Cardiopulmonary Exercise Testing
Physiology and Interpretation

Mutasim Abu-Hasan, MD
Pediatric Allergy and Pulmonary
University of Florida
Cardiopulmonary Exercise Testing
Physiology and Interpretation

• Exercise physiology

• Patterns of physiologic abnormalities during exercise

• Diagnostic value of exercise testing
Systems Involved in Exercise

- Musculoskeletal
- Cardiovascular
- Respiratory
Physiology of Exercise

Lungs

Heart

Muscle

Air → \( \text{O}_2 \) → Heart → \( \text{CO}_2 + \text{ATP} \) → Muscle

\( \text{O}_2 \) → Lungs → \( \text{CO}_2 \)
Metabolic Responses to Exercise

• Muscles use carbohydrates (glycogen) as energy substrates. When depleted, fat or protein are then used

• Substrates are oxidized to produce ATP and CO$_2$ as end-products
Metabolic Responses to Exercise

- For each mole of O\(_2\) used in carbohydrate metabolism, 1 mole of CO\(_2\) is produced.

- The ratio of CO\(_2\) production to O\(_2\) consumption is called the respiratory quotient (RQ).

- RQ of carbohydrate is 1, of fat is 0.71, of protein is 0.82.

- If O\(_2\) delivery to muscles is limited then energy is generated by anaerobic metabolism of glycogen.
Glycogen → Pyruvate

Pyruvate → Lactate (anaerobic)

O₂ → ATP (aerobic)

ATP → Creb’s Cycle

ATP → CO₂

Lactate + HCO₃⁻ → CO₂
Cardiovascular Responses to Exercise

• Cardiac Responses
  – Increased cardiac output (CO)

  \[ CO = \text{Stroke volume (SV)} \times \text{Heart rate (PR)} \]

• Vascular Responses:
  – Decreased systemic vascular resistance
How high CO can go during Exercise?

- At Rest
  \[
  CO = SV \times PR \\
  6 \text{ LPM} = 0.1 \text{ L} \times 60 \text{ BPM}
  \]

- At Peak exercise:
  \[
  CO = Vs \times PR \\
  30 \text{ LPM} = 0.15 \text{ L} \times 200 \text{ BPM}
  \]
Cardiovascular responses to exercise

- Cardiac output can be increased 3-6 fold and therefore is the limiting system
- Heart rate increases linearly with increased work load
- Stroke volume is increased early in exercise but further demand in increased cardiac output is met by further increase in PR
Cardiovascular Response to Exercise

- Vascular resistance in muscles is decreased
- Vascular resistance to other organs (i.e. skin, gut, kidney’s) is increased
- Systolic BP is increased but diastolic BP is decreased
Ventilatory Responses

• Minute ventilation (VE) is increased

\[ \text{VE} = \text{Tidal Volume (Vt)} \times \text{Respiratory rate (RR)} \]

• Improved gas exchange:
  – Alveolar recruitment
  – Decreased pulmonary vascular resistance
  – Decreased VD/VT ratio
How high VE can go during Exercise?

• At Rest:
  \[ VE = V_t \times RR \]
  \[ 5 \text{ LPM} = 0.5 \text{ L} \times 10 \text{ BPM} \]

• At Peak Exercise:
  \[ VE = V_t \times RR \]
  \[ 150 \text{ LPM} = 3 \text{ L} \times 50 \text{ BPM} \]
Ventilatory Responses

• Minute ventilation is increased 30 times during exercise

• Tidal volume is normally increased up to 60% of Vital Capacity (VC)

• Further increase in VE is achieved by increase in RR
Ventilatory Response to Exercise

- VE during exercise can increase by 30 times resting VE

- At maximal exercise VE is still 80% of maximal voluntary ventilation at rest (MVV)

- At early stages of exercise VE increase is linear but curvilinear after reaching AT
Ventilatory VS Cardiovascular

- Reaching maximal cardiac output is the limiting factor in exercise normally.

- Once maximal CO is reached, continued exercise is achieved by anaerobic metabolism.

- Ventilatory Reserve:  
  \[
  20-40\% = \frac{(MVV-VE)}{MVV}
  \]
Physiology of Exercise

Lungs

Heart

Muscle

Air

O₂

CO₂

O₂

CO₂

O₂

CO₂

O₂ + Glucose

Mitochondria

CO₂ + ATP

O₂ + ATP

CO₂

O₂

CO₂

O₂

CO₂

CO₂

O₂
Causes of Exercise Limitations

- Pulmonary disease (obstructive, restrictive, gas exchange)
- Cardiovascular (ischemic, congenital, valvular, poor conditioning)
- Musculoskeletal abnormalities
- Metabolic/Hematologic
Causes of Exercise Limitations

- Pulmonary disease (obstructive, restrictive, gas exchange)
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Types Exercise Testing

- Exercise limitations due to known chronic lung disease (COPD, ILD, CF)
  - Gas Exchange Analysis
  - Six minute walk test

- Exercise-Induced Pathophysiology
  - Bronchoprovocation Test
  - Stress Test
Bronchoprovocation

- Standard 6 minute of treadmill running or cycling at 85% of maximal heart rate
- PFT at baseline and every five minutes after finish to a maximum of 30 minutes
- A drop of 10-20% in baseline FEV1 has been used by different studies
Treadmill Exercise Testing

4 mph, 10% grade, heart rate at 85% of potential aerobic capacity for age

Exercise aborted because of dyspnea and wheezing
Inhaled Bronchodilator given
Physician diagnosis EIA vs Symptoms vs EIB

Sports Participants
N=256
9.4% EIB

Prior Diagnosis
N=76
14% EIB

Symptoms
N=38
18.4% EIB
No symptoms
N=38
10.4% EIB

No Prior Diagnosis
N=180
7.2% EIB

Symptoms
N=25
8.0% EIB
No symptoms
N=125
7.1% EIB
NOT ALL EXERCISE INDUCED SYMPTOMS IS ASTHMA
### Spirometry

<table>
<thead>
<tr>
<th>Test</th>
<th>Units</th>
<th>Ref</th>
<th>95% CI</th>
<th>Pre</th>
<th>% Ref</th>
<th>Post</th>
<th>% Ref</th>
<th>% Chg</th>
</tr>
</thead>
<tbody>
<tr>
<td>FVC</td>
<td>Liters</td>
<td>3.23</td>
<td>(3.0 - 3.5)</td>
<td>3.52</td>
<td>109</td>
<td></td>
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<tr>
<td>FEV1</td>
<td>Liters</td>
<td>2.65</td>
<td>(2.4 - 2.9)</td>
<td>2.77</td>
<td>105</td>
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<tr>
<td>FEV1/FVC</td>
<td>%</td>
<td>86</td>
<td></td>
<td>79</td>
<td></td>
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<tr>
<td>FEF25-75%</td>
<td>L/sec</td>
<td>3.62</td>
<td>(3.2 - 4.1)</td>
<td>2.54</td>
<td>70</td>
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<tr>
<td>FEF50%</td>
<td>L/sec</td>
<td>3.58</td>
<td>(2.3 - 4.9)</td>
<td>3.08</td>
<td>86</td>
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<tr>
<td>FEF75%</td>
<td>L/sec</td>
<td>1.73</td>
<td>(1.4 - 2.1)</td>
<td>1.22</td>
<td>70</td>
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<tr>
<td>PEF</td>
<td>L/sec</td>
<td>4.52</td>
<td>(4.2 - 4.8)</td>
<td>5.15</td>
<td>114</td>
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<tr>
<td>FIF50%</td>
<td>L/sec</td>
<td>1.94</td>
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<tr>
<td>FEF/FIF50</td>
<td></td>
<td>1.59</td>
<td></td>
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</table>

### Flow vs Time

- **Flow**
  - Blue - pre
  - Red - post

### Volume vs Time

- **Volume**
  - 0 to 8
- **Time**
  - -1 to 8

### SaO2, FIO2

- SaO2 %
- FIO2 %
Spirometry Before and After Exercise

- Inspiratory and expiratory "Wheezeing" and dyspnea began during bronchoprovocation
- Initially normal; then severe airflow obstruction apparent on both inspiration and expiration
CPET: Gas Exchange Analysis

- Incremental increased in exercise intensity till maximum

- Monitor:
  - EKG
  - O2 Saturation
  - Air Flow/Volume
  - O2 consumption
  - O2 production
# CardioPulmonary Exercise Test Results

## Spirometry

<table>
<thead>
<tr>
<th></th>
<th>Predicted</th>
<th>Measured</th>
<th>% Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>FVC (L)</td>
<td>3.85</td>
<td>2.48</td>
<td>64</td>
</tr>
<tr>
<td>FEV1 (L)</td>
<td>3.35</td>
<td>1.84</td>
<td>55</td>
</tr>
<tr>
<td>MVV (L)</td>
<td>144</td>
<td>93</td>
<td>64</td>
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</table>

## Resting Data

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>HR (bpm)</td>
<td>74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SpO2</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPB (mmHg)</td>
<td>121</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DPB (mmHg)</td>
<td>51</td>
<td></td>
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</tbody>
</table>

## Peak Cardiovascular Responses

<table>
<thead>
<tr>
<th></th>
<th>Predicted</th>
<th>Measured</th>
<th>% Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO2 (ml/kg/min)</td>
<td>50.1</td>
<td>30.1</td>
<td>60</td>
</tr>
<tr>
<td>VO2 (l/min)</td>
<td>3.624</td>
<td>1.573</td>
<td>43</td>
</tr>
<tr>
<td>VCO2 (l/min)</td>
<td>2.327</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work (Watts)</td>
<td>212</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Anaerobic Threshold (AT) (l/min)</td>
<td>&gt; 1.450</td>
<td>1.343</td>
<td>43</td>
</tr>
<tr>
<td>AT (% Predicted Max VO2)</td>
<td>&gt; 40%</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Heart Rate (bpm)</td>
<td>192</td>
<td>179</td>
<td>93</td>
</tr>
<tr>
<td>O2 Pulse (ml/beat)</td>
<td>13.1</td>
<td>8.8</td>
<td>67</td>
</tr>
<tr>
<td>Systolic Blood Pressure (Max)</td>
<td>181</td>
<td>121</td>
<td>67</td>
</tr>
<tr>
<td>Diastolic Blood Pressure (Max)</td>
<td>85-105</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>Heart Rate Reserve (bpm)</td>
<td>&lt;15</td>
<td>13</td>
<td></td>
</tr>
</tbody>
</table>

## Peak Ventilatory Responses

<p>| | | | |</p>
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<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>VE Max (l/min) BTPS</td>
<td>74.8</td>
<td>73.6</td>
<td>98</td>
</tr>
<tr>
<td>Tidal Volume (VT) (L)</td>
<td>1.019</td>
<td>1.644</td>
<td>161</td>
</tr>
<tr>
<td>Respiratory Rate (RR)</td>
<td>&lt;50</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>Breathing Reserve (%)</td>
<td>20-40</td>
<td>21</td>
<td></td>
</tr>
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</table>

## Gas-Exchange Responses

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>End Tidal CO2 (Peak PetCO2)</td>
<td>36.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>End Tidal O2 (Peak PetO2)</td>
<td>123.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VE/VO2 @ AT</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VE/VCO2 @ AT</td>
<td>27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VD/VT (Est) @ Rest</td>
<td>0.30</td>
<td>0.20</td>
<td>67</td>
</tr>
<tr>
<td>VD/VT (Est) Peak</td>
<td>0.18</td>
<td>0.10</td>
<td>56</td>
</tr>
<tr>
<td>Respiratory Quotient (RQ)(Peak)</td>
<td>1.1-1.3</td>
<td>1.48</td>
<td></td>
</tr>
<tr>
<td>SpO2 (O2 Sat-Pulse Ox) @ Peak</td>
<td>98</td>
<td>81</td>
<td>83</td>
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</tbody>
</table>

## Calibration Results

<table>
<thead>
<tr>
<th></th>
<th>Flow Cal:</th>
<th>Pred Volume:</th>
<th>Expire Avg:</th>
<th>Inspire Avg:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Cal:</td>
<td></td>
<td>3.00</td>
<td>2.99</td>
<td>3.00</td>
</tr>
<tr>
<td>Predicted</td>
<td>Cal1 O2</td>
<td>16.00</td>
<td>Cal 1 CO2</td>
<td>Cal 2 O2</td>
</tr>
<tr>
<td>Measured</td>
<td>Cal2 O2</td>
<td>26.00</td>
<td>Cal 2 CO2</td>
<td>Cal 2 CO2</td>
</tr>
<tr>
<td>Transit (msec)</td>
<td>0.565</td>
<td>0.463</td>
<td>Ambient O2</td>
<td>Ambient CO2</td>
</tr>
<tr>
<td>Response (msec)</td>
<td>0.112</td>
<td>0.089</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Physician:** ABU HASAN MUTASAM

Version: IVS-0101-21-2
Parameters Measured

- Cardiovascular Parameters
  - VO₂
  - HR
  - O₂ pulse (VO₂/HR)
  - AT

- Ventilatory Parameters
  - VE, VT
  - Respiratory reserve = (MVV - maxVE)/MVV

- Gas exchange parameters
  - VD/VT, VE/VO₂, VE/VCO₂
Diagnostic Value

• Exercise capacity

• Cardiovascular vs Ventilatory limitation

• Response to therapy

• Personalized exercise rehabilitation program
Anaerobic Threshold
Ventilatory VS Cardiovascular

- Low Vt
- High RR
- High VE/VO2
- Low Ventilatory Reserve

- Low O2 pulse
- High PR
- High PR/VO2
- High Ventilatory Reserve
Ventilation Limitation
(Restrictive Lung Disease)
Ventilatroy Limitation

(Restrictive Lung Disease)
Cardiovascular Limitation
Causes of Exercise Limitation

- 143 patients
- Median age 14 years (range 6-21)
- Male: Female is 1:1.4
- 98 patients with prior asthma diagnosis
- 101 patients were treated with bronchodilators or steroids.

Diagnoses

- EIB
- VCD
- Restrictive
- EIL
- EIH
- EISVtach
- Physiologic

Counts:
- EIB: 74
- VCD: 13
- Restrictive: 15
- EIL: 1
- EIH: 1
- EISVtach: 2
- Physiologic: 11
Conclusions

• Exercise testing is based on physiology and pathophysiology

• Causes of exercise limitations are varied

• Different diagnostic tests and equipment (spirometry, endoscopy, gas-exchange analysis) may be needed