Chapter 8

Cardiovascular Adaptations to an Exercise Program

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10.13.14
What You Will Learn in this Chapter

• How regular engagement in endurance exercise training increases one’s maximal oxygen uptake ($\text{VO}_2\text{max}$)

• How regular engagement in endurance exercise training can change cardiac output (\(\dot{Q}\))

• How regular engagement in endurance exercise training can remodel heart & peripheral vasculature

• How isometric, or resistance, exercise training causes specific cardiovascular adaptations
Introduction to Cardiovascular (CV) Adaptations to an Exercise Program

• CV system increases demand for O$_2$ delivery when:
  - Regular endurance training is performed 3-4x/week
  - Is progressed over weeks & months

• When individual’s CV system reaches its genetic optimum for delivery of O$_2$ to working muscles:
  - Further training stress may not result in additional increases in CV function
Introduction to Cardiovascular Adaptations to an Exercise Program

• The CV system will:
  ▪ increase its optimal use of $O_2$ delivered
  ▪ increase tissue’s capacity to use lactate (La-) from type IIa & IIb fibers as an energy source for
    • Muscle & heart contraction (La- shuttle)
    • Brain metabolism
Adaptations to Endurance Training (>2 Years)

Figure 8.1
Increases in VO$_2$ above Rest Are Necessary to Perform Dynamic (or Aerobic) Exercise

• Primary physiologic measure of circulatory capacity that distinguishes individuals with differing amounts of aerobic fitness is
  
  ▪ VO$_2$max normalized to body weight
Group Differences in VO$_2$ max Values

**Figure 8.2**

The bar graph compares VO$_2$ max values for different groups:
- Sedentary (S) group with a value of 30 mL O$_2$/kg/min.
- Normally active (NA) group with a value of 45 mL O$_2$/kg/min.
- Normally active group after 3 months of training (T) with a value of 53 mL O$_2$/kg/min.
- Elite athletes (EA) group with a value of 85 mL O$_2$/kg/min.

The graph shows the response of VO$_2$ max to different levels of exertion in watts. The values are indicated at key points throughout the range of watts from 0 to 400.
Lab 6: Interpreting the Results of Your Maximal Oxygen Uptake

<table>
<thead>
<tr>
<th>Gender</th>
<th>Age</th>
<th>Poor</th>
<th>Fair</th>
<th>Average</th>
<th>Good</th>
<th>Excellent</th>
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<td>13 - 20.9</td>
<td>21 - 32.9</td>
<td>33 - 36.9</td>
<td>≥ 37</td>
</tr>
</tbody>
</table>

- Heath fitness standard
- High physical fitness standard
Increases in VO$_2$ above Rest Are Necessary to Perform Dynamic (or Aerobic) Exercise

• There is a large range of values of VO$_2$max in
  ▪ Healthy young adults

• These are reflective of an individual’s:
  ▪ Daily physical activities
  ▪ Dietary habits
  ▪ General C-V health
  ▪ Genetic makeup
Increases in VO$_2$ above Rest Are Necessary to Perform Dynamic (or Aerobic) Exercise

• In patients with severe cardiopulmonary disease
  ▪ Values < 20 ml O$_2$/kg/min are often measured
    • See next slide…

• In elite endurance athletes, values that
  ▪ Exceed 85 to 90 ml O$_2$/kg/min in males and 70 to 75 ml O$_2$/kg/min are not unusual
    • Back in Figure 8.2
Comparative Functional Classifications of Patients with Heart Disease

<table>
<thead>
<tr>
<th>Classification</th>
<th>Criteria</th>
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<tbody>
<tr>
<td>Class I</td>
<td>Patients with heart disease who have no symptoms of any kind; ordinary physical activity does not cause fatigue, palpitation, dyspnea, or anginal pain</td>
</tr>
<tr>
<td>Class II</td>
<td>Patients who are comfortable at rest but have symptoms with ordinary physical activity</td>
</tr>
<tr>
<td>Class III</td>
<td>Patients who are comfortable at rest but have symptoms with less than ordinary effort</td>
</tr>
<tr>
<td>Class IV</td>
<td>Patients who have symptoms at rest</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: High risk for developing heart failure</td>
<td>Hypertension, diabetes mellitus, CAD, family history of cardiomyopathy</td>
</tr>
<tr>
<td>B: Asymptomatic heart failure</td>
<td>Previous MI, LV dysfunction, valvular heart disease</td>
</tr>
<tr>
<td>C: Symptomatic heart failure</td>
<td>Structural heart disease, dyspnea and fatigue, impaired exercise tolerance</td>
</tr>
<tr>
<td>D: Refractory end-stage heart failure</td>
<td>Marked symptoms at rest despite maximal medical therapy</td>
</tr>
</tbody>
</table>

Table 8.1
Increases in VO$_2$ above Rest Are Necessary to Perform Dynamic (or Aerobic) Exercise

• In addition to genetic component of training-induced increase in VO$_2$max
  ▪ Number of other factors affect amount of change in VO$_2$max following an exercise training program

• The Factors include:
  1. Individual’s VO$_2$ max at start of training
  2. Age of individual in training
  3. Muscle mass involved
  4. Frequency, intensity, & duration of training
  5. Specificity
Maximal Oxygen Uptake

• Individual with greater VO$_2$max at the start of training
  ▪ The smaller the increase in VO$_2$max that occurs after a given amount of training

• Adult’s age at beginning of training affects amount of improvement one can expect to see
  ▪ Older individual’s
    • e.g. less increase in VO$_2$max after training
Changes in VO\textsubscript{2} max with Age

Figure 8.3
Beginning Age

- Intensity of training relative to maximum HR
  - Will be less
    - Recommended at 60% x [MHR - RHR] + RHR

- Therefore, total amount of total work & cardiac work performed by older subjects in a given amount of time (3, 6, 9, or 12 months)
  - Will be far less than that of younger subjects

- This will result in
  - Much less increase in older individual’s VO$_2$max regardless of an aging effect
Beginning Muscle Mass

• Absolute increase in VO$_2$max after training is
  ▪ Directly related to amount of muscle mass used during training program

• For example
  ▪ Increase in VO$_2$max following a training program using arm ergometer exercise will be less than if cycling (2 leg) exercise was used
Frequency, Intensity, and Duration

• Adaptive responses to endurance training are dependent on:
  1. Frequency
  2. Intensity
  3. Duration

• Increases in CV adaptation will continue to occur until
  - Individual’s genetic optimum potential is reached
(Figure 8.1)
Specificity of Training

• Even though you can train an elite endurance swimmer to have a high VO$_2$max by using running as mode of training
  
  - Her swimming performance will be well below that of other elite swimmers trained with swimming
  
  - Coaches and trainers should make every effort to avoid violation of this principle of training.
Specificity

• When measures of VO₂ max & endurance performance on a field test are correlated
  ▪ Relationship is strong (r = 0.90)
  • Suggesting VO₂ max predicts endurance performance or vice versa
The Relationship Between the 12 Minute Run and Maximum Oxygen Uptake

Figure 8.4

\[ \dot{V}O_2^{\text{max}} \text{ (mLO}_2/\text{kg/min)} \]

Distance run in 12 mins (miles)

\[ r = 0.9 \]
Specificity

• However, if one were to compare individual world-class or elite middle-distance runners & marathoners
  ▪ It would not always be the one with highest VO\textsubscript{2}max who would win

• What does this mean?

• Winning an endurance events is not always exclusive to one’s VO\textsubscript{2}max level
Specificity

• **Includes a multitude of factors:**
  1. Specificity of training
  2. Capacity of one’s metabolic system to support muscle work over time
  3. Muscle fiber type & plasticity
  4. Neuroendocrine regulation
  5. Psychological traits
  6. Degree of acclimatization to environmental challenges
Endurance Exercise Training Results in Rapid Central Circulatory Adaptations

- General health status is a key factor
- The next slide provides a cross-sectional comparison of these variables:
  - *Patient with heart disease*: $VO_2\text{max} = 1.5 \text{ L/min}$
  - *Average fit sedentary individual*: $VO_2\text{max} = 3.0 \text{ L/min}$
  - *Elite endurance-trained athlete*: $VO_2\text{max} = 5.6 \text{ L/min}$
Maximal Cardiovascular Factors Including Maximum Oxygen Uptake

Figure 8.5

<table>
<thead>
<tr>
<th></th>
<th>Patient with heart disease</th>
<th>Sedentary normal man</th>
<th>Athlete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen uptake (l/min)</td>
<td>1.5</td>
<td>3.0</td>
<td>5.6</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>175</td>
<td>190</td>
<td>180</td>
</tr>
<tr>
<td>Stroke volume (ml)</td>
<td>57</td>
<td>100</td>
<td>180</td>
</tr>
<tr>
<td>Cardiac output (l/min)</td>
<td></td>
<td>10.1</td>
<td>19.0</td>
</tr>
<tr>
<td>A-V $O_2$ difference (ml/100ml)</td>
<td>15.0</td>
<td>15.8</td>
<td>17.0</td>
</tr>
</tbody>
</table>
Physiological Changes at the Start of an Aerobic Exercise Session

- Increased ventilation (work of the alveoli)
- Increased heart rate, stroke volume, and cardiac output (work of the heart)
- Increased blood flow to the working muscles for oxygen delivery and use by the working muscles. (work of the hemoglobin)
Benefits of Aerobic Training

- Higher Maximum Oxygen Uptake (VO₂ max)
- An increase in the oxygen carrying capacity of the blood
- A decrease in resting heart rate
- An increase in heart size and cardiac efficiency (stroke volume)
- A lower heart rate at any given exercise workload
- An increase in the size and number of mitochondria in muscle fibers
- An increase in the number of functional capillaries
- Faster recovery time
- Lower blood pressure and blood lipid levels
- More fat burning enzymes
Health Benefits of Aerobic Exercise

• Improved appearance.
• Maintenance of proper body weight.
• Reduction in coronary heart disease risk.
• Increased efficiency of the heart and lungs.
• Increased energy level.
• Reduced stress response.
• Delay in acquired aging.
• Improved mental productivity.
• Enhanced self-concept.
• Decrease risk of “hypokinetic” conditions & diseases.

Endurance Exercise Training Results in Rapid Central Circulatory Adaptations

• Difference in maximal SV between the 3 types of individuals (figure 8.5) results in differences in
  ▪ Maximal Q
  ▪ VO$_2$max

• Effect of an individual’s left heart pump function on max SV at MHRs is generally accepted as:
  ▪ Limiting factor to an individual’s
    • Maximal Q
    • VO$_2$max
Endurance Exercise Training Programs Result in Increases in Maximal Cardiac Output (Q)

- Endurance exercise training can result in
  - Near doubling of an elite athlete’s max \( \dot{Q} \)
    - Without changing resting or submaximal \( \dot{Q} \)
  - Furthermore, linear relationship between \( \dot{Q} \) & \( \dot{VO}_2 \) max
    - Unchanged by endurance exercise training (see next slide…)
The Relationship Between VO$_2$ max and Cardiac Output

![Graph showing the relationship between VO$_2$ max and cardiac output in trained and untrained individuals.](Image)

- The graph illustrates the increase in cardiac output (Q) with increasing workload for both trained and untrained individuals.
- The x-axis represents workload, and the y-axis represents cardiac output (Q) in L/min.
- The graph shows that trained individuals have a higher cardiac output at various workloads compared to untrained individuals.

Figure 8.6 p 266
Endurance Exercise Training Programs Result in Decreases in Resting and Submaximal Heart Rates

- Endurance exercise training results in
  - Decrease ranging from 10-40 bpm in RHRs & submaximal workload HRs, but
  - Only minor differences in MHR
Relationship Between Heart Rate and VO2 (L/min)
Endurance Exercise Training Programs Result in Decreases in Resting and Submaximal Heart Rates

These differences in RHRs & submaximal HRs between endurance-trained & untrained individuals are due to:

• Increase in degree of vagal control on cells of sinoatrial (SA) node
  ▪ The intrinsic firing rate

• An increased vagal (parasympathetic) control
  ▪ Reduces SA node cell’s firing rate
  ▪ Decreases HR

• Decrease in vagal control (sympathetic)
  ▪ Increases SA node cell’s firing rate & HR
Endurance Exercise Training Programs Result in Decreases in Resting and Submaximal Heart Rates

• If we plot HR response to exercise in relation to a person’s % VO$_2$max
  ▪ Difference between trained & untrained individuals disappears (next slide....)
Heart Rate vs. a Percent(%) of VO\textsubscript{2} max

![Graph showing heart rate (HR) vs. percent of VO\textsubscript{2} max](image)

Figure 8.7
Adaptations of Stroke Volume to a Program of Endurance Exercise Training

- The average sedentary individual’s SV plateaus
  - Relative workload of 40% VO₂ max
  - It is maintained relatively constant up to 100% VO₂ max

- However, highly trained endurance athlete
  - SV continues to increase up to 100% VO₂ max
Changes in Stroke Volume with Increased Workloads

Figure 8.11

Graph showing the changes in stroke volume (SV) as a percentage of maximum oxygen uptake (VO₂ max) with respect to workload intensity. The graph compares trained and untrained individuals. The trained group shows a steeper increase in SV compared to the untrained group.

Rest - 100% VO₂ max

SV (ml/beat)

Trained

Untrained

Figure 8.11
Adaptations of Stroke Volume to a Program of Endurance Exercise Training

- Appearance of plateau of SV at 40% VO$_2$max in sedentary healthy individuals appears to be related to three factors:
  1. Balance between cardiac filling time (a factor of R-R interval) & volume (Starling’s effect)
  2. Rate of venous return
  3. Its effect on cardiac filling volume
Adaptations of Stroke Volume to a Program of Endurance Exercise Training

• Continuously increasing SV up to VO$_2$max in endurance exercise-trained athlete suggests
  - Venous return volume entering heart for each decrease in R-R interval (increase in HR) is
    • Greater & enables a greater ejection fraction volume to be achieved for each beat via
      • Frank–Starling mechanism
    • Increases in myocardial contractility in direct relation to increasing VO$_2$ required for increasing workloads
Adaptations of Stroke Volume to a Program of Endurance Exercise Training

For these changes to occur, the following five adaptive responses to endurance training are required:

1. Pericardial restraint & remodeling of pericardium
2. Cardiac remodeling & hypertrophy
3. Possible increases in cardiac contractility
4. Vascular remodeling & growth
5. Blood volume expansion
Cardiac Remodeling & Hypertrophy and Blood Volume

• Cardiac hypertrophy that results from training program is directly related to:
  • Intensity & duration of exercise training program
  • Changes in cardiorespiratory endurance or VO$_2$max

• Why?
Heart initially adapts to increased preload of larger central blood volume during exercise by:

- Increasing its left ventricular (LV) mass (*concentric hypertrophy*; see next slide)
  - Results: Increase in heart’s LV wall thickness

As training continues & blood volumes increase:

- Heart’s ventricular chambers increase their volumes without reducing thickness of chamber walls
- Called *eccentric hypertrophy* (see next slide)
Changes in Heart Structure Due to Endurance Training

Figure 8.14

(a) Concentric hypertrophy

(b) Eccentric hypertrophy
Arteriovenous Oxygen Difference

• Main difference in extraction is observed in:
  ▪ Trained skeletal muscle capillary bed

• Although some suggest increase in maximal $O_2$ extraction from blood, or A-VO$_2$ difference can
  ▪ Increase VO$_2$max after an endurance exercise training program by as much as 50%

• A more generally accepted increase suggests
  ▪ It is < 20%
  ▪ See next slide....
Average CV Changes with Years of Endurance Training

Figure 8.23
Resistance Exercise Training

• Results in only 1 major change in CV function
  ▪ Large *concentric hypertrophy* of heart

• Resistance exercise training primarily uses
  ▪ Anaerobic metabolism to provide energy for muscle to contract

• Hence, there is relatively little change in one’s VO$_2$max
Resistance Exercise Training

• If VO$_2$max does increase, it is probably more related to:
  ▪ Dynamic component of exercise training program, such as:
    • Circuit weight training

• In addition:
  ▪ RHR
  ▪ BP
  ▪ Total blood volume are unchanged
The Heart & Resistance Exercise Training

• Resistance exercise-trained athlete usually has
  ▪ Concentric cardiac hypertrophy of LV
  ▪ Disproportional thickening of intraventricular septum
  ▪ Posterior walls without LV chamber enlargement
The Six Principles of Training

1. Overload
2. Specificity
3. Progression
4. Rest/recovery
5. Reversibility “Use it or Lose it”
6. Diminished returns
The Principle of Reversibility

In a cardiovascular deconditioning study at the University of Texas, five (2 active & 3 sedentary) men underwent complete bed rest for 21 days

- **Active subjects**
  - Lost significantly more VO$_2$max than sedentary subjects
  - Group rate of loss of VO$_2$max was later calculated to be 250 ml O$_2$/kg/min/year, or 26%

- **After the 21 days of bed rest**
  - Each subject underwent a supervised endurance exercise training program for 60 days (5 d/wk)
The Importance of an Active Lifestyle

• Previous research emphasizes the need to maintain an active lifestyle to optimize one’s life expectancy

• After completion of 21 days of complete bed rest in the Dallas study
  ▪ Subjects were intensively aerobically trained using a program of
    • Walk, jog, & run for a period of 60 days
Lifestyle (cont.)

- Two subjects who were active before bed rest were only able to train their VO\(_2\)\text{max} back to their pre–bed-rest VO\(_2\)\text{max}

- In contrast, 3 subjects who were sedentary before bed rest were able to increase their VO\(_2\)\text{max} some 33% greater than their pre–bed-rest value
Cardiovascular Deconditioning Study

• **Sedentary subjects**
  - Restored their low VO$_2$max to their initial values in 10-11 days
  - At end of 60-day training period exceeded their initial pre-bed rest VO$_2$max value by 40%

• **In contrast, 2 active subjects required**
  - Full 60 days of endurance exercise training to return to their pre-bed rest VO$_2$max values (next slide)
VO2 max Response to Bed Rest & Training

Figure 8.29
Sedentary Living

• After completion of Dallas bed-rest study
  ▪ Same subjects underwent follow-up VO$_2$max testing 30 & 40 years later

• Results documented that
  ▪ Subject’s VO$_2$max declined 27%
  ▪ Was equivalent to 26% decline caused by 21 days of bed rest

• However, between ages of 50 to 60 yr
  ▪ Annual decline of VO$_2$max was 4x greater (55 ml/min/year) than that which had occurred between ages of 20 & 50 yr (12 ml/min/year)
Sedentary Living

• In comparison with rate of loss of 1.04 ml O$_2$/kg/min/year VO$_2$max of well-trained endurance athletes aged 20-35 year who became sedentary between the ages of 40 & 60 years
  ▪ Bed rest had a 250x greater deconditioning effect
Age-Related Decreases in VO₂ max

Figure 8.30

Slope = $-0.25 \text{ l} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} \cdot \text{yr}^{-1}$
- Bed rest – Fig. 8.29

Slope = $-1.04 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} \cdot \text{yr}^{-1}$
- Retired athletes

Slope = $-0.4 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} \cdot \text{yr}^{-1}$
- General population
Age-Related Decreases in VO$_2$ max with Training

**Figure 8.31**

![Graph showing age-related decreases in VO$_2$ max with and without training.](image)
In Practice: Health/Fitness

<table>
<thead>
<tr>
<th>Heart rate</th>
<th>Stroke volume</th>
<th>What is the efficiency of the heart?</th>
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</thead>
</table>

What would happen to your clients heart rate and stroke volume after engaging in an overall fitness exercise program of 6-8 weeks?
**In Practice: Athletic Performance**

<table>
<thead>
<tr>
<th>22-year-old soccer player</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resting heart rate (HR)?</td>
</tr>
<tr>
<td>Submaximal heart rate?</td>
</tr>
<tr>
<td>How would her HR compare to an elite endurance athlete?</td>
</tr>
<tr>
<td>How would her HR compare to untrained friend?</td>
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</table>

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>
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<th>Question</th>
</tr>
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<tbody>
<tr>
<td>What happens to strength?</td>
</tr>
<tr>
<td>What should they do with their breathing?</td>
</tr>
<tr>
<td>What type of exercises are good?</td>
</tr>
<tr>
<td>Isometric compared to dynamic exercises?</td>
</tr>
<tr>
<td>What is exercise intensity?</td>
</tr>
</tbody>
</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

Slideshow was developed by:
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Professor of Public Health
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