iii. Respiratory and Circulatory Systems

iii. Respiratory and Circulatory Systems – Breathing and exchange of gases, Body fluids and circulation

Respiratory System: Breathing and Exchange of Gases

Overview of Respiratory Anatomy

1. **Conducting Zone**
   - Includes the nose, pharynx, larynx, trachea, bronchi, and bronchioles.
   - Functions to warm, humidify, and filter inhaled air. Lined with pseudostratified ciliated epithelium, mucus-secreting goblet cells.
   - No gas exchange occurs here; it is known as the **anatomical dead space**.
2. **Respiratory Zone**
   - Respiratory bronchioles, alveolar ducts, and alveoli.
   - **Alveoli** are the primary sites of gas exchange; extremely thin walls facilitate diffusion between air and pulmonary capillaries.
3. **Alveolar Structure**
   - **Type I Pneumocytes**: Squamous epithelial cells forming most of the alveolar surface area (gas exchange).
   - **Type II Pneumocytes**: Produce and secrete **surfactant**, which reduces surface tension, preventing alveolar collapse (atelectasis).
   - **Alveolar Macrophages** (Dust Cells): Remove particulate matter/pathogens.

Mechanics of Breathing (Ventilation)

1. **Inspiration**
   - Diaphragm contraction (major inspiratory muscle) flattens the dome, increasing thoracic volume. External intercostal muscles elevate ribs, expanding the thoracic cavity.
   - **Intrapleural Pressure** becomes more negative, leading to expansion of alveoli and **inflow of air**.
2. **Expiration**
   - Typically passive during quiet breathing: the diaphragm relaxes, elastic recoil of the lungs and chest wall decreases thoracic volume.
   - Forced expiration (e.g., during exercise) involves internal intercostals and abdominal muscles.
3. **Lung Compliance and Elastic Recoil**
   - **Compliance**: Change in lung volume per unit change in transpulmonary pressure. Enhanced by surfactant and healthy lung parenchyma.
   - **Elastic Recoil**: Opposing force that drives expiration, dependent on elastic fibers and alveolar surface tension.
4. **Spirometry**
   - Measures lung volumes and capacities (e.g., tidal volume, vital capacity, residual volume).
   - Evaluates respiratory function; abnormal patterns distinguish obstructive vs. restrictive lung diseases.

Gas Exchange

1. **Partial Pressures and Diffusion**
   - **Dalton's Law**: Total pressure of a gas mixture is the sum of partial pressures of individual gases.
   - In alveoli, **PO_2** is lower and **PCO_2** is higher than in inspired air due to mixing with residual volume and continuous exchange with blood.
   - **Fick's Law** of diffusion: Rate of gas transfer ∝ (surface area × partial pressure gradient) / thickness of the membrane.
2. **Pulmonary Circulation**
   - Low-pressure, high-flow system. Each alveolus is surrounded by dense capillary networks.
   - **Ventilation-Perfusion (V/Q) Matching**: Optimal matching of alveolar airflow (ventilation) to capillary blood flow (perfusion) ensures efficient gas exchange.
3. **Oxygen and Carbon Dioxide Transport**
   - **O_2 Transport**: ~98.5% bound to hemoglobin (Hb) in RBCs; ~1.5% dissolved in plasma. The **Hb-O_2**

dissociation curve is sigmoidal; influenced by pH, temperature, CO_2, and 2,3-BPG (Bohr effect).
    - **CO_2 Transport**: ~10% dissolved in plasma, ~20% bound to Hb as carbaminohemoglobin, ~70% converted to bicarbonate (HCO_3^-) via carbonic anhydrase in RBCs (Chloride shift exchanges Cl^- with HCO_3^-).
4. **Regulation of Breathing**
    - **Medullary Respiratory Centers** (dorsal and ventral respiratory groups) generate basic rhythmic breathing.
    - **Pontine Centers** (pneumotaxic, apneustic) modulate medullary signals.
    - **Chemoreceptors**:
        - **Central** (in medulla) primarily respond to CO_2 (via pH changes in cerebrospinal fluid).
        - **Peripherals** (carotid and aortic bodies) respond to low PO_2 (<60 mmHg), high PCO_2, and low pH.
    - **Neural and Chemical Feedback**: Adjust ventilatory rate and depth to maintain arterial PO_2 ~95-100 mmHg and PCO_2 ~40 mmHg.

Circulatory System: Body Fluids and Circulation

Components of Body Fluids

1. **Blood**
    - Plasma (~55%): Water, electrolytes (Na^+, Cl^-, HCO_3^-, K^+), proteins (albumin, globulins, fibrinogen), nutrients, waste products.
    - Formed Elements (~45%): RBCs (erythrocytes), WBCs (leukocytes), and platelets (thrombocytes).
    - **Hematocrit**: Percentage of RBCs in total blood volume. Typically ~45% in males, ~40% in females.
2. **Interstitial Fluid (ISF)**
    - Surrounds tissue cells; formed by filtration and diffusion from capillaries.
    - Composition similar to plasma but lower protein content.
3. **Lymph**
    - Formed from interstitial fluid entering lymphatic vessels; returns to circulation via thoracic duct or right lymphatic duct.

The Heart and Cardiac Cycle

1. **Heart Anatomy**
    - Four chambers: Right atrium and ventricle (pulmonary circuit), left atrium and ventricle (systemic circuit).
    - **Valves**: Tricuspid, pulmonary semilunar, mitral (bicuspid), aortic semilunar; ensure unidirectional flow.
2. **Cardiac Cycle Phases**
    - **Atrial Systole**: Contraction of atria forces additional blood into ventricles.
    - **Ventricular Systole**: Increase in pressure closes AV valves and eventually opens semilunar valves, ejecting blood into pulmonary trunk and aorta.
    - **Diastole**: Relaxation, semilunar valves close, ventricles fill passively from atria.
3. **Conduction System**
    - **SA (Sinoatrial) Node**: Pacemaker setting intrinsic rate (~100 bpm, modulated by autonomic nerves).
    - **AV (Atrioventricular) Node**: Delays conduction, allowing ventricles to fill before contraction.
    - **Bundle of His** and **Purkinje Fibers**: Rapidly transmit impulses throughout ventricles for coordinated contraction.
4. **Regulation of Heart Rate and Contractility**
    - **Sympathetic Stimulation** (β_1-adrenergic receptors) increases rate (chronotropy) and contractility (inotropy).
    - **Parasympathetic Vagus Nerve** (muscarinic receptors) decreases heart rate.
    - **Hormones** (adrenaline, thyroid hormones) and **ion concentrations** (Ca^{2+}, K^+) also modulate cardiac function.

Blood Vessels and Hemodynamics

1. **Blood Vessel Types**
    - **Arteries**: Thick-walled, high-pressure distribution vessels. Elastic fibers dampen pulsatile flow.

- **Arterioles**: Main resistance vessels controlling regional blood flow (regulated by sympathetic tone, local metabolites).
- **Capillaries**: Thin-walled, site of nutrient and gas exchange. Types include continuous, fenestrated, sinusoidal.
- **Venules and Veins**: Low-pressure return vessels, valves prevent backflow, serve as volume reservoirs.

2. **Blood Pressure and Flow**
   - Governed by **Ohm's Law**: Flow = ΔP / Resistance.
   - **Systemic Arterial Pressure** regulated by cardiac output (CO = HR × SV) and peripheral resistance (TPR).
   - **Mean Arterial Pressure (MAP)** ~ Diastolic Pressure + (Pulse Pressure/3), ensures organ perfusion.
3. **Microcirculation and Capillary Exchange**
   - **Starling Forces**: Hydrostatic pressure vs. oncotic (colloid osmotic) pressure balance fluid movement across capillary beds.
   - Net filtration at arteriole end, net absorption at venule end; excess fluid drained by lymphatics.
4. **Regulation of Circulation**
   - **Baroreceptor Reflex** (carotid sinus, aortic arch): Rapid adjustments of heart rate and vascular tone via CNS integration.
   - **Chemoreceptor Reflexes** (carotid, aortic bodies): Sense changes in O_2, CO_2, pH, adjust ventilation and cardiovascular function.
   - **Renin-Angiotensin-Aldosterone System (RAAS)**: Long-term control of blood volume and pressure.
   - **Local Autoregulation**: Tissues adjust blood flow based on metabolic needs (e.g., vasodilation in response to low O_2, high CO_2, adenosine, nitric oxide).

Integration of Respiratory and Circulatory Functions

1. **O_2 and CO_2 Transport**
   - Adequate pulmonary ventilation ensures alveolar PO_2 is high enough for hemoglobin saturation.
   - Cardiac output and regional blood flow must meet tissue demands for O_2 and nutrient delivery, CO_2 and waste removal.
2. **Exercise Physiology**
   - Increased metabolic demands require elevated ventilation (hyperpnea) and cardiac output.
   - Redistribution of blood flow to active skeletal muscles (via vasodilation and sympathetic constriction in less active regions).
   - Hemoglobin–O_2 dissociation curve shifts (Bohr effect) favor O_2 release in active tissues.
3. **Clinical Correlations**
   - **Hypoxia** (low tissue oxygen) or **Hypercapnia** (high CO_2) may result from respiratory or circulatory insufficiency.
   - **COPD, Asthma**: Obstructions alter airway resistance, impair gas exchange.
   - **Heart Failure, Shock**: Deficient cardiac output or circulatory volume compromises tissue perfusion and gas exchange.
   - **High Altitude**: Lower ambient PO_2 → increased ventilation, erythropoietin-mediated RBC production, adaptation to maintain oxygenation.

Concluding Remarks

Breathing and gas exchange in the **respiratory system** and the **transport of nutrients, gases, and wastes** by the **circulatory system** are tightly integrated to sustain aerobic metabolism. **Ventilation** (movement of air into and out of the lungs) must be matched to **perfusion** (blood flow), ensuring efficient oxygen uptake and carbon dioxide elimination. Concomitantly, the **cardiovascular system** maintains the pressure and flow necessary to deliver oxygenated blood to tissues and return deoxygenated blood to the lungs.

This synergy is modulated by **neural**, **hormonal**, and **local** feedback mechanisms that dynamically adjust respiratory and cardiovascular parameters according to metabolic demands, maintaining homeostasis across varied physiological states—from rest to strenuous exercise. Understanding these fundamental physiological processes underpins clinical approaches to **respiratory** and **cardiovascular** pathologies, where targeted interventions can restore or augment vital transport functions essential for life.