Chapter 9: Circulatory Adaptations to Exercise

Introduction

• Exercise poses a major challenge to homeostasis due to increased muscular demand for oxygen
• During heavy exercise, oxygen demands may ↑ by 15 to 25 times
• Two major adjustments of blood flow are;
  – ↑ cardiac output
  – Redistribution of blood flow
• A thorough understanding of the cardiovascular system is essential to exercise physiology

Objectives

• Give an overview of the design and function of the circulatory system
• Describe cardiac cycle & associated electrical activity recorded via electrocardiogram
• Discuss the pattern of redistribution of blood flow during exercise
• Outline the circulatory responses to various types of exercise

Objectives

• Identify the factors that regulate local blood flow during exercise
• List & discuss those factors responsible for regulation of stroke volume during exercise
• Discuss the regulation of cardiac output during exercise

The Cardiovascular System

Purposes

1. Transport O₂ to tissues and removal of waste (CO₂)
2. Transport of nutrients to tissues
3. Regulation of body temperature

The Circulatory System

• Heart
  – Pumps blood
• Arteries and arterioles
  – Carry blood away from the heart
• Capillaries
  – Exchange of nutrients with tissues
• Veins and venules
  – Carry blood toward the heart
Structure of the Heart

Fig 9.1

Pulmonary and Systemic Circuits

Systemic circuit
- Left side of the heart
- Pumps oxygenated blood to the whole body via arteries
- Returns deoxygenated blood to the right heart via veins

Pulmonary circuit
- Right side of the heart
- Pumps deoxygenated blood to the lungs via pulmonary arteries
- Returns oxygenated blood to the left heart via pulmonary veins

The Myocardium

Fig 9.2

The Cardiac Cycle: alternating pattern

Systole
- Contraction phase

Diastole
- Relaxation phase

Arterial Blood Pressure

- Expressed as systolic/diastolic
  - Normal is 120/80 mmHg
  - High is ≥140/90 mmHg
- Systolic pressure (top number)
  - Pressure generated during ventricular contraction (systole)
- Diastolic pressure
  - Pressure in the arteries during cardiac relaxation (diastole)
Blood Pressure

- Pulse pressure
  - Difference between systolic and diastolic
  \[ \text{Pulse Pressure} = \text{Systolic} - \text{Diastolic} \]
- Mean arterial pressure (MAP)
  - Average pressure in the arteries
  \[ \text{MAP} = \text{Diastolic} + \frac{1}{3}(\text{pulse pressure}) \]

Mean Arterial Pressure

Blood pressure of 120/80 mm Hg

\[ \text{MAP} = 80 \text{ mm Hg} + .33(120-80) \]
\[ = 80 \text{ mm Hg} + 13 \]
\[ = 93 \text{ mm Hg} \]

Measurement of B P

- Inflated cuff stops arterial blood flow
- Release of pressure, flow resumes
  - Systolic
  - Sound stops
  - Diastolic

Factors That Influence Arterial Blood Pressure

- Blood volume increases
- Heart rate increases
- Stroke volume increases
- Blood pressure increases
- Blood viscosity increases
- Peripheral resistance increases

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)
Electrocardiogram

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

Cardiac Cycle & ECG

Diagnostic Use of the ECG

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

Abnormal ECG

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

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

- 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-increased 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 Output = Heart Rate x Stroke Volume

- Mean arterial pressure
- Parasympathetic nerves
- Sympathetic nerves
- Contraction strength
- EDV
- Stretch

**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

Hemodynamics
Based on interrelationships between:
- Pressure
- Resistance
- Flow

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

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

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

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

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

Changes in Cardiovascular Variables During Exercise
Redistribution of Blood Flow
- Muscle blood flow ↑ to working skeletal muscle
- Splanchnic blood flow ↓ to less active organs
  - Liver, kidneys, GI tract

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

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% VO$_{2\text{max}}$
- 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 \times \text{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)

Cardiovascular Adjustments to Exercise
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

Fig 9.24