The Respiratory System

- Cells produce energy
  - For maintenance, growth, defense, and division
  - Through mechanisms that use oxygen and produce carbon dioxide
Introduction to the Respiratory System

- Oxygen
  - Is obtained from the air by diffusion across delicate exchange surfaces of lungs
  - Is carried to cells by the cardiovascular system, which also returns carbon dioxide to the lungs
Components of the Respiratory System

- Five Functions of the Respiratory System
  - Provides extensive gas exchange surface area between air and circulating blood
  - Moves air to and from exchange surfaces of lungs
  - Protects respiratory surfaces from outside environment
  - Produces sounds
  - Participates in olfactory sense
Components of the Respiratory System

- Organization of the Respiratory System
  - The respiratory system is divided into
    - **Upper respiratory system**: above the larynx
    - **Lower respiratory system**: below the larynx
Components of the Respiratory System

- The Respiratory Tract
  - Consists of a conducting portion
    - From nasal cavity to terminal bronchioles
  - Consists of a respiratory portion
    - The respiratory bronchioles and alveoli
Components of the Respiratory System

- Alveoli
  - Are air-filled pockets within the lungs
    - Where all gas exchange takes place
Components of the Respiratory System

Figure 23–1 The Components of the Respiratory System.
Components of the Respiratory System

- The Respiratory Epithelium
  - For gases to exchange efficiently
    - Alveoli walls must be very thin (<1 μm)
    - Surface area must be very great (about 35 times the surface area of the body)
Components of the Respiratory System

- The **Respiratory Mucosa**
  - Consists of
    - An epithelial layer
    - An areolar layer called the *lamina propria*
  - Lines the conducting portion of respiratory system
Components of the Respiratory System

- **The Lamina Propria**
  - Underlying layer of areolar tissue that supports the respiratory epithelium
  - In the upper respiratory system, trachea, and bronchi
    - It contains mucous glands that secrete onto epithelial surface
  - In the conducting portion of lower respiratory system
    - It contains smooth muscle cells that encircle lumen of bronchioles
Components of the Respiratory System

Figure 23–2a The Respiratory Epithelium of the Nasal Cavity and Conducting System: A Surface View.
Components of the Respiratory System

Figure 23–2b, c The Respiratory Epithelium of the Nasal Cavity and Conducting System.
Components of the Respiratory System

- Structure of Respiratory Epithelium
  - Changes along respiratory tract
Components of the Respiratory System

- Alveolar Epithelium
  - Is a very delicate, simple squamous epithelium
  - Contains scattered and specialized cells
  - Lines exchange surfaces of alveoli
Components of the Respiratory System

- The Respiratory Defense System
  - Consists of a series of filtration mechanisms
  - Removes particles and pathogens
Components of the Respiratory System

- Components of the **Respiratory Defense System**
  - Mucous cells and mucous glands
    - Produce mucus that bathes exposed surfaces
  - Cilia
    - Sweep debris trapped in mucus toward the pharynx (*mucus escalator*)
  - Filtration in nasal cavity removes large particles
  - Alveolar macrophages engulf small particles that reach lungs
The Nose

- Air enters the respiratory system
  - Through nostrils or external nares
  - Into nasal vestibule

- Nasal hairs
  - Are in nasal vestibule
  - Are the first particle filtration system
Upper Respiratory Tract

- The Nasal Cavity
  - The nasal septum
    - Divides nasal cavity into left and right
  - Mucous secretions from paranasal sinus and tears
    - Clean and moisten the nasal cavity
  - Superior portion of nasal cavity is the olfactory region
    - Provides sense of smell
Upper Respiratory Tract

- Air flow from vestibule to internal nares
  - Through superior, middle, and inferior meatuses
- **Meatuses** are constricted passageways that produce air turbulence
  - Warm and humidify incoming air
  - Trap particles
Upper Respiratory Tract

- The Palates
  - Hard palate
    - Forms floor of nasal cavity
    - Separates nasal and oral cavities
  - Soft palate
    - Extends posterior to hard palate
    - Divides superior nasopharynx from lower pharynx
Upper Respiratory Tract

- **Air Flow**
  - Nasal cavity opens into nasopharynx through **internal nares**

- **The Nasal Mucosa**
  - Warms and humidifies inhaled air for arrival at lower respiratory organs
  - Breathing through mouth bypasses this important step
Upper Respiratory Tract

Figure 23–3a, b Structures of the Upper Respiratory System.
Figure 23–3a, b Structures of the Upper Respiratory System.
Figure 23–3c Structures of the Upper Respiratory System.
The Pharynx

- A chamber shared by digestive and respiratory systems
- Extends from internal nares to entrances to larynx and esophagus
- Divided into the nasopharynx, the oropharynx, and the laryngopharynx
Upper Respiratory Tract

- **The Nasopharynx** (superior portion of pharynx)
  - Contains pharyngeal tonsils and openings to left and right auditory tubes

- **The Oropharynx** (middle portion of pharynx)
  - Communicates with oral cavity

- **The Laryngopharynx** (inferior portion of pharynx)
  - Extends from hyoid bone to entrance of larynx and esophagus
Air Flow

- From the pharynx enters the larynx
  - A cartilaginous structure that surrounds the glottis, which is a narrow opening
The Larynx

- Cartilages of the Larynx
  - Three large, unpaired cartilages form the larynx
    - Thyroid cartilage
    - Cricoid cartilage
    - Epiglottis
The Larynx

- The Thyroid Cartilage
  - Also called the Adam’s apple
  - Is hyaline cartilage
  - Forms anterior and lateral walls of larynx
  - Ligaments attach to hyoid bone, epiglottis, and laryngeal cartilages
The Larynx

- The Cricoid Cartilage
  - Is hyaline cartilage
  - Forms posterior portion of larynx
  - Ligaments attach to first tracheal cartilage
  - Articulates with arytenoid cartilages
The Larynx

- The Epiglottis
  - Composed of elastic cartilage
  - Ligaments attach to thyroid cartilage and hyoid bone
The Larynx

- **Cartilage Functions**
  - Thyroid and cricoid cartilages support and protect
    - The glottis
    - The entrance to trachea
  - During swallowing
    - The larynx is elevated
    - The epiglottis folds back over glottis
  - Prevents entry of food and liquids into respiratory tract
The Larynx

- Larynx also contains three pairs of smaller hyaline cartilages
  - Arytenoid cartilages
  - Corniculate cartilages
  - Cuneiform cartilages
Figure 23–4a, b The Anatomy of the Larynx.
Figure 23–4c The Anatomy of the Larynx.
The Larynx

- Cartilage Functions
  - Corniculate and arytenoid cartilages function in
    - Opening and closing of glottis
    - Production of sound
The Larynx

- Ligaments of the Larynx
  - Vestibular ligaments and vocal ligaments
    - Extend between thyroid cartilage and arytenoid cartilages
    - Are covered by folds of laryngeal epithelium that project into glottis
The Larynx

- The Vestibular Ligaments
  - Lie within vestibular folds
    - Which protect delicate vocal folds

- Sound Production
  - Air passing through glottis
    - Vibrates vocal folds
    - Produces sound waves
The Larynx

- Sound is varied by
  - Tension on vocal folds
    - Vocal folds involved with sound are known as **vocal cords**
  - Voluntary muscles (position arytenoid cartilage relative to thyroid cartilage)

- Speech is produced by
  - Phonation
    - Sound production at the larynx
  - Articulation
    - Modification of sound by other structures
Figure 23–5 The Glottis and Surrounding Structures.
The Larynx

The Laryngeal Musculature

The larynx is associated with

- Muscles of neck and pharynx
- Intrinsic muscles that:
  - control vocal folds
  - open and close glottis
The Trachea

- The Trachea
  - Also called the windpipe
  - Extends from the cricoid cartilage into mediastinum
    - Where it branches into right and left pulmonary bronchi

- The Submucosa
  - Beneath mucosa of trachea
  - Contains mucous glands
Figure 23–6b The Anatomy of the Trachea: A Cross-Sectional View.
The Trachea

- The Tracheal Cartilages
  - 15–20 tracheal cartilages
    - Strengthen and protect airway
    - Discontinuous where trachea contacts esophagus
  - Ends of each tracheal cartilage are connected by
    - An elastic ligament and trachealis muscle
The Trachea

- The Primary Bronchi
  - Right and left primary bronchi
    - Separated by an internal ridge (the carina)
- The Right Primary Bronchus
  - Is larger in diameter than the left
  - Descends at a steeper angle
The Trachea

- Structure of Primary Bronchi
  - Each primary bronchus
    - Travels to a groove (**hilum**) along medial surface of the lung
Figure 23–6 The Anatomy of the Trachea: A Diagrammatic Anterior View.
The Lungs

- **Hilum**
  - Where pulmonary nerves, blood vessels, lymphatics enter lung
  - Anchored in meshwork of connective tissue

- **The Root of the Lung**
  - Complex of connective tissues, nerves, and vessels in hilum
    - Anchored to the mediastinum
The Lungs

- The Lungs
  - Left and right lungs
    - Are in left and right pleural cavities
  - The base
    - Inferior portion of each lung rests on superior surface of diaphragm
  - Lobes of the lungs
    - Lungs have lobes separated by deep fissures
The Lungs

- The right lung has three lobes
  - Superior, middle, and inferior
  - Separated by horizontal and oblique fissures
- The left lung has two lobes
  - Superior and inferior
  - Separated by an oblique fissure
The Lungs

- Lung Shape
  - Right lung
    - Is wider
    - Is displaced upward by liver
  - Left lung
    - Is longer
    - Is displaced leftward by the heart forming the cardiac notch
Figure 23–7a The Gross Anatomy of the Lungs.
The Lungs

Figure 23–7b The Gross Anatomy of the Lungs.
The Lungs

Figure 23–7b The Gross Anatomy of the Lungs.
Figure 23–8 The Relationship between the Lungs and Heart.
The Lungs

- **The Bronchial Tree**
  - Is formed by the primary bronchi and their branches

- **Extrapulmonary Bronchi**
  - The left and right bronchi branches outside the lungs

- **Intrapulmonary Bronchi**
  - Branches within the lungs
The Lungs

- A Primary Bronchus
  - Branches to form secondary bronchi (lobar bronchi)
  - One secondary bronchus goes to each lobe

- Secondary Bronchi
  - Branch to form tertiary bronchi, also called the segmental bronchi
  - Each segmental bronchus
    - Supplies air to a single bronchopulmonary segment
The Lungs

- Bronchopulmonary Segments
  - The right lung has 10
  - The left lung has 8 or 9

- Bronchial Structure
  - The walls of primary, secondary, and tertiary bronchi
    - Contain progressively less cartilage and more smooth muscle
    - Increased smooth muscle tension affects airway constriction and resistance
The Lungs

- Bronchitis
  - Inflammation of bronchial walls
    - Causes constriction and breathing difficulty
The Lungs

- The Bronchioles
  - Each tertiary bronchus branches into multiple bronchioles
  - Bronchioles branch into terminal bronchioles
    - One tertiary bronchus forms about 6500 terminal bronchioles

- Bronchiole Structure
  - Bronchioles
    - Have no cartilage
    - Are dominated by smooth muscle
The Lungs

- Autonomic Control
  - Regulates smooth muscle
    - Controls diameter of bronchioles
    - Controls airflow and resistance in lungs
  - Bronchodilation
    - Dilation of bronchial airways
    - Caused by sympathetic ANS activation
    - Reduces resistance
The Lungs

- Bronchoconstriction
  - Constricts bronchi
  - Caused by:
    - parasympathetic ANS activation
    - histamine release (allergic reactions)
The Lungs

- Asthma
  - Excessive stimulation and bronchoconstriction
  - Stimulation severely restricts airflow

- Trabeculae
  - Fibrous connective tissue partitions from root of lung
  - Contain supportive tissues and lymphatic vessels
  - Branch repeatedly
  - Divide lobes into increasingly smaller compartments
The Lungs

- **Pulmonary Lobules**
  - Are the smallest compartments of the lung
  - Are divided by the smallest trabecular partitions (interlobular septa)
The Lungs

Figure 23–9 The Bronchi and Lobules of the Lung.
Figure 23–9 The Bronchi and Lobules of the Lung.
The Lungs

- Surfaces of the Lungs
  - Each terminal bronchiole delivers air to a single pulmonary lobule
  - Each pulmonary lobule is supplied by pulmonary arteries and veins

- Exchange surfaces within the lobule
  - Each terminal bronchiole branches to form several respiratory bronchioles, where gas exchange takes place
The Lungs

- An Alveolus
  - Respiratory bronchioles are connected to alveoli along alveolar ducts
  - Alveolar ducts end at alveolar sacs
    - Common chambers connected to many individual alveoli
  - Has an extensive network of capillaries
  - Is surrounded by elastic fibers
The Lungs

Figure 23–10 Respiratory Tissue.
Figure 23–11a Alveolar Organization: Basic Structure of a Portion of Single Lobule.
Figure 23–11b Alveolar Organization: A Diagrammatic View of Structure.
The Lungs

- **Alveolar Epithelium**
  - Consists of simple squamous epithelium
  - Consists of thin, delicate *pneumocytes type I*
  - Patrolled by *alveolar macrophages*, also called *dust cells*
  - Contains *pneumocytes type II* (septal cells) that produce *surfactant*
The Lungs

- **Surfactant**
  - Is an oily secretion
  - Contains phospholipids and proteins
  - Coats alveolar surfaces and reduces surface tension
The Lungs

- **Respiratory Distress**
  - Difficult respiration
    - Due to alveolar collapse
    - Caused when pneumocytes type II do not produce enough surfactant

- **Respiratory Membrane**
  - The thin membrane of alveoli where gas exchange takes place
The Lungs

- Three Layers of the Respiratory Membrane
  - Squamous epithelial lining of alveolus
  - Endothelial cells lining an adjacent capillary
  - Fused basal laminae between alveolar and endothelial cells
Figure 23–11c Alveolar Organization: The Respiratory Membrane.
The Lungs

- Diffusion
  - Across respiratory membrane is very rapid
    - Because distance is short
    - Gases (O₂ and CO₂) are lipid soluble

- Inflammation of Lobules
  - Also called pneumonia
    - Causes fluid to leak into alveoli
    - Compromises function of respiratory membrane
The Lungs

- Blood Supply to Respiratory Surfaces
  - Each lobule receives an arteriole and a venule
  1. Respiratory exchange surfaces receive blood:
     - From arteries of pulmonary circuit
  2. A capillary network surrounds each alveolus:
     - As part of the respiratory membrane
  3. Blood from alveolar capillaries:
     - Passes through pulmonary venules and veins
     - Returns to left atrium
The Lungs

- Blood Supply to the Lungs
  - Capillaries supplied by bronchial arteries
    - Provide oxygen and nutrients to tissues of conducting passageways of lung
  - Venous blood bypasses the systemic circuit and flows into pulmonary veins
The Lungs

- **Blood Pressure**
  - In pulmonary circuit is low (30 mm Hg)
  - Pulmonary vessels are easily blocked by blood clots, fat, or air bubbles, causing **pulmonary embolism**
The Lungs

- The Pleural Cavities and Pleural Membranes
  - Two pleural cavities
    - Are separated by the mediastinum
  - Each pleural cavity
    - Holds a lung
    - Is lined with a serous membrane (the pleura)
The Lungs

- The Pleura
  - Consists of two layers
    - Parietal pleura
    - Visceral pleura
  - Pleural fluid
    - Lubricates space between two layers
Respiration refers to two integrated processes

- **External respiration**
  - Includes all processes involved in exchanging $O_2$ and $CO_2$ with the environment

- **Internal respiration**
  - Also called cellular respiration
  - Involves the uptake of $O_2$ and production of $CO_2$ within individual cells
Figure 23–12 An Overview of the Key Steps in External Respiration.
Introduction to Gas Exchange

- Three Processes of External Respiration
  1. Pulmonary ventilation (breathing)
  2. Gas diffusion:
     - Across membranes and capillaries
  3. Transport of $O_2$ and $CO_2$:
     - Between alveolar capillaries
     - Between capillary beds in other tissues
Pulmonary Ventilation

- Pulmonary Ventilation
  - Is the physical movement of air in and out of respiratory tract
  - Provides alveolar ventilation

- Atmospheric Pressure
  - The weight of air
    - Has several important physiological effects
Pulmonary Ventilation

- Boyle’s Law
  - Defines the relationship between gas pressure and volume:
    \[ P = \frac{1}{V} \]
  - In a contained gas
    - External pressure forces molecules closer together
    - Movement of gas molecules exerts pressure on container
Pulmonary Ventilation

Figure 23–13 Gas Pressure and Volume Relationships.
Pulmonary Ventilation

- Pressure and Airflow to the Lungs
  - Air flows from area of higher pressure to area of lower pressure

- A Respiratory Cycle
  - Consists of
    - An inspiration (inhalation)
    - An expiration (exhalation)
Pulmonary Ventilation

- Pulmonary Ventilation
  - Causes volume changes that create changes in pressure
  - Volume of thoracic cavity changes
    - With expansion or contraction of diaphragm or rib cage
Figure 23–14 Mechanisms of Pulmonary Ventilation.
Pulmonary Ventilation

- **Compliance**
  - An indicator of expandability
  - Low compliance requires greater force
  - High compliance requires less force

- **Factors That Affect Compliance**
  - Connective tissue structure of the lungs
  - Level of surfactant production
  - Mobility of the thoracic cage
Pulmonary Ventilation

- Pressure Changes during Inhalation and Exhalation
  - Can be measured inside or outside the lungs
  - Normal atmospheric pressure:
    - 1 atm or $P_{atm}$ at sea level: 760 mm Hg
The **Intrapulmonary Pressure**

- Also called *intra-alveolar pressure*
- Is relative to $P_{atm}$
- In relaxed breathing, the difference between $P_{atm}$ and intrapulmonary pressure is small
  - About $-1$ mm Hg on inhalation or $+1$ mm Hg on exhalation
Pulmonary Ventilation

- Maximum Intrapulmonary Pressure
  - Maximum straining, a dangerous activity, can increase range
    - From -30 mm Hg to +100 mm Hg
The **Intrapleural Pressure**

- Pressure in space between parietal and visceral pleura
- Averages -4 mm Hg
- Maximum of -18 mm Hg
- Remains below $P_{atm}$ throughout respiratory cycle
### TABLE 23–1  The Four Most Common Methods of Reporting Gas Pressures

**millimeters of mercury** (mm Hg): This is the most common method of reporting blood pressure and gas pressures. Normal atmospheric pressure is approximately 760 mm Hg.

**torr**: This unit of measurement is preferred by many respiratory therapists; it is also commonly used in Europe and in some technical journals. One torr is equivalent to 1 mm Hg; in other words, normal atmospheric pressure is equal to 760 torr.

**centimeters of water** (cm H$_2$O): In a hospital setting, anesthetic gas pressures and oxygen pressures are commonly measured in centimeters of water. One cm H$_2$O is equivalent to 0.735 mm Hg; normal atmospheric pressure is 1033.6 cm H$_2$O.

**pounds per square inch** (psi): Pressures in compressed gas cylinders and other industrial applications are generally reported in psi. Normal atmospheric pressure at sea level is approximately 15 psi.
Pulmonary Ventilation

- **The Respiratory Cycle**
  - Cyclical changes in intrapleural pressure operate the respiratory pump
    - Which aids in venous return to heart
Pulmonary Ventilation

- **Tidal Volume**
  - Amount of air moved in and out of lungs in a single respiratory cycle

- **Injury to the Chest Wall**
  - **Pneumothorax** allows air into pleural cavity
  - **Atelectasis** (also called a collapsed lung) is a result of pneumothorax
Figure 23–15 Pressure and Volume Changes during Inhalation and Exhalation.
Pulmonary Ventilation

- The Respiratory Muscles
  - Most important are
    - The diaphragm
    - External intercostal muscles of the ribs
  - Accessory respiratory muscles:
    - activated when respiration increases significantly
The Mechanics of Breathing

- Inhalation
  - Always active
- Exhalation
  - Active or passive
The Mechanics of Breathing

1. Diaphragm:
   - Contraction draws air into lungs
   - 75% of normal air movement

2. External intercostal muscles:
   - Assist inhalation
   - 25% of normal air movement

3. Accessory muscles assist in elevating ribs:
   - Sternocleidomastoid
   - Serratus anterior
   - Pectoralis minor
   - Scalene muscles
Pulmonary Ventilation

Figure 23–16a, b The Respiratory Muscles.
Muscles of Active Exhalation

- **Internal intercostal and transversus thoracis muscles**
  - Depress the ribs

- **Abdominal muscles**
  - Compress the abdomen
  - Force diaphragm upward
Figure 23–16c, d The Respiratory Muscles.
Pulmonary Ventilation

- Modes of Breathing
  - Respiratory movements are classified
    - By pattern of muscle activity
    - Into quiet breathing and forced breathing
Pulmonary Ventilation

- **Quiet Breathing (Eupnea)**
  - Involves active inhalation and passive exhalation
  - **Diaphragmatic breathing or deep breathing**
    - Is dominated by diaphragm
  - **Costal breathing or shallow breathing**
    - Is dominated by ribcage movements
Pulmonary Ventilation

- **Elastic Rebound**
  - When inhalation muscles relax
    - Elastic components of muscles and lungs recoil
    - Returning lungs and alveoli to original position
Pulmonary Ventilation

- **Forced Breathing**
  - Also called *hyperpnea*
  - Involves active inhalation and exhalation
  - Assisted by accessory muscles
  - Maximum levels occur in exhaustion
Pulmonary Ventilation

- **Respiratory Rates and Volumes**
  - Respiratory system adapts to changing oxygen demands by varying
    - The number of breaths per minute (**respiratory rate**)
    - The volume of air moved per breath (**tidal volume**)

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Pulmonary Ventilation

- The **Respiratory Minute Volume**
  - Amount of air moved per minute
  - Is calculated by:
    \[ \text{respiratory rate} \times \text{tidal volume} \]
  - Measures pulmonary ventilation
Anatomic Dead Space

- Only a part of respiratory minute volume reaches alveolar exchange surfaces
- Volume of air remaining in conducting passages is **anatomic dead space**
Alveolar Ventilation

- Amount of air reaching alveoli each minute
- Calculated as:

\[(\text{tidal volume} - \text{anatomic dead space}) \times \text{respiratory rate}\]
Pulmonary Ventilation

- Alveolar Gas Content
  - Alveoli contain less $O_2$, more $CO_2$ than atmospheric air
    - Because air mixes with exhaled air
Alveolar Ventilation Rate

- Determined by respiratory rate and tidal volume
  - For a given respiratory rate:
    - increasing tidal volume increases alveolar ventilation rate
  - For a given tidal volume:
    - increasing respiratory rate increases alveolar ventilation

Lung Volume

- Total lung volume is divided into a series of volumes and capacities useful in diagnosing problems
Pulmonary Ventilation

- Four Pulmonary Volumes
  - Resting tidal volume
    - In a normal respiratory cycle
  - Expiratory reserve volume (ERV)
    - After a normal exhalation
Pulmonary Ventilation

- Four Pulmonary Volumes
  - Residual volume
    - After maximal exhalation
    - Minimal volume (in a collapsed lung)
  - Inspiratory reserve volume (IRV)
    - After a normal inspiration
Pulmonary Ventilation

- Four Calculated Respiratory Capacities
  - **Inspiratory capacity**
    - Tidal volume + inspiratory reserve volume
  - **Functional residual capacity (FRC)**
    - Expiratory reserve volume + residual volume
  - **Vital capacity**
    - Expiratory reserve volume + tidal volume + inspiratory reserve volume
  - **Total lung capacity**
    - Vital capacity + residual volume
Figure 23–17 Pulmonary Volumes and Capacities.
Pulmonary Ventilation

- **Pulmonary Function Tests**
  - Measure rates and volumes of air movements
Gas Exchange

- Gas Exchange
  - Occurs between blood and alveolar air
  - Across the respiratory membrane

- Depends on
  - Partial pressures of the gases
  - Diffusion of molecules between gas and liquid
Gas Exchange

- The Gas Laws
  - Diffusion occurs in response to concentration gradients
  - Rate of diffusion depends on physical principles, or gas laws
    - *For example*, Boyle’s law
Gas Exchange

- Composition of Air
  - Nitrogen (N\(_2\)) is about 78.6%
  - Oxygen (O\(_2\)) is about 20.9%
  - Water vapor (H\(_2\)O) is about 0.5%
  - Carbon dioxide (CO\(_2\)) is about 0.04%
Gas Exchange

- Dalton’s Law and Partial Pressures
  - Atmospheric pressure (760 mm Hg)
    - Produced by air molecules bumping into each other
  - Each gas contributes to the total pressure
    - In proportion to its number of molecules (Dalton’s law)
Gas Exchange

- Partial Pressure
  - The pressure contributed by each gas in the atmosphere
  - All *partial pressures* together add up to 760 mm Hg
Gas Exchange

- Henry’s Law
  - When gas under pressure comes in contact with liquid
    - Gas dissolves in liquid until equilibrium is reached
  - At a given temperature
    - Amount of a gas in solution is proportional to partial pressure of that gas
Figure 23–18 Henry’s Law and the Relationship between Solubility and Pressure.
Gas Exchange

- **Gas Content**
  - The actual amount of a gas in solution (at given partial pressure and temperature) depends on the solubility of that gas in that particular liquid.
Gas Exchange

- **Solubility in Body Fluids**
  - $\text{CO}_2$ is very soluble
  - $\text{O}_2$ is less soluble
  - $\text{N}_2$ has very low solubility
Gas Exchange

- Normal Partial Pressures
  - In pulmonary vein plasma
    - $P_{CO_2} = 40$ mm Hg
    - $P_{O_2} = 100$ mm Hg
    - $P_{N_2} = 573$ mm Hg
### TABLE 23–2  Partial Pressures (mm Hg) and Normal Gas Concentrations (%) in Air

<table>
<thead>
<tr>
<th>Source of Sample</th>
<th>Nitrogen (N₂)</th>
<th>Oxygen (O₂)</th>
<th>Carbon Dioxide (CO₂)</th>
<th>Water Vapor (H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inhaled air (dry)</td>
<td>597 (78.6%)</td>
<td>159 (20.9%)</td>
<td>0.3 (0.04%)</td>
<td>3.7 (0.5%)</td>
</tr>
<tr>
<td>Alveolar air (saturated)</td>
<td>573 (75.4%)</td>
<td>100 (13.2%)</td>
<td>40 (5.2%)</td>
<td>47 (6.2%)</td>
</tr>
<tr>
<td>Exhaled air (saturated)</td>
<td>569 (74.8%)</td>
<td>116 (15.3%)</td>
<td>28 (3.7%)</td>
<td>47 (6.2%)</td>
</tr>
</tbody>
</table>
Gas Exchange

- Diffusion and the Respiratory Membrane
  - Direction and rate of diffusion of gases across the respiratory membrane determine different partial pressures and solubilities
Gas Exchange

- **Efficiency of Gas Exchange Due to**
  - Substantial differences in partial pressure across the respiratory membrane
  - Distances involved in gas exchange are short
  - $\text{O}_2$ and $\text{CO}_2$ are lipid soluble
  - Total surface area is large
  - Blood flow and airflow are coordinated
Gas Exchange

- O₂ and CO₂
  - Blood arriving in pulmonary arteries has
    - Low \( P_{O_2} \)
    - High \( P_{CO_2} \)
  - The concentration gradient causes
    - O₂ to enter blood
    - CO₂ to leave blood
  - Rapid exchange allows blood and alveolar air to reach equilibrium
Gas Exchange

- Mixing
  - Oxygenated blood mixes with unoxygenated blood from conducting passageways
  - Lowers the PO$_2$ of blood entering systemic circuit (drops to about 95 mm Hg)
Gas Exchange

- Interstitial Fluid
  - $P_{O_2}$ 40 mm Hg
  - $P_{CO_2}$ 45 mm Hg
- Concentration gradient in peripheral capillaries is opposite of lungs
  - $CO_2$ diffuses into blood
  - $O_2$ diffuses out of blood
Gas Exchange

- Gas Pickup and Delivery
  - Blood plasma cannot transport enough $\text{O}_2$ or $\text{CO}_2$ to meet physiological needs
Gas Exchange

Figure 23–19a An Overview of Respiratory Processes and Partial Pressures in Respiration.
Gas Exchange

Figure 23–19b An Overview of Respiratory Processes and Partial Pressures in Respiration.
Gas Transport

- Red Blood Cells (RBCs)
  - Transport O$_2$ to, and CO$_2$ from, peripheral tissues
  - Remove O$_2$ and CO$_2$ from plasma, allowing gases to diffuse into blood
Gas Transport

- **Oxygen Transport**
  - $\text{O}_2$ binds to iron ions in hemoglobin (Hb) molecules
    - In a reversible reaction
  - Each RBC has about 280 million Hb molecules
    - Each binds four oxygen molecules
Gas Transport

- **Hemoglobin Saturation**
  - The percentage of heme units in a hemoglobin molecule
  - That contain bound oxygen
Gas Transport

- Environmental Factors Affecting Hemoglobin
  - $P_{O_2}$ of blood
  - Blood pH
  - Temperature
  - Metabolic activity within RBCs
Gas Transport

- Oxygen–Hemoglobin Saturation Curve
  - Is a graph relating the saturation of hemoglobin to partial pressure of oxygen
    - Higher $P_{O_2}$ results in greater Hb saturation
  - Is a curve rather than a straight line
    - Because Hb changes shape each time a molecule of $O_2$ is bound
  - Each $O_2$ bound makes next $O_2$ binding easier
  - Allows Hb to bind $O_2$ when $O_2$ levels are low
Gas Transport

- **Oxygen Reserves**
  - $O_2$ diffuses
    - From peripheral capillaries (high $P_{O_2}$)
    - Into interstitial fluid (low $P_{O_2}$)
  - Amount of $O_2$ released depends on interstitial $P_{O_2}$
  - Up to 3/4 may be reserved by RBCs
Gas Transport

- Carbon Monoxide
  - CO from burning fuels
    - Binds strongly to hemoglobin
    - Takes the place of O$_2$
  - Can result in carbon monoxide poisoning
The Oxygen–Hemoglobin Saturation Curve

- Is standardized for normal blood (pH 7.4, 37°C)
- When pH drops or temperature rises
  - More oxygen is released
  - Curve shifts to right
- When pH rises or temperature drops
  - Less oxygen is released
  - Curve shifts to left
Figure 23–20 An Oxygen—Hemoglobin Saturation Curve.
Gas Transport

- The Bohr Effect
  - Is the effect of pH on hemoglobin-saturation curve
  - Caused by CO_2
    - CO_2 diffuses into RBC
    - An enzyme, called **carbonic anhydrase**, catalyzes reaction with H_2O
    - Produces carbonic acid (H_2CO_3)
  - Carbonic acid (H_2CO_3)
    - Dissociates into hydrogen ion (H^+) and bicarbonate ion (HCO_3^-)
  - Hydrogen ions diffuse out of RBC, lowering pH
Figure 23–21 The Effects of pH and Temperature on Hemoglobin Saturation.
Gas Transport

- **2,3-bisphosphoglycerate (BPG)**
  - RBCs generate ATP by glycolysis
    - Forming lactic acid and BPG
  - BPG directly affects $O_2$ binding and release
    - More BPG, more oxygen released
Gas Transport

- BPG Levels
  - BPG levels rise
    - When pH increases
    - When stimulated by certain hormones
  - If BPG levels are too low
    - Hemoglobin will not release oxygen
Gas Transport

- **Fetal and Adult Hemoglobin**
  - The structure of fetal hemoglobin
    - Differs from that of adult Hb
  - At the same $P_{O_2}$
    - Fetal Hb binds more $O_2$ than adult Hb
    - Which allows fetus to take $O_2$ from maternal blood
Figure 23–22 A Functional Comparison of Fetal and Adult Hemoglobin.
Gas Transport

- Carbon Dioxide Transport (CO₂)
  - Is generated as a by-product of aerobic metabolism (cellular respiration)
  - CO₂ in the bloodstream
    - May be:
      - converted to carbonic acid
      - bound to protein portion of hemoglobin
      - dissolved in plasma
Gas Transport

- Bicarbonate Ions
  - Move into plasma by an exchange mechanism (the **chloride shift**) that takes in $\text{Cl}^-$ ions without using ATP
Figure 23–23 Carbon Dioxide Transport in Blood.
Gas Transport

- CO$_2$ in the Bloodstream
  - 70% is transported as carbonic acid (H$_2$CO$_3$)
    - Which dissociates into H$^+$ and bicarbonate (HCO$_3^-$)
  - 23% is bound to amino groups of globular proteins in Hb molecule
    - Forming carbaminohemoglobin
  - 7% is transported as CO$_2$ dissolved in plasma
Figure 23–24a A Summary of the Primary Gas Transport Mechanisms: Oxygen Transport.
Gas Transport

Figure 23–24b A Summary of the Primary Gas Transport Mechanisms: Carbon Dioxide Transport.
Control of Respiration

- Peripheral and alveolar capillaries maintain balance during gas diffusion by
  - Changes in blood flow and oxygen delivery
  - Changes in depth and rate of respiration
Control of Respiration

- $O_2$ delivery in tissues and pickup at lungs are regulated by:
  
  1. Rising $P_{CO_2}$ levels:
     - relaxes smooth muscle in arterioles and capillaries
     - increases blood flow
  
  2. Coordination of lung perfusion and alveolar ventilation:
     - shifting blood flow
  
  3. $P_{CO_2}$ levels:
     - control bronchoconstriction and bronchodilation
Control of Respiration

- The Respiratory Centers of the Brain
  - When oxygen demand rises
    - Cardiac output and respiratory rates increase under neural control:
      - have both voluntary and involuntary components
Control of Respiration

- **Involuntary Centers**
  - Regulate respiratory muscles
  - In response to sensory information

- **Voluntary Centers**
  - In cerebral cortex affect
    - Respiratory centers of pons and medulla oblongata
    - Motor neurons that control respiratory muscles
Control of Respiration

- The Respiratory Centers
  - Three pairs of nuclei in the reticular formation of medulla oblongata and pons

- Respiratory Rhythmicity Centers of the Medulla Oblongata
  - Set the pace of respiration
  - Can be divided into two groups
    - Dorsal respiratory group (DRG)
    - Ventral respiratory group (VRG)
Control of Respiration

- **Dorsal Respiratory Group (DRG)**
  - Inspiratory center
  - Functions in quiet and forced breathing

- **Ventral Respiratory Group (VRG)**
  - Inspiratory and expiratory center
  - Functions only in forced breathing
Control of Respiration

- Quiet Breathing
  - Brief activity in the DRG
    - Stimulates inspiratory muscles
  - DRG neurons become inactive
    - Allowing passive exhalation
Control of Respiration

- Forced Breathing
  - Increased activity in DRG
    - Stimulates VRG
    - Which activates accessory inspiratory muscles
  - After inhalation
    - Expiratory center neurons stimulate active exhalation
Control of Respiration

Figure 23–25 Basic Regulatory Patterns of Respiration.
Control of Respiration

- The Apneustic and Pneumotaxic Centers of the Pons
  - Paired nuclei that adjust output of respiratory rhythmicity centers
    - Regulating respiratory rate and depth of respiration

- Apneustic Center
  - Provides continuous stimulation to its DRG center
Control of Respiration

- Pneumotaxic Centers
  - Inhibit the apneustic centers
  - Promote passive or active exhalation
Control of Respiration

- Respiratory Centers and Reflex Controls
  - Interactions between VRG and DRG
    - Establish basic pace and depth of respiration
  - The pneumotaxic center
    - Modifies the pace
Control of Respiration

Figure 23–26 Respiratory Centers and Reflex Controls.
Control of Respiration

- SIDS
  - Also known as sudden infant death syndrome
  - Disrupts normal respiratory reflex pattern
  - May result from connection problems between pacemaker complex and respiratory centers
Control of Respiration

- Respiratory Reflexes
  - Changes in patterns of respiration induced by sensory input
Control of Respiration

- **Five Sensory Modifiers of Respiratory Center Activities**
  - **Chemoreceptors** are sensitive to $P_{CO_2}$, $P_{O_2}$, or pH of blood or cerebrospinal fluid
  - **Baroreceptors** in aortic or carotid sinuses are sensitive to changes in blood pressure
  - **Stretch receptors** respond to changes in lung volume
  - **Irritating physical or chemical stimuli** in nasal cavity, larynx, or bronchial tree
  - **Other sensations** including pain, changes in body temperature, abnormal visceral sensations
Control of Respiration

- Chemoreceptor Reflexes
  - Respiratory centers are strongly influenced by chemoreceptor input from
    - Cranial nerve IX
    - Cranial nerve X
    - Receptors that monitor cerebrospinal fluid
Control of Respiration

- Cranial Nerve IX
  - The glossopharyngeal nerve
    - From carotid bodies
    - Stimulated by changes in blood pH or $P_{O_2}$

- Cranial Nerve X
  - The vagus nerve
    - From aortic bodies
    - Stimulated by changes in blood pH or $P_{O_2}$
Control of Respiration

- Receptors Monitoring CSF
  - Are on ventrolateral surface of medulla oblongata
  - Respond to $P_{CO_2}$ and pH of CSF
Control of Respiration

- Chemoreceptor Stimulation
  - Leads to increased depth and rate of respiration
  - Is subject to adaptation
    - Decreased sensitivity due to chronic stimulation
Control of Respiration

- **Hypercapnia**
  - An increase in arterial $P_{\text{CO}_2}$
  - Stimulates chemoreceptors in the medulla oblongata
  - To restore homeostasis
Control of Respiration

- **Hypercapnia and Hypocapnia**
  - **Hypoventilation** is a common cause of **hypercapnia**
  - Abnormally low respiration rate:
    - Allows CO$_2$ buildup in blood
  - Excessive ventilation, **hyperventilation**, results in abnormally low P$_{CO_2}$ (hypocapnia)
    - Stimulates chemoreceptors to decrease respiratory rate
Figure 23–27 The Chemoreceptor Response to Changes in PCO₂
Control of Respiration

- Baroreceptor Reflexes
  - Carotid and aortic baroreceptor stimulation
    - Affects blood pressure and respiratory centers
  - When blood pressure falls
    - Respiration increases
  - When blood pressure increases
    - Respiration decreases
Control of Respiration

- The Hering-Breuer Reflexes
  - Two baroreceptor reflexes involved in forced breathing
    - **Inflation reflex:**
      - prevents overexpansion of lungs
    - **Deflation reflex:**
      - inhibits expiratory centers
      - stimulates inspiratory centers during lung deflation
Control of Respiration

- Protective Reflexes
  - Triggered by receptors in epithelium of respiratory tract when lungs are exposed to
    - Toxic vapors
    - Chemical irritants
    - Mechanical stimulation
  - Cause sneezing, coughing, and laryngeal spasm
Control of Respiration

- **Apnea**
  - A period of suspended respiration
  - Normally followed by explosive exhalation to clear airways
    - Sneezing and coughing

- **Laryngeal Spasm**
  - Temporarily closes airway
    - To prevent foreign substances from entering
Control of Respiration

- Voluntary Control of Respiration
  1. Strong emotions:
     - can stimulate respiratory centers in hypothalamus
  2. Emotional stress:
     - can activate sympathetic or parasympathetic division of ANS
     - causing bronchodilation or bronchoconstriction
  3. Anticipation of strenuous exercise:
     - can increase respiratory rate and cardiac output
     - by sympathetic stimulation
Control of Respiration

Changes in the Respiratory System at Birth

1. Before birth:
   - pulmonary vessels are collapsed
   - lungs contain no air

2. During delivery:
   - placental connection is lost
   - blood $P_O_2$ falls
   - $P_CO_2$ rises
Control of Respiration

- Changes in the Respiratory System at Birth

3. At birth:
   - newborn overcomes force of surface tension to inflate bronchial tree and alveoli and take first breath

4. Large drop in pressure at first breath:
   - pulls blood into pulmonary circulation
   - closing foramen ovale and ductus arteriosus
   - redirecting fetal blood circulation patterns

5. Subsequent breaths:
   - fully inflate alveoli
Three Effects of Aging on the Respiratory System

1. Elastic tissues deteriorate:
   - altering lung compliance
   - lowering vital capacity

2. Arthritic changes:
   - restrict chest movements
   - limit respiratory minute volume

3. Emphysema:
   - affects individuals over age 50
   - depending on exposure to respiratory irritants (e.g., cigarette smoke)
Figure 23–28 Decline in Respiratory Performance with Age and Smoking.
Integration with Other Systems

- Maintaining homeostatic $O_2$ and $CO_2$ levels in peripheral tissues requires coordination between several systems
  - Particularly the respiratory and cardiovascular systems
Integration with Other Systems

- Coordination of Respiratory and Cardiovascular Systems
  - Improves efficiency of gas exchange by controlling lung perfusion
  - Increases respiratory drive through chemoreceptor stimulation
  - Raises cardiac output and blood flow through baroreceptor stimulation
### The Respiratory System in Perspective

<table>
<thead>
<tr>
<th>System</th>
<th>Functional Relationships</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integumentary System</td>
<td>- Protects portions of upper respiratory system; hairs guard entry to external nares</td>
</tr>
<tr>
<td>Skeletal System</td>
<td>- Movements of the ribs important in breathing; axial skeleton surrounds and protects lungs</td>
</tr>
<tr>
<td>Muscular System</td>
<td>- Muscular activity generates carbon dioxide; respiratory muscles fill and empty lungs; other muscles control entrances to respiratory tract; intrinsic laryngeal muscles control airflow through larynx and produce sound</td>
</tr>
</tbody>
</table>

Figure 23–29 Functional Relationships between the Respiratory System and Other Systems.
Integration with Other Systems

Figure 23–29 Functional Relationships between the Respiratory System and Other Systems.

THE RESPIRATORY SYSTEM IN PERSPECTIVE

Nervous System

• Monitors respiratory volume and blood gas levels; controls pace and depth of respiration

Endocrine System

• Epinephrine and norepinephrine stimulate respiratory activity and dilate respiratory passageways
• Converting enzyme along capillaries of lung converts angiotensin I to angiotensin II

Cardiovascular System

• Red blood cells transport oxygen and carbon dioxide between the lungs and peripheral tissues
• Activation of angiotensin II by converting enzyme important in regulation of blood pressure and volume; bicarbonate ions contribute to buffering capacity of blood
**THE RESPIRATORY SYSTEM IN PERSPECTIVE**

### Lymphoid System
- Tonsils protect against infection at entrance to respiratory tract; lymphatic vessels monitor lymph drainage from lungs and mobilize specific defenses when infection occurs.
- Alveolar phagocytes present antigens to trigger specific defenses; respiratory defense system traps pathogens, protects deeper tissues.

### Digestive System
- Provides substrates, vitamins, water, and ions that are necessary to all cells of the respiratory system.
- Increased thoracic and abdominal pressure through contraction of respiratory muscles can assist in defecation.

### Urinary System
- Eliminates organic wastes generated by cells of the respiratory system; maintains normal fluid and ion balance in the blood.
- Assists in the regulation of pH by eliminating carbon dioxide.

### Reproductive System
- Changes in respiratory rate and depth occur during sexual arousal.

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Figure 23–29 Functional Relationships between the Respiratory System and Other Systems.