Chapter 19 The Urinary System Fluid and Electrolyte Balance

Chapter Outline
- The Concept of Balance
- Water Balance
- Sodium Balance
- Potassium Balance
- Calcium Balance
- Interactions between Fluid and Electrolyte Regulation
- Acid-Base Balance

19.1 The Concept of Balance
- To maintain homeostasis, what comes in the body must eventually be used or excreted
- To be in balance: Input + Production = Utilization + Output

Factors Affecting the Plasma Composition
- Kidneys regulate solute and water content, which also determines volume
  - Composition also affected by exchange between different compartments of body such as cell, connective tissue, gastrointestinal tract; and through sweating and respiration

Exchanges Affecting Plasma Content (Figure 19.1)
Solute and Water Balance (Figure 19.2)
- Balance: Input = output
- Positive balance: input > output
- Negative balance: input < output

19.2. Water Balance
- Water intake + metabolically produced = water output + water used

Functions of water
- An important solvent that allows nutrients to be dissolved and transported
- Maintain pressure.
- Stabilize body temperature.

Factors Affecting Water Balance (Figure 19.3)
- Normovolemia = normal blood volume
- Hypervolemia = high blood volume due to positive water balance
- Hypovolemia = low blood volume due to negative water balance

Osmolarity and Water Movement
- Water diffuses down concentration gradient from low osmolarity (high [water]) to high osmolarity
- Osmolarity of body fluids = 300 mOsm
- Kidneys compensate for changes in osmolarity of extracellular fluid by regulating water reabsorption

Water Reabsorption in Renal Tubules (Figure 19.5)
- Water is reabsorbed passively by osmosis. Based on osmotic gradients established by counter-current multiplier
- 70% water reabsorbed in proximal tubule: Not regulated
- 20% reabsorbed in distal tubule: Regulated by antidiuretic hormone (ADH, also called vasopressin)
- 10% reabsorbed in collecting ducts: Regulated by ADH

Medullary Osmotic Gradient for Water Reabsorption
• Osmolarity of interstitial fluid of renal medulla varies with depth
  o Lower osmolarity near cortex
  o Greater osmolarity near renal pelvis
• Osmotic gradient established by counter-current multiplier
• Dependent on loop of Henle

The Medullary Osmotic Gradient (Figure 19.6)

Result of Counter-Current Multiplier (Figure 19.7)
• Fluid in proximal tubule and cortical interstitial fluid = 300 mOsm
• Fluid in descending limb—osmolarity increases as it descends
• Fluid in ascending limb—osmolarity decreases as it ascends
• Osmolarity in medullary interstitial fluid increases from cortex 300 mOsm to renal pelvis (1000 mOsm)
• Fluid in distal tubule = 100 mOsm

Urea helps to maintain the medullary osmotic gradient (19.8)
• 40% urea remains in renal tubules to retain water.
• Urea contributes to 40% medullary osmotic gradients when they are transported to from filtrate to medullary peritubular fluid

Vasa Recta: Countercurrent Exchanger (Figure 19.9)
• Vasa recta prevent the dissipating the medullary osmotic gradient by losing water and gaining solute on their way into medulla and gaining water, losing solutes on the way out of medulla.

Water Reabsorption in Distal Tubules and Collecting Ducts (Figure 19.10)
• Dependent on osmotic gradient established by counter-current multiplier
• Dependent on epithelium permeability to water
  o Aquaporin-3: present in basolateral membrane always
  o Aquaporin-2: present in apical membrane only when ADH present in blood

Obligatory Water Loss is the minimum volume of water that must be excreted in the urine per day
• Max osmolarity urine = 1400 mOsm
• Obligated water loss (440 mL) is necessary to eliminate non-reabsorbed solutes

Regulated Water Reabsorption (Figure 19.11)
• When membrane of late distal tubule and the collecting ducts is impermeable to water, more water is excreted in urine.
• ADH stimulates the water reabsorption by
  • Stimulating the synthesis and the insertion of water channels (aquaporin-2) into apical membrane
  • Increasing the permeability of the collecting duct to urea, therefore increasing the gradient for water reabsorption

Regulation of ADH Secretion
• ADH secretion is stimulated by the
  o Increased osmolarity of ECF (Figure 19.12)
  o Decreased blood volume and BP (Figure 19.13)

GFR and Water Excretion
• GFR is normally autoregulated
  o Decreases in blood pressure to less than 80 mm Hg → ↓GFR → ↓ water filtered → ↓ water excretion
  o Increases in blood pressure (>180 mmHg) is opposite to what happens in decreased blood pressure

19.3. Sodium Balance
• Sodium is the primary solute in ECF. It is critical for normal osmotic pressure and function of
excitable cells

- Hypernatremia = high plasma sodium
- Hyponatremia = low plasma sodium

**Renal Handling of Sodium**

- Freely filtered
- Reabsorbed in proximal tubule (70%), distal tubule, and collecting duct
  - Active reabsorption
  - Na⁺/K⁺ pump on basolateral membrane drives reabsorption
- No secretion

**Mechanism of Sodium Transport**

- Overall sodium is actively reabsorbed at all renal segments.
  - Na⁺/K⁺ pump on basolateral membrane drives reabsorption
  - Passively transport across the apical membrane
- Sodium reabsorption in the proximal tubule is coupled to the reabsorption of other solutes
- Sodium reabsorption in the distal tubule is coupled to the secretion of K⁺ and H⁺

**Regulation of Sodium Reabsorption**

- By aldosterone and atrial natriuretic peptide (ANP)
- At principal cells of distal tubule and collecting duct

**Effects of Aldosterone on Sodium Reabsorption**

- Aldosterone is a steroid hormone released from adrenal cortex. It increases ____ reabsorption and ____ secretion
- Aldosterone acts on principal cells of distal tubules and collecting ducts
  - Increases number of Na⁺/K⁺ pumps on basolateral membrane
  - Increases number of open Na⁺ and K⁺ channels on apical membrane

**Renin-Angiotensin-Aldosterone System (Figure 19.16)**

- Angiotensinogen is released by the ______. It is converted to angiotensin I by _____.
- Renin is released by the juxtaglomerular cells in the ______.
- Angiotensin I is converted to angiotensin II by this enzyme ____ (angiotensin converting enzyme).

**Angiotensin II Effect on MAP (Figure 19.17)**

- Angiotensin II stimulates
  - ____ of systemic arterioles.
  - The adrenal cortex to increase the secretion of ____ i
  - The posterior pituitary gland to secret ____ .
  - Hypothalamic neurons to increase ____ sensation and fluid intake.

- As a consequence MAP ____.

**Renin and Stimulation of Renin Release (Figure 18.18)**

- Renin = proteolytic enzyme
- Decreased MAP stimulates renin secretion from ________.

**Role of Atrial Natriuretic Peptide (ANP)**

- ANP is secreted by the cells in atria wall.
- ANP increases ____ excretion by increasing GFR and decreasing sodium reabsorption.

19.4. Potassium Balance

- Potassium crucial to function of excitable cells
- Hyperkalemia = high plasma potassium
• Hypokalemia = low plasma potassium

**Renal Handling of Potassium Ions**
• Glomerulus—freely filtered
• Proximal tubules—reabsorbed
• Distal tubules and collecting ducts—reabsorbed and secreted
• The net effect: reabsorption

**Mechanism of Potassium Movement**
• Reabsorption in proximal tubule (Figure 19.20a):
  o Epithelial cells
    ▪ Basolateral membrane: Na⁺/K⁺ pump
    ▪ Apical membrane: unknown
  o Between cells
• Secretion on the distal tubule and collecting duct (Figure 19.20 b)
  o Principle cells
    ▪ Basolateral membrane: Na⁺/K⁺ pump
    ▪ Apical membrane: potassium channels

**Regulation of Potassium Secretion by Aldosterone**
• Potassium secretion in distal tubules and collecting ducts is regulated
• _________ stimulates the secretion of potassium
  o Renin-angiotensin-aldosterone system stimulates aldosterone release
  o K⁺ in plasma directly stimulates aldosterone release. As K⁺ increases, more aldosterone released

**19.5. Calcium Balance**
• Calcium balance critical because calcium triggers exocytosis; secretion; muscle contraction and increases contractility of cardiac and smooth muscle
• Hypercalcemia = high plasma calcium
• Hypocalcemia = low plasma calcium

**Routes of Calcium Exchange**
**Organs and Hormones Involved in Calcium Balance**
• Organs: Kidneys, digestive tract; bone and skin
• Hormones: PTH, calcitriol (Vitamin D₃) and calcitonin
• Blood calcium
  o Bound to carrier proteins: Ca²⁺ + Protein ←→ Ca-Protein
  o Free in plasma: Free calcium—freely filtered at glomerulus

**Renal Handling of Calcium**
• 70% reabsorbed in proximal tubules
• 19–20% reabsorbed in thick ascending limbs of the loops of Henle
• 9–10% reabsorbed in distal tubules
• Reabsorption in loops of Henle and distal tubules is regulated

**PTH and Calcium Balance (Figure 19.22)**
**Role of Vitamin D (Figure 19.23):** Stimulate calcium absorption by GI and reabsorption by kidney

**Role of Calcitonin in Calcium Balance**
• Calcitonin is secreted from C cells of thyroid gland. Its release is triggered by high plasma [Ca²⁺]. It increases bone formation and decrease calcium reabsorption by kidneys
19.6. Interactions between Fluid and Electrolyte Balance
• Increase in solute reabsorption increases osmotic gradient for water reabsorption
• ADH increases number of sodium channels in apical membrane of principal cells
• Angiotensin II increases ADH secretion
• ANP decreases ADH secretion

19.7. Acid-Base Balance
• Normal pH of arterial blood = 7.35–7.45
  o pH < 7.35 = acidosis
  o pH > 7.45 = alkalosis
• Complications with acid-base disturbance
  o Conformation change in protein structure
  o Changes in excitability of neurons
  o Changes in potassium balance
  o Cardiac arrhythmias
  o Vasodilation

Inputs and Outputs of Acid Respiratory Disturbances
Carbon dioxide is a source of acid
\[
\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{HCO}_3^- + \text{H}^+
\]
• Normal \(P_{\text{CO}_2}\) arterial blood = 40 mm Hg
• Sources of \(\text{CO}_2\): metabolism
• Output of \(\text{CO}_2\): through respiratory system
• Increases in plasma \([\text{CO}_2]\) \(\rightarrow\) respiratory acidosis
• Decreases in plasma \([\text{CO}_2]\) \(\rightarrow\) respiratory alkalosis

Metabolic Acidosis= Decrease pH through something other than carbon dioxide.
Possible causes: High protein diet; high fat diet; heavy exercise; severe diarrhea (loss of bicarbonate) and renal dysfunction

Metabolic Alkalosis= Increase pH through something other than carbon dioxide.
Contributing factors include excessive vomiting (loss of hydrogen ions); consumption of alkaline products (baking soda) and renal dysfunction

Three Lines of Defense Mechanisms against Acid-Base Disturbances

Frist Line of Defense: Buffering of \(\text{H}^+\)
• Quickest defense against changes in pH
• Limited capacity, buffered hydrogen ions must be eliminated.
• Most important ECF buffer = bicarbonate
  \[
  \text{HCO}_3^- + \text{H}^+ \leftrightarrow \text{H}_2\text{CO}_3
  \]
• ICF Buffers
  o Proteins: Protein\textsuperscript{−} + H\textsuperscript{+} \(\leftrightarrow\) H\textbull{•}Protein
  o Phosphates: \(\text{HPO}_4^{2-} + \text{H}^+ \leftrightarrow \text{H}_2\text{PO}_4^-\)

Second line of defense: Respiratory Compensation (Figure 19.25)
• Takes minutes to have effect
• Cannot restore the pH to normal by acting alone
  o Regulates pH by varying ventilation
    ▪ Increase ventilation \(\rightarrow\) decreases \(\text{CO}_2\)
    ▪ Decrease ventilation \(\rightarrow\) increases \(\text{CO}_2\)

Third Line of defense: Renal Compensation
• Strongest defense
• Increase in acidity causes
  o Increased secretion of hydrogen ions
  o Increased reabsorption of bicarbonate
  o Increased synthesis of new bicarbonate

**Renal Handling of Hydrogen and Bicarbonate Ions (Figure 29.27)**
• Proximal tubule: Bicarbonate reabsorption coupled to hydrogen ion secretion
• Distal tubule and collecting duct: Secretion of hydrogen ions coupled to synthesis of new bicarbonate ions

**Glutamine in Renal Compensation during Severe Acidosis**
• Regulation of hydrogen ion secretion, bicarbonate reabsorption, and bicarbonate synthesis by kidneys usually sufficient
• Severe acidosis: Glutamine metabolism to produce new bicarbonate and secrete hydrogen in form of ammonium (Figure 19.28)

**Acid-Base Disturbances/Compensation (Figure 19.29)**