Chapter 9, Part 2
Cardiocirculatory Adjustments to Exercise

Electrical Activity of the Heart
- Contraction of the heart depends on electrical stimulation of the myocardium
- Impulse is initiated in the right atrium and spreads throughout entire heart
- May be recorded on an electrocardiogram (ECG)

Cardiac Cycle
- Electrical events
- Polarization-opposite effects
  - Cells are negatively charged on the inside
  - Cells are positively charged on the outside
- Electrical potential difference

Conduction System
- Heart has inherent contractile rhythm
- Beats without nerve innervation
- SA node
  - Pacemaker
  - Highest inherent rhythm
  - "Self-excite" or depolarizes
  - Starts electrical impulse that moves throughout heart by means of electrical conduction system

Conduction System of the Heart

Electrocardiogram
- Records the electrical activity of the heart
- P-wave
  - Atrial depolarization
- QRS complex
  - Ventricular depolarization
- T-wave
  - Ventricular repolarization
Electrical Events

- Electrical impulse results in changes in electrical activity (voltage)
- Recorded on ECG from electrodes placed on skin
- Electrical events precede mechanical events (pressure and volume changes)

Mechanical Events

- P wave followed by atrial contraction
- QRS
  - Isometric contraction (AV, pulmonic, aortic valves close)
  - Followed by ventricular contraction
- ST segment-maximal ejection of blood

Electrical Events

- P wave – atrial depolarization
- QRS complex-ventricular depolarization
- T wave – ventricular repolarization

Mechanical Events

- Q-T = systole
- T-Q = diastole
Diagnostic Use of the ECG

- ECG abnormalities may indicate coronary heart disease
  - ST-segment depression can indicate myocardial ischemia

Cardiac Output

The amount of blood pumped by the heart each minute
- Product of heart rate and stroke volume
  \[ Q = HR \times SV \]
  - Heart rate (bt/min) = number of beats per minute
  - Stroke volume (ml/bt) = amount of blood ejected in each beat

Regulation of Heart Rate

- Decrease in HR
  - Parasympathetic nervous system
    - Via vagus nerve
    - Slows HR by inhibiting SA node
- Increase in HR
  - Sympathetic nervous system
    - Via cardiac accelerator nerves
    - Increases HR by stimulating SA node

Nervous System Regulation of Heart Rate

Regulation of Stroke Volume

- End-diastolic volume (EDV)
  - Volume of blood in the ventricles at the end of diastole ("preload")
- Average aortic blood pressure
  - Pressure the heart must pump against to eject blood ("afterload")
- Strength of the ventricular contraction
  - "Contractility"
End-Diastolic Volume (Preload)

- Frank-Starling mechanism
  - Greater preload results in stretch of ventricles and in a more forceful contraction
- Affected by:
  - Venoconstriction
  - Skeletal muscle pump
  - Respiratory pump

End-Diastolic Volume (Preload)

- Venoconstriction
  - Increases venous return by reducing volume of blood in veins
  - Moves blood back towards heart

End-Diastolic Volume (Preload)

- The Skeletal Muscle Pump
  - Rhythmic skeletal muscle contractions force blood in the extremities toward the heart
  - One-way valves in veins prevent backflow of blood

End-Diastolic Volume

- Respiratory pump
  - Rhythmic pattern of breathing (mechanical pump)
  - Inspiration decreases pressure in thorax
    - Venous flow increases—increases VR
  -Expiration increases pressure in thorax
    - Slows venous flow

Average Aortic Pressure

- Afterload
  - Affects size of stroke volume
  - Pressure generated by LV to exceed pressure in aorta
  - Afterload—barrier to ejection of blood from ventricles and is determined by average aortic pressure

Average Aortic Pressure

- Aortic pressure is inversely related to stroke volume
- High afterload results in a decreased stroke volume
  - Requires greater force generation by the myocardium to eject blood into the aorta
- Reducing aortic pressure results in higher stroke volume
Ventricular Contractility

- Increased contractility results in higher stroke volume
  - Circulating epinephrine and norepinephrine
  - Direct sympathetic stimulation of heart

Factors that Regulate Cardiac Output

Cardiac = Heart Rate x Stroke Volume

- Mean arterial pressure
- EDV

Fig 9.13

Hemodynamics

The study of the physical principles of blood flow

Physical Characteristics of Blood

- Plasma
  - Liquid portion of blood
  - Contains ions, proteins, hormones
- Cells
  - Red blood cells
    - Contain hemoglobin to carry oxygen
  - White blood cells
  - Platelets
    - Important in blood clotting

Hematocrit

Percent of blood composed of cells

Based on interrelationships between:

- Pressure
- Resistance
- Flow

Fig 9.14
Hemodynamics: Pressure

- Blood flows from high → low pressure
  - Proportional to the difference between MAP and right atrial pressure (ΔP)

![Fig 9.15](image)

Hemodynamics: Resistance

- Resistance depends upon:
  - Length of the vessel
  - Viscosity of the blood
  - Radius of the vessel
  - A small change in vessel diameter can have a dramatic impact on resistance!

\[
\text{Resistance} = \frac{\text{Length} \times \text{viscosity}}{\text{Radius}^4}
\]

Hemodynamics: Blood Flow

- Directly proportional to the pressure difference between the two ends of the system
- Inversely proportional to resistance

Flow = \frac{\Delta \text{Pressure}}{\text{Resistance}}

Sources of Vascular Resistance

- MAP decreases throughout the systemic circulation
- Largest drop occurs across the arterioles
  - Arterioles are called "resistance vessels"

Pressure Changes Across the Systemic Circulation

![Fig 9.16](image)
Oxygen Delivery During Exercise

- Oxygen demand by muscles during exercise is many times greater than at rest
- Increased O₂ delivery accomplished by:
  - Increased cardiac output
  - Redistribution of blood flow to skeletal muscle

Changes in Cardiac Output

- Cardiac output increases due to:
  - Increased HR
    - Linear increase to max
    - Max HR = 220 - Age (years)
  - Increased SV
    - Plateau at ~40% VO₂max
  - Oxygen uptake by the muscle also increases
    - Higher arteriovenous difference

Arterio-Venous Oxygen Difference

- Venous O₂ concentration = 15 vol%
  - 15 ml/100 ml blood or 15 ml/dL blood
  - Or 150 ml O₂/L blood

Arterio-Venous Oxygen Difference

- a-vO₂Δ
- Arterial side = 20 vol%
- Venous side = 15-16 vol%
- Difference is 4-5 vol%
**Arterio-Venous Oxygen Difference**
- Arterial side = 20 vol%
- Venous side = 5 vol%
- Difference = 15 vol%

**Redistribution of Blood Flow**
- Muscle blood flow ↑ to working skeletal muscle
- Splanchnic blood flow ↓ to less active organs
  - Liver, kidneys, GI tract

**Cardiac Output**

**Increased Blood Flow to Skeletal Muscle During Exercise**
- Withdrawal of sympathetic vasoconstriction
- Autoregulation:
  - Blood flow increased to meet metabolic demands of tissue
  - $O_2$ tension, $CO_2$ tension, pH, potassium, adenosine, nitric oxide

**Blood Pressure Control**
- 1. Cardiac Output
  - Increases in quantity of blood moving per unit of time (minute) will increase systolic blood pressure
- 2. Peripheral vascular beds
  - Vasodilation decreases resistance and can lower diastolic blood pressure
Circulatory Responses to Exercise

- Heart rate and blood pressure
- Depend on:
  - Type, intensity, and duration of exercise
  - Environmental condition
  - Emotional influence

Transition From Rest → Exercise and Exercise → Recovery

- Rapid increase in HR, SV, cardiac output
- Plateau in submaximal (below lactate threshold) exercise
- Recovery depends on:
  - Duration and intensity of exercise
  - Training state of subject

Incremental Exercise

- Heart rate and cardiac output
  - Increases linearly with increasing work rate
  - Reaches plateau at 100% VO2max
- Systolic blood pressure
  - Increases with increasing work rate
- Double product
  - Increases linearly with exercise intensity
  - Indicates the work of the heart
Double product = heart rate x systolic BP

Arm vs. Leg Exercise

- At the same oxygen uptake arm work results in higher:
  - Heart rate
    - Due to higher sympathetic stimulation
  - Blood pressure
    - Due to vasoconstriction of large inactive muscle mass

Prolonged Exercise

- Cardiac output is maintained
  - Gradual decrease in stroke volume
  - Gradual increase in heart rate
- Cardiovascular drift
  - Due to dehydration and increased skin blood flow (rising body temperature)
Summary of Cardiovascular Control During Exercise

- Initial signal to “drive” cardiovascular system comes from higher brain centers
- Fine-tuned by feedback from:
  - Chemoreceptors
  - Mechanoreceptors
  - Baroreceptors

Karvonen’s Theory

- For training intensity
  - Target heart rate (THR)
  - Resting heart rate (RHR)
  - Max heart rate (MHR)

Karvonen’s Theory

- THR = RHR + .6 (MHR – RHR)
- RHR = 70 b/min
- MHR = 200 b/min

- THR = 70 + [.6 (200-70)]
- THR = 70 + [.6 (130)]
- THR = 70 + 78
- THR = 148 b/min
Cardiac Output

- Q = HR bt/min x SV ml/bt
- Rest-low end
  - Q = 70 bt/min x 70 ml/bt
  - Q = 4900 ml/min
  - Q = 4.9 L/min
- Rest-high end
  - Q = 70 bt/min x 90 ml/bt
  - Q = 6300 ml/bt
  - Q = 6.3 L/min

Cardiac Output

- Max-low end
  - Q = 200 bt/min x 180 ml/bt
  - Q = 36,000 ml/min
  - Q = 36 L/min
- Max-high end
  - Q = 200 bt/min x 210 ml/bt
  - Q = 42,000 ml/min
  - Q = 42 L/min

Fick Equation

- \[ Q = \frac{V_O^2}{A-V_O^2 \Delta} (ml O_2/min) \]
- \[ A-V_O^2 \Delta (ml O_2/L blood) \]

Algebraic Transformation

\[ VO_2 (ml O_2/min) = Q (L/min) \times A-V_O^2 \Delta (ml O_2/L blood) \]

Calculations

- Maximal exercise test resulted in the following information on a 35 year old trained subject
  - HR = 190 bt/min
  - SV = 90 ml/bt
  - Arterial O_2 = 22 vol%
  - Venous O_2 = 7 vol%

Calculations

- HR = 190 bt/min
- SV = 90 ml/bt
- Arterial O_2 = 22 vol%
- Venous O_2 = 7 vol%

Calculations

- SV = 75 ml/beat
- HR = 82 beats/min
- A-VO_2\Delta = 49 ml/L

\[ VO_2 = \]
Calculations

• VO$_2$ = 3100 ml/min
• HR = 200 beats/min
• SV = 112 ml/beat
• Q = L/min
• A-VO$_2$$\Delta$ = ml/L
• A-VO$_2$$\Delta$ = vol%

Calculations

• VO$_2$ = 263 ml/min
• HR = 45 beats/min
• SV = 115 ml/beat
• Q = L/min
• A-VO$_2$$\Delta$ = ml/L
• A-VO$_2$$\Delta$ = vol%

Calculations

• HR = 190 beats/min
• SV = 189 ml/beat
• Q = L/min
• A-VO$_2$$\Delta$ = 155 ml/L
• A-VO$_2$$\Delta$ = vol%
• VO$_2$ =