Cardiopulmonary Exercise Testing

DM Seminar

25 Feb 2005
CPET

- Introduction
- Indications
- Technical aspects
- Physiologic basis
- Exercise limitation
- Interpretation of CPET
- Future directions
Introduction

• Initially was tool of research physiologists
• Has become tool to help the clinicians in evaluating undiagnosed exercise intolerance or exercise related symptoms
• When questions remain after clinical examination and basic clinical data including CXR, PFT and resting ECG
Introduction

• Provides *global assessment* of integrative exercise response involving pulmonary, cardiovascular, hematopoietic, neuropsychological and skeletal muscle systems

• Resting cardio-pulmonary function tests cannot predict the exercise performance and functional capacity
Field tests

• 6 min walk test and shuttle test easy to perform, related to activities of daily living
• lack of reference values
• absence of physiological measures
• healthy subjects fairly good correlation with VO$_2$ max is observed
• Pitfalls: occult IHD, combined diseases

When to do

• Evaluate exercise capacity
• Undiagnosed exercise intolerance
• Cardiovascular diseases
• Respiratory diseases/symptoms (EIA)
• Preoperative evaluation
• Pulmonary rehabilitation
• Impairment/disability assessment
Exercise Intolerance

- Assessment of exercise capacity
- Pathophysiologic basis of exercise limitation
- Contribution of cardiac /respiratory disease
- Symptoms disproportionate to routine tests
Cardio Resp diseases

Cardiovascular COPD/ILD/PVD
Functional classific Functional assess
Exercise Rx Gas exchange
Heart Tx selection After intervention
Oxygen Rx

ATS /ACCP Statement, 2003
Preoperative evaluation

- Lung resection: VO2 peak less than 50-60% associated with increased morbidity and mortality after lung resection
  
  *Morice RC et al Chest 1996*

- Elderly undergoing major Abdominal surgery

- LVRS for Emphysema

  *ATS/ACCP statement 2003*
Other uses

- Disability assessment: occupational/co-morbid diseases
- Exercise prescription: pulmonary and cardiac rehabilitation
- Evaluation of LVRS: NETT trial used max work rate achieved as primary outcome measure
- Evaluation for lung & heart transplantation
Absolute Contraindications

- Rate of death during testing 2-5/lakh tests
  - AMI (3-5 days) or unstable angina
  - Uncontrolled arrhythmia with hemodynamic compromise
  - Syncope
  - Respiratory or Heart failure
  - Active endocarditis or myocarditis
  - Severe AS
  - Pulmonary embolism or Lower limb DVT
  - Uncontrolled asthma

ATS / ACCP Statement, 2003
Relative contraindications

- Left main coronary stenosis
- Moderate Stenotic valvular heart disease
- Severe untreated HTN (>200/120)
- Tachy or bradyarrhythmia /AV block
- Hypertrophic Cardiomyopathy
- Significant Pulmonary Hypertension
- Advanced pregnancy
- Orthopedic disease

*ATS /ACCP Statement 2003*
Types of equipment

- **Cycle Ergometers**
  - Computer controlled programme
  - Work rate easily quantified
  - Most preferred mode of exercise

- **Motor driven Treadmill**
  - Difficult to quantify work
  - Predicting VO₂ becomes difficult

- **Arm Crank Ergometers**
  - Neurologic / orthopedic disability lower limbs
  - Peak VO₂ achieved ~ 70% of leg exercises
## Exercise equipment

<table>
<thead>
<tr>
<th></th>
<th>Cycle</th>
<th>Treadmill</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Vo}_2 \text{max} )</td>
<td>lower</td>
<td>higher [5-10%]</td>
</tr>
<tr>
<td>Work rate measurement</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Blood gas collection</td>
<td>easier</td>
<td>more difficult</td>
</tr>
<tr>
<td>Noise and artifacts</td>
<td>less</td>
<td>more</td>
</tr>
<tr>
<td>Safety</td>
<td>safer</td>
<td>less safe?</td>
</tr>
<tr>
<td>Weight bearing in obese</td>
<td>less</td>
<td>more</td>
</tr>
<tr>
<td>Degree of leg muscle training</td>
<td>less</td>
<td>more</td>
</tr>
<tr>
<td>More appropriate for:</td>
<td>patients</td>
<td>active normal subjects</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cheaper</th>
<th>Expensive</th>
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<tbody>
<tr>
<td></td>
<td>(5-10%)</td>
</tr>
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</table>
Other equipment

- Airflow Volume transducers
  - Pneumotachograph
  - mass flow sensor
- Gas analyzers
  - mass spectrometer (gold standard, costly)
  - oxygen cell (Zirconium oxide)
  - CO2 sensor (Infra red light)
Gas exchange equipment

- Breath by breath analyzer
  - most popular method
  - Online analysis by sensor
  - Values averaged every 30-60 sec (noise)
- Mixing chamber
- Douglas Bag
Other data recorded

- Electrocardiography
- Noninvasive blood pressure
- Pulse oximetry
- Arterial blood gas (if indicated)
- Invasive arterial BP
Arterial blood gas

- Invasive anaerobic threshold (AT)- Lactate
- COPD/ILD/PVD(Significant desaturation)
- Accuracy of oximetry reduced SpO2 < 88%
- Oxygen prescription
- SpO2 unreliable in following
  - Dark skin color
  - Weak pulses in cardiac diseases
Quality control

- Supervision by cardiologist/Pulmonologist (trained in exercise physiology & testing)
- Calibrate flow transducers
- Calibrate breath by breath systems
- Calibrate CO₂ and O₂ analyzers
- Noninvasive BP
- Healthy member “test” to validate the measured VO₂, Vₑ and VCO₂ with database values
Schematic representation
Incremental Treadmill protocol

- Bruce protocol (suited for healthy, or mild diseases as high WR which increases)
- Modified Naughton protocol (low initial WR gradual build up suitable for patients)
- Balke protocol (constant speed, slope increased 1% every minute)
- Modified Balke protocol (slope increased by constant amount every min)
Incremental protocol

1. HISTORY, PFTs, ECG
2. MAXIMAL INCREMENTAL EXERCISE ON A CYCLE ERGOMETER
3. Familiarization, Symptoms (Borg Scale)
4. CARDIOPULMONARY MEASUREMENTS
   - 3 min Resting
   - 3 min Unloaded Cycling (optional)
   - 10 min Incremental / Ramp
     Exercise (5 to 30 W/min)
5. 10 min Recovery
   (3 min unloaded cycling)
   ECG Monitoring
Constant work rate protocol

- Done at 50-70% of maximal work rate
- 5-10 min achieves 70-90% VO$_2$ max IET
- For assessing response to interventions - LVRS, LTOT, pulm rehabilitation
- Analysis of Exercise FV Loops and dynamic hyperinflation, gas exchange kinetics
Stop exercise

- Ischemic chest pain
- Ischemic ECG changes
- Complex ectopy
- Second or third degree heart block
- Fall in systolic pressure > 20 mm Hg
- Hypertension (250/120 mm Hg)
- Symptomatic desaturation: SpO2 < 80%
- Signs of respiratory failure
Parameters measured

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Non-Invasive</th>
<th>Invasive (ABGs)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>External work</strong></td>
<td>WR</td>
<td></td>
</tr>
<tr>
<td><strong>Metabolic gas exchange</strong></td>
<td>$\dot{V}O_2$, $\dot{V}CO_2$, RER, AT</td>
<td>Lactate</td>
</tr>
<tr>
<td><strong>Cardiovascular</strong></td>
<td>HR, ECG, BP, $O_2$ pulse</td>
<td></td>
</tr>
<tr>
<td><strong>Ventilatory</strong></td>
<td>$\dot{V}t$, $Vt$, fr</td>
<td></td>
</tr>
<tr>
<td><strong>Pulmonary gas exchange</strong></td>
<td>$Sp_{O_2}$, $\dot{V}t/\dot{V}CO_2$, $\dot{V}t/\dot{V}O_2$, $PET_{O_2}$, $PET_{CO_2}$</td>
<td>$Pa_{O_2}$, $Sa_{O_2}$, $P$(a-a)$O_2$, $VC/Vt$</td>
</tr>
<tr>
<td><strong>Acid-base</strong></td>
<td></td>
<td>$pH$, $Pa_{CO_2}$, standard $HCO_3^-$</td>
</tr>
<tr>
<td><strong>Symptoms</strong></td>
<td>Dyspnea, fatigue, chest pain</td>
<td></td>
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</table>
Oxygen Uptake (VO$_2$)

Factors affecting VO$_2$
- Oxygen carrying capacity (Hb%, SaO$_2$)
- Cardiac function (Cardiac output)
- Distribution of blood to tissues
- Extraction by tissues (capillary density, mitochondria density & function, perfusion and diffusion)
VO$_2$ max

• Maximum VO$_2$ plateau achieved during maximal incremental exercise
• Best index of aerobic capacity & cardiorespiratory fitness
• Peak VO$_2$ if clear plateau not achieved due to symptom limitation of exercise
• Predicted VO$_2$ max calculated (N >84% predicted)
  Male: W x (50.75-0.372xA)
  female: W+43 x (22.78-0.17xA)
VO₂ – WR relation

Linear relation normal

Reduction of slope indicates - Inadequate O₂ transport / utilization

Disease of heart, lung or circulation
Musculoskeletal disease
Poor effort
Oxygen uptake

• Resting VO2: 3.5 ml/kg/min (250 ml/min)
• VO2 max: 30-50ml/kg/min (15 times basal)
• Trained athletes: 80ml/kg/min
• Decrease in VO2 max is a general indicator of reduced exercise capacity
• Cause of exercise limitation determined by pattern of response & other variables
Oxygen pulse

- Ratio of oxygen uptake to HR (N >80%)
- Amount of oxygen extracted per heart beat
- Reflects the product of stroke volume & oxygen extraction
- Indicates cardiac dysfunction (assuming O2 extraction is normal)
- Low O₂ pulse:
  - Cardiovascular disease
  - Deconditioning/poor effort
  - Early exercise limitation (respiratory disease)
CO$_2$ Output (VCO$_2$)

- CO$_2$ output during exercise depends on cardiac output, CO$_2$ carrying capacity and tissue exchange.
- VCO$_2$ increases nearly linear with VO$_2$ at lower work rates, after the AT the VCO$_2$ increases steeply as lactate is buffered by bicarbonate at higher work loads.
Anaerobic Threshold - V slope method
Anaerobic threshold

- Occurs at 50-60% of $\text{VO}_2$ max predicted in normal (wide range of normal 35-80%)
- Indicates the upper limit of exercise that can be performed aerobically
- $\text{AT below 40% predicted VO}_2$ max indicate cardio-pulmonary disease or limitation of $O_2$ supply to tissues or mitochondrial dysfunction in muscle
Anaerobic threshold

Noninvasive
- V slope method
- Modified V slope method
- Ventilatory equivalent method

Invasive (Arterial)
- lactate
- Bicarbonate
Cardiac parameters

• Cardiac output (CO) increases linearly with VO$_2$ and does not vary with training
• Initial increase CO by increase HR and SV at low work, later exclusively by HR increase at high work loads
• Heart rate reserve: difference of max HR achieved and max predicted HR
• Normal < 15bpm
HR-VO2 relation

Linear relation

Age predicted maximal HR used to signal maximal effort

Pred max HR = 220 - age
or 210 - Age X 0.65
Ventilation parameters

- Minute ventilation ($V_E$) increases with exercise: increase $V_T$ at mod work (up to 50-60 % of VC) and later by increase Fr at high work loads.
- Normal subjects Fr increases by 1-3 fold.
- Athletes Fr increases by 5-7 folds.
Ventilatory reserve

- Difference or ratio between max minute ventilation during exercise ($V_E$ max) and the maximal voluntary ventilation (MVV)
- Normal reserve > 15% of MVV (range 72+/−15%)
- MVV calculated as FEV$_1$ x 40 (approximates the measured value)
- Pulmonary diseases have reduced reserve
- Cardiac diseases have normal reserve
VE and VO2

Relation complex

Usually nonlinear
VE and VCO2

Healthy subjects linear relation
(23 - 25 L VE required to remove one litre CO2)

Psychogenic / Anxiety disorders assoc with increased VE/VCO2 hypcapnia with respir alkalosis
End tidal O2 and CO2

Isocapnic buffering

buffering of the lactate (after AT) increased production of the CO2 and ventilation increases proportionately so the alveolar & arterial CO2 do not change. With further, accumulation of lactate, -VE increases and CO2 falls.
Normal parameters

<table>
<thead>
<tr>
<th>Variables</th>
<th>Criteria of Normality</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{V}<em>{O_2}$max or $\dot{V}</em>{O_2}$peak</td>
<td>$&gt; 84%$ predicted</td>
</tr>
<tr>
<td>Anaerobic threshold</td>
<td>$&gt; 40%$ $\dot{V}_{O_2}$max predicted; wide range of normal (40-80%)</td>
</tr>
<tr>
<td>Heart rate (HR)</td>
<td>HRmax $&gt; 90%$ age predicted</td>
</tr>
<tr>
<td>Heart rate reserve (HRR)</td>
<td>HRR $&lt; 15$ beats/min</td>
</tr>
<tr>
<td>Blood pressure</td>
<td>$&lt; 220/90$</td>
</tr>
<tr>
<td>$O_2$ pulse ($\dot{V}_{O_2}$/HR)</td>
<td>$&gt; 80%$</td>
</tr>
<tr>
<td>Ventilatory reserve (VR)</td>
<td>MVV $- \dot{V}<em>{R\text{max}}$: $&gt; 11$ L or $\dot{V}</em>{R\text{max}}$/MVV $\times 100$: $&lt; 85%$.</td>
</tr>
<tr>
<td>Wide normal range: $72 \pm 15%$</td>
<td></td>
</tr>
<tr>
<td>Respiratory frequency ($f_i$)</td>
<td>$&lt; 60$ breaths/min</td>
</tr>
<tr>
<td>$V_t/VCO_2$ (at AT)</td>
<td>$&lt; 34$</td>
</tr>
<tr>
<td>$V_D/V_T$</td>
<td>$&lt; 0.28; &lt; 0.30$ for age $&gt; 40$ years</td>
</tr>
<tr>
<td>$P_{a_2}$</td>
<td>$&gt; 80$ mm Hg</td>
</tr>
<tr>
<td>$P_{(a-a)O_2}$</td>
<td>$&lt; 35$ mm Hg</td>
</tr>
</tbody>
</table>
## Summary: Response patterns

<table>
<thead>
<tr>
<th>Variable</th>
<th>Respir Disease</th>
<th>Cardiac Disease</th>
<th>Pulm vascular</th>
<th>Deconditioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO₂ max</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>AT</td>
<td>N/low</td>
<td>Low</td>
<td>N/low</td>
<td>N/low</td>
</tr>
<tr>
<td>HR Reserve</td>
<td>Increase</td>
<td>reduced</td>
<td>N/low</td>
<td>Normal</td>
</tr>
<tr>
<td>Ventilatn Reserve</td>
<td>low</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>P(A-a) O₂</td>
<td>COPD</td>
<td>Normal</td>
<td>Increased</td>
<td>Normal</td>
</tr>
</tbody>
</table>

|                    | ILD            |                  |               |                |

*Note: COPD = Chronic Obstructive Pulmonary Disease, ILD = Interstitial Lung Disease.*
Interpretation

Results are rarely clear-cut, and interpretation may be challenging, sometimes very difficult

- Review clinical and laboratory information
- Identify key variables: $V_E$ max, MVV, HR, SaO2
- Compare exercise responses with appropriate normal reference values
- Evaluate cause exercise limitation
- Patterns of exercise responses
Cardiomyopathy

A

B

C

D

E

F

G

H

I
Cardiac disease

- Reduced peak work rate and peak VO2
- Low AT (early onset metabolic acidosis)
- Low oxygen pulse
- High HR response (↓ reserve)
- Ventilatory reserve normal
- No desaturation
COPD

- Reduced peak work rate and peak VO$_2$
- Noninvasive AT: ABG may avoid false positive
- Reduced ventilatory reserve (>100%)
- Peak HR reduced (significant HRR)
- O$_2$ pulse reduced proportionate to VO$_2$ peak
- Hypoxemia - especially in emphysema (~DLCO)
- Hypercapnia (V/Q abnormalities and reduced drive in severe cases)
ILD

- Reduced peak work rate and peak VO₂
- AT N/reduced
- Reduced ventilatory reserve (>100%)
- Abnormal breathing pattern (high Fr, low VT)
- Significant hypoxemia (~ resting DLCO)
- Wide P(A-a)O₂ gradient
- Low HRR- coexisting Cor pulmonale
Pulmonary Diseases

A

B

C

D

E

F

G

H

I
Pulm Vascular disease

- Reduced peak work rate and peak VO$_2$
- AT reduced (early metabolic acidosis)
- Reduced Oxygen pulse
- Ventilatory reserve normal
- HRR usually near normal (low- Cor pulmonale)
- Significant hypoxemia
- Wide P(A-a)O$_2$ gradient
Deconditioning (Unfitness)

- Reduced peak peak VO$_2$ (lower limit of N)
- Low AT
- Reduced O2 pulse
- Normal peak HR (no HRR)
- Normal ventilatory reserve
- Diff to distinguish from early cardiac disease - history and response to training
- May be coexistent with chronic diseases
Interpretation of CPET

History Physical Examination, PFTs, ECG, consistency of results, effort, Symptoms (Borg Scale)

\[ \dot{V}O_2 \text{ max} \]

NORMAL

Patterns of response

- Normal
- \( \dot{V}O_2 / \text{kg} \)
- Obesity: \( \dot{V}O_2 \)
- Early cardiopulmonary disease

LOW

HR, \( \dot{V}E, SaO_2 \)

Physiologic / symptom limitation?

Patterns of response (based on integrated evaluation including other cardiopulmonary variables)

- Hyperventilation / Anxiety: Abnormal breathing pattern, \( \dot{V}E, \text{PetCO}_2 \)
- Poor Effort
- Neuromuscular
- Deconditioning
- Cardiovascular
- Mitochondrial Myopathy
- Pulmonary Vascular Disease
- ILD
- COPD
Future directions

• Reference normal values from multicenter studies required (few studies from India)
• Evidence based interpretation using standardized methodology & protocols
• Impact of pattern based analysis on clinical decision making
• Evaluate new exercise protocols (constant work rate, exponential exercise)
• Role of invasive vs noninvasive CPET