Respiratory System

- What is respiration?
- Physiology of respiratory system
- Mechanics of breathing
- Parameters of respiration
- Mechanical measurements
- Instrumentation
  - Diagnostic and monitoring
  - Therapy
Respiration = exchange of gases

\[ C + H + \text{nutrients} \xrightarrow{O_2} \text{heat} + \text{energy} \xrightarrow{\text{metabolism}} H_2O + CO_2 \]

- Internal respiration - in tissues
- External respiration - in lungs
  - Oxygenate blood
  - Eliminate CO\(_2\) in a controlled manner
Pulmonary function

• Air intake
  – fresh air, humidified and warmed up
  – mixed up with the gases present

• In the lungs
  – $O_2$ diffuses from alveoli to pulmonary capillaries.
  – $CO_2$ in the reverse order

• Exchange of gases in the tissues
  – $O_2$ to fluid that baths the tissues $\Rightarrow$ to cells
  – $CO_2$ from cells $\Rightarrow$ tissue fluid $\Rightarrow$ blood circulation.
Physiology

- Nasal cavities
- Pharynx (epiglottis - valve)
- Larynx (voice box)
- Trachea (wind pipe)
- bronchi ⇒ bronchioles
- Lungs
  - right with 3 lobes
  - left with two lobes
- Pleura - sac covering lungs
  - parietal - attached to chest
  - visceral - attached to lungs
  - potential cavities in between
Laws for gases

- Boyle’s, when $T = \text{constant}$

\[
\frac{V_1}{V_2} = \frac{P_1}{P_2}
\]

- Charle’s, for $P = \text{constant}$

\[
\frac{V_1}{V_2} = \frac{T_1}{T_2}
\]

- Dalton’s, $P_{\text{total}} = P_1 + P_2 + \ldots + P_n$
Internal respiration

Figure 9-1  Internal respiration—exchange of $O_2$ and $CO_2$ between the capillary and the body cell.
Internal respiration (carriage of gases)

- $\text{O}_2$ is 95% carried by:
  - RBC in form of oxyhemoglobin
  - At the end, the RBC is $\sim 75\%$ saturated with $\text{O}_2$
  - $T$ and activity $\uparrow \Rightarrow$ more $\text{O}_2$ released (oxygen dissociation)

- $\text{CO}_2$ is carried by:
  - Only 30% of RBC
  - Rest by plasma

Figure 9-2 Oxygen dissociation curve.

\[ T = 37^\circ \text{F} \]
External (lung) respiration

• Inspiration - intake
  – 79% N, 20.96% O₂ and 0.04% CO₂
• Expiration - exhaust of waste gases
  – 79% N, 17% O₂ and 4% CO₂
• Two process:
  – Physical process - mechanics of breathing
  – Chemical process - reaction of gases with liquids (exchange of gases)
Mechanics of breathing

- Lungs are passive Muscles responsible:
  - intercostal muscles
  - diaphragm
- Inspiration is active
  - -3mmHg pressure diff.
- Expiration is passive
  - Muscles relax → +3mmHg
- Compliance (ability to expand), $\Delta V/\Delta P$
- Airway resistance
- **Alveolar surface**
  - 3/4 covered with capillaries
  - Surface area ~ 80m²
- **Hypoventilation**
  - not sufficient to keep normal value of CO₂
- **Hyperventilation**
  - Abnormally long and deep breathing
- **Dyspnea**
  - Abnormal breathless
- **Hypercapnia**
  - Excessive CO₂ in blood

- Diameter ≈ 0.02 cm
- ≈ 300 million alveoli

Diameter ≈ 0.02 cm
Respiration rate and depth are controlled by:
- nervous system
- CO₂ conc. in blood (pH ~ 7.4)

\[ CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^- \]
Parameters of respiration

• Two important points:
  – How to determine them ⇒ measurement
  – How to correct them if something goes wrong ⇒ therapy

• Lung volumes ⇒ capacities
  – Dead air and dead space; only portion of the inspired air reaches alveoli (150 ml ⇒ ~ 30% of total lung V)

• Lung compliance and elasticity

• Intrathoracic pressures
Figure 8.3. Lung volumes and capacities. (From W.F. Evans, *Anatomy and Physiology, The Basic Principles*, Prentice-Hall, Inc., 1971, by permission.)
Lung volumes and capacities

- Tidal volume - TV
  - Air ventilated during normal depth of breathing
- Inspiratory reserve volume - IRV
- Expiratory reserve volume - ERV
- Residual volume - RV
- Closing volume - CV
  - Due to obstruction
  - No ventilation

- Vital capacity - VC
  = TV + IRV + ERV
- Total lung capacity - TLC
  = VC + RV
- Inspiratory capacity - IC
  = IRV + TV
- Functional residual capacity - FRC
  = RV + ERV
- Closing capacity - CC
Lung volumes and capacities

Volume of gas space in the lungs

- TLC
- IC
- VC
- ERV
- FRC
- CC
- RV
- CV
- VT

(Degassed state)

Time
• Limitations:
  – All volume and capacities are static measures while respiration is dynamic activity
  – Rate of gas exchange $\alpha$ rate inspiration and expiration

• Respiratory minute volume - RMM
  – Overall output of the respiratory system
  – RMM = TV $\times$ # of respiratory cycles / minute
  – RMM = alveolar vent. / min. + dead space vent. /min.

• Two standards for measurement
  – Body Temperature ambient Pressure and gas Saturated with vapor - BTPS
  – Standard Temp. ambient Pressure and dry gas - STPS
Forced breathing tests

• To test the muscular power associated and airway resistance

• Forced vital capacity - FVC
  – Vital capacity measurement taken as quickly as possible with respect to time - timed vital capacity

• Forced expiratory volume (FEV)
  – Volume taken in a given seconds $FEV_1$, $FEV_3$
  – Sometimes expressed as $FEV = \% FVC$
  – Mid

• FVC sometimes is difficult, then
  – Peak flow = maximum flow rate is measured
Figure 9.9  Idealized statically determined expiratory pressure–volume relations for the lung. The positions and slopes for lungs with different elastic properties are shown relative to scales of absolute volume and pressure difference.
• Mid expiratory flow rate
  – $\text{FEV}_{25\% - 75\%}$

• Maximal expiration flow rate (MEF)
  – Rate during the first one liter after 200 ml being exhausted

• Maximal breathing capacity (MBC) or maximal voluntary ventilation (MVV)
  – Maximum amount of air breathed in and out in a sustained interval
  – Used to assess the integrity of the breathing mechanism
Figure 8.7. Typical spirogram. Read right to left. (See text for explanation.)
Volume versus flow plots of FVC

FVC maneuver waveforms, two trials

Predicted values (See Appendix C)

Pre-bronc. trial

Post-bronc. trial

Exhalation

FVC

FEV1

Inspiratory
Volume flow of gas at the airways opening against its integral (or volume change in a spirometer) subtracted from FVC ⇒ MEFV

Integral of expired-gas volume flow (or volume change in a spirometer) subtracted from FVC against time ⇒ timed vital capacity (TVC)

**Figure 9.11** Alternative methods of displaying data produced during a forced vital capacity expiration. Equivalent information can be obtained from each type of curve; however, reductions in expiratory flow are subjectively more apparent on the MEFV curve than on the timed spirogram.
Mechanical measurements

- For many parameters, direct measurement
  - Lung volumes $\Rightarrow$ lung capacities
  - Forced measurements $\Rightarrow$ compliance of lungs and rib cage + airway resistance

- Compliance is non-linear
  - requires volumes and intrathoracic pressure
  - For dynamic measurements, tidal volume is used and $P$ is measured at the end inspiratory and end expiratory volume levels where the flow is zero

- Airway resistance: $P \Rightarrow R \uparrow$ (insp); expir. $\Rightarrow R \downarrow$

$$Compliance = \frac{\text{volume} \uparrow \text{in lungs}}{\text{unit} \uparrow \text{in } P \text{ in lungs}}$$
Measurement of Gas Concentration in Pulmonary Function - Basics

• Mass per volume is not commonly used;
  – instead, partial pressure or molar fraction $F_x = \frac{V_x}{V}$
    equivalent molar fraction is used

• Measurement on discrete samples or continuous
  – Input by a thin capillary tube or catheter
  – Problems due to water vapor
    • Heating the tube to reduce condensation
  – Time delay between input and output
Principles of Measurement

• Chemical analyses using liquid chemical agents that absorb or react particular species of gases

• Electronic instruments to study various properties of gases
  – Fast and accurate measurement
  – Need standards & careful calibration
Devices for Measurements in Gas Phase

- Detects and analyze several gas species simultaneously:
  - Mass spectrometer
    - Ion beam is sorted according to molecular weight basis
    - Dispersion techniques: magnetic field, quadruple electric field or time of flight
- Test for a few gases individually
  - infrared analyzers
- Sensitive to only one gas important to respiratory system
  - paramagnetic oxygen sensor
Mass Spectroscopy

Figure 9.12  Essential elements of a medical mass spectrometer.
Thermal Conductivity Detectors (TCD)

• Thermal conductivity of a gas is inversely proportional to its molecular weight
  – thermal conductivities of H$_2$ and He $\sim$ 6.5* those of N$_2$ and O$_2$

• TCDs are developed for
  – gas chromatography
  – instruments designed to analyze gas mixtures for He or H$_2$

• Heated elements operate in constant current mode connected to Wheatstone bridge.
Figure 9.16 Thermal-conductivity detector for a gas chromatograph. Reference gas is the same as the carrier gas.
Infrared Spectroscopy

• Most gases absorb light at highly characteristic infrared wavelengths (fingerprints)
• Power absorbed transferred into heat & temp rises
• Gases with dissimilar atoms absorb (CO, CO$_2$, N$_2$O, H$_2$O), but symmetric molecules like O$_2$, N$_2$ and H$_2$ and noble gases do not
  – Beer's law: $Pt = Po10^{-aLC}$ where
    • Po: radiant energy arriving at the cuvette
    • Pt: Radiant energy leaving the cuvette
    • a: absorptivity of the sample
    • L: Length of the path through the sample
    • C: Concentration of the absorbing sample
General arrangement of components for IR spectroscopy

- Transmission systems
  - Nondispersive infrared (NDIR) analyzers
  - Power transmitted at a specific wavelength

- Photoacoustic systems
  - Wide-band (black body) source to irradiate the sample
  - Powered absorbed by the sample is measured
Figure 9.17 Infrared analyzer. This type of device is commonly used to measure gas-phase concentrations of gases such as CO₂, CO, N₂O, halothane and others.
Photoacoustic Analyzers

• IR energy is absorbed by test gas
• Sound pressure waves produced
• Found application in anesthesia monitoring
  – Three gases monitored simultaneously, CO₂, N₂O and anesthetic agent
  – Three sounds produced at different pitches
• Fast, accurate and stable results claimed
Raman Spectroscopy

• Light passing through a gas is scattered mostly at the same frequency but a very small fraction is scattered at a different frequency called the Raman spectrum.

• Spectrum of monochromatic radiation scattered is characteristic of the substance.

• Measurement is done generally perpendicular to the direction of incidence.

• Two optical pathways at opposite sides
  – One for CO\textsubscript{2} with proper filter
  – Other for other gases selected by filters on a rotating wheel.
Emission Spectroscopy

- Used for measuring concentration of a single gas species
- Gas is ionized at a very low pressure
  - Respiratory gases ionized at 600 to 1500 Vdc
  - Emit light in the range of 310 to 480 nm
- Mostly used for N\textsubscript{2} analyses
Figure 9.14  \( \text{N}_2 \) analyzer employing emission spectroscopy.
Measurement of Oxygen Concentration

- Oxygen cannot be measured by emission and IR absorption equipment

- Paramagnetic oxygen sensors
  - Oxygen is attracted by magnetic field
  - Most gases are diamagnetic - repelled by magnetic field
  - Test body rests with globes positioned in the region of highest magnetic-field concentration if a gas mixture has no paramagnetic components due to uniform distribution of the gas in the chamber
  - In case of a paramagnetic gas present, globes will be displaced due to increased density of the gas near the poles.

- Measurement of oxygen concentration is done either
  - Detecting the deflection of the globes of the test body, or
  - Determining the pressure required to hold it in position
Figure 9.15 Oxygen analyzers  (a) Diagram of the top view of a balance-type paramagnetic oxygen analyzer. The test body either is allowed to rotate (as shown) or is held in place by countertorque, which is measured to determine the oxygen concentration in the gas mixture. (b) Diagram of a differential pressure and a magnetoacoustic oxygen analyzer (see text for descriptions).
Respiratory Therapy Equipment

• **Purpose**
  – Mechanical assistance
  – Provide higher $O_2$ concentr in hypoxic patients
  – Provide therapeutic gases and medication

• **Devices**
  – Inhilerators - passive devices without any assistance to provide higher $O_2$ concentration
  – Ventilators and respirators
  – Humidifiers - generally part of a ventilator
  – Nebulizers
  – Aspirators
Ventilators and Respirators

- Supply humidity and aerosol medication to pulmonary tree.
- Generally +P during inhalation and expiration is passive.
- Three different modes of operation:
  - Assist - inspiration is triggered by patient
  - Control - breathing is controlled by a timer
  - Assist-control
  - Manual trigger from the control panel
• Inflation continues until one of the following occurs:
  – Pre-determined pressure in proximal or upper airways 🔄 pressure/cycled;
  – Pre-determined volume delivered 🔄 volume/cycled;
  – Air or O₂ for a predetermined time 🔄 time/cycled
Intermittent Positive Pressure (IPPB) Therapy

- +P during inspiration, expiration passively
- Promote uniform ventilation
- Facilitate better $O_2$ and $CO_2$ exchange
- Aspirate antibiotic drugs
- Relieve bronchospasm
- Assist in removal bronchopulmonary secretions (drainage)
- Exercise respiratory muscles
Figure 11-7  IPPB respirator. (a) Functional block diagram. (b) Internal structure of the Bennett valve.
Oxygen Therapy

- Treatment of oxygen deficiency
  - pneumonia
  - pulmonary edema (swell.)
  - obstruction to breathing
  - coronary thrombosis
  - complication after surgery
- Oxygen mixed with water vapor, medicine, other gases & anesthetics
- Gas regulator / flowmeter
- Humidifier / nebulizer
- Oxygen mask / tent administering systems

Figure 11-3  Flow gages. (a) Thorpe uncompensated. (b) Bourdon uncompensated. (c) Figure compensated.
Humidifiers

- Alveolar-capillary gas transfer membranes require high humidity to be efficient.
- Add water vapor to medical gases administered.
- Pass gas through sterile water that produces tiny bubbles.
- Must be sterilized after each use.

Ohio jet

Puritan-Bennett bubble-jet
Inst for Diagnostic & Monitoring

- Spirometry - for all volumes except RV
  - Direct spirometer - volume is measured directly
    - Water sealed
    - Dry seal (piston type)
    - Bellow (wedge)
  - Integrating (indirect) spirometer - flow rate is measured and volume is determined by integration
    - Electronic
    - Computerized

- For residual volume
- Gas flow measurements
- Gas concentration measurement
Water sealed (bell jar) spirometry

- Almost all lung vols and caps except RV
- Kymograph speed 30 - 200 mm/min
- Jar caps 9 or 13 lt
- Easily removable flutter valves mouthpiece and CO₂ absorbant
  - minimal breathing resistance
Figure 9.6  A water-sealed spirometer set up to measure slow lung-volume changes. The soda-lime and one-way-valve arrangement prevent buildup of CO₂ during rebreathing.
Waterless spirometers

• **Wedge (bellow) type - Cromwell fig 8.5**
  – The air to be breathed is held in a chamber enclosed by two parallel metal pans hinged to each other along one edge.
  – The space between the two pans is enclosed by a flexible bellow to form the chamber.
  – One of the pans is fixed and it contains the inlet tube.
  – The other swings freely with respect to the first one and it’s displacement is measured.
  – It imposes almost undetectable resistance, provides electrical output proportional to both volume and airflow.

• **Lightweight piston type**
  – A piston moving in a cylinder is used.
  – A rubber seal between the piston and cylinder walls provides the airtight chamber.
Integrating (indirect) Spirometers

• Electronic type: airflow is measured ⇒ volumes and capacities determined
  – Airflow
    • small turbines
    • heated wires or thermistors - no directional info

• Bronchspirometer: before operation, dual measurements in both sides separately

• Computerized - μP controlled machines give all necessary o/p in display form with the patient’s data
Figure 8.7. Typical spirogram. Read right to left. (See text for explanation.)
Measurement of Residual Volume

• Closed circuit technique
  – A marker gas (H or He) is inhaled, then
  – it’s concentration is determined in the exhausted air
  – from the ratio of concentrations RV is calculated.

• Open circuit or nitrogen (N) wash-out method
  – inhale pure O$_2$;
  – determine N concentration in expired air
  – N wash-out curve is drawn ⇒ RV ⇒ FRC & TLC

• Using body plethysmogram, one can determine FRC and from FRC ⇒ RV
Measurement of Closing Volume

• Bolus method
  – a marker gas (argon, xenon or helium) is inspired at residual volume level
  – inhale air at maximal level and exhale slowly (8 - 10 s)
  – monitor concentration of gas at the mouth-piece and plot against volume

• Nitrogen method
  – Fill lungs with pure O₂ and exhaust all the air possible
  – plot concentration of nitrogen against volume
  – at closing volume level, conc of N rises sharply.

• Closing volume is expressed in % VC
Figure 9.7  Diagram of an $N_2$ washout experiment  The expired gas can be collected in a spirometer, as shown here, or in a rubberized-canvas or plastic Douglas bag. $N_2$ content is then determined off-line. An alternative is to measure expiratory flow and nitrogen concentration continuously to determine the volume flow of expired nitrogen, which can be integrated to yield an estimate of the volume of nitrogen expired.
Figure 9.16  Distributions of volume and gas species at RV and TLC for a vital-capacity inspiration of air or pure oxygen.
Figure 9.17  Single-breath nitrogen-washout maneuver  (a) An idealized model of a lung at the end of a vital-capacity inspiration of pure $O_2$, preceded by breathing of normal air. (b) Single-breath $N_2$-washout curves for idealized lung, normal lung, and abnormal lung. Parameters of these curves include anatomical dead space, slope of phase III, and closing volume.
Body Plethysmograph

- FRC measurements
- Compliance and airway resistance
- Intra-alveolar pressure
  - for intra-thoracic P, balloon to esophagus

Figure 9.8 A pressure-type total-body plethysmograph, used to determine lung volume with the shutter closed and changes in alveolar pressure with the shutter open. Airway resistance can also be computed if volume flow of gas is measured at the airway opening. Since atmospheric pressure is constant, changes in the pressures of interest can be obtained from measurement made relative to atmospheric pressure.
Measurement of Gas Flow Rate

- Volume flow rate = mass flow rate / density of gas
- Breathing is a cyclic activity
  - with alternating (bi-directional) gas flow
  - many tests require unidirectional measurement of flow
  - precision and accuracy demanded vary greatly.
- Requirements for respiratory gas-flow measurement:
  - entire flow stream pass through or into the instrument
  - should not obstruct flow or produce back pressure
  - should not be affected by gas concentrations and particle in the flow of respiratory gases
  - no toxic material or excessive heat added
  - disposable or easily sterilizable sensors
Commonly used Volume Flowmeters

- **Rotating-vane:** small turbine in the flow path with rotation related to the volume flow of gas.
  - Optical detection of rotation
  - Mass of moving parts and friction reduces the f resp.
  - Can measure bi-directional flow, useful for clinical screening

- **Ultrasonic:** similar to transit-time flowmeters
  - Measures unidirectional flow, suitable for clinical monitoring

- **Thermal convection:**
  - Metal wires, metal films and thermistors as sensing elements, generally in self-heating modes
  - Nonlinear function of mass flow rate ⇒ linearizer circuits

- **Differential pressure flowmeters**
Sensors and bridge circuits for thermal-convection type flowmeters
Figure 10-6  A common form of flow rate transducer.

Figure 9.4  Pneumotachometer for measurements at the mouth  (a) Diameter adapter that acts as a diffuser.  (b) An application in which a constant flow is used to clear the dead space.
Figure 9.3 Pneumotachometer flow-resistance elements. (a) Screen. (b) Close-packed channels or capillary tubes.
Gas Exchange and Distribution

- **Measurements of gaseous exchange and diffusion** (movement of gas molecules from a point of higher pressure to a point of lower pressure to equalize the pressure difference) - lungs ability to exchange gases
  - chemical analysis methods:
    - a gas sample of ~ 0.5 ml is introduced into a reaction chamber and volume of absorbed gas is determined
  - diffusion capacity using CO
  - gas concentrations in pulmonary function

- **Measurements of gas distribution** - ability of blood to transport gases.
Diffusion Capacity

- Measured using CO with concent. < 1%0.25
  - CO resembles O₂ in solubility and molecular weight
  - can be determined using infrared (IR) analyzers

\[
\frac{1}{TF} = \frac{1}{Dm} + \frac{1}{\theta Vc}
\]

- Transfer factor
diffusion capacity
  of lungs for CO

- Volume of blood in capillaries

- Rate of reaction of CO with oxyhemog.

- Diffusion capacity of alveolar membrane
• Transfer factor (TF) or diffusion capacity of whole lung is around 20 - 30 ml/min/mmHg
  – proportional to depth of inspiration
  – increases in exercise
  – decreases in anemia or low hemoglobin

• Single breath or rebreathing (steady-state)

\[ TF = \frac{\text{ml CO taken up}}{\text{min}} \div \frac{P_{CO} \text{ in alveoly (mmHg/ml)}} \]
Measurements of Gas Distribution

• In carrying O\(_2\):
  – Percent of oxygenation of hemoglobin
  – Partial pressures of O\(_2\) in arterial and venous blood

• In carrying CO\(_2\) :
  – CO\(_2\) dissolves ⇔ carbonic acid ⇔ pH
  – Partial pressures of CO\(_2\) in arterial and venous blood

• Electrodes are used to determine P\(_{O2}\) , P\(_{CO2}\) in blood
Pneumographs

- Indicates existence of respiration and displays rate data
- impedance pneumogram
- mercury strain gage (mostly absolute)
- piezoresistive strain gage