Chapter 7

The Cardiovascular System and Exercise
What You Will Learn in this Chapter

• How the CV system functions during dynamic & resistance exercise
• Specifics about HR & BP adaptations to exercise
• How cardiac output & VO$_2$ change to meet metabolic demands of exercise
• How circulatory system is regulated during exercise
• How blood vessels are regulated to re-distribute circulation to exercising muscles
The Human Circulatory System
Animation: The Circulatory System
Blood Flow Through the Heart

Superior vena cava (returns blood from head, upper limbs)
Right pulmonary veins (return blood from right lung)
Pulmonary semilunar valve (shown open)
Right atrium
Right atrioventricular valve (shown open)
Right ventricle
Inferior vena cava (returns blood from trunk, legs)

To systemic circulation (upper body)

Aorta
Right and left pulmonary arteries (to lungs)
Left pulmonary veins (return blood from left lung)
Left atrium
Aortic semilunar valve (shown open)
Left atrioventricular valve (shown open)
Left ventricle
Septum

KEY
- Red: O₂-rich blood
- Blue: O₂-poor blood

Blood flow through the heart

Figure 7.1 p. 213
The Autonomic Nervous System (ANS)

- Includes both sympathetic & parasympathetic (vagal) nerves that regulate actions of
  - Ductless glands, viscera, blood vessels, & all organs that contain involuntary muscles
Key Terms Related to Heart Function

• **Heart rate (HR)**
  - Number of times heart beats (contracts) in 1 minute

• **Stroke volume (SV)**
  - Volume of blood pumped during 1 heart beat

• **Cardiac output (Q)**
  - Volume of blood pumped in one minute of time

• **A-VO₂ difference**
  - the difference in oxygen saturation of arterial and venous blood
Cardiovascular Function

Key Formulas

\[ \dot{Q} = \text{HR} \times \text{SV} \]

\[ \dot{V}O_2 \text{ l/min} = \dot{Q} \times \text{AVO}_2 \text{ diff} \]

\[ \dot{V}O_2 \text{ ml/kg/min} = \frac{\dot{V}O_2 \text{ l/min} \times 1000 \text{ ml/l}}{\text{wt. (kg)}} \]
How Does the Heart Beat in a Synchronized (Efficient) Fashion?
Thru the Flow of Waves of Bioelectrical Depolarization within the Heart
Depolarization in the Heart

P wave = Atrial depolarization
PR segment = AV nodal delay
QRS complex = Ventricular depolarization (atria repolarizing simultaneously)
ST segment = Time during which ventricles are contracting and emptying
T wave = Ventricular repolarization
TP interval = Time during which ventricles are relaxing and filling

Figure 7.3 p. 216
Electrocardiography and Heart Conditions

Figure 7.4  p. 217
The Cardiac Cycle
The Heart as a Pump

• As HR increases during exercise because of
  ▪ Increased sympathetic activity & parasympathetic withdrawal
    • Time to fill ventricle with venous return decreases

• Volume of venous blood returned for each beat
  ▪ Needs to proportionally increase, and
  ▪ Transmission speed of electrical activity in AV node needs to increase to
    • Maintain and/or increase heart’s cardiac output (Q)
The Heart as a Pump

• Heart
  ▪ Beats at different rates
  ▪ Rate is dependent on whether body is at rest or at work

• Resting HR
  ▪ Average person = 72 bpm
  ▪ Within normal limits = 50 to 80 bpm
  ▪ Elite endurance performers = 30 to 40 bpm

Non-endurance-trained individuals with HRs this low would be clinically diagnosed with sinus bradycardia, or may be in a ventricular escape rhythm & usually have symptoms of light-headedness, dizziness, & fainting
Blood Pressure Is Determined by the Heart Pumping Blood into the Blood Vessels

• **BP is similar to garden hose:**
  - Before turning on tap
    • Hose has no pressure inside
  - After turning on tap
    • Hose fills with water

• Because walls of hose are restraining water to flow only inside the hose, pressure builds up in relation to:
  - Amount of water flow
  - Resistance walls of hose impart on water flow
Blood Pressure Is Determined by the Heart Pumping Blood into the Blood Vessels

• **BP is determined by:**
  - How much blood heart pumps through blood vessel
  - Resistance arterial walls provide against blood flowing through them

• **Systolic blood pressure (SBP)**
  - Peak pressure exerted by pressure wave of blood against the blood vessel walls

• **Diastolic blood pressure (DBP)**
  - Lowest pressure exerted by pressure wave of blood against the blood vessel walls
Arterial Blood Pressure

Figure 7.7  p. 220
Blood Pressure Is Determined by the Heart Pumping Blood into the Blood Vessels

- **Mean blood pressure or mean arterial pressure (MAP)**
  - Average pressure exerted by pressure wave of blood against blood vessel walls

- **Total peripheral resistance (TPR)**
  - Total resistance to blood flow within the CV system
Mean Blood Pressure Formula

$$\text{MBP} = \text{DBP} + \frac{1}{3} \ (\text{PP})$$  where $\text{PP} =$ the difference between the systolic and diastolic pressures

Example: Jane has a resting blood pressure of 106/70
$$\text{MBP} = 70 + \frac{1}{3} \ (106 - 70)$$
$$\text{MBP} = 70 + \frac{1}{3} \ (36)$$
$$\text{MBP} = 70 + 12$$
$$\text{MBP} = 82$$
Measuring BP

- BP can be measured in 2 different ways:
  - With a standard cuff
  - Directly through arterial catheterization

- More common method termed:
  - Brachial auscultation
Brachial Auscultation

Figure 7.8 p. 221

(a) Use of a sphygmomanometer in determining blood pressure

(b) Blood flow through the brachial artery in relation to cuff pressure and sounds

Pressure-recording device
Inflatable cuff
Stethoscope

When blood pressure is 120/80:

1. No sound is heard because no blood is flowing.

When cuff pressure is greater than 120 mm Hg and exceeds blood pressure throughout the cardiac cycle:

No blood flows through the vessel.

When cuff pressure is between 120 and 80 mm Hg:

Blood flow through the vessel is turbulent whenever blood pressure exceeds cuff pressure.

The first sound is heard at peak systolic pressure.

Intermittent sounds are produced by turbulent spurts of flow as blood pressure cyclically exceeds cuff pressure.

When cuff pressure is less than 80 mm Hg and is below blood pressure throughout the cardiac cycle:

Blood flows through the vessel in smooth, laminar fashion.

The last sound is heard at minimum diastolic pressure.

No sound is heard thereafter because of uninterrupted, smooth, laminar flow.
BPs that Occur Throughout Systemic Circulation
Cardiovascular System under Conditions of Exercise

• **There are two types of exercise:**
  - Dynamic, or aerobic
  - Isometric (static), or resistance

• **Dynamic or aerobic exercise**
  - Involves rhythmic concentric or eccentric contractions
    - Change muscle length & joint angles without generating large intramuscular forces
  - Primarily uses aerobic energy production
  - Sometimes called *aerobic exercise*
Characteristics of Aerobic Exercise

Continuous
Large Muscle Groups
Rhythmic
Little or No Immediate Muscle Fatigue
Cardiovascular System under Conditions of Exercise

• **Isometric, or static exercise:**
  - Primarily involves anaerobic energy production
  - Involves a sustained contraction that does not change muscle length & joint angles

• **Isometric exercise results in:**
  - Large increases in intramuscular force in direct relation to absolute intensity of contraction or
  - Percentage of the individual’s maximal voluntary contraction (% MVC)

• Next slide compares average CV responses of a 30% MVC isometric exercise with that of maximal dynamic exercise
Cardiovascular System under Different Conditions of Exercise

Figure 7.10
Cardiovascular System under Conditions of Exercise

• During progressive increases in dynamic exercise intensity
  ▪ Circulatory response is directly related to an increase in exercise intensity until one’s VO₂ max is achieved
Cardiovascular System under Conditions of Exercise

- **During isometric exercise**
  - Magnitude of circulatory response is related to:
    - Intensity (% MVC) of exercise
    - Amount of muscle mass being contracted
  - Increase in cardiac output ($\dot{Q}$) is a result of:
    - Increased HR and SV
Dynamic Exercise Increases the Rate of Circulation and the Demands on the Body

• During dynamic exercise
  ▪ Rate of circulation increases up to a max of 5-6x > at rest
Oxygen Uptake Increases during Dynamic Exercise

• **Cardiac output (\( \dot{Q} \))**
  - Increases during dynamic exercise
  - HR and SV increases
  - Oxygen via blood flow to the working muscles increases
Oxygen Uptake Increases during Dynamic Exercise

• Link between rate of \( \text{VO}_2 \) (in \( \text{L/min} \)) & \( \dot{Q} \) (L/min) is expressed as:
  \[ \text{VO}_2 \ (\text{L/min}) = \dot{Q} \ (\text{L/min}) \times (\text{A-V}) \text{ O}_2 \text{ difference} \ (\text{ml/L}) \]

• This equation is known as \textit{Fick equation}

• \((\text{A-V}) \text{ O}_2 \text{ difference} = \text{difference between O}_2 \text{ content of arterial blood & venous blood} \)
Linear Relationship Exists Between $\dot{Q}$ & $\dot{VO}_2$ from Rest to Maximal Exercise

Figure 7.12
Heart Rate and Stroke Volume

- Increases in \( \dot{Q} \) that occur during exercise in a normal healthy upright adult result from:
  - Increased HR
  - Increased SV
Heart Rate Increases during Dynamic Exercise

• Relationship between HR & $\dot{VO}_2$
  - Linear
  - Reproducible for each individual

• The slope of relationship between $VO_2$ & HR is dependent on:
  - Individual’s $VO_2$max (CR Fitness Level)
  - Individual’s range of HR response
  - See next slide…
Stroke Volume Increases during Dynamic Exercise

• **Stroke Volume**
  - Amount of blood pumped by heart in each beat
  - Represents difference between heart’s
    - End-diastolic volume (EDV) – “filling”
    - End-systolic volume (ESV) – “emptying”
  - See Next Slide

• This relationship can be expressed as:
  - \( SV \text{ (ml/beat)} = EDV \text{ (ml)} - ESV \text{ (ml)} \)
Application: Left Ventricular Volumes in Cycling Exercise

Supine

Upright

Ventricular volumes

EDV

Stroke volume

ESV

Figure 7.15
Stroke Volume Increases during Dynamic Exercise

- **Central blood volume (CBV)**
  - Volume of blood in
    - Heart chambers
    - Lungs
    - Central arterial blood vessels

- **Ejection fraction**
  - Amount of blood pumped each beat (SV) divided by EDV (total amount of blood in the ventricle)
<table>
<thead>
<tr>
<th>Measure</th>
<th>Typical Value</th>
<th>Normal Range</th>
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</thead>
<tbody>
<tr>
<td>end-diastolic volume (EDV)</td>
<td>120 ml</td>
<td>65–240 ml</td>
</tr>
<tr>
<td>end-systolic volume (ESV)</td>
<td>50 ml</td>
<td>16–143 ml</td>
</tr>
<tr>
<td>stroke volume (SV)</td>
<td>70 ml</td>
<td>55–100 ml</td>
</tr>
<tr>
<td>ejection fraction ($E_t$)</td>
<td>58%</td>
<td>55–70%</td>
</tr>
<tr>
<td>heart rate (HR)</td>
<td>72 bpm</td>
<td>60–80</td>
</tr>
<tr>
<td>cardiac output ($\dot{Q}$)</td>
<td>4.9 L/minute</td>
<td>4.0–8.0 L/ min</td>
</tr>
</tbody>
</table>
Stroke Volume Increases during Dynamic Exercise

• **Muscle pump**
  - “Second heart” in venous side of circulation
  - These contracting skeletal muscles work in conjunction with competent venous valves to effectively drive blood back to heart

• **Preload**
  - Right atrial pressure for right ventricle
  - Pulmonary wedge pressure for the left ventricle
Stroke Volume Increases during Dynamic Exercise

- **Frank–Starling mechanism**
  - Named after 2 investigators who identified that as length of ventricular fibers are stretched
    - Contraction force of fiber becomes greater
  - This translates to an increase in venous return leading to an
    - Increased EDV
    - Increased SV
Venous Return Increases during Dynamic Exercise

- Two additional mechanisms affect venous return at rest & during exercise:
  - Muscle pump (next slide)
  - Respiratory pump

- They are generally regarded as:
  - Auxiliary circulatory pumps
Muscle Pump

• During dynamic exercise, combination of
  ▪ Skeletal muscles contracting
  ▪ Venous valve inhibiting retrograde flow away from heart operates to
    • Provides pumping action of blood toward heart

• Immediately after a muscle contraction
  ▪ Veins exiting from contracted muscle are empty
  ▪ Intravenous pressure approximates zero (next slide)
Venous Valves

Open venous valve permits flow of blood toward heart

Vein pressure 0 mm Hg

Contracted skeletal muscle

Closed venous valve prevents backflow of blood

Artery pressure 90 mm Hg

Action of venous valves, permitting flow of blood toward heart and preventing backflow of blood

Figure 7.16
Respiratory Pump

- Pumping action of respiratory system
  - Known as *respiratory pump*
  - Increases venous return

- Illustrated by
  - Changes in intrapleural pressures during breathing
  - Together with flows measured in inferior vena cava in thorax & in abdomen
  - Flows in splanchnic circulation
  - Valsalva maneuver
Respiratory Muscle Pump

![Graph showing intrapleural pressure and flow through various venae cavae and splanchnic outflow during inspiration and expiration.](image)
The Arteriovenous Oxygen Difference Widens During Dynamic Exercise

• Whole-body AV-O₂ difference widens from rest to maximal dynamic exercise
  ▪ See next slide…

• As intensity of exercise increases
  ▪ A small amount of water is extracted from blood for thermoregulation, resulting in
    • Increased hemo-concentration
    • Increased O₂-carrying capacity/unit volume of blood

• However, hemo-concentration
  ▪ Does not alter arterial O₂ saturation or content
Relationship of Oxygen Content to Oxygen Uptake

Figure 7.18

- Oxygen content
- Systemic arteriovenous $O_2$ difference
- Mixed venous $O_2$ content

Oxygen content (ml 100 · ml$^{-1}$) vs. Oxygen uptake (1 · min$^{-1}$)
Dual Pump Action of the Heart

Figure 7.19
Resistance Arteries, or Arterioles, Provide Resistance to Blood Flow and Modify Blood Pressure

- Major challenge to circulatory system during dynamic or isometric exercise is to
  - Regulate arterial BP
  - Provide adequate \( O_2 \) blood flow to exercising muscles
  - See next slide…

- Resistance to blood flow is affected by
  - Number of physical properties of blood vessels
  - Blood

- Resistance is directly proportional to:
  - Length of vessel
  - Viscosity (thickness or density) of blood
  - Inversely proportional to fourth power of radius

- Resistance = \( \text{Length} \times \frac{\text{Viscosity}}{\text{Radius}^4} \)
Regulation of Blood Flow and Blood Pressure During Exercise

Figure 7.20

- **Blood pressure regulation**
  - Vasoconstriction
    - Adrenergic and non-adrenergic mechanisms
  - Vasodilation
    - Metabolic byproducts
- **Oxygen delivery**
Arteries

• Have large diameters
• Offer little resistance to blood flow coming from heart
• Main conduit vessels for blood to deliver oxygen to tissues & organs of body

• Vessel wall of artery is constructed in
  - Layers of tissue endothelium, smooth muscle cells, collagen & elastin fibers (next slide)
Blood Vessels

Figure 7.21
Arteries

• **Collagen**
  - Provides strength

• **Elastin**
  - Enables vessel to buffer fluctuating increases & decreases in its velocity of blood flow
  - Enables pulsatile pressure wave exiting heart to be transduced, such that as it reaches the resistance arteries, or arterioles, & capillaries
    - Blood flow velocity: continuous & not pulsatile
    - Pressure reservoir
Arteries Act as a Pressure Reservoir

(a) Heart contracting and emptying

(b) Heart relaxing and filling
Cerebral Circulation

• **Cerebral circulation**
  ▪ Network of blood vessels that circulates blood throughout the brain

• **Cerebral autoregulation (CA)**
  ▪ Primary means of regulating brain blood flow
    • Using blood vessel auto-regulation over a wide range of BP (60-150 mm Hg)
Autonomic Nervous System Affects Blood Pressure

• **Arterial baroreflexes**
  - Include pressure-sensitive receptors in carotid sinus & aortic arch
    - Signal CNS that BP is too low or too high

• **This results in a reflex response to:**
  - Increase or decrease BP
Cardiovascular Responses to Isometric Exercise Are Greatly Different than Dynamic Exercise

• CV responses to light workload isometric exercise are only
  ▪ Qualitatively different from responses to heavy workload isometric exercise

• However, CV responses are different from dynamic exercise when performing equivalent exercise workloads
Cardiovascular Responses to Isometric Exercise Are Greatly Different than Dynamic Exercise

- **During isometric exercise**
  - Increases in intramuscular pressure restrict blood flow to exercising muscle
    - This reduces delivery of $O_2$ to exercising muscle
  - Subsequently, more anaerobic energy production is required to maintain heavy work of contraction
    - Leading to an accumulation of metabolites
Cardiovascular Responses to Isometric Exercise Are Greatly Different than Dynamic Exercise

- The accumulation of metabolites activates chemical sensors within muscle that tell CV control center that
  - Not enough $O_2$ is being delivered to muscle

- This message triggers a central stimulation of CV system to try to
  - Increase blood flow to exercising muscle
Cardiovascular Responses to Dynamic Exercise

• During a maximum effort military (overhead) press
  ▪ Arterial pressures exceeded
  ▪ Diastolic arterial pressure = 350 mm Hg
  ▪ Systolic pressures = 480 mm Hg
  ▪ For a calculated MAP = 393 mm Hg
BP Response to Weight Training

![Graph showing blood pressure response during weight training](image)

- **Rest**
- **Curl** (1 arm) 95% 1RM to failure
- **Leg press** (1 leg) 95% 1RM to failure
- **Leg press** (2 legs) 95% 1RM to failure
- **Leg press** (2 legs) 100% 1RM

Figure 7.30
Cardiovascular Responses to Isometric Exercise

• If isometric contraction is performed while holding breath (Valsalva Maneuver)
  ▪ Brain blood flow & BP responses are accentuated

• This effect may prove to be dangerous for people with weak cerebral vascularization
Neural Influences on Mean Arterial BP

Parasympathetic stimulation

Heart

↓ Heart rate

↓ Cardiac output

↓ Blood pressure

Sympathetic stimulation

Heart

↑ Heart rate

↑ Cardiac output

↑ Blood pressure

Arterioles

↑ Vasoconstriction

↑ Stroke volume

↑ Total peripheral resistance

↑ Blood pressure

Veins

↑ Vasoconstriction

↑ Venous return

↑ Stroke volume

↑ Cardiac output

↑ Blood pressure

Figure 7.33
Main goals of this regulatory system are to:

1. Increase $\dot{Q}$ to deliver $O_2$ to working muscles
2. Redistribute increase in $\dot{Q}$ to working muscles & brain
3. Regulate arterial BP to provide adequate perfusion pressures in relation to $O_2$ demand without damaging the brain (next slide)
Arterial BP vs. Maximum Oxygen Uptake

Figure 7.35
What would happen to your clients heart rate and blood pressure after engaging in an overall fitness exercise program of 6-8 weeks?
### In Practice: Medicine

<table>
<thead>
<tr>
<th>Central command</th>
</tr>
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<tbody>
<tr>
<td>Exercise pressor reflex</td>
</tr>
<tr>
<td>Arterial baroreflexes</td>
</tr>
</tbody>
</table>

What would happen to your clients cardiovascular system after engaging in an overall fitness exercise program of 6-8 weeks?
In Practice: Athletic Performance

22-year-old soccer player

Resting heart rate (HR)?

Submaximal heart rate?

How would her RHR compare to an elite endurance athlete?

How would RHR compare to untrained friend?

What would happen to an athlete’s cardiovascular system after engaging in a high-intensity exercise program of 6-8 weeks?
## In Practice: Rehabilitation

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
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<tbody>
<tr>
<td>What happens to strength?</td>
<td></td>
</tr>
<tr>
<td>What should they do with their breath?</td>
<td></td>
</tr>
<tr>
<td>What type of exercise are good?</td>
<td></td>
</tr>
<tr>
<td>How many sets and reps?</td>
<td></td>
</tr>
<tr>
<td>What is exercise intensity?</td>
<td></td>
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</table>

What would happen to a cardiac rehab patient’s skeletal muscle system after engaging in a resistance exercise program of 6-8 weeks?
The End