Cardiac Function

Cardiac Cycle

- Early Diastole – Isovolumic Ventricular Relaxation
  - Ventricular contraction stops and ventricle relaxes
  - Ventricular pressure falls below aortic pressure
  - Aortic valve closes
  - AV valve still closed as ventricular pressure is higher than atrial

Cardiac Cycle

- Mid to Late Diastole
  - AV valve opens as atrial exceeds ventricular pressure and ventricular filling begins – rapid at first and then slows***
  - **Insures that filling is not impaired during exercise when heart rate is high and time in diastole is decreasing
  - Blood enters the atrium from the pulmonary veins so ventricle receives blood throughout diastole (80% of ventricular filling occurs before atrial contraction)
  - P wave of ECG – depolarization of atria – near end of diastole

Cardiac Cycle

- Mid to Late Diastole
  - Atrial contraction (atrial pressure increases) – slightly higher than ventricular pressure – adding a small volume to ventricles
  - After contraction, atrial pressure falls
  - Aortic valve is closed (aortic pressure > ventricular pressure) and pressure is falling as blood moves out of vascular tree
  - Ventricular pressure rises slightly as volume increases
    - EDV (end-diastolic volume) – volume in ventricle prior to systole
Cardiac Cycle

• Systole
  – Wave of depolarization passes through the ventricles (QRS)
  – Ventricular contraction – steep rise in ventricular pressure
  – AV valve closes (ventricular pressure > atria) – preventing backflow into atria
  – Isovolumic Ventricular Contraction (aortic valve is closed – early systole – no change in volume as pressure increases
  – Ventricular pressure exceeds aortic pressure
  – Aortic valve opens – ventricular ejection

Cardiac Cycle

• Systole –
  – Ventricle not empty completely
  – End Systolic Volume – volume remaining after ejection
  – Aortic pressure increases as blood leaves ventricle
  – Peak aortic pressure occurs before end of ventricular ejection – rate of blood ejection fastest in early systole and slows and is less than the rate leaving the aorta
  – Aortic volume and pressure decrease

Cardiac Cycle

End-Diastolic Volume (EDV)
  • During diastole, filling increases ventricular volume to 110 – 120 mL

Stroke Volume (SV)
  • During systole, ejection decreases ventricular volume by 70 mL

End-Systolic Volume (ESV)
  • End-diastolic – stroke volume = end-systolic volume
  • 40 – 50 mL

Ejection fraction (EF)
  • Stroke volume + end-diastolic volume = ejection fraction
  • ~ 60%

Extrinsic Modulation of HR
(superimposed on inherent rhythm)

• Central Command
• ANS - Nerves that supply myocardium
• Chemical messengers in the blood

Nervous System

• Central – brain and spinal cord
• Peripheral – spinal and cranial nerves
  – Afferent neurons – forward sensory information from peripheral receptors to brain
  – Efferent neurons – transmit information from brain to peripheral tissues
    • Somatic or motor system
      – CNS to skeletal muscle - voluntary
    • Autonomic system
      – CNS to heart, smooth muscle and endocrine glands – involuntary
        » Sympathetic (fight or flight)
        » Parasympathetic (rest and digest)
Activation of Somatic NS

• Conscious thought
• Afferent input from periphery
  – Mechanoreceptors (pressure, stretch and contraction)
  – Proprioceptors (spatial orientation) in muscles, tendons, and joints
• Always produces an excitatory response
• Acetylcholine - neurotransmitter

Activation of the Autonomic NS

• Specialized external sensory receptors
  (taste, sound, sight, smell and/or pain)
• Thermoreceptors
• Proprioceptors
• Mechanoreceptors
• Chemoreceptors
• Excitatory or Inhibitory effects

Types of Autonomic Neurons

• Release Ach (cholinergic fibers)
  – Excitatory or inhibitory to target cells of ANS depending on the receptor
  – PS pre- and postganglionic fibers
  – S preganglionic fibers
• Release NE (adrenergic fibers) – S postganglionic fibers
• Adrenal Medulla releases Epinephrine (80% E and 20% NE) – when preganglionic S nerves innervating the tissue are activated

Sympathetic Component of ANS

• Preganglionic sympathetic neurons exist in the gray matter of the spinal cord
• Preganglionic fibers emerge from the thoracic and lumbar segments of spinal cord
• Postganglionic fibers innervate the
  – heart (SA, AV nodes, conduction system, and cardiac myocytes) – NE binds $\beta_1$ adrenoreceptors
  • Increase chronotropy – rate
  • Increase Inotropy – contractility
• Postganglionic thoracic fibers innervate
  – blood vessels
  • Constricts resistance and capacitance vessels – NE binds $\alpha_1$ adrenoreceptors (except in heart where vasodilates)
  – E has a higher affinity for $\beta$ than $\alpha$ receptors
Parasympathetic Component of ANS

- Preganglionic parasympathetic neurons arise from the brain stem and sacral spinal cord
- 10th cranial nerve arises from brainstem – vagus nerve
  - Carries about 80% of all parasympathetic (cholinergic) fibers
  - Preganglionic fibers travel to heart and synapse with short postganglionic fibers that innervate the heart
- Parasympathetic ganglia are located near or on the target tissue
  - Preganglionic parasympathetic neurons are typically quite long
  - Postganglionic parasympathetic neurons are typically quite short

Parasympathetic Component of ANS

- Postganglionic parasympathetic neurons run to the target tissue
- Release neurohormone acetylcholine
- Slows HR (vagus nerves)
- Innervates SA (R vagus), and AV nodes and ventricles (L vagus)
- No effect on myocardial contractility
- No role in regulation of systemic vascular resistance but serve to regulate blood flow within specific organs
- Note: Sympathetic NS provides tonic stimulation of heart and vasculature, vasodilation occurs by a reduction in sympathetic activity

Cardiovascular Control Center (Central Command)

- Located in the ventrolateral medulla of brainstem
- Primary control of HR during exercise
- Somatomotor center in motor cortex modulates medullary activity (central command)
- Motor activity feeds forward through the medulla
- Coordinates the rapid adjustment of heart and blood vessels to maintain flow

Central Command: Input from Higher Centers

- Operates during preexercise anticipatory period and during exercise
- Provides the greatest control over heart rate during exercise
- More muscle mass activation, more stimulation of medulla
Anticipation of Exercise

• Cortex relays information to hypothalamic centers to coordinate autonomic outflow to cardiovascular system
• Increase HR and Q and MAP – prime the cardiovascular system for exercise
• Sympathetic activation of the adrenal glands – constrictor response except in heart and skeletal muscles

Exercise and Central Command

• Central Command stimulates the cardiovascular control center
• Increase HR, Q, and vasoconstriction
• Vagus tone decreases
• Muscle pump and cyclical changes in intrathoracic pressure caused by breathing facilitate venous return
• Cardiovascular center further stimulated by increased temperature in hypothalamus

Exercise and Central Command

• Peripheral input from muscles
  – Chemoreceptors and Mechanoreceptors in muscle send information to CNS via afferent fibers – information processed by hypothalamus and cardiovascular center to increase sympathetic outflow to heart and vasculature

Exercise and Central Command

• Metabolic regulation of blood flow – redirects blood to active muscles during exercise
  – Occurs in response to tissue demands for oxygen and fuels and responses to CO₂, hydrogen ions, and temperature
  – When blood flow is inadequate, vasodilator metabolites accumulate, act on the smooth muscle bands of arteriole walls causing vasodilation

Vasodilators

• Adenosine (breakdown of ATP)
• Low P_{O₂}
• high P_{CO₂}
• low pH
• lactic acid
Chemical Autoregulation of Blood Flow

- Smooth muscle relaxes and contracts in response to chemical substances released by the endothelium
  - Nitric oxide – produced by vessel shear stress, stretch and chemicals
  - Rapidly spreads through cell membranes to smooth muscle in arterial wall, binds and activates the enzyme guanylyl cyclase producing relaxation
  - Exerts effect in skeletal muscle, skin and myocardial tissue
  - Allows vasodilation in working muscle

Baroreceptors and Exercise

- Arterial blood pressure regulated through negative feedback system
- Baroreceptors – mechanoreceptors in carotid sinus and aortic arch
- Afferent fibers from carotid sinus travel to brain stem, synapsing with NTS (nucleus tractus solitarius – modulates the activity of cardiovascular control centers in the medulla)
- Respond to the stretch on vessel walls produced by increases in arterial blood pressure – increases the firing rate of receptors and nerves

Baroreceptors

- Each receptor has its own individual threshold and sensitivity to changes in pressure – as pressure increases additional receptors are recruited (60 – 180 mm Hg)
- Exert a tonic inhibitory influence on sympathetic outflow from medulla
- Establish a BP set-point

Baroreceptors and Exercise

- At onset of exercise the set-point increases – decreases the firing rate (inhibition on SNS) so HR and BP increase
- Modification of set-point prevents a reflex bradycardia
Supine to Standing

- Gravity causes venous pooling
- Decreases venous return, preload, Q and MAP
- Decrease stretch on baroreceptors decreases firing
- Increased sympathetic activity (less inhibition)
- Vasoconstriction increases systemic vascular resistance, HR, and Q

Carotid Sinus Reflex

- Mechanical stimulation increases firing rate
- Decreases sympathetic and increases parasympathetic outflow from the medulla
- Used to abort certain types of arrhythmias

Monitoring of Carotid Pulse

- Little or no effect on HR at rest or during exercise or recovery
- Concern – use radial or brachial pulse

Cardiovascular Response to Static Exercise

- Depends on the intensity of contraction held for a specified time period – expressed as a % of MVC
- Q increases due to increase in HR – more intensity, greater increase
- SV – no change or decrease with higher intensity contractions
  - Decreased preload – high intrathoracic pressure
  - Increased afterload due to elevated MAP
- Rapid increase in SBP and DBP (pressor response – inappropriate increase in pressure for the amount of work produced by contracting muscle)

Cardiovascular Response to Static Exercise

- High intramuscular tension – mechanical constriction of blood vessels which impedes blood flow
- Metabolic by-products form – stimulate sensory nerve endings
- TPR decreases slightly
- RPP increases a lot due to increase in HR and SBP for a small increase in oxygen consumption
- Can get total occlusion of arterial flow at >15% of MVC in certain muscle groups
Static Exercise Modifies Response to Dynamic Exercise (Lind et al.)

- Walked 3 mph, 22% grade
  - No hand grip
  - With isometric hand grip of 50% MVC
- During gripping
  - SBP increased 45 mm Hg
  - DBP increased 40 mm Hg

Cardiovascular Response to Dynamic Resistance Exercise

- Dissociation between the energy demand and the cardiorespiratory system
  - Much of energy derived from anaerobic sources
  - Mechanical restriction of blood flow
- Always a static component
- Magnitude of CDV response depends on the load and number of repetitions
- Large, transient decreases in plasma volume

Cardiovascular Response to Dynamic Resistance Exercise

- Heavier load, repetitions constant
  - SBP increases with resistance
  - DBP – increase or no change depending on method of measurement (auscultation vs intra-arterial measurement)

Cardiovascular Response to Dynamic Resistance Exercise

- Given load to fatigue – maximal work
  - Q highest with lightest load
  - SV similar regardless of load
  - HR highest with lightest load (not all agree)
Cardiovascular Response to Dynamic Resistance Exercise

• Set to failure with heavy load – HR and MAP increase to failure
  – BP averaged 320/250 mm Hg (Valsalva)

Valsalva Maneuver

• Expiratory effort with glottis closed
• Not breath-holding alone
  – Intrathoracic pressure increases
  – Causes collapse of veins in chest cavity
  – Blood pressure increases
  – If held, blood pressures drops due to decrease in venous return
Minimizing the BP Response to Dynamic Resistance Training

- Decrease resistance
- Decrease size of muscle mass utilized
- Select exercises that require minimal stabilization
- Breathing
- Do not perform sets to fatigue

Dynamic Arm vs Leg Work

- SBP, DBP, MAP, and RPP higher with UE
  - Vasoconstriction in large inactive musculature of legs
  - Vasodilation in small muscle groups
  - Smaller muscle mass in arms requires a greater %age of available mass to perform the work
  - Greater sympathetic stimulation
  - Static component of arm crank ergometer

Dynamic Arm vs Leg Work

- Submaximal VO₂ – higher for UE (larger as intensity increases)
  - Recruitment of additional musculature to stabilize torso
  - Lower mechanical efficiency in UE due to extra cost of static contractions (no contribution to mechanical work)
- VO₂peak – higher with LE exercise (30% lower with UE)
  - Increased feedback stimulation to medullar from peripheral receptors in active tissue

**TABLE 15-3. Comparison of systolic and diastolic blood pressure during arm and leg exercise at similar percentages of the maximal oxygen intake**

<table>
<thead>
<tr>
<th>PERCENT OF MAX VO₂</th>
<th>SYSTOLIC PRESSURE (mm Hg)</th>
<th>SYSTOLIC PRESSURE (mm Hg)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>ARMS</td>
<td>LEGS</td>
</tr>
<tr>
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<td>75</td>
<td>205</td>
<td>160</td>
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</tbody>
</table>


Dynamic Arm vs Leg Work

- Q similar
  - SV is lower with UE (30-40% less) – absence of LE skeletal muscle pump and increased sympathetic stimulation which increases TPR
  - HR higher with UE due to a greater sympathetic stimulation
    - More feed forward stimulation form central command to medullary control center
- Max HR is lower for UE (90-95% of LE)
  - Due to smaller muscle mass in UE, input into medullary cardiovascular control center is less at max
- Higher RPEs for UE
- **specificity**
Transplantation

- Why is resting HR high?
- Why doesn’t HR increase much with exercise?
- What is the mechanism for the increase?
- Does SV increase with exercise?
- **Primary mechanism for increasing Q"