution
Cell in a hypotonic solution
Balance

- Fluid and electrolyte homeostasis is maintained in the body
  - Neutral balance: input = output
  - Positive balance: input > output
  - Negative balance: input < output
Solutes – dissolved particles

- **Electrolytes – charged particles**
  - **Cations** – positively charged ions
    - Na\(^+\), K\(^+\), Ca\(^{++}\), H\(^+\)
  - **Anions** – negatively charged ions
    - Cl\(^-\), HCO\(_3^-\), PO\(_4^{3-}\)

- **Non-electrolytes - Uncharged**
  - Proteins, urea, glucose, O\(_2\), CO\(_2\)
Body fluids are:

- Electrically neutral
- Osmotically maintained

Specific number of particles per volume of fluid
Homeostasis maintained by:

- Ion transport
- Water movement
- Kidney function
Basic Definitions

MW (Molecular Weight) = sum of the weights of atoms in a molecule

mEq (milliequivalents) = MW (in mg)/ valence

mOsm (milliosmoles) = number of particles in a solution
Movement of body fluids
“Where sodium goes, water follows.”

Diffusion – movement of particles down a concentration gradient.

Osmosis – diffusion of water across a selectively permeable membrane

Active transport – movement of particles up a concentration gradient; requires energy
The diagram illustrates the forces involved in the flow of blood through a capillary. At the arteriolar end:

- Outward force, including hydrostatic pressure: 41.3 mm Hg
- Inward force of osmotic pressure: 28 mm Hg
- Net outward pressure: 13.3 mm Hg

At the venular end:

- Outward force, including hydrostatic pressure: 21.3 mm Hg
- Inward force of osmotic pressure: 28 mm Hg
- Net inward pressure: 6.7 mm Hg
Normal Physiology

- **Na\(^+\) resorption secondary to aldosterone**
  - Occurs in distal convoluted tubules
  - Active exchange for K\(^+\) and H\(^+\) ions
  - Maintains extracellular volume and osmolarity

- **Water resorption secondary to antidiuretic hormone**
  - Occurs in collecting ducts
  - Modulated by intracranial osmoreceptors and atrial stretch receptors
Normal Physiology

Na\(^+\) modulation

- Renal perfusion decreases
- JG apparatus secretes renin
- Renin cleaves angiotensinogen to angiotensin I
- Angiotensin I converted to II by ACE
- Angiotensin II stimulates aldosterone secretion from adrenal cortex
- Extracellular volume expansion as water follows Na\(^+\)
- Renin secretion ceases
- Renal perfusion increases
- Aldosterone increases Na\(^+\) resorption in exchange for K\(^+\) in DCT
Normal Physiology

Na+ modulation

Result:

increased water consumption
increased water conservation
Increased water in body
increased volume and
decreased Na+ concentration
Dysfunction and/or Trauma

Leads to:

- Decreased amount of water in body
- Increased amount of Na$^+$ in the body
- Increased blood osmolality
- Decreased circulating blood volume
Regulation of body water

- ADH – antidiuretic hormone + thirst
  - Decreased amount of water in body
  - Increased amount of Na+ in the body
  - Increased blood osmolality
  - Decreased circulating blood volume

- Stimulate osmoreceptors in hypothalamus
  - ADH released from posterior pituitary
  - Increased thirst
Normal Physiology

Free H₂O modulation

Intracranial osmoreceptors detect increased plasma osmolarity

Plasma osmolarity increases

Adenohypophysis (posterior pituitary) secretes ADH

Renal collecting ducts become more permeable to water

Adenohypophysis ceases ADH secretion

Plasma osmolarity decreases

Renal collecting ducts become less permeable to water

Intracranial osmoreceptors detect decreased osmolarity
Acid/Base Balance

- The management of Hydrogen ions
  - measured as pH
  - maintained at 7.4 +/- 0.05
- Three mechanisms (differing effective intervals)
  - buffering systems in plasma
  - ventilatory changes for CO₂ excretion
  - Renal tubular excretion of Hydrogen ions
Acid/Base Balance

- Henderson-Hasselbalch
- Remember
  - $\text{H}_2\text{O} + \text{CO}_2 = \text{H}_2\text{CO}_3 = \text{HCO}_3^- + \text{H}^+$

$$\text{pH} = 6.1 + \log[\text{HCO}_3^-]/0.03 \times \text{PaCO}_2$$

or

$$[\text{H}^+] = 24 \times \text{PaCO}_2/ [\text{HCO}_3^-]$$
Acid/Base Balance

Extracellular Regulation

Pulmonary regulation of PaCO$_2$ and renal tubular regulation of HCO$_3^-$ are important determinants of extracellular pH.

Basically, the pH is determined by the ratio of $[\text{HCO}_3^-]/[\text{H}_2\text{CO}_3]$.

- Normally 20:1 (7.40)
- As one increases, the other increases to re-establish the 20:1 ratio
Acid/Base Balance
Intracellular Regulation

- **Intracellular buffering**
  - Excessive CO$_2$ retention or excretion
    - 50% of fixed acid loads (lactate)
    - 95% of hydrogen ion changes
  - Reciprocal K$^+$ ion exchange
    - Alkalosis
      - H$^+$ moves extracellularly
      - K$^+$ moves intracellularly
    - Acidosis
      - H$^+$ moves intracellularly
      - K$^+$ moves extracellularly
- This can have significant clinical effect, especially regarding myocardial function
Fluids and Electolytes in the Postoperative Period

- Maintenance
- Resuscitation
- Replacement of Losses
Fluids and Electrolytes in the Postoperative Period

- **Maintenance**
  - Normal daily outputs
    - Urine = 12-15 cc/kg
    - Stool = 3 cc/kg
    - Sweat = 1.5 cc/kg
    - Respiratory and Skin insensible losses = 10 cc/kg
      - Increased by 8%/degree F for fever
  - Normal daily endogenous input
    - Oxidation of carbohydrates and fat = 3 cc/kg
  - Standard nomograms estimate daily requirements
Average daily intake of water

Total intake (2,500 mL)
- Water in beverages (1,500 mL or 60%)
- Water in moist food (750 mL or 30%)
- Water of metabolism (250 mL or 10%)

Average daily output of water

Total output (2,500 mL)
- Water lost in urine (1,500 mL or 60%)
- Water lost through skin and lungs (700 mL or 28%)
- Water lost in feces (150 mL or 6%)
- Water lost in sweat (150 mL or 6%)
Fluids and Electrolytes in the Postoperative Period

- **Third Space Fluid Losses**
  - Fluids sequestered into extracellular and intersitial spaces
    - Peritonitis
    - Intestinal obstruction
    - Soft tissue inflammation/edema
    - Traumatic losses

- **Evidence of diminished volume**
  - Hemodynamic changes
    - Tachycardia
    - Narrowed pulse pressures
    - Hypotension
Edema

The accumulation of fluid within the interstitial spaces.

Leads to:
- increased hydrostatic pressure
- lowered plasma osmotic pressure
- increased capillary membrane permeability
- lymphatic channel obstruction
Hydrostatic pressure increases

Venous obstruction:
  thrombophlebitis (inflammation of veins)
  hepatic obstruction
  tight clothing on extremities
  prolonged standing

Salt or water retention
  congestive heart failure
  renal failure
Decreased plasma osmotic pressure

↓ plasma albumin (liver disease or protein malnutrition)

plasma proteins lost in:

glomerular diseases of kidney

hemorrhage, burns, open wounds and cirrhosis of liver
Increased capillary permeability:

Inflammation

immune responses

Lymphatic channels blocked:

surgical removal
infection involving lymphatics
lymphedema
Electrolyte imbalances: Sodium

- Hypernatremia (high levels of sodium)
  - Plasma Na+ > 145 mEq / L
  - Due to ↑ Na+ or ↓ water
  - Water moves from ICF → ECF
  - Cells dehydrate
Cell membrane

1. Water loss from extracellular fluid compartment

2. Solute concentration increases in extracellular fluid compartment

Nucleus

3. Water leaves intracellular fluid compartment by osmosis
Hypernatremia

- **Causes**
  - Hypertonic IV soln.
  - Oversecretion of aldosterone
  - Loss of pure water
    - Long term sweating with chronic fever
    - Respiratory infection → water vapor loss
    - Diabetes – polyuria
  - Insufficient intake of water (hypodipsia)
Clinical manifestations of Hypernatremia

- Thirst
- Lethargy
- Neurological dysfunction due to dehydration of brain cells
- Decreased vascular volume
Treatment of Hypernatremia

- Lower serum Na+
  - Isotonic salt-free IV fluid
  - Oral solutions preferable
Hyponatremia

- Overall decrease in Na+ in ECF
- Two types: depletional and dilutional

Depletional Hyponatremia

**Na+ loss:**
- diuretics, chronic vomiting
- Chronic diarrhea
- Decreased aldosterone
- Decreased Na+ intake
Dilutional Hyponatremia:

- Renal dysfunction with ↑ intake of hypotonic fluids
- Excessive sweating → increased thirst → intake of excessive amounts of pure water
- Syndrome of Inappropriate ADH (SIADH) or oliguric renal failure, severe congestive heart failure, cirrhosis all lead to:
  - Impaired renal excretion of water
- Hyperglycemia – attracts water
Clinical manifestations of Hyponatremia

- **Neurological symptoms**
  - Lethargy, headache, confusion, apprehension, depressed reflexes, seizures and coma

- **Muscle symptoms**
  - Cramps, weakness, fatigue

- **Gastrointestinal symptoms**
  - Nausea, vomiting, abdominal cramps, and diarrhea

- **Tx** – limit water intake or discontinue meds
Hypokalemia

- Serum $K^+ < 3.5$ mEq /L
- Beware if diabetic
  - Insulin gets $K^+$ into cell
  - Ketoacidosis – $H^+$ replaces $K^+$, which is lost in urine
- $\beta$ – adrenergic drugs or epinephrine
Causes of Hypokalemia

- Decreased intake of $K^+$
- Increased $K^+$ loss
  - Chronic diuretics
  - Acid/base imbalance
  - Trauma and stress
  - Increased aldosterone
  - Redistribution between ICF and ECF
Clinical manifestations of Hypokalemia

- Neuromuscular disorders
  - Weakness, flaccid paralysis, respiratory arrest, constipation
- Dysrhythmias, appearance of U wave
- Postural hypotension
- Cardiac arrest
- Others – table 6-5

Treatment-
- Increase K$^+$ intake, but slowly, preferably by foods
Hyperkalemia

- Serum K+ > 5.5 mEq / L
- Check for renal disease
- Massive cellular trauma
- Insulin deficiency
- Addison’s disease
- Potassium sparing diuretics
- Decreased blood pH
- Exercise causes K+ to move out of cells
Clinical manifestations of Hyperkalemia

- **Early** – hyperactive muscles, paresthesia
- **Late** - Muscle weakness, flaccid paralysis
- Change in ECG pattern
- Dysrhythmias
- Bradycardia, heart block, cardiac arrest
Treatment of Hyperkalemia

- If time, decrease intake and increase renal excretion
- Insulin + glucose
- Bicarbonate
- Ca^{++} counters effect on heart
Calcium Imbalances

- Most in ECF
- Regulated by:
  - Parathyroid hormone
    - ↑Blood $\text{Ca}^{++}$ by stimulating osteoclasts
    - ↑GI absorption and renal retention
  - Calcitonin from the thyroid gland
    - Promotes bone formation
    - ↑renal excretion
Hypercalcemia

Results from:

- Hyperparathyroidism
- Hypothyroid states
- Renal disease
- Excessive intake of vitamin D
- Milk-alkali syndrome
- Certain drugs
- Malignant tumors – hypercalcemia of malignancy
  - Tumor products promote bone breakdown
  - Tumor growth in bone causing Ca^{++} release
Hypercalcemia

- Usually also see hypophosphatemia

- Effects:
  - Many nonspecific – fatigue, weakness, lethargy
  - Increases formation of kidney stones and pancreatic stones
  - Muscle cramps
  - Bradycardia, cardiac arrest
  - Pain
  - GI activity also common
    - Nausea, abdominal cramps
    - Diarrhea / constipation
  - Metastatic calcification
Hypocalcemia

- Hyperactive neuromuscular reflexes and tetany differentiate it from hypercalcemia
- Convulsions in severe cases
- Caused by:
  - Renal failure
  - Lack of vitamin D
  - Suppression of parathyroid function
  - Hypersecretion of calcitonin
  - Malabsorption states
  - Abnormal intestinal acidity and acid/base balance
  - Widespread infection or peritoneal inflammation
Hypocalcemia

- **Diagnosis:**
  - Chvostek’s sign
  - Trousseau’s sign

- **Treatment**
  - IV calcium for acute
  - Oral calcium and vitamin D for chronic