Fluid Compartments

- Total body water volume = 40 L, 60% body weight
  - Extracellular fluid volume = 15 L, 20% body weight
    - Intracellular fluid volume = 25 L, 40% body weight
    - Interstitial fluid volume = 12 L, 80% of ECF
    - Plasma volume = 3 L, 20% of ECF

Figure 26.1
Water is the universal solvent

Solutes are broadly classified into:

- Electrolytes – inorganic salts, all acids and bases, and some proteins- can dissociate in water
- Nonelectrolytes – (organic) examples include glucose, lipids, creatinine, most proteins and urea

Electrolytes have greater osmotic power than nonelectrolytes — Na+ is the most important

Water moves according to osmotic gradients
Electrolyte normal values

- Na+  135-145 mEq/L
- K+   3.5-5 mEq/L
- Ca+  4.3-5.3 mEq/L

- There are several others those above really important
  - Measured in milliequivalents per liter
    - # of electrical charges per liter of solution
Sodium (Na+)

- Most abundant cation in ECF
  - thanks to sodium potassium pump

- Primary role: regulation of ECF volume
  - Thus also regulates BP and ICF volume
    - Hypernatremia: excess Na+ in blood
    - Hyponatremia: low Na+ in blood
Potassium (K+)

- Most abundant cation in ICF
- Regulates neuron and muscle function
  - Maintains RMP
- Hyperkalemia: excess blood K+
- Hypokalemia: inadequate blood K+
Proteins in the blood

- Large molecules that typically remain in plasma
- Function to pull water from the interstitial space back into the capillaries
- Also holds water in the intracellular space
Osmolarity

- Concentration of solute particles in one liter (or gram) of water, reflects the ability to cause osmosis

- The higher the osmolarity of a solution the higher the amount of solutes present
Fluid shifts: Capillaries

**Key to pressure values:**
- $HP_c$ at arterial end = 35 mm Hg
- $HP_{if} = 0$ mm Hg
- $OP_{if} = 1$ mm Hg
- $HP_c$ at venous end = 17 mm Hg
- $OP_c = 26$ mm Hg

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Fluid shifts

ICF  InstF  Plasma

depends on membrane permeability and osmolarity of ECF
hydrostatic pressure colloid osmotic pressure (lymphatics take extra fluid)

Hydrostatic pressure = capillary blood pressure (forces fluid out of capillary) higher at the arterial end of the capillary and lower at the venous end

Colloid osmotic pressure = pressure of plasma proteins “drawing water into” the capillary (osmosis) – same at the arterial and venous ends

Result: fluid moves out of the capillary at the arterial end and into the capillary at the venous end, more fluid moves out than into the capillary. (lymphatic vessels of lymphatic system take up extra fluid)
Water Intake and Output

Average intake per day

- Metabolism 10%
- Foods 30%
- Beverages 60%

Total Average Intake: 250 ml + 750 ml + 1500 ml = 2500 ml

Average output per day

- Feces 4%
- Sweat 8%
- Insensible losses via skin and lungs 28%
- Urine 60%

Total Average Output: 100 ml + 200 ml + 700 ml + 1500 ml = 2500 ml

Figure 26.4
Regulation of Water **Intake:**

**Thirst Reflex**

- ↑ plasma osmolarity = ↑ Thirst (hypothalamus)
  - Drink fluids/water decreases plasma osmolarity
  - Hypothalamus also triggers release of ADH

- Inhibiting/quenching thirst:
  - Stretching of the stomach receptors
  - Moistening of the mucosa
Plasma osmolality ↑

Saliva ↓

Osmoreceptors in hypothalamus

Dry mouth

Plasma volume* ↓

Blood pressure ↓

Granular cells in kidney

Renin-angiotensin mechanism

Angiotensin II ↑

Hypothalamic thirst center

Sensation of thirst; person takes a drink

Water moistens mouth, throat; stretches stomach, intestine

Water absorbed from GI tract

Plasma osmolality ↓

(*Minor stimulus)

Key:

← Increases, stimulates

← Reduces, inhibits

Initial stimulus

Physiological response

Result

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Water Output

- Obligatory water loss
  - Insensible water loss
    - water loss through skin, lungs, feces, perspiration, etc.
  - Sensible water loss
    - water loss in urine
    - Minimum of 500mL daily to excrete wastes

- Actual daily water loss (in addition to obligatory) depends on exercise, diet, intake etc.
Regulation of Water Output

- ADH
- Aldosterone
- Cardiovascular Baroreceptors
- Atrial Natriuretic Peptide (factor/hormone)
- Others: estrogens, progesterone, glucocorticoids
Regulation of Water Output: ADH

- **Source:** Hypothalamus stored in posterior pituitary

- **Stimulus:** ↑ osmolarity of ECF or ↓ plasma vol. or BP

- **Function:** ↑ reabsorption of water in collecting duct of kidney (by increasing water permeability) ...
  - ↓ water excreted
  - Forms concentrated urine
Regulation of Water Output: Aldosterone

- **Source:** Adrenal cortex

- **Stimulus:**
  - Renin-Angiotensin mechanism:
    - JG apparatus responds to decreased stretch (↓ BP or vol), ↓ filtrate osmolarity (solute conc.), sympathetic NS
    - ↓ Na + or ↑ K+ in plasma

- **Function:** ↑ Na+ and water reabsorption in DCT of kidney and ↑ K+ excretion in urine
Regulation of Water Output:

Cardiovascular Baroreceptors

- Baroreceptors pickup stretch >> Less = low BP >> stimulate sympathetic nervous system
  - Vasoconstriction
  - Renin release > Angiotensin II > inc BP
Regulation of Water Output:

**Atrial Natriuretic Peptide (ANP)**

- **Source:** atria
- **Stimulus:** high blood pressure
- **Functions:** Decrease blood volume and pressure by inhibiting renin release. Result is ↑ Na+ and water excretion in urine/ also vasodilation
Other Water Balance Hormones

- Estrogens
  - Enhance NaCl reabsorption (water retention)

- Progesterones
  - Decrease Na reabsorption (water loss)

- Glucocorticoids (cortisol)
  - Enhance Na reabsorption
  - Increase GFR
    - High levels promote edema
Disorders of Water Balance

- Type of fluid imbalance depends on cause and type of fluid loss:
  - Dehydration
  - Hypotonic hydration
  - Edema
Disorders of Water Balance: Dehydration

- Water lost from ECF followed by osmotic movement of water from ICF to ECF

- Causes:
  - gastrointestinal tract irritation is most common
  - Hemorrhage
  - Decreased water intake &/or excess solute intake
  - Lack of ADH

- Symptoms of dehydration:
  - Weight loss, ↓ BP ↑ HR
Disorders of Water Balance: Dehydration

(a) Mechanism of dehydration
Disorders of Water Balance:

Hypotonic Hydration

- A.k.a. water intoxication, overhydration
- Excess water in ECF and hyponatremia (low Na+ in ECF) causing excess fluid movement into the cells

Causes:
- Excess water intake in short period
- Renal failure

Symptoms:
- Nausea, vomiting, muscle cramps, cerebral edema, acute weight gain, increased BP, pulmonary edema
Disorders of Water Balance:
Hypotonic Hydration

Figure 26.7b

1. Excessive $\text{H}_2\text{O}$ enters the ECF
2. ECF osmotic pressure falls
3. $\text{H}_2\text{O}$ moves into cells by osmosis; cells swell

(b) Mechanism of hypotonic hydration
Disorders of Water Balance: Edema

- Excess fluid in the interstitial space / tissue swelling
- Causes:
  - Increased BP &/or increased capillary permeability
  - Incompetent venous valves, localized blood vessel blockage, lymphatic blockage
  - Congestive heart failure, hypertension, high blood volume
- Symptoms:
  - Tissue swelling
Acid-Base Balance

- pH scale:
  - 0: Acid
  - 7: Neutral
  - 14: Base

- Blood pH = 7.35 - 7.45
- Blood pH > 7.45 = alkalosis
- Blood pH < 7.35 = acidosis

Nearly all biochemical reactions are influenced by pH
Behavior of Strong Acids & Bases

- **Acid: H+ donor**
  - Strong acids dissociate completely (donate all H+)
  - Weak acids do not dissociate completely (donate less H+)

- **Base: H+ acceptor**
  - Strong bases dissociate completely (receive H+ quickly)
  - Weak bases dissociate partially (receive H+ slowly)
Sources for H+

- Most produced by cellular metabolism
  - Phosphoric acid
  - Lactic acid
  - Fatty acids & ketone bodies
  - CO2 conversion to HCO3- in blood (for transport)
Regulation of Acid-Base Balance

- Concentration of hydrogen ions regulated by:
  - Chemical buffer systems
    - carbonic acid/ bicarbonate
      - most important chemical buffer
      - Acts within seconds
  - Respiratory regulation
    - Acts within 1-3 minutes
  - Renal regulation
    - Requires hours-days to effect pH changes
Regulation of Acid-Base Balance: Chemical Buffer Systems

- Chemical buffers: system of one or more molecules that act to resist pH changes when strong acid or base is added

- Most important chemical buffer system:
  - Bicarbonate buffer system

- Others: phosphate buffer system & protein buffer system
Bicarbonate Buffer System

- CO$_2$ + H$_2$O $\rightleftharpoons$ H$_2$CO$_3$ $\rightleftharpoons$ H$^+$ + HCO$_3^-$

  Carbon dioxide  Carbonic acid  bicarbonate ion

- Important parameters:
  - H$_2$CO$_3$ regulation via CO$_2$ regulation  Lungs
  - HCO$_3^-$ regulation  Kidneys
Regulation of Acid-Base Balance: 

Respiratory Regulation

- CO2 retention (excess) = acidosis
- CO2 loss (excess loss) = alkalosis

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

- Compensation:
  - Excess CO2 $\rightarrow$ ↑ respiratory rate and depth $\rightarrow$ blow off CO2 and H+ goes into H2O (shift equation to left)
  - Inadequate CO2 $\rightarrow$ ↓ respiratory rate and depth (conserve CO2 and H+) (shift equation to the right)
Regulation of Acid-Base Balance:

Renal Regulation

- Kidney makes, reabsorbs and excretes $\text{HCO}_3^-$
- Reabsorb $\text{HCO}_3^-$ & excrete $\text{H}^+$

Compensation:
- As $\text{CO}_2$ content of blood $\uparrow$ (acidosis), $\text{H}^+$ is excreted and $\text{HCO}_3^-$ is retained
- As $\text{CO}_2$ content of blood $\downarrow$ (alkalosis), is $\text{HCO}_3^-$ excreted and $\text{H}^+$ is retained
Respiratory Abnormalities of Acid-Base Balance

- Result from failure of respiratory system to perform normal pH balancing role
- Normal values: pH 7.35-7.45
  - pCO2 35-45 mmHg

- Imbalances:
  - Respiratory acidosis = pCO2 above 45mmHg (most common)
    - Due to decreased ventilation or gas exchange
  - Respiratory alkalosis = pCO2 below 35mmHg
    - Result of hyperventilation due to stress or pain
Respiratory Acidosis

- Most common acid-base imbalance
- pH < 7.35 ; pCO2 > 45 mmHg
- Cause: hypoventilation
  - CO2 retention, impaired lung function (i.e. emphysema, chronic bronchitis, cystic fibrosis), narcotic overdose
- Symptoms: headache, disorientation, cardiac palpitations
- Renal compensation: HCO3-
Respiratory Alkalosis

- pH > 7.45; pCO2 < 35mmHg
- Cause: Hyperventilation
  - Pain, anxiety, fear, hypoxia (i.e. asthma, pneumonia, high altitude)
- Symptoms: numbness, tetany, deep and rapid respiration, etc
- Renal compensation: HCO3- loss
Metabolic Abnormalities of Acid-Base Balance

- Any pH imbalance not caused by abnormal blood CO2 levels
- Normal values: pH 7.35-7.45
  HCO3- 22-26 mEq/L

- Imbalances:
  - Metabolic acidosis = HCO3- below 22mEq/L
  - Metabolic alkalosis = HCO3- above 26mEq/L
Metabolic Acidosis

- Second most common acid-base imbalance
- pH < 7.35; HCO₃⁻ < 22mEq/L
- Causes: diarrhea, diabetes mellitus (uncontrolled), starvation, renal disease, too much alcohol ingestion, accumulation of lactic acid
- Symptoms: hyperventilation, disorientation, weakness, etc
- Respiratory compensation: ↑resp. rate to “blow off” CO₂
Metabolic Alkalosis

- pH > 7.45 ; HCO3- > 26 mmHg
- Causes: Vomiting, excess antacid intake, excess aldosterone
- Symptoms: numbness, tetany, cramps
- Respiratory compensation: ↓ Respiratory rate
Respiratory & Renal Compensations

- When an acid-base imbalance occurs then other systems try to compensate.
- The respiratory will attempt to compensate for the kidneys (metabolic) and vice versa.
- You can have a patient who has a severe condition and will have a normal blood pH— you must look at the details—usually will still alter pH.
- Examine changes in depth and breathing rate, in pCO2 levels, and in bicarbonate levels- to determine respiratory or metabolic causes and compensations.
Respiratory & Renal Compensations

In the following: what is the condition? Is there compensation? If yes is it renal or respiratory?

1. pH 7.5: PCO$_2$ 24 mmHg; HCO$_3$ 23 mEq/L
2. pH 7.6; PCO$_2$ 46 mmHg; HCO$_3$ 43mEq/L
3. pH 7.2; PCO$_2$ 50 mmHg; HCO$_3$ 32 mEq/L
4. pH 7.5; PCO$_2$ 22 mmHg; HCO$_3$ 20 mEq/L
5. pH 7.25; PCO$_2$ 38 mmHg; HCO$_3$ 20 mEq/L

Normal ranges: pH 7.35-7.45; PCO2 35-45mmHg; HCO3- 22-26mEq/L
Determining Cause of Acidosis/Alkalosis

- Be systematic:
  - Check pH
  - Check pCO2
    - This will tell you the cause of pH
    - Remember Respiratory system is FAST ACTING
  - Check bicarbonate (HCO3-)

- Ex. If pH indicates acidosis (low pH), pCO2 levels are high (=respiratory acidosis), bicarb will be high if renal is compensating (regular bicarb if not)
Answers:

1. Respiratory alkalosis (low PCO2), no renal compensation (HCO3 in normal range)
2. Metabolic alkalosis- (high HCO3), high PCO2 indicates respiratory compensation
3. Respiratory acidosis- (high PCO2), high HCO3 indicates renal compensation
4. Respiratory alkalosis (low PCO2), low HCO3 indicates renal compensation
5. Metabolic acidosis (low HCO3), normal PCO2 indicates NO respiratory compensation
Respiratory & Renal Compensations

- **Respiratory compensations:**
  - **Metabolic acidosis** – blood pH below 7.35 - the respiratory rate and depth are elevated - since it is metabolic the bicarbonate level is lower than normal - and the respiratory system is attempting to compensate by blowing off CO2 as it does so pCO2 levels fall below normal.
  - If it were respiratory acidosis - you would see again a low pH but the respiratory rate and depth would be lower than normal (or impairment of gas exchange) — and an increase in pCO2 the reason for the acidosis -
  - **Metabolic alkalosis** - high pH resulting from high bicarbonate levels respiratory compensates by - slow shallow breathing to increase pCO2 levels increasing H+ concentration
Renal Compensations

- Metabolic (renal) compensations:
  - Respiratory acidosis - low pH; both PCO2 and Bicarbonate (HCO3-) levels are high—low rate depth of breathing causes the increase in PCO2 and the kidneys attempt to compensate by increasing bicarbonate.
  - Respiratory alkalosis - high pH, PCO2 is low and bicarbonate is low—low PCO2 is the cause and kidneys attempt to compensate with bicarbonate secretion.
Effects of acidosis and alkalosis

- Blood pH below 7.0
  - depressed nervous system - coma and death

- pH above 7.8
  - overexcited nervous system - muscle tetany, nervousness and convulsions - respiratory failure