Chapter 2

Fluid, Electrolyte, and Acid-Base Imbalances

From Bloom A, Ireland J: Color Atlas of Diabetes, *ed 2, St. Louis, Mosby, 1992.*

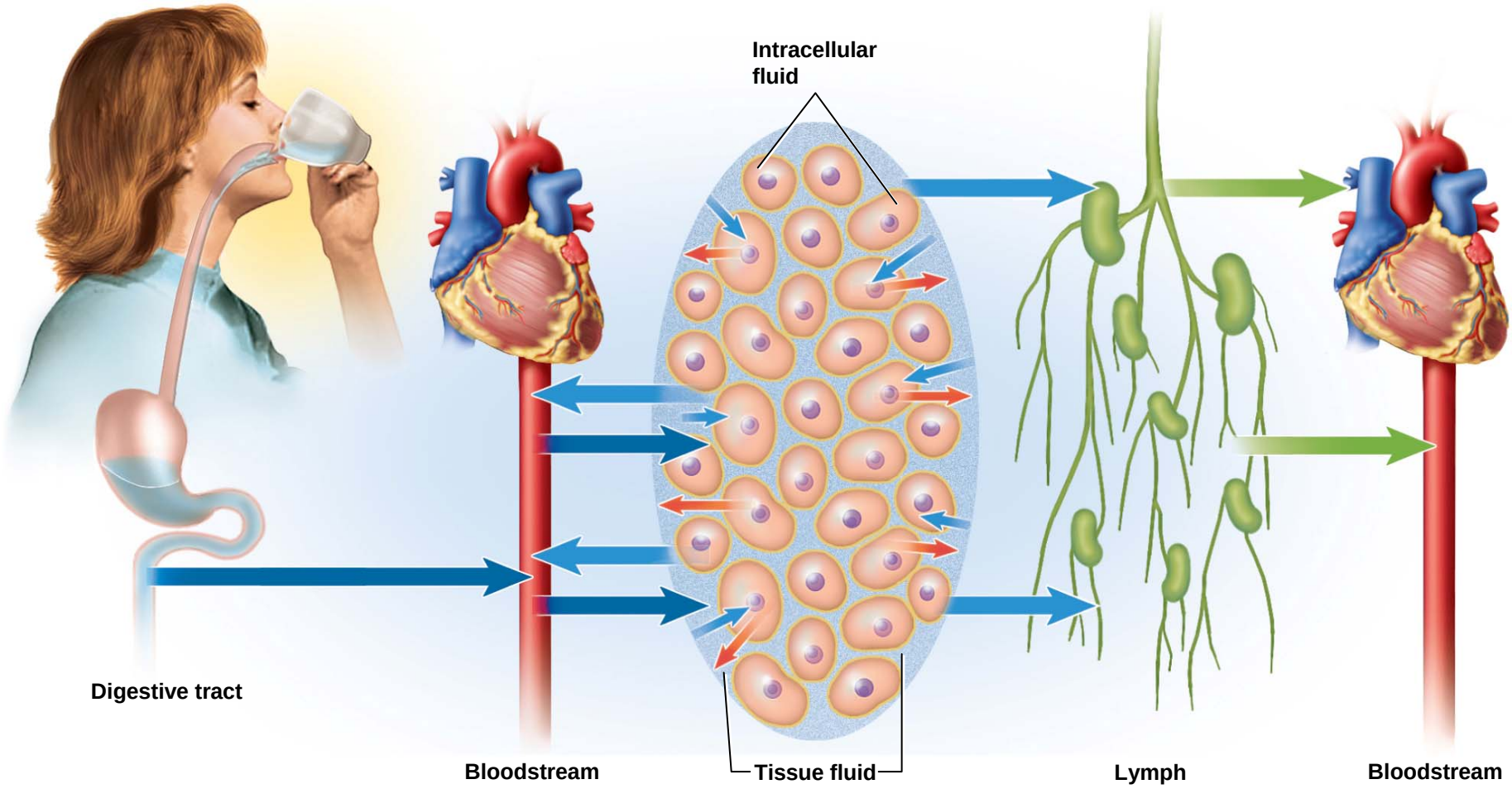
Review of Concepts and Processes

- The major component of the body is water.
- Water is located in these compartments:
  - Intracellular fluid (ICF) compartment
  - Extracellular fluid (ECF) compartment
- Balance of water between these compartments essential for homeostasis

Fluid Compartments (cont'd.)

- Intracellular compartment (ICF)
- Extracellular compartment (ECF)
  - Intravascular fluid (IVF) or blood
  - Interstitial fluid (ISF) or intercellular fluid
  - Cerebrospinal fluid (CSF)
  - Transcellular fluids // Present in various secretions // e.g. Pericardial cavity & Synovial cavities

Water Movement Between Fluid Compartments



Fluid Compartments

- About 60% of an adult's body weight is water.
- About 70% of an infant's body weight is water.
- Females - higher percentage of fatty tissue = lower water content than males
- Older adults and obese persons - lower proportion of water
- Individuals with less fluid reserve are more likely to be adversely affected by any fluid or electrolyte imbalance. e.g. dehydration from extreme heat

TABLE 2-1 Fluid Compartments in the Body

	Volume	Approximate Percentage of Body Weight		
	Adult Male (L)	Male (%)	Female (%)	Infant (%)
Intracellular fluid	28	40	33	40
Extracellular fluid	15	20	17	30
Plasma	(4-5)	(4)	(4)	(4)
Interstitial fluid	(10.5)	(15)	(9)	(25)
Other		(1)	(1)	(1)
Total water	43	60	50	70

Note: In elderly women, water content is reduced to approximately 45% of body weight.

Intake and Output of Water

- The amount of water entering the body should equal the amount of water leaving the body.
- Water Balance

Fluid Balance

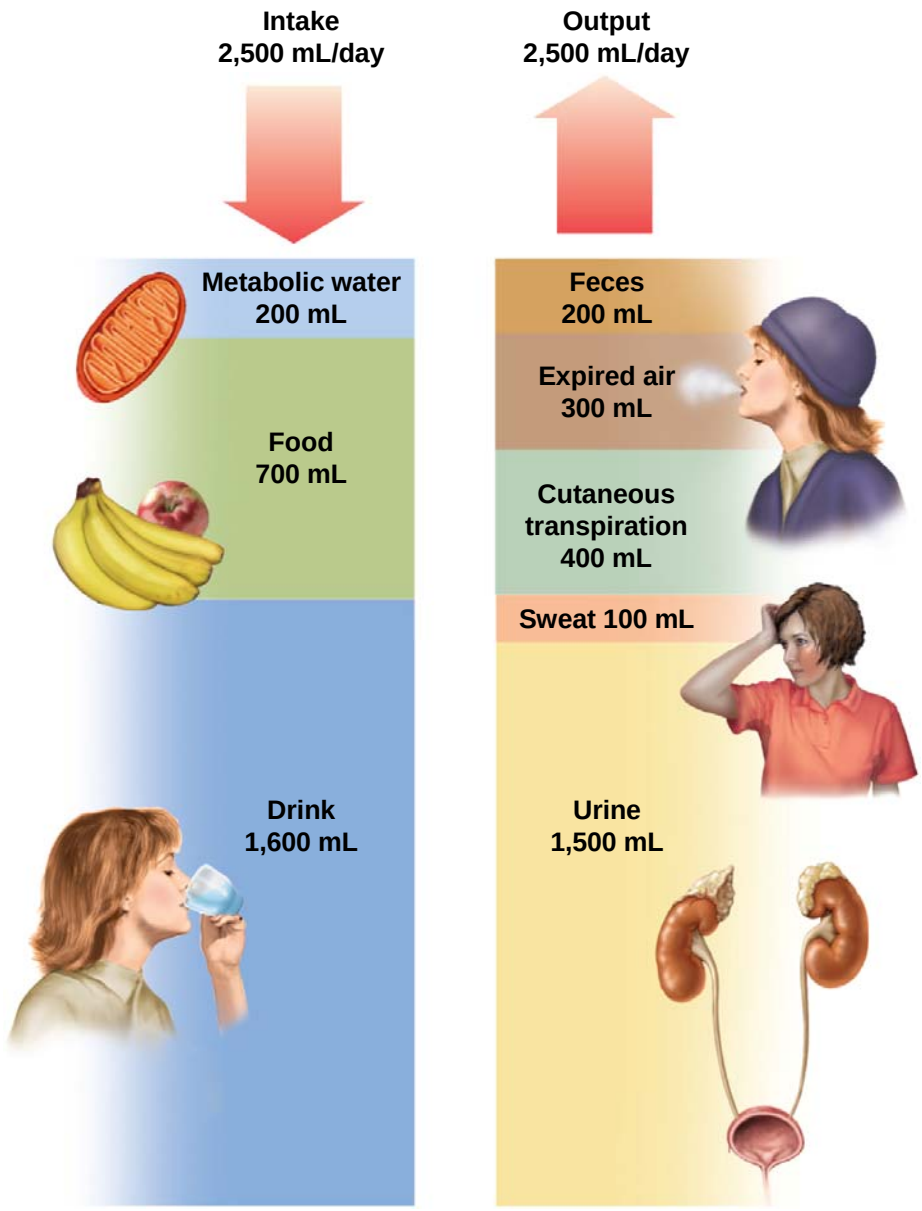


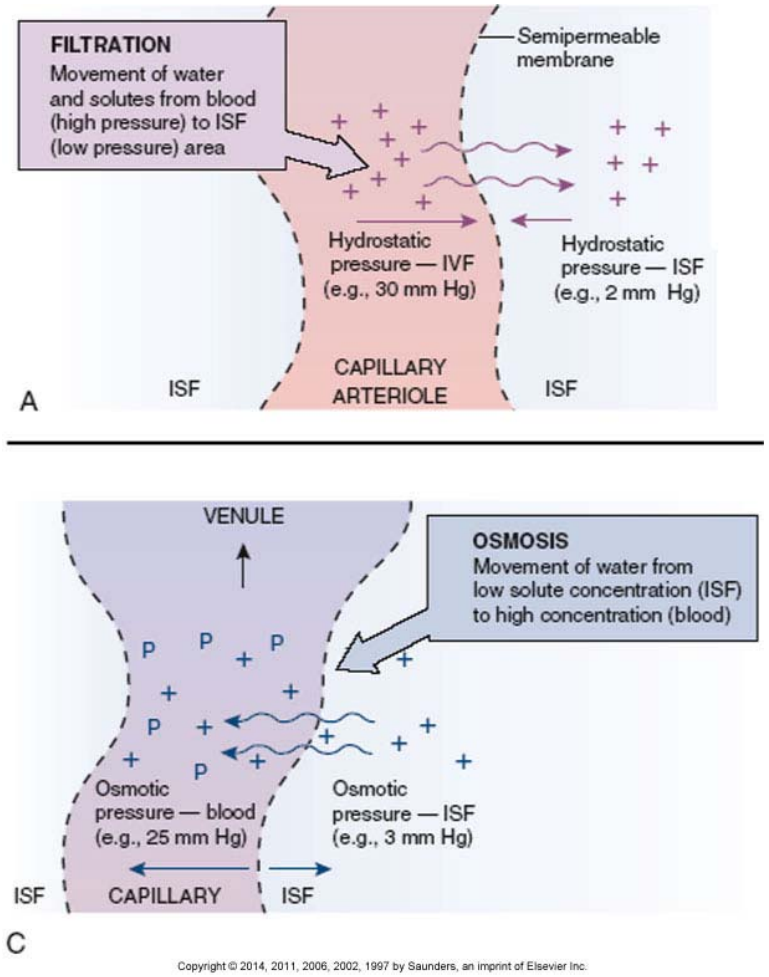
TABLE 2-2 Sources and Losses of Water

Sources (mL)		Losses (mL)	
Liquids	1200	Urine	1400
Solid foods	1000	Feces	200
Cell metabolism	300	Insensible losses	
		Lungs	400
		Skin	500
Total	2500		2500

Movement of Water

- “Water” compartments are created by semi permeable membranes
- Fluid circulates throughout the body crossing membranes via filtration and osmosis.
- Water moves between compartments via:
  - Hydrostatic pressure
  - Osmotic pressure

Movements of Water between Compartments



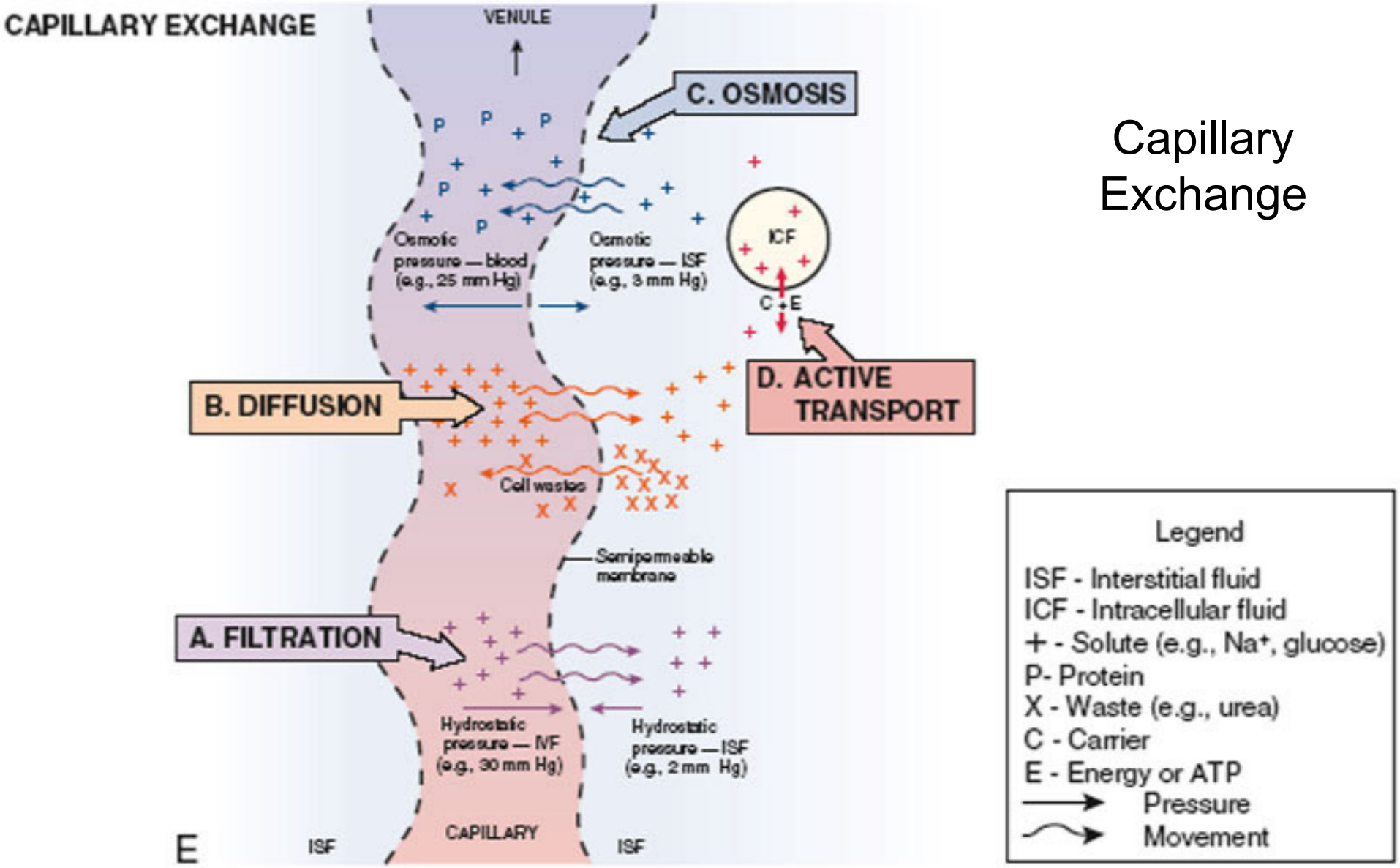
Control of Fluid Balance

- Thirst mechanism // Osmoreceptors in the hypothalamus
- Antidiuretic hormone // Promotes resorption of water into blood from kidney tubules
- Aldosterone // Determines resorption of sodium ions and water
- Atrial natriuretic peptide // Regulates fluid, sodium, and potassium levels

Fluid Excess - Edema

- excessive amount of fluid in the interstitial compartment
  - Causes swelling or enlargement of tissue
  - May be localized or throughout the body
  - May impair tissue perfusion
  - May trap drugs in ISF

Capillary Exchange



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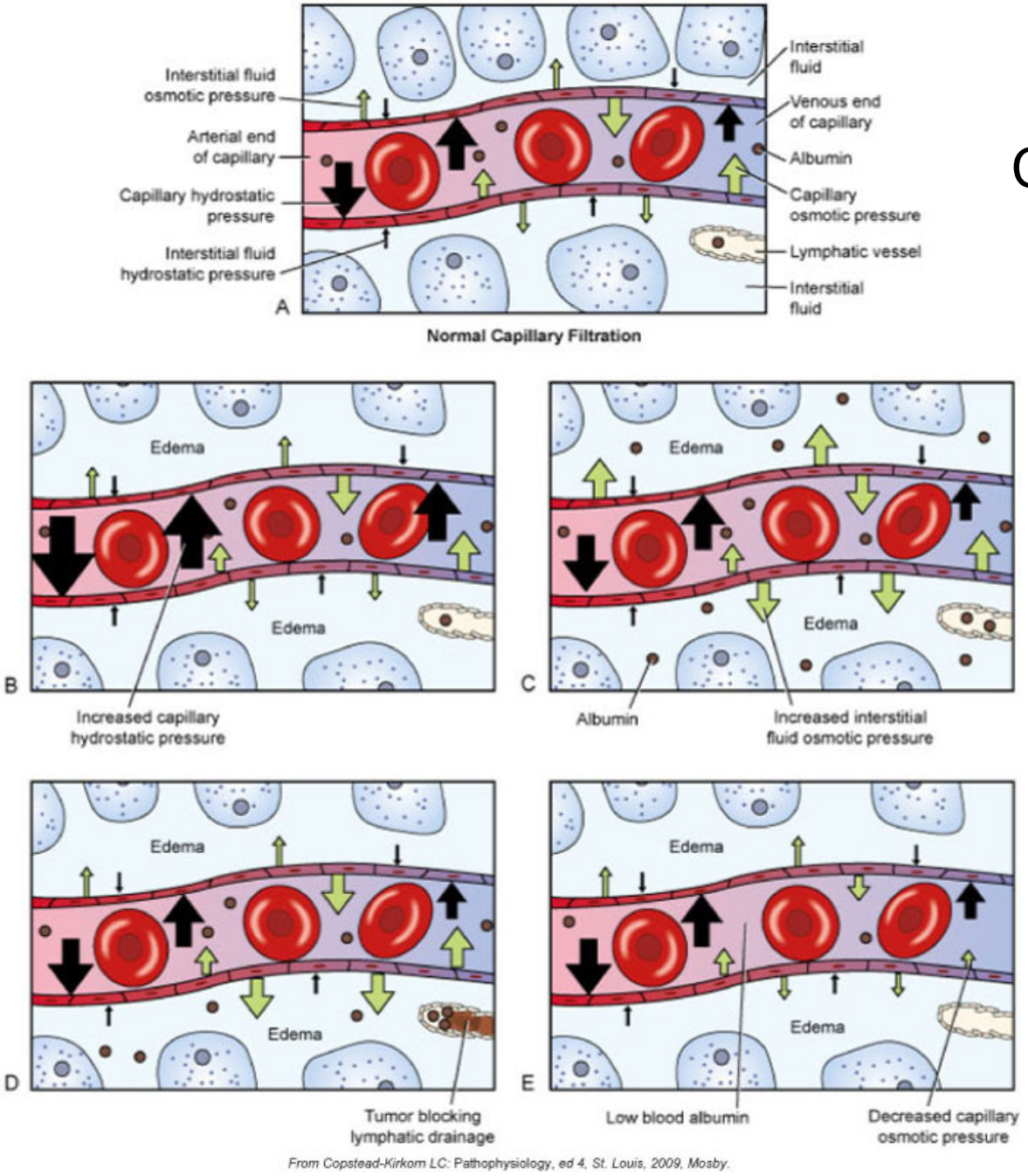
Causes of Edema

- Increased capillary hydrostatic pressure
  - Caused by higher blood pressure or increased blood volume
  - Forces increased fluid out of capillaries into tissue
  - Cause of pulmonary edema
- Loss of plasma proteins
  - Particularly albumin
  - Results in decreased plasma osmotic pressure

Causes of Edema



From Copstead-Kirkorn LC: Pathophysiology, ed 4, St. Louis, 2009, Mosby.

Causes of Edema

- Obstruction of lymphatic circulation // Causes localized edema
    - Excessive fluid and protein not returned to general circulation
- Increased capillary permeability // Usually causes localized edema
    - May result from an inflammatory response or infection
    - Histamines and other chemical mediators increase capillary permeability.
    - Can also result from some bacterial toxins or large burn wounds and result in widespread edema

Effects of Edema

- Swelling // Pale or red in color
- Pitting edema // Presence of excess interstitial fluid
  - Moves aside when pressure is applied by finger
  - Depression—"pit" remains when finger is removed
- Increase in body weight // With generalized edema

Effects of Edema (cont'd.)

From Bloom A, Ireland J: Color Atlas of Diabetes, ed 2, St. Louis, Mosby, 1992.

Effects of Edema

- Functional impairment
  - Restricts range of joint movement
  - Reduced vital capacity
  - Impaired diastole
- Pain
  - Edema exerts pressure on nerves locally.
  - Headache with cerebral edema
  - Stretching of capsule in organs (kidney, liver)
- Impaired arterial circulation // Ischemia leading to tissue breakdown

Effects of Edema (cont'd.)

- Dental practice
  - Difficult to take accurate impressions
  - Dentures do not fit well
- Edema in skin
  - Susceptible to tissue breakdown from pressure

Fluid Deficit - Dehydration

- Insufficient body fluid
  - Inadequate intake
  - Excessive loss
  - Both
- Fluid loss often measured by change in body weight
- Dehydration more serious in infants and older adults
- Water loss may be accompanied by loss of electrolytes and proteins (e.g., diarrhea).

Causes of Dehydration

- Vomiting and diarrhea
- Excessive sweating with loss of sodium and water
- Diabetic ketoacidosis // Loss of fluid, electrolytes, and glucose in the urine
- Insufficient water intake in older adults or unconscious persons
- Use of concentrated formula in infants

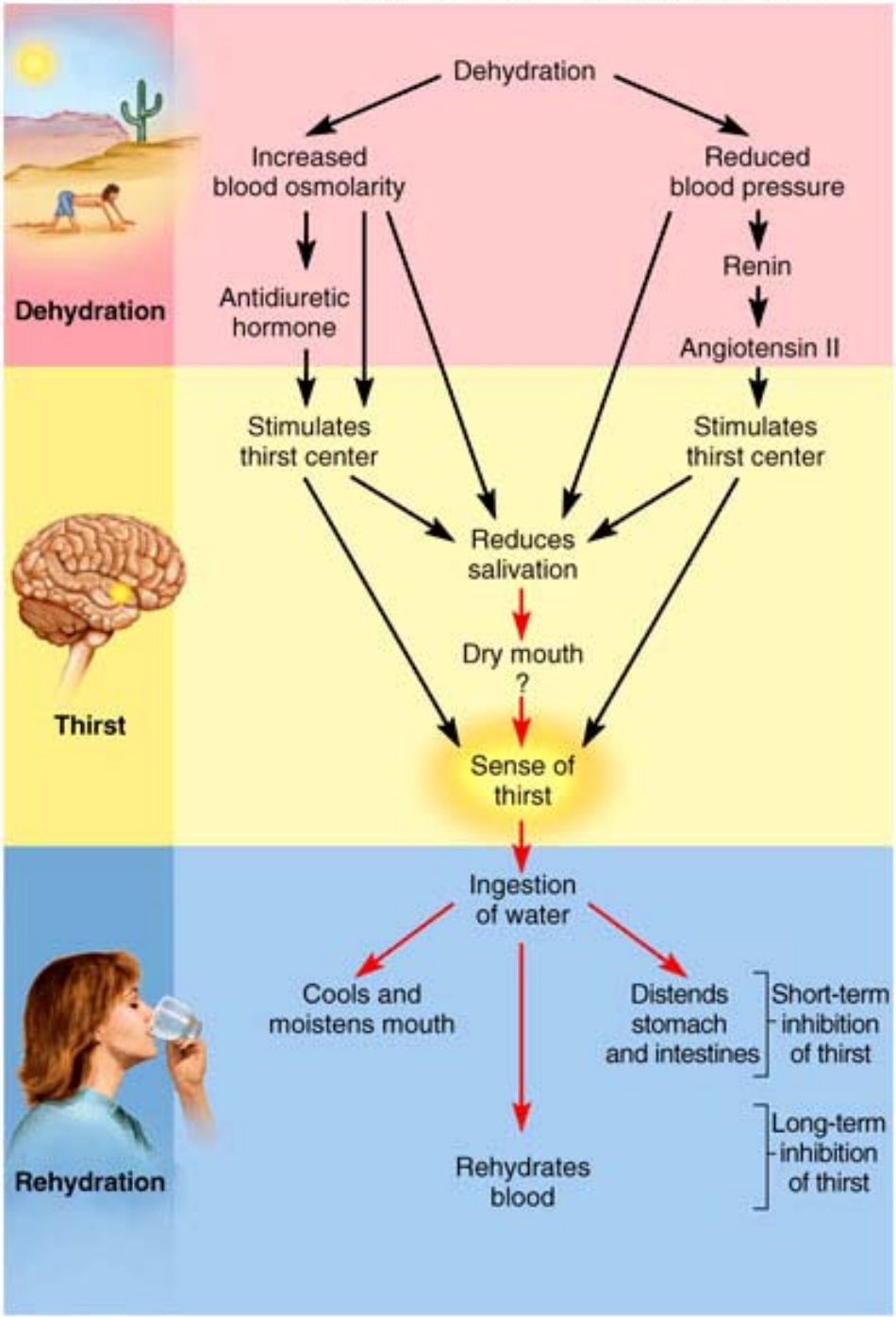
Effects of Dehydration

- Dry mucous membranes in the mouth
- Decreased skin turgor or elasticity
- Lower blood pressure, weak pulse, and fatigue
- Decreased mental function, confusion, loss of consciousness

Manifestations of Dehydration

Sunken eyes

- Sunken fontanelles in infant
- Lower blood pressure, rapid weak pulse
- Increased hematocrit
- Increased temperature
- Decreasing level of consciousness
- Urine—low volume and high specific gravity



Dehydration, Thirst, and Rehydration

TABLE 2-3 Comparison of Signs and Symptoms of Fluid Excess (Edema) and Fluid Deficit (Dehydration)

Fluid Excess (Edema)	Fluid Deficit (Dehydration)
Localized swelling (feet, hands, periorbital area, ascites)	Sunken, soft eyes
Pale, gray, or red skin color	Decreased skin turgor, dry mucous membranes
Weight gain	Thirst, weight loss
Slow, bounding pulse; high blood pressure	Rapid, weak, thready pulse, low blood pressure, and orthostatic hypotension
Lethargy, possible seizures	Fatigue, weakness, dizziness, possible stupor
Pulmonary congestion, cough, rales	Increased body temperature
Laboratory values:	Laboratory values:
Decreased hematocrit	Increased hematocrit
Decreased serum sodium	Increased electrolytes (or variable)
Urine: low specific gravity, high volume	Urine: high specific gravity, low volume

Note: Signs may vary depending on the cause of the imbalance.

Attempts to Compensate for Fluid Loss

- Increasing thirst
- Increasing heart rate
- Constriction of cutaneous blood vessels
- Producing less urine
- Concentration of urine

Third-Spacing of Fluid

- Fluid shifts out of the blood into a body cavity or tissue and can no longer re-enter vascular compartment.
  - High osmotic pressure of ISF, as in burns
  - Increased capillary permeability, as in some gram-negative infections

TABLE 2-4 Distribution of Major Electrolytes

Ions	Intracellular (mEq/L)	Blood (mEq/L)
Cations		
Sodium (Na)	10	142
Potassium (K)	160	4
Calcium (Ca)	Variable	5
Magnesium (Mg)	35	3
Anions		
Bicarbonate (HCO_3^-)	8	27
Chloride (Cl^-)	2	103
Phosphate (HPO_4^-)	140	2

Note: There are variations in "normal" values among individuals.
The concentration of electrolytes in plasma varies slightly from that in the interstitial fluid or other types of extracellular fluids.
The number of anions, including those present in small quantities, is equivalent to the concentration of cations in the intracellular compartment (or the plasma) so as to maintain electrical neutrality (equal negative and positive charges) in any compartment.

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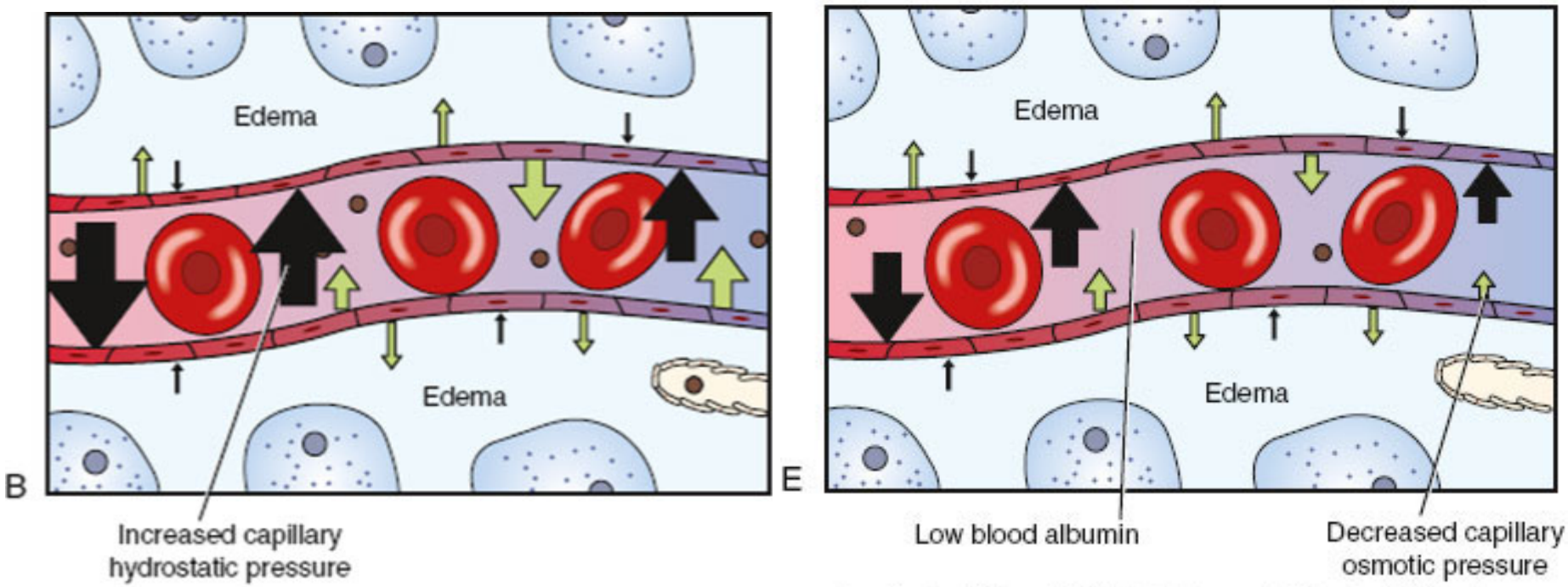
Movements of Electrolytes Between Compartments



From Copstead-Kirkorn LC: *Pathophysiology*, ed 4, St. Louis, 2009, Mosby.

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Sodium Imbalance

- Review of sodium
  - Primary cation in ECF
  - Sodium diffuses between vascular and interstitial fluids.
  - Transport out of cells by sodium-potassium pump (3 Na out and 2 K in)
  - Actively secreted into mucus and other secretions
  - Exists in form of sodium chloride and sodium bicarbonate
  - Ingested in food and beverages

Sodium

- DRI is 0.5 g/day
- Typical American consumes 5 to 7 mg/day
- Adult male secretes 5 g of sodium per day
- Under influence of aldosterone the urine can be sodium free
- Antiport exchanges sodium for potassium

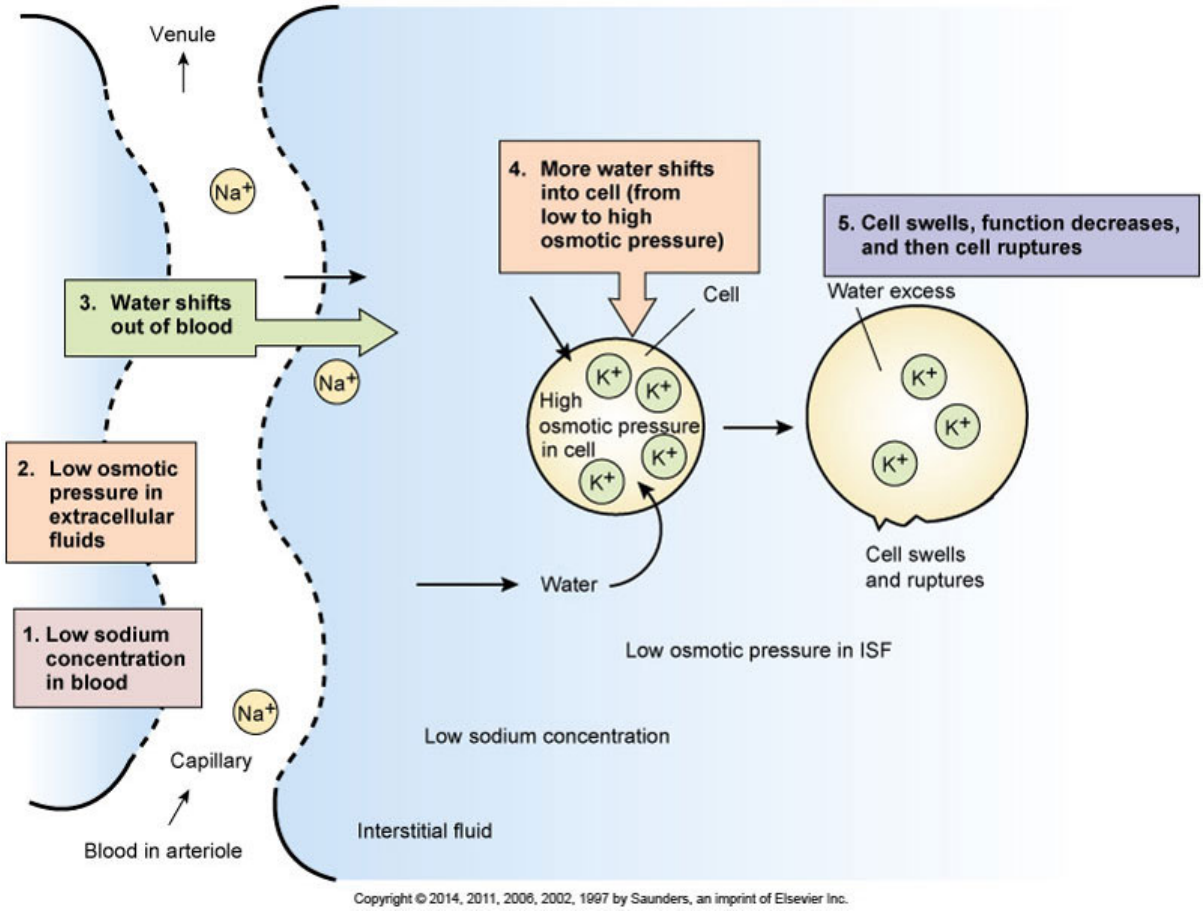
Hyponatremia

- Causes
  - Losses from excessive sweating, vomiting, diarrhea
  - Use of certain diuretic drugs combined with low-salt diet
  - Hormonal imbalances
    - Insufficient aldosterone
    - Adrenal insufficiency
    - Excess ADH secretion
  - Diuresis
  - Excessive water intake

Effects of Hyponatremia

- Low sodium levels // Cause fluid imbalance in compartments
    - Fatigue, muscle cramps, abdominal discomfort or cramps, nausea, vomiting
- Decreased osmotic pressure in ECF compartment
    - Fluid shift into cells // Hypovolemia and decreased blood pressure
    - Cerebral edema // Confusion, headache, weakness, seizures

Hyponatremia and Fluid Shift into Cells



Hypernatremia

- Cause is imbalance in sodium and water
  - Insufficient ADH (diabetes insipidus) // Results in large volume of dilute urine
  - Failure of the thirst mechanism
  - Watery diarrhea & prolonged periods of rapid respiration
  - Ingestion of large amounts of sodium without enough water

Effects of Hypernatremia

- Weakness & agitation
- Dry, rough mucous membranes
- Edema
- Increased thirst (if thirst mechanism is functional)
- Increased blood pressure

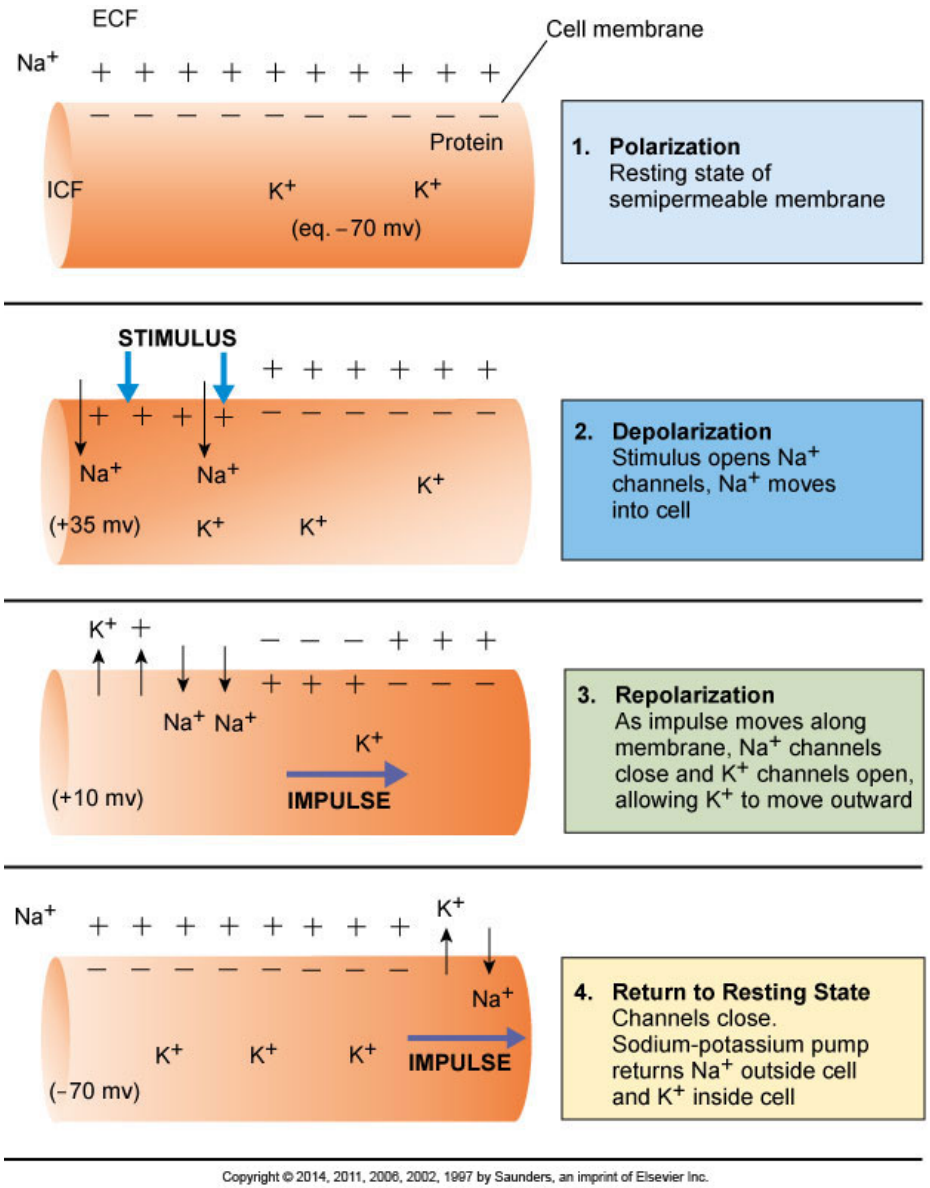
Review of Potassium Imbalance

- Major intracellular cation
- Serum levels are low, with a narrow range.
- Excreted primarily in urine / but retained by antiport when kidneys excrete H+
- Insulin promotes movement of potassium into cells
- Level influenced by acid-base balance
- Excess potassium ions in interstitial fluid may lead to hyperkalemia.
- Abnormal potassium levels (high or low) cause changes in cardiac conduction and are ***life-threatening!***

TABLE 2-6 Signs of Potassium Imbalance

Hypokalemia	Hyperkalemia
Cardiac arrhythmias, cardiac arrest	Arrhythmias, cardiac arrest
Anorexia, nausea, constipation	Nausea, diarrhea
Fatigue, muscle twitch, weakness, leg cramps	Muscle weakness, paralysis beginning in legs
Shallow respirations, paresthesias	Paresthesias—fingers, toes, face, tongue
Postural hypotension, polyuria, and nocturia	Oliguria
Serum pH elevated—7.45 (alkalosis)	Serum pH decreased—7.35 (acidosis)

Role of sodium and potassium ions in the conduction of an impulse (action potentials)



Causes of Hypokalemia

- Definition of hypokalemia // Serum K^+ < 3.5 mEq/L
- Causes
  - Excessive losses caused by diarrhea
  - Diuresis associated with some diuretic drugs
  - Excessive aldosterone or glucocorticoids // Example: Cushing syndrome
  - Decreased dietary intake // May occur with alcoholism, eating disorders, starvation
  - Treatment of diabetic ketoacidosis with insulin

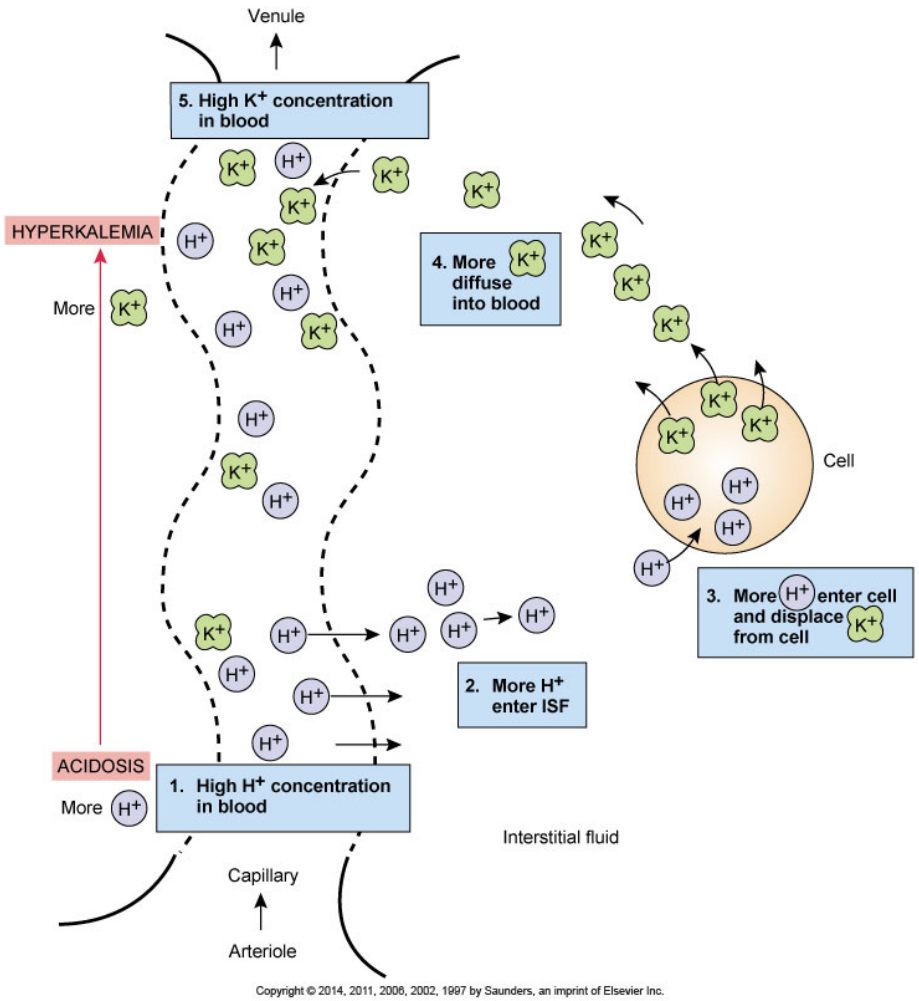
Effects of Hypokalemia

- Cardiac dysrhythmias // Caused by impaired repolarization leading to cardiac arrest
- Interference with neuromuscular function // Muscles less responsive to stimuli
- Paresthesias—“pins and needles”
- Decreased digestive tract motility
- Severe hypokalemia results in: Shallow respirations // Failure to concentrate urine and polyuria

Causes of Hyperkalemia

- Definition of hyperkalemia // Serum K^+ > 5 mEq/L
- Causes
  - Renal failure
  - Deficit of aldosterone
  - “Potassium-sparing” diuretics
  - Leakage of intracellular potassium into extracellular fluids // In patients with extensive tissue damage
  - Displacement of potassium from cells by prolonged or severe acidosis

Relationship of Hydrogen and Potassium Ions



Effects of Hyperkalemia

- Cardiac dysrhythmias // May progress to cardiac arrest (how dogs are killed)
- Muscle weakness common
  - Progresses to paralysis
  - May cause respiratory arrest
  - Impairs neuromuscular activity
- Fatigue, nausea, paresthesias

Calcium Imbalance

- Review of calcium
  - Important extracellular cation
  - Ingested in food
  - Stored in bone
  - Excreted in urine and feces
  - Balance controlled by parathyroid hormone (PTH) and calcitonin
  - Vitamin D promotes calcium absorption from intestine // Ingested or synthesized in skin in the presence of ultraviolet rays // Activated in kidneys

Functions of Calcium

- Provides structural strength for bones and teeth
- Maintenance of the stability of nerve membranes
- Required for muscle contractions
- Necessary for many metabolic processes and enzyme reactions
- Essential for blood clotting

Causes of Hypocalcemia

- Hypoparathyroidism
- Malabsorption syndrome
- Deficient serum albumin
- Increased serum pH level
- Renal failure

Effects of Hypocalcemia

- Increase in the permeability and excitability of nerve membranes
  - Spontaneous stimulation of skeletal muscle
    - Muscle twitching
    - Carpopedal spasm
  - Tetany
- Weak heart contractions
  - Delayed conduction // Leads to dysrhythmias and decreased blood pressure

Causes of Hypercalcemia

- Uncontrolled release of calcium ions from bones // Neoplasms—malignant bone tumors
- Hyperparathyroidism
- Demineralization caused by immobility // Decrease stress on bone > decrease osteoblast activity
- Increased calcium intake // Excessive vitamin D // or excess dietary calcium
- Milk-alkali syndrome

Effects of Hypercalcemia

- Depressed neuromuscular activity
  - Muscle weakness, loss of muscle tone
  - Lethargy, stupor, personality changes
  - Anorexia, nausea
- Interference with ADH function // less absorption of water // decrease in renal function
- Increased strength in cardiac contractions // dysrhythmias may occur.

Magnesium Imbalances

- Intracellular ion
- Hypomagnesemia
  - Results from malabsorption or malnutrition; often associated with alcoholism
  - Caused by use of diuretics, diabetic ketoacidosis, hyperthyroidism, hyperaldosteronism
- Hypermagnesemia
  - Occurs with renal failure
  - Depresses neuromuscular function
  - Decreased reflexes

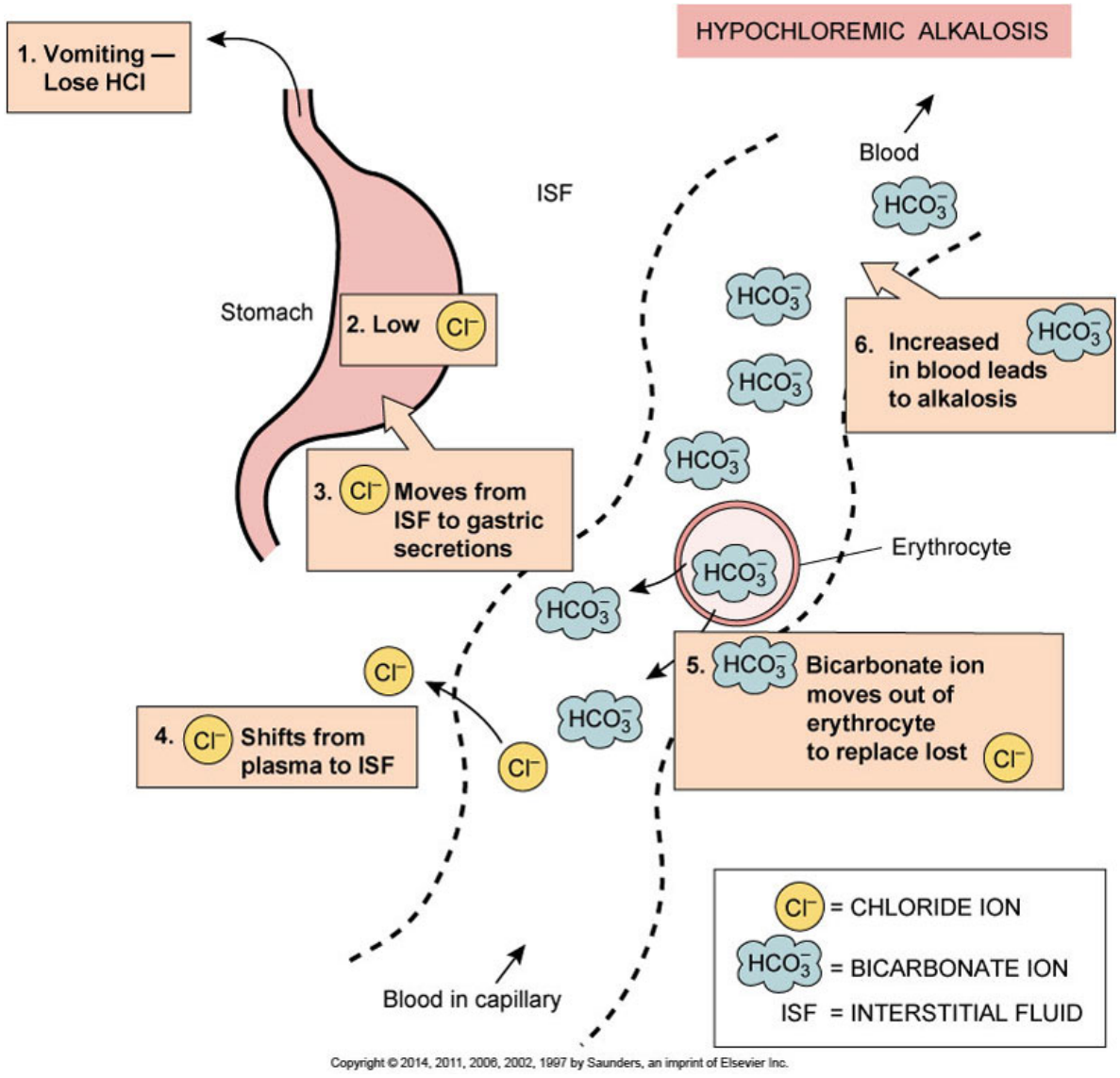
Phosphate Imbalances

- Bone and tooth mineralization
- Important in metabolism—ATP
- Phosphate buffer system—acid-base balance
- Integral part of the cell membrane
- Reciprocal relationship with serum calcium
- Hypophosphatemia // Malabsorption syndromes, diarrhea, excessive antacids
- Hyperphosphatemia // From renal failure

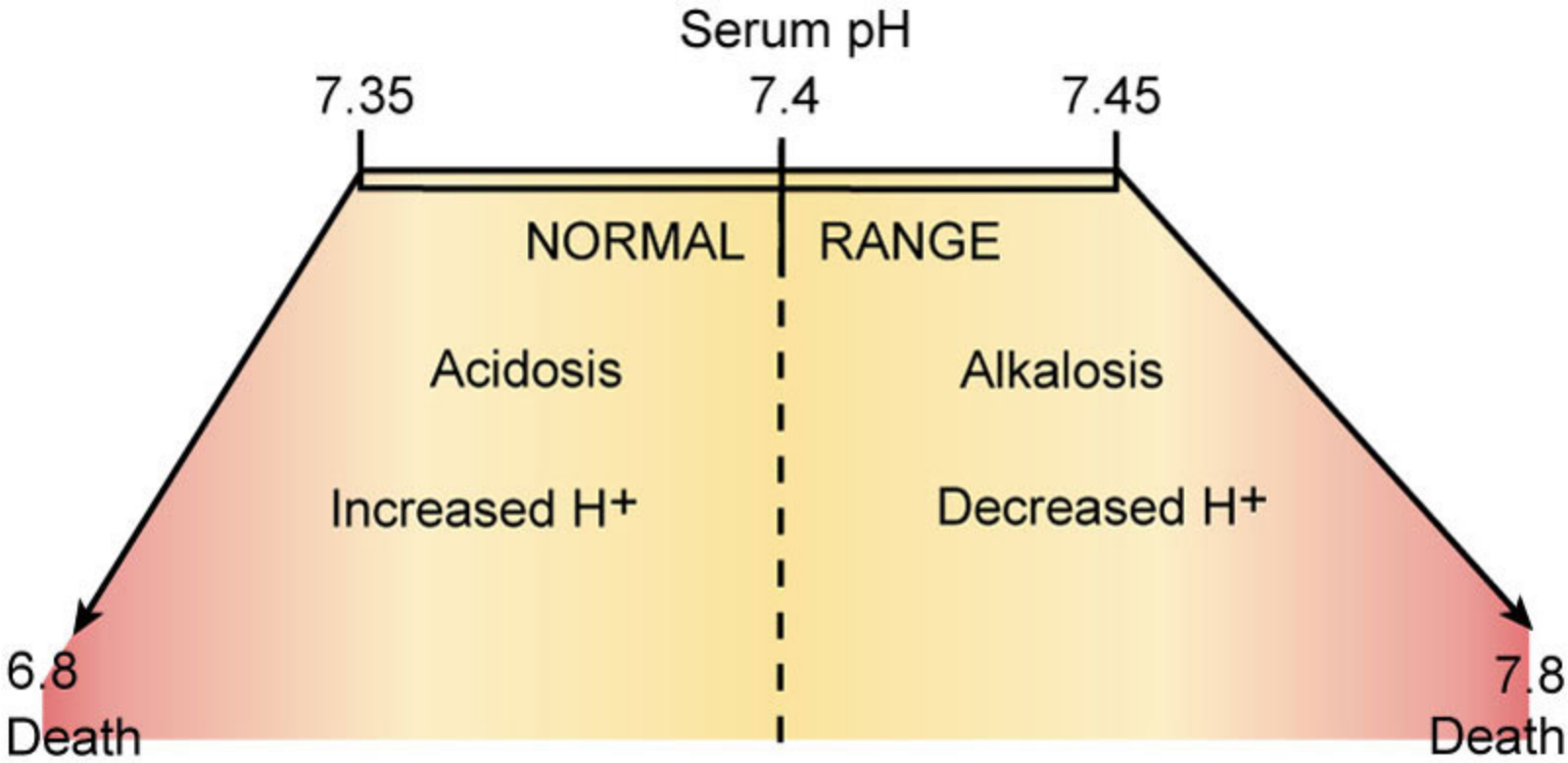
Chloride Imbalance

- Major extracellular anion
- Chloride levels related to sodium levels
- Chloride and bicarbonate ions can shift in response to acid-base imbalances.
- Hypochloremia // Usually associated with alkalosis // Early stages of vomiting—loss of hydrochloric acid
- Hyperchloremia // Excessive sodium chloride intake

Chloride Shift



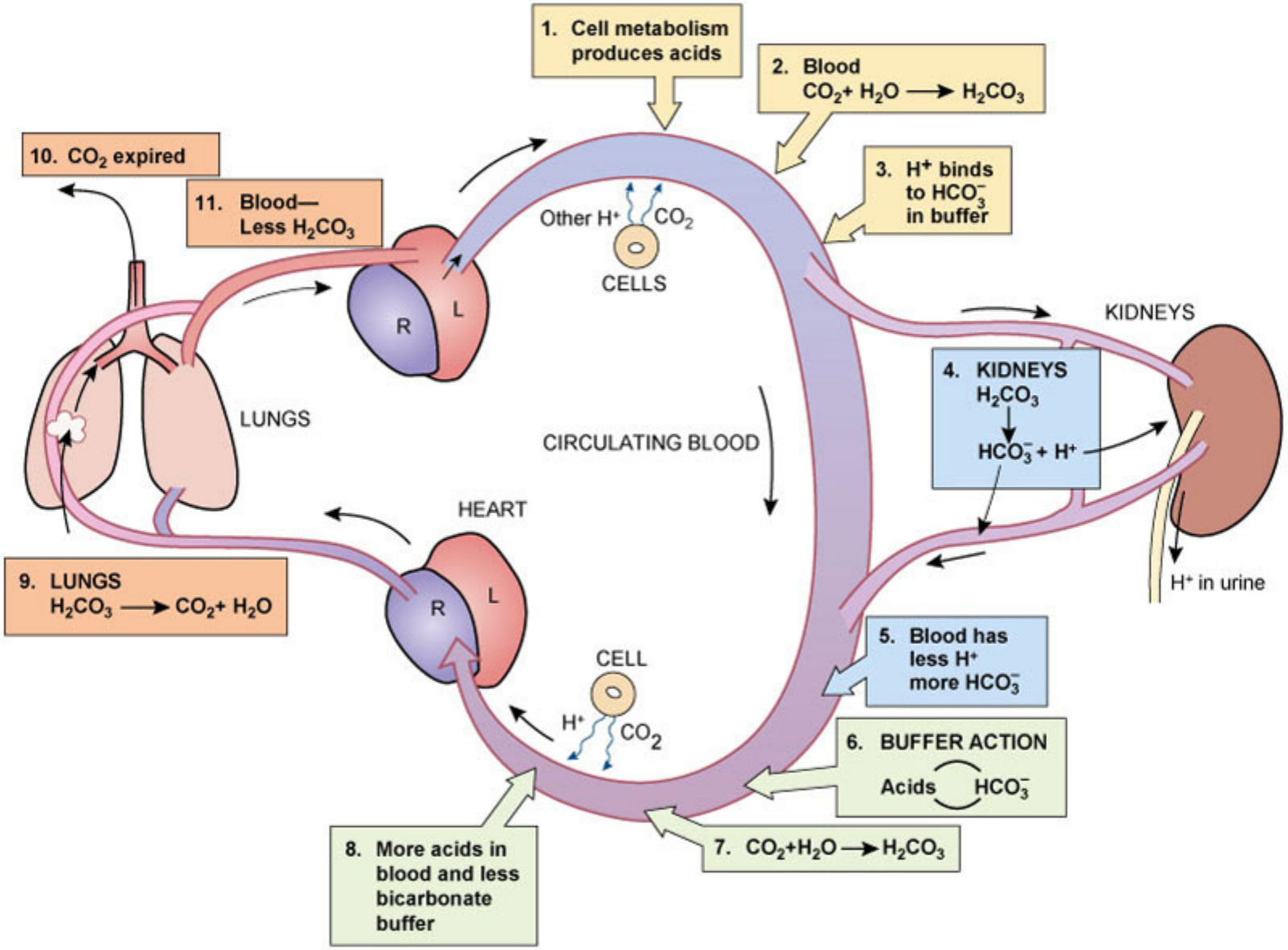
Hydrogen Ion and pH Scale



Control of Serum pH

- Buffer pairs in the blood respond to pH changes immediately. (chemical buffers)
- Respiratory system can alter carbonic acid levels to change pH. (physiologic buffer)
- Kidneys can modify the excretion rate of acids and absorption of bicarbonate ions to regulate pH. (physiologic buffer)
  - Most significant control mechanism // move pH more
  - Slowest mechanism

Changes in Acids, Bicarbonate Ion, and Serum pH in Circulating Blood



Buffer Systems

- Sodium bicarbonate–carbonic acid system
  - Major ECF buffer
  - Controlled by the respiratory system and kidneys
- Other buffering systems:
  - Phosphate
  - Serum protein / hemoglobin

Compensation Mechanisms for pH Imbalance

- Compensation limited, usually short term
- *Does not remove the cause of imbalance*
- Compensation occurs to balance the *relative proportion* of hydrogen ions and bicarbonate ions in circulation:
  - Buffers
  - Change in respiration
  - Change in renal function

Decompensation

- Occurs when:
  - Causative problem becomes more severe
  - Additional problems occur
  - Compensation mechanisms are exceeded or fail
- Requires intervention to maintain homeostasis
- **LIFE-THREATENING**!

Acid-Base Imbalance

- Acidosis (below pH 7.35)
  - Excess hydrogen ions
  - Decrease in serum pH
- Alkalosis (above pH 7.45
  - Deficit of hydrogen ions
  - Increase in serum pH

TABLE 2-8 Acid-Base Imbalances

	Acidosis	Alkalosis
Respiratory		
Causes	Slow shallow respirations (e.g., drugs) Respiratory congestion	Hyperventilation (anxiety, aspirin overdose)
Effect	Increased PCO_2	Decreased PCO_2
Compensation	Kidneys excrete more hydrogen ion and reabsorb more bicarbonate	Kidneys excrete less hydrogen ion and reabsorb less bicarbonate
Laboratory	Elevated PCO_2 Elevated serum bicarbonate Compensated—serum pH = 7.35 to 7.4 Decompensated—serum pH < 7.5	Low PCO_2 Low serum bicarbonate Compensated—serum pH = 7.4 to 7.45 Decompensated—serum pH > 7.45
Metabolic		
Causes	Shock Diabetic ketoacidosis Renal failure Diarrhea	Vomiting (early stage) Excessive antacid intake
Effect	Decreased serum bicarbonate ion	Increased serum bicarbonate ion
Compensation	Rapid, deep respirations Kidneys excrete more acid and increase bicarbonate absorption	Slow, shallow respirations Kidneys excrete less acid and decrease bicarbonate absorption
Laboratory	Low serum bicarbonate Low PCO_2 Compensated—serum pH = 7.35 to 7.4 Decompensated—serum pH < 7.35	Elevated serum bicarbonate Elevated PCO_2 Compensated—serum pH = 7.4 to 7.45 Decompensated—serum pH > 7.45

Respiratory Acidosis

- Acute problems
  - Pneumonia, airway obstruction, chest injuries
  - Drugs that depress the respiratory control center
- Chronic respiratory acidosis // Common with chronic obstructive pulmonary disease
- Decompensated respiratory acidosis // May develop if impairment becomes severe or if compensation mechanisms fail

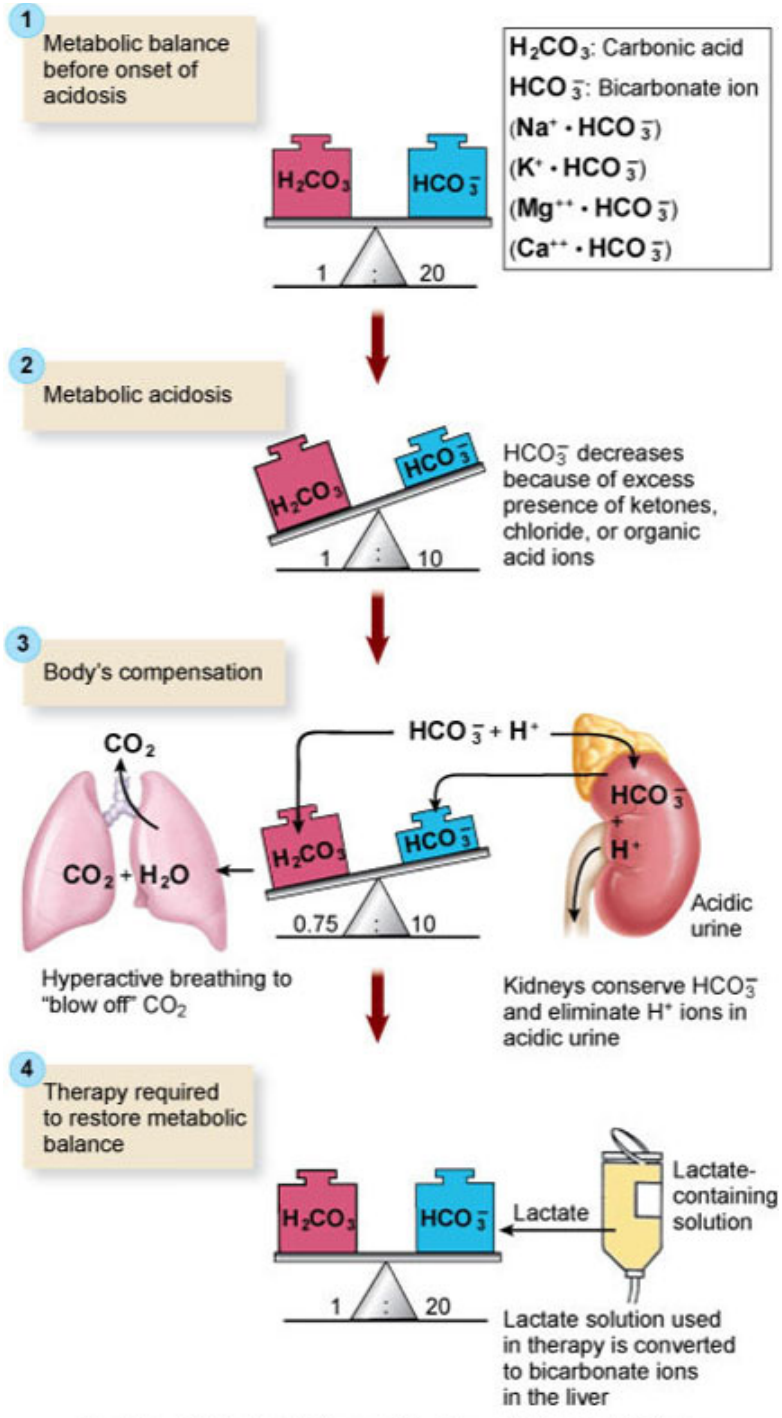
Metabolic Acidosis

- Excessive loss of bicarbonate ions to buffer hydrogen // Diarrhea—loss of bicarbonate from intestines
- Increased use of serum bicarbonate
- Renal disease or failure
  - Decreased excretion of acids
  - Decreased production of bicarbonate ions
- Decompensated metabolic acidosis // Additional factor interferes with compensation.

Effects of Acidosis

- Impaired nervous system function
  - Headache
  - Lethargy
  - Weakness
  - Confusion
  - Coma and death
- Compensation
  - Deep rapid breathing
  - Secretion of urine with a low pH

Changes in Blood Gases with Acidosis



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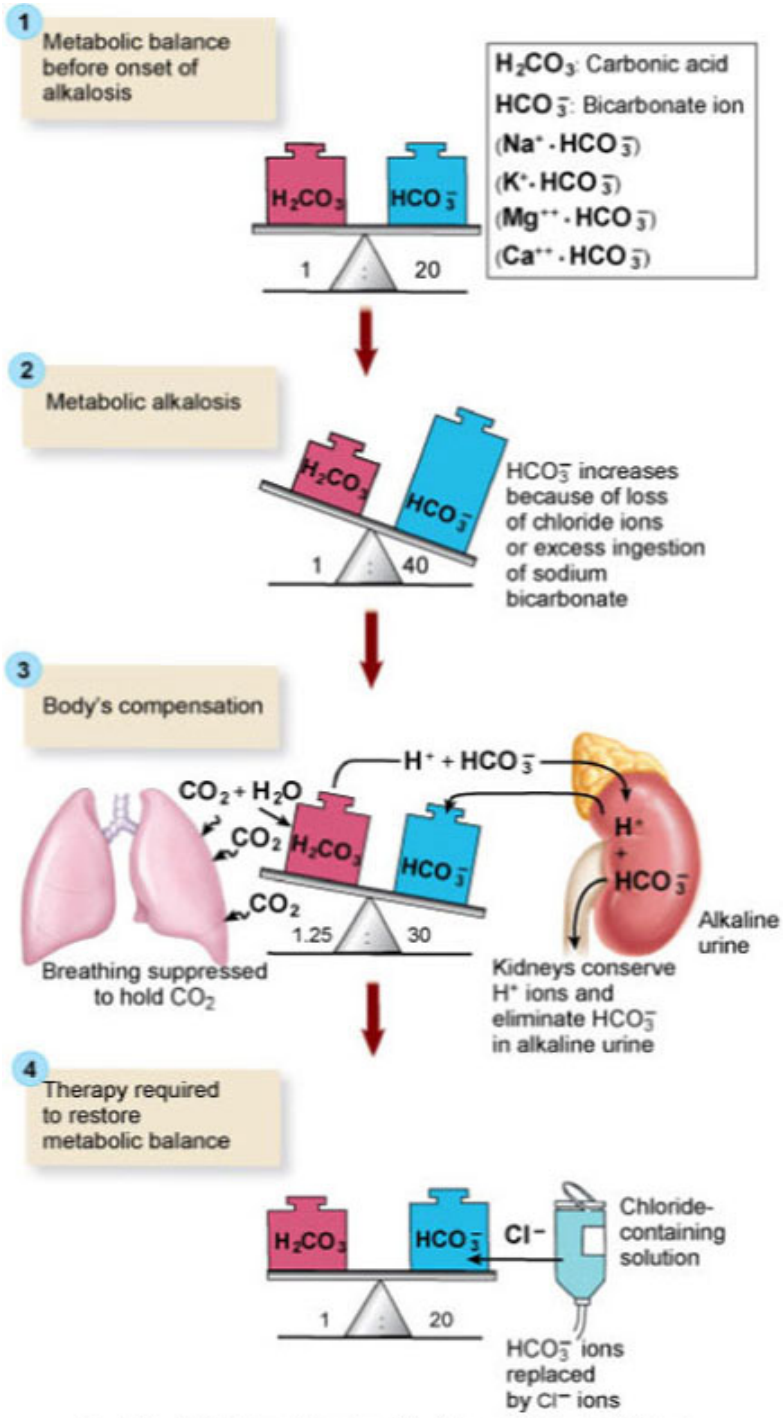
Changes in Blood Gases with Acidosis



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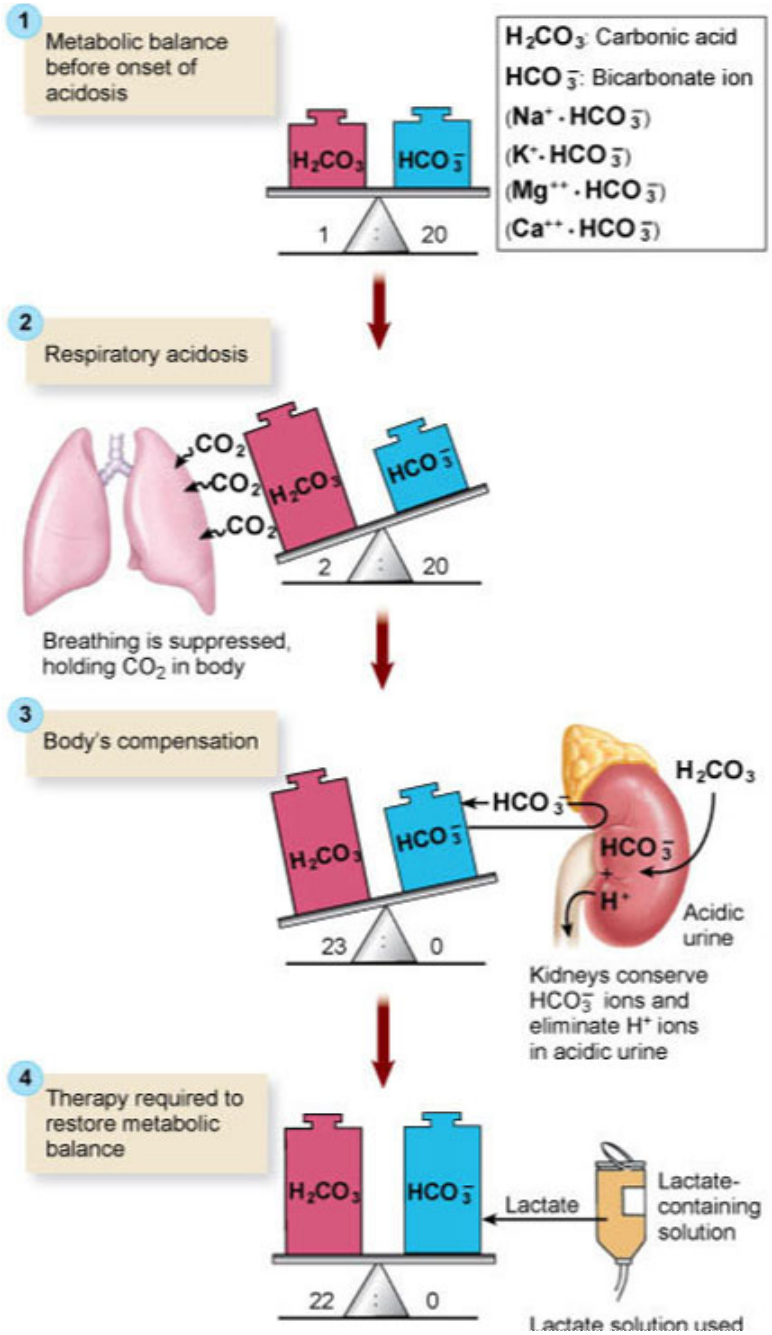
Changes in Blood Gases with Acidosis



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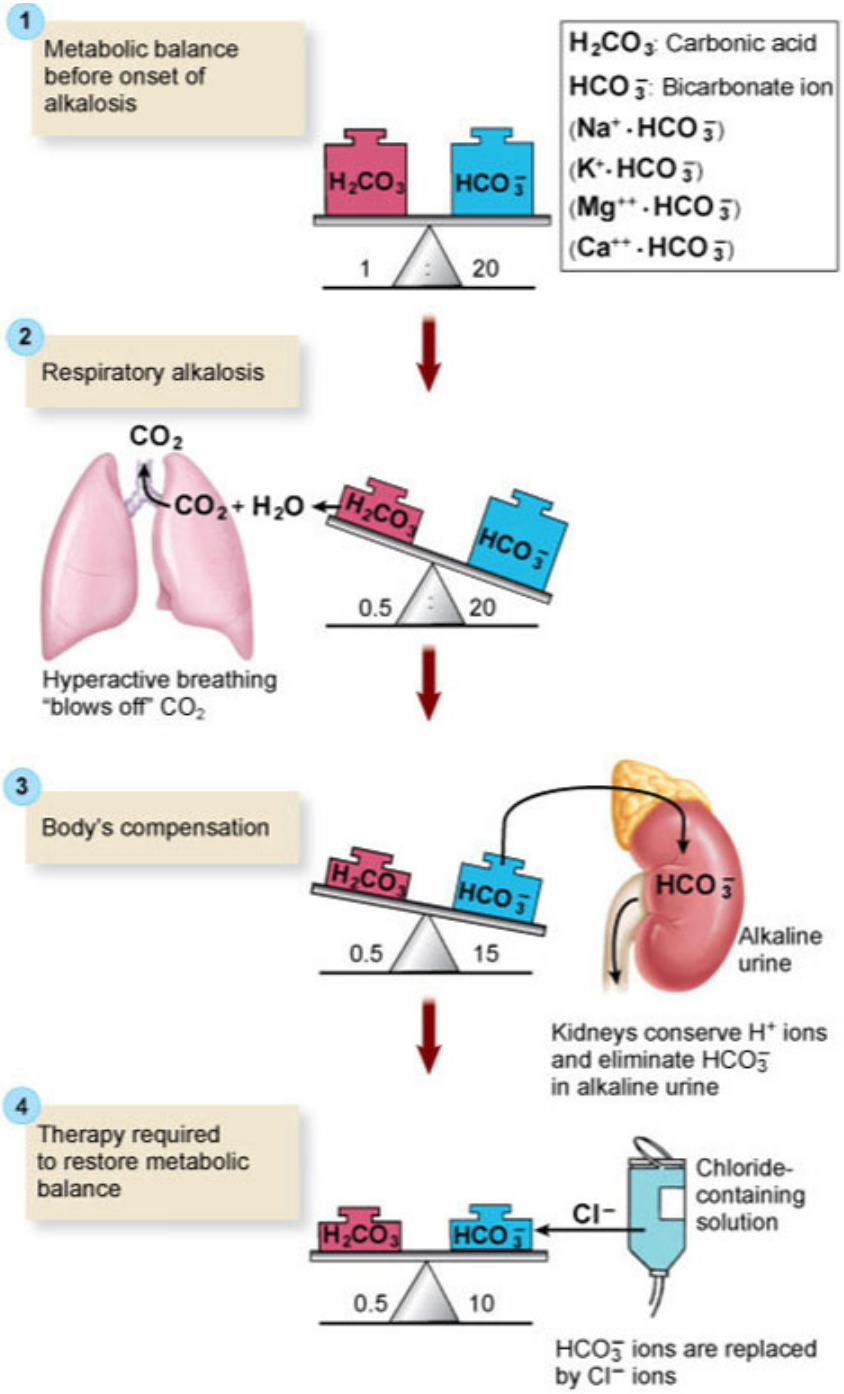

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TABLE 2-9 Examples of Acidosis

Respiratory Acidosis—Individual with Emphysema Retaining CO_2		
Stage 1:	Kidneys compensate for slight increase in P_{CO_2} by increasing excretion of acids and production of bicarbonate	No change in serum levels
Stage 2:	Increased retention of CO_2. Respiratory acidosis	Elevated P_{CO_2}
Stage 3:	Compensation. Kidneys reabsorb more bicarbonate	Elevated serum ions. bicarbonate
Stage 4:	Compensated respiratory acidosis: Abnormal serum values indicate problem and compensation adequate to maintain ratio and normal serum pH.	Serum pH = 7.35
Stage 5:	Decompensated respiratory acidosis: Patient acquires pneumonia, and much more CO_2 is retained. Also, kidneys cannot maintain compensation. Ratio is no longer normal, CNS depression, coma, and serum pH drops below the normal range.	Serum pH = 7.31

Alkalosis

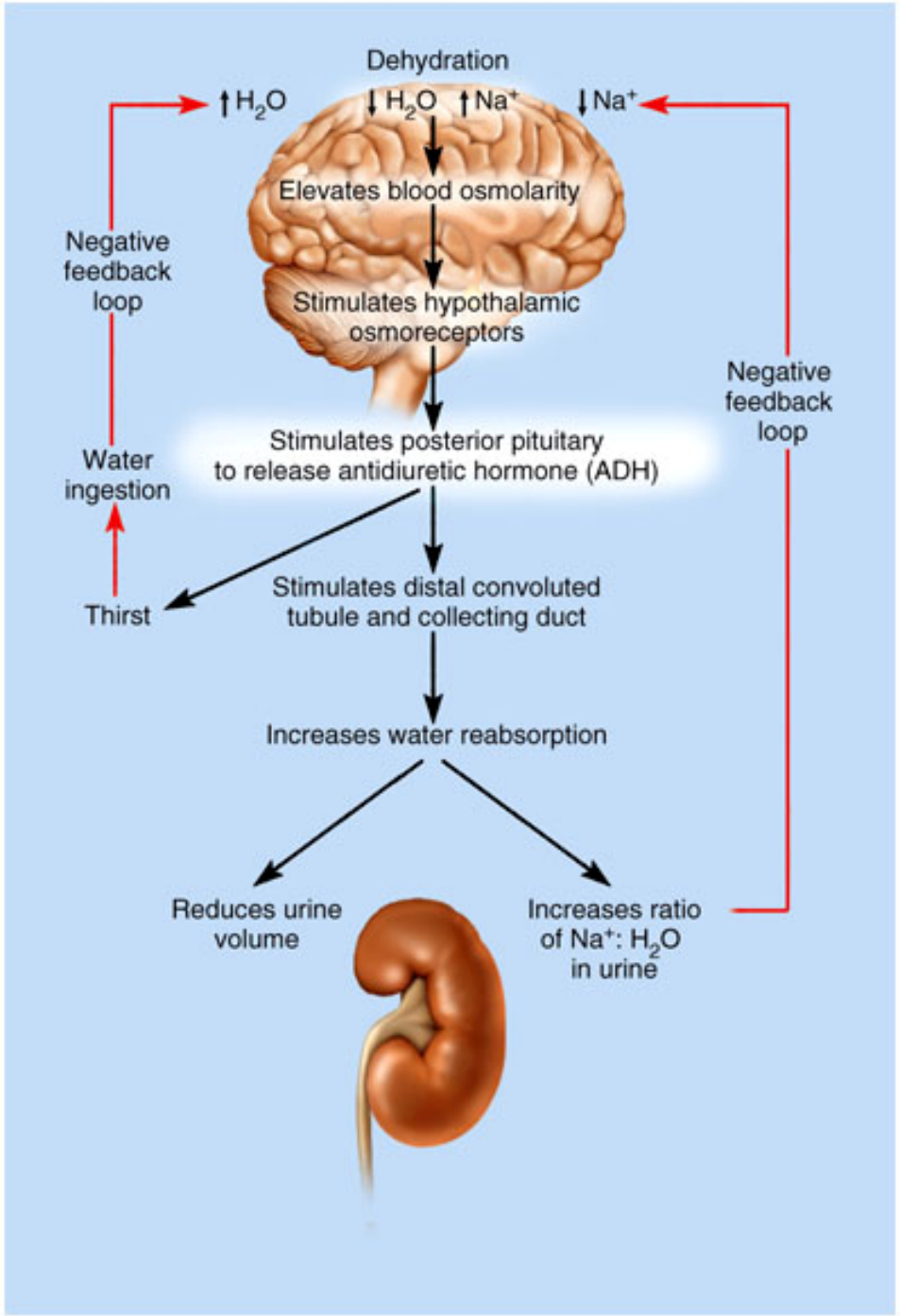
- Respiratory alkalosis
  - Hyperventilation
    - Caused by anxiety, high fever, overdose of aspirin
    - Head injuries
    - Brainstem tumor
- Metabolic alkalosis
  - Increase in serum bicarbonate ion
    - Loss of hydrochloric acid from stomach
    - Hypokalemia
    - Excessive ingestion of antacids

Effects of Alkalosis

- Increased irritability of the nervous system causes:
  - Restlessness
  - Muscle twitching
  - Tingling and numbness of the fingers
  - Tetany
  - Seizures
  - Coma

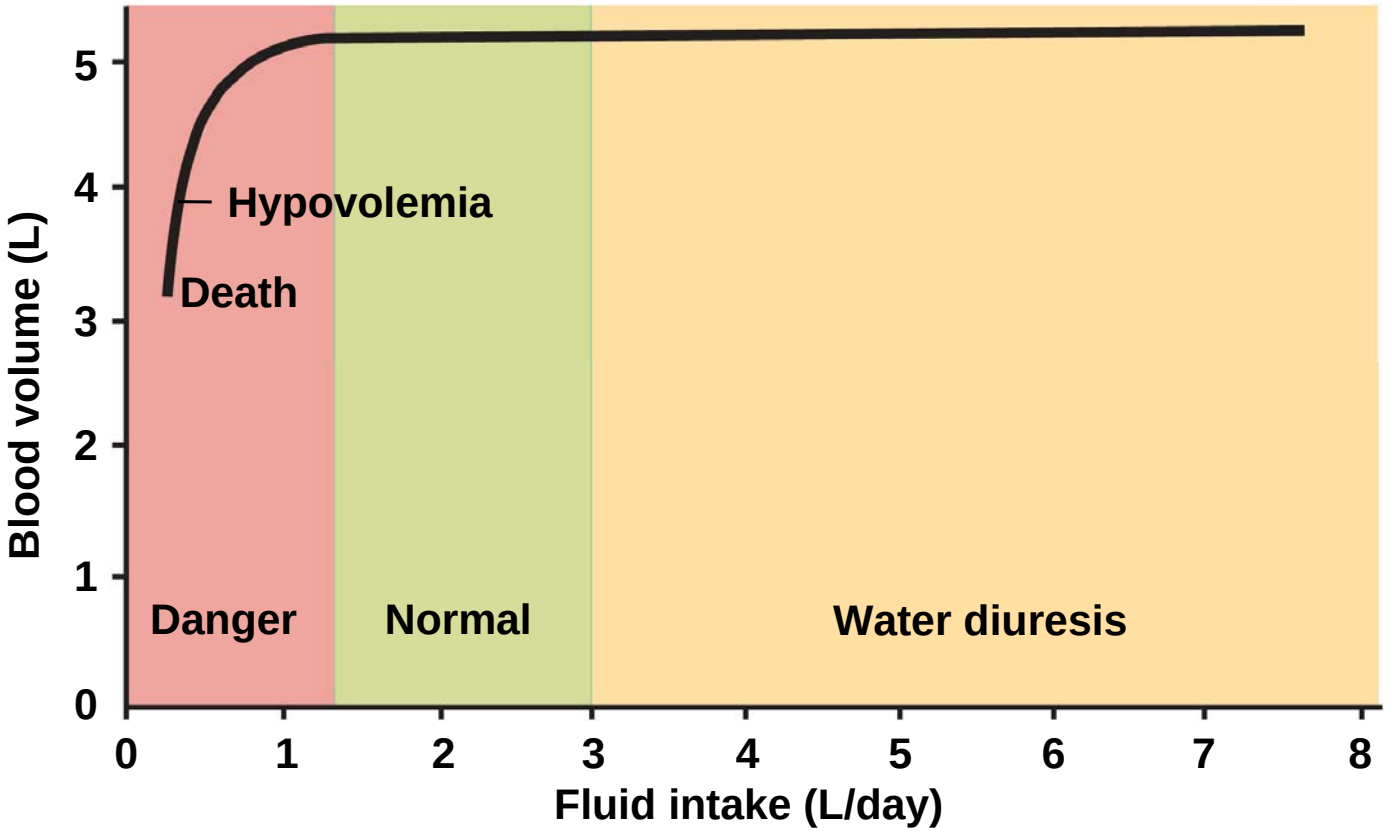
Treatment of Imbalances

- Treatment of underlying cause
- Immediate corrective measures to include fluid and electrolyte replacement or removal
  - Caution is required when adjusting fluid levels to ensure appropriate electrolyte balance.
- Addition of bicarbonate to the blood to reverse acidosis
- Modification of diet to maintain better electrolyte balance



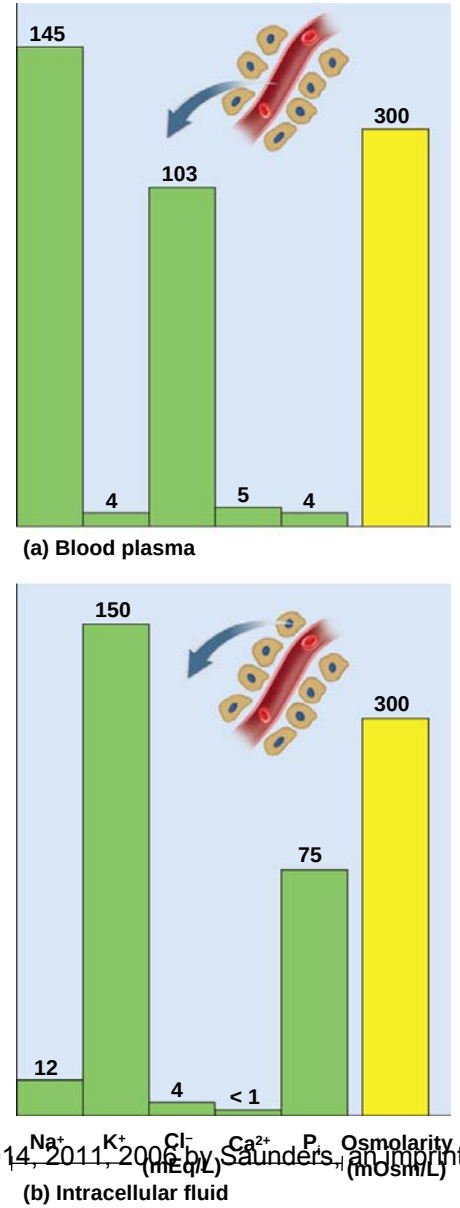
Secretion and Effects of ADH

Blood Volume and Fluid Intake

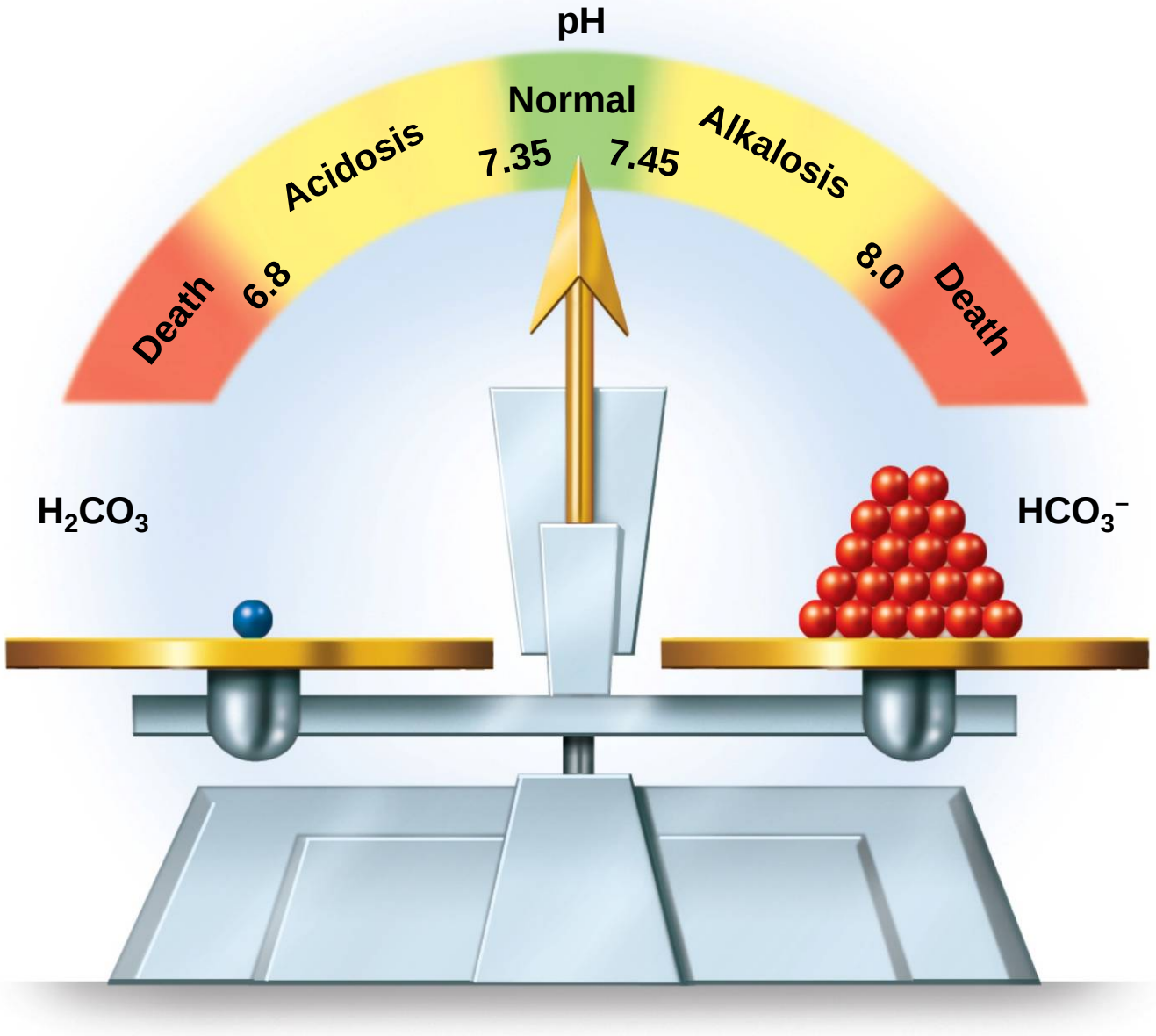


kidneys compensate very well for excessive fluid intake, but not for inadequate fluid intake

Electrolyte Concentrations

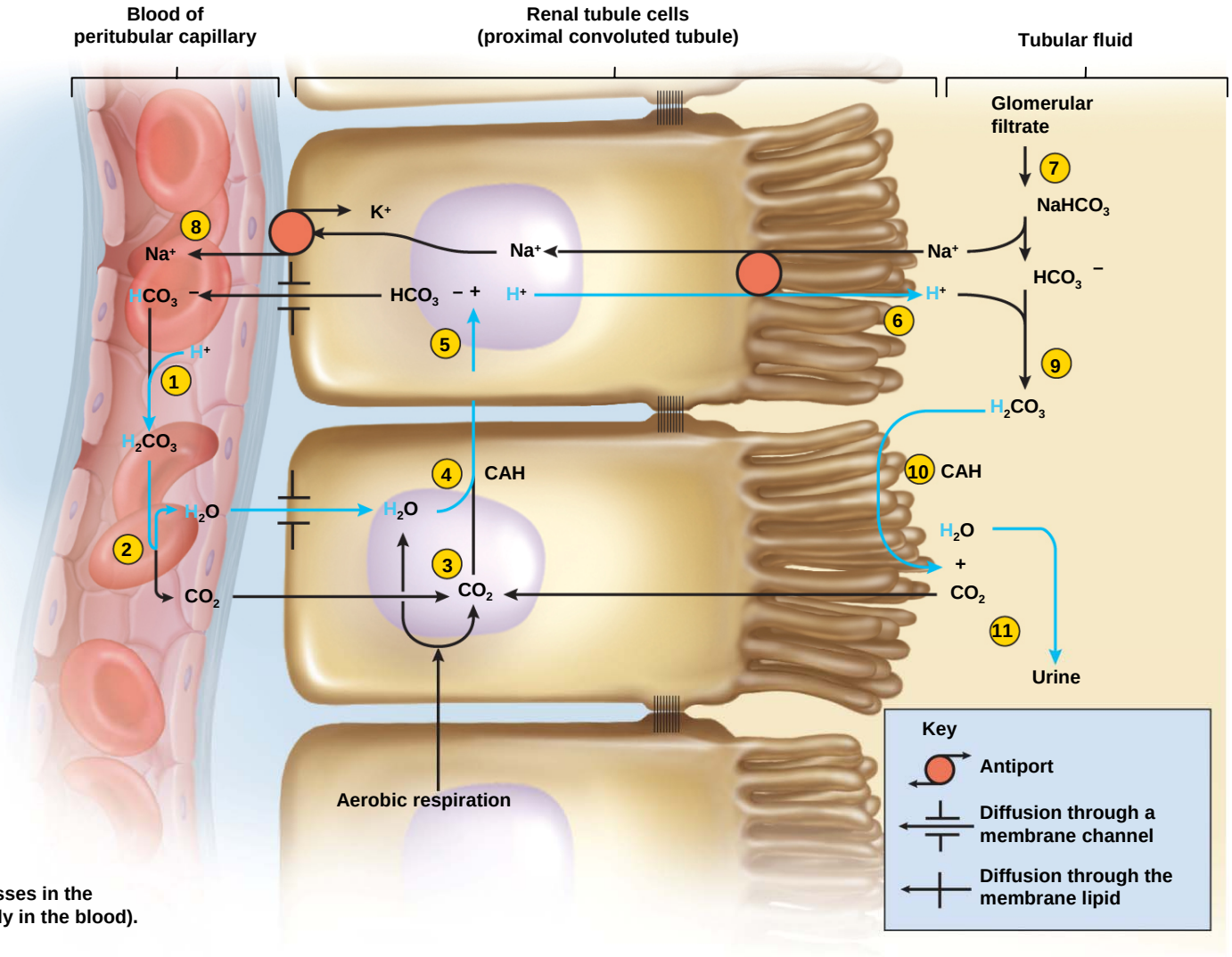


Acid-Base Balance

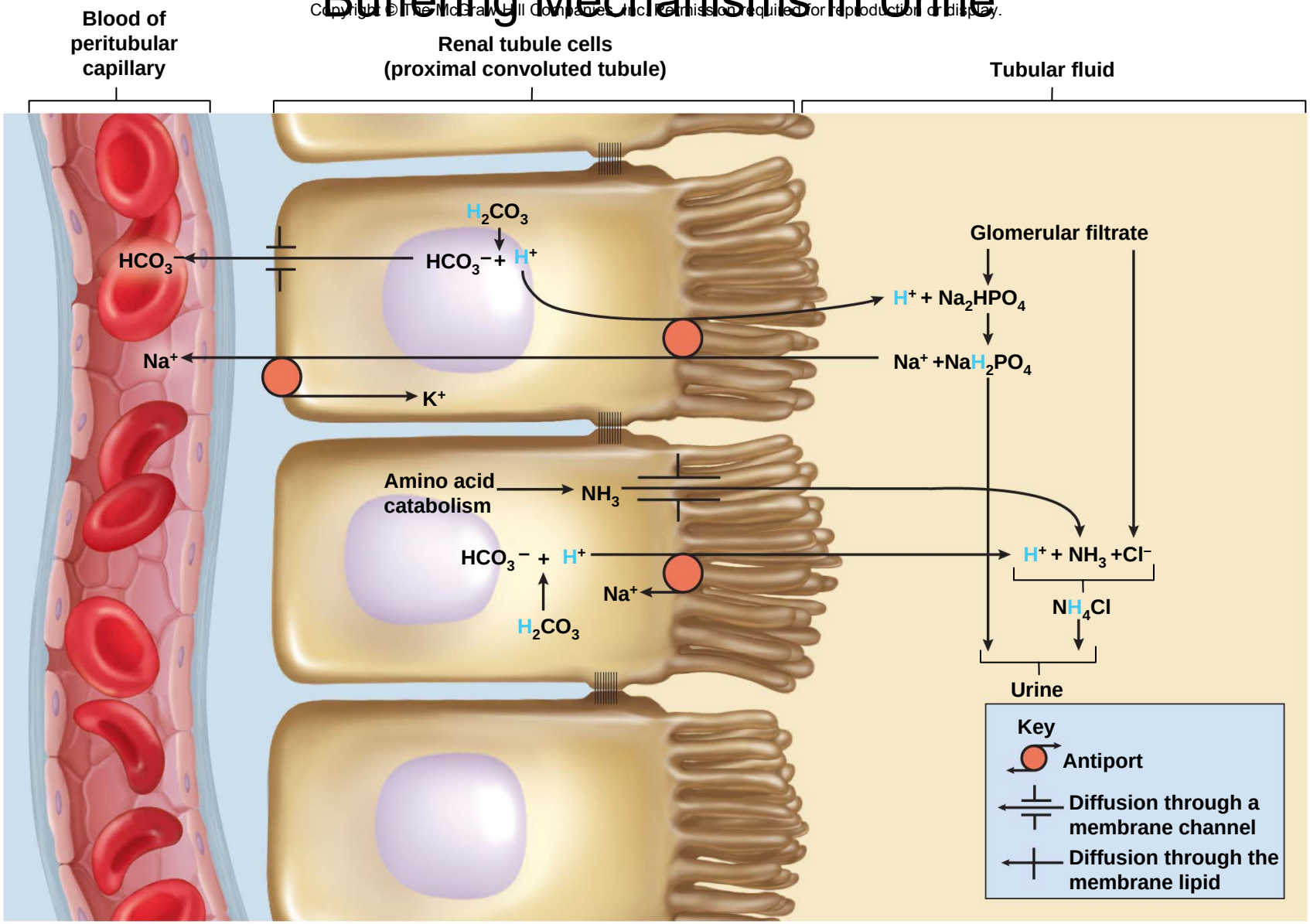


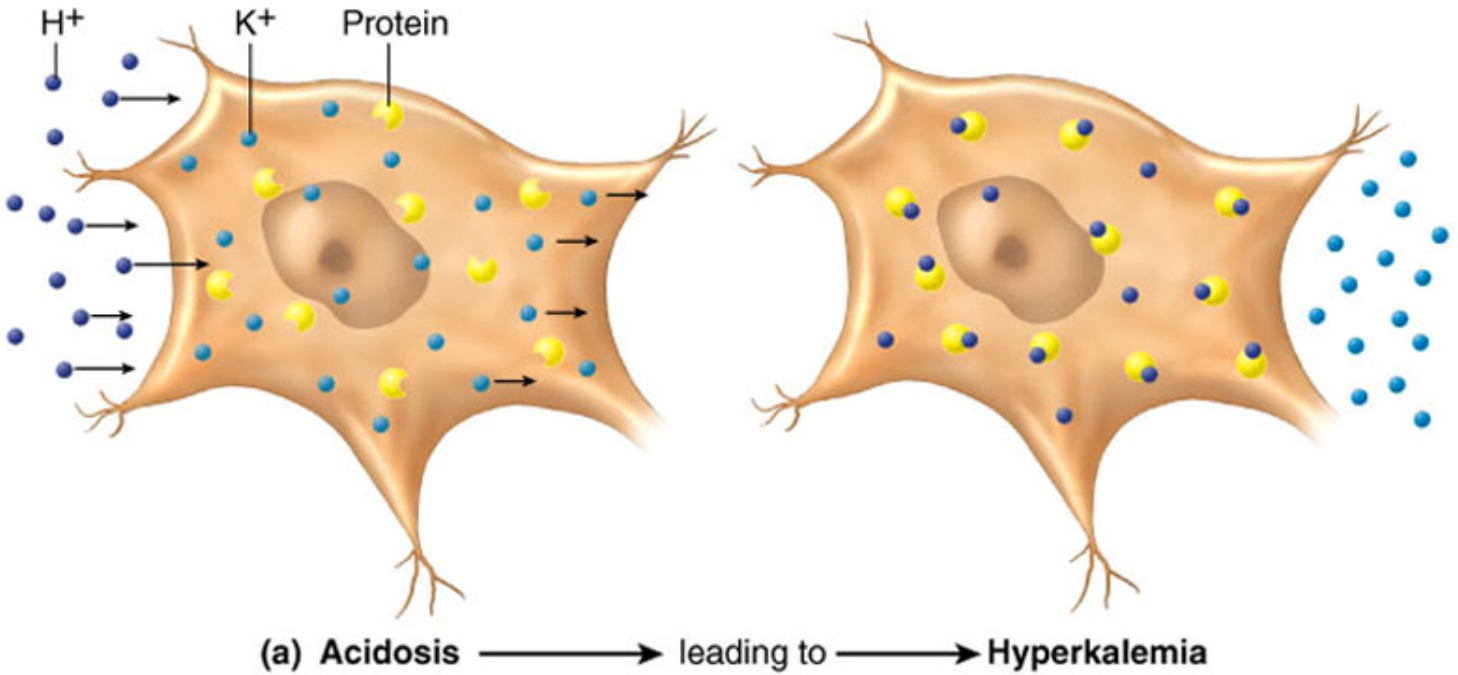
H^+ Secretion and Excretion in Kidney

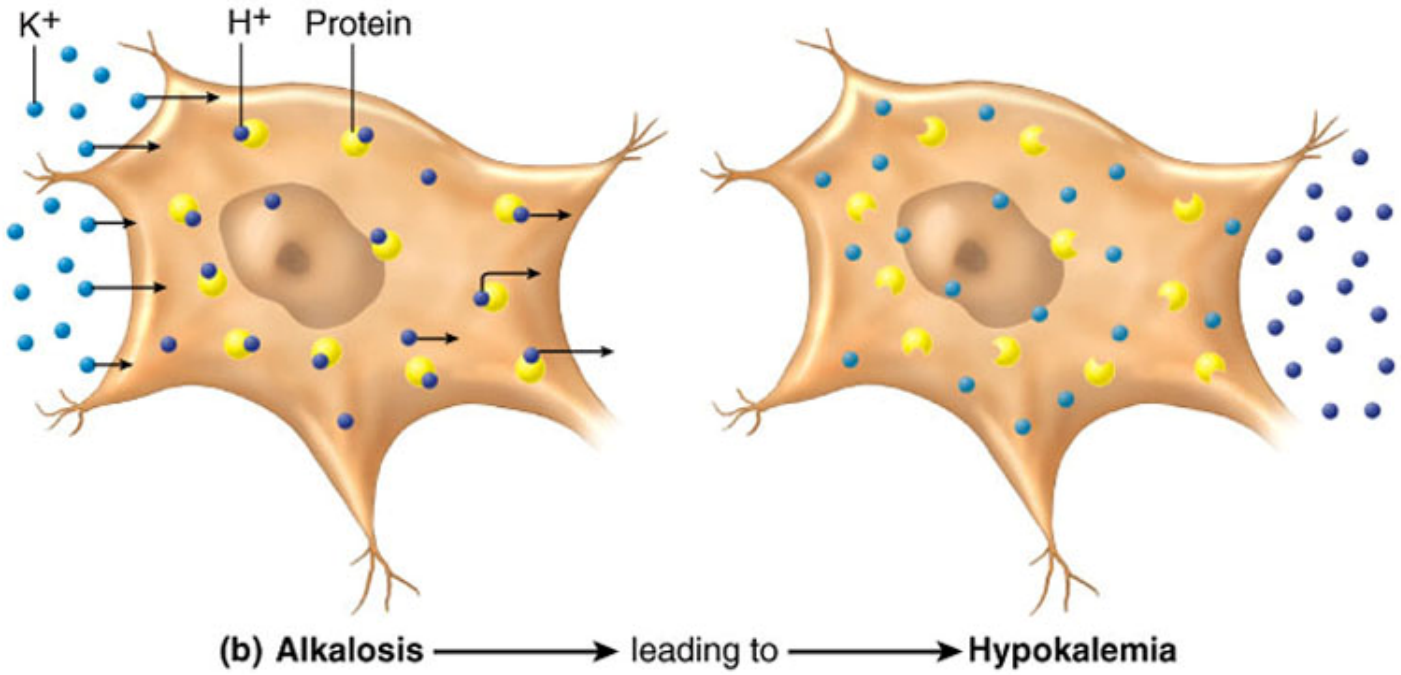
1. H^+ in blood reacts with HCO_3^- to form H_2CO_3.
2. H_2CO_3 decomposes into H_2O and CO_2, which enter the tubule cell.
3. Tubule cells acquire CO_2 from blood, tubular fluid, and their own aerobic respiration.
4. Carbonic anhydrase (CAH) combines H_2O and CO_2 to re-form H_2CO_3.
5. H_2CO_3 ionizes to form HCO_3^- (which returns to the blood) and H^+.
6. Na^+–H^+ antiport exchanges H^+ for Na^+.
7. $NaHCO_3$ from glomerular filtrate decomposes into Na^+ and HCO_3^-. Na^+ is pumped into tubule cell.
8. Na^+ is removed by Na^+–K^+ pump at the base of the cell.
9. HCO_3^- reacts with H^+ from tubule cell to form H_2CO_3.
10. CAH on brush border decomposes H_2CO_3 11111to H_2O and CO_2 again.
11. CO_2 enters the tubular cell and H_2O passes in the urine (carrying the H^+ that was originally in the blood).



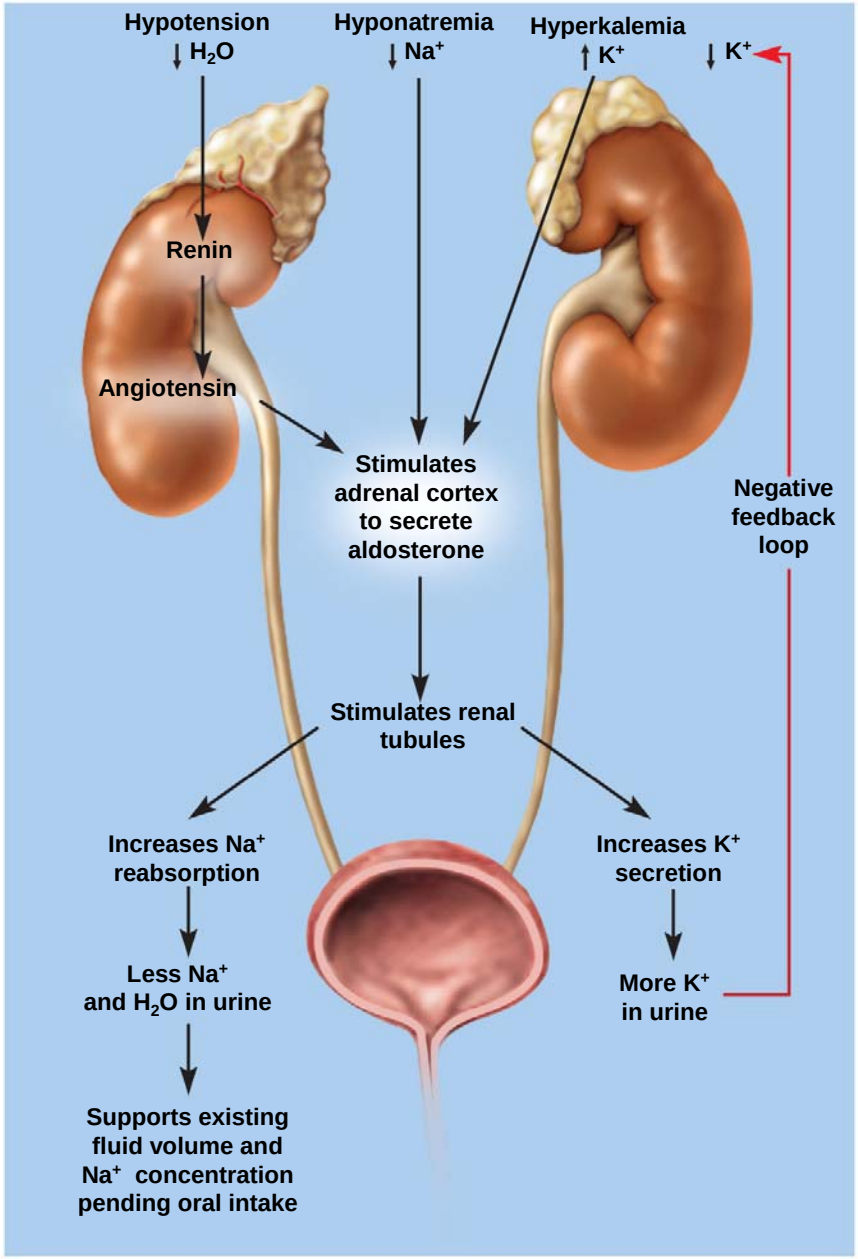
Buffering Mechanisms in Urine






K+
H+
Protein
(b) Alkalosis
leading to
Hypokalemia

Secretion and Effects of Aldosterone



LO

Potassium & Membrane Potentials