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

Fig 9.7

- Sinoatrial node (SA node)
- Atrioventricular node (AV node)
- Atrioventricular bundle (bundle of His)
- Interventricular septum
- Conduction myofibers (Purkinje fibers)
- Apex of heart
- Interatrial septum
- Right and left bundle branches
Electrocardiogram

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

![Electrocardiogram Diagram](image)

**Fig 9.9**
Cardiac Cycle & ECG

Figure 9.10
An illustration of the relationship between the heart's electrical events and the recording of the ECG. Panels a–d illustrate atrial depolarization and the formation of the P-wave. Panels e–f illustrate ventricular depolarization and formation of the QRS complex. Finally, panel g illustrates repolarization of the ventricles and formation of the T-wave.
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)
Electrical events

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

Fig 9.8
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

Fig 9.11
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

Fig 9.12
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 = Heart Rate x Stroke Volume Output

Parasympathetic nerves → Mean arterial pressure

Mean arterial pressure → Contraction strength

Contraction strength → EDV

EDV → Stretch

Stretch → Frank-Starling

Frank-Starling → Sympathetic nerves

Sympathetic nerves → Heart Rate x Stroke Volume

Heart Rate x Stroke Volume → Cardiac Output
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

Fig 9.14
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)
Blood Flow Through the Systemic Circuit

\[ \Delta P = 100 - 0 = 100 \text{ mm Hg} \]

Pressure = 0 mm Hg

Mean arterial pressure \( \sim 100 \text{ mm Hg} \)
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

Fig 9.16
Oxygen Delivery During Exercise

- Oxygen demand by muscles during exercise is many times greater than at rest.
- Increased $O_2$ 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
      \[ \text{Max HR} = 220 - \text{Age (years)} \]
  - Increased SV
    - Plateau at \(~40\%\) \(\text{VO}_2\text{max}\)
- Oxygen uptake by the muscle also increases
  - Higher arteriovenous difference
Changes in Cardiovascular Variables During Exercise

Fig 9.17
Arterio-Venous Oxygen Difference

- Represents the difference in oxygen content of blood between arteries and veins
  - The amount of oxygen used by the cells for metabolism
- Arterial concentration = 20 vol%  
  - vol% means 20 ml/100 ml of blood or 20 ml/dL blood  
  - vol% means the volume of O\textsubscript{2} per liter of blood  
  - Means that 200 ml O\textsubscript{2} in 1 L blood (1000 ml)
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

- $a-vO_2\Delta$
- 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 $\uparrow$ to working skeletal muscle

• Splanchnic blood flow $\downarrow$ to less active organs
  – Liver, kidneys, GI tract
Cardiac Output

![Cardiac Output Diagram]

- **Skeletal muscle**
- **Other organs**

Blood flow (% cardiac output)

- Rest
- Maximal

$\dot{V}O_2$

Exercise
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
Fig 9.19

Cardiac output
= 25 l/min.

Cardiac output
= 5 l/min.

Heavy exercise

Rest

Heavy exercise

Rest

25 l/min
100%
3 - 5%
4 - 5%
2 - 4%
0.5 - 1%
3 - 4%
80 - 85%

~20 l/min.

~0.75 l/min.
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 $\rightarrow$ Exercise and Exercise $\rightarrow$ 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 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

Fig 9.21
Fig 9.21

Mean Arterial Blood Pressure

Blood pressure (mm Hg)

Heart Rate

Heart rate (beats · min⁻¹)

Exercise oxygen uptake (ℓ · min⁻¹)

Arm exercise

Leg exercise

Arm exercise

Leg exercise
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)
HR, SV, and CO During Prolonged Exercise

Fig 9.22

- **Cardiac output (l.min⁻¹)**: Remains constant at 15 l.min⁻¹.
- **Stroke volume (ml. beat⁻¹)**: Decreases linearly from 120 ml. beat⁻¹ to 80 ml. beat⁻¹.
- **Heart rate (beats.min⁻¹)**: Increases linearly from 120 beats.min⁻¹ to 180 beats.min⁻¹ over 90 minutes of exercise.
Cardiovascular Adjustments to Exercise

Fig 9.23
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
A Summary of Cardiovascular Control During Exercise

Fig 9.24
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
  – $Q = 200 \text{ bt/min} \times 180 \text{ ml/bt}$
  – $Q = 36,000 \text{ ml/min}$
  – $Q = 36 \text{ L/min}$

• Max-high end
  – $Q = 200 \text{ bt/min} \times 210 \text{ ml/bt}$
  – $Q = 42,000 \text{ ml/min}$
  – $Q = 42 \text{ L/min}$
Fick Equation

• \( Q = \frac{VO_2}{A-VO_2\Delta} \) (ml O\(_2\)/min)
  
  \( A-VO_2\Delta \) (ml O\(_2\)/L blood)

Algebraic Transformation

\( VO_2 \) (ml O\(_2\)/min) = \( Q \) (L/min) \* \( A-VO_2\Delta \) (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 O₂ = 22 vol%
- Venous O₂ = 7 vol%

- Cardiac output =
- A-VO₂Δ (vol%) =
- A-VO₂Δ (mIO₂/L blood) =
- VO₂ =
Calculations

- SV = 75 ml/beat
- HR = 82 beats/min
- A-VO$_2$Δ = 49 ml/L

- VO$_2$ =
Calculations

- \( \text{VO}_2 = 3100 \text{ ml/min} \)
- \( \text{HR} = 200 \text{ beats/min} \)
- \( \text{SV} = 112 \text{ ml/beat} \)
- \( Q = \text{ L/min} \)
- \( \Delta \text{A-VO}_2 = \text{ ml/L} \)
- \( \Delta \text{A-VO}_2 = \text{ vol}\% \)
Calculations

- $\text{VO}_2 = 263 \text{ ml/min}$
- $\text{HR} = 45 \text{ beats/min}$
- $\text{SV} = 115 \text{ ml/beat}$
- $Q = \text{L/min}$
- $A-\text{VO}_{2}\Delta = \text{ml/L}$
- $A-\text{VO}_{2}\Delta = \text{vol\%}$
Calculations

- HR = 190 beats/min
- SV = 189 ml/beat
- $Q = L/min$
- $A-VO_2\Delta = 155 \text{ ml/L}$
- $A-VO_2\Delta = \text{ vol}\%$
- $VO_2 =$