Cardiopulmonary Exercise Testing (CPET) & Advanced Diagnostic Testing

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Objectives:
1. Summarize the spectrum of exercise limitation after complicated ICU course
2. Describe the relative contribution of factors responsible for oxygen delivery using the Fick equation.
3. Understand the CPET profile of a cardiac and pulmonary vascular limitation to exercise.
4. Summarize contemporary concepts of invasive exercise hemodynamics.

Scenario:
You are seeing a 47-year-old man about 3 months after discharge from an 8-week hospitalization. He was admitted to another hospital for pneumonia that was treated with appropriate antibiotics. His hospitalization was complicated by sudden decompensation due to acute bilateral pulmonary emboli prompting transfer to a higher level of care. On arrival to the academic medical center, he was in shock and treated with systemic thrombolitics. His hypoxemia and hypotension improved significantly, but his course was complicated by empyema, pneumothorax, and persistent air leak. He slowly improved, was extubated after ~10 days, and his thoracostomy tube was converted to an empyema tube, which was ultimately removed. He has been maintained on a direct oral anticoagulant (DOAC) with excellent compliance.

Today in the office, he reports slow improvement. He finished PT, but he feels that his exercise capacity has not returned to his pre-illness baseline. In the past he could exercise for 1 hour on an elliptical daily, whereas now he can only manage 20-30 minutes due to dyspnea. He has also noted readings down to 85% on his home pulse oximeter at times. He has no chest pain, dizziness, cough, or lower extremity edema. His exam is unremarkable, including normal strength. PFTs and an echo obtained prior to his visit showed:

- **PFTs:** FEV1 75%, FVC 75%, FEV1/FVC Ratio 0.77, TLC 76%, MIP/MEP WNL, DLCO 81%

- **2D Echocardiography:** Normal LV size and function, normal left-sided valves. No LVH or signs of diastolic dysfunction. RV normal size and function, IVC collapsing, PASP ~25

A recent chest radiograph revealed mild pleural thickening on the side of his prior empyema but was otherwise normal.
Question 1: In general, what mechanisms of exercise limitation might be considered in a post-ICU patient? Based on the information provided, what could account for exercise limitation in this particular patient?

Specific considerations for this patient with post-ICU-stay exercise limitation include generalized deconditioning after a prolonged hospitalization, restrictive lung disease due to a primary lung or pleural insult, sequelae from critical illness myopathy, residual stress-induced cardiomyopathy, anemia, upper airway pathology, or chronic thromboembolic disease (CTED).

Question 2: What do we know generally about the incidence of exercise limitation after an episode of pulmonary embolism? What mechanisms could be implicated?

Recent studies have indicated a high prevalence of objective exercise limitation (50-70% at 6-12 months) after an episode of acute PE, as defined by a reduced maximal VO$_2$ on CPET. Chronic Thromboembolic Pulmonary Hypertension (CTEPH), which requires demonstration of both persistent pulmonary arterial thrombotic material and resting pulmonary hypertension, is thought to occur with an incidence of up to 4% post-acute PE. This is felt to lie on the extreme end of a spectrum of disease, with a higher proportion of patients demonstrating various combinations of exercise limitation, right ventricular dysfunction, and/or perfusion abnormalities, but without resting pulmonary hypertension. This is referred to as chronic thromboembolic disease (CTED), or sometimes the “post-PE syndrome.” Various studies have shown a 25-50% rate of persistent perfusion defects on V/Q scanning during variable follow-up post-PE, with an ~20% prevalence of persistent RV dysfunction, and ~10% prevalence of moderate or severe dyspnea.

If there is significant vascular obstruction present, both impaired cardiac output response as well as increased dead space contribute to symptoms and limitation. Recent data based on CPET analysis, however, suggest that many of these patients may simply be deconditioned, and, interestingly, the extent of residual perfusion deficits or RV dysfunction do not necessarily correlate well with reduced VO$_{2\text{max}}$.

Question 3: State the Fick equation.

VO$_2$ = CO x (CaO$_2$ - CvO$_2$)

Question 4: What pathophysiological processes are “packaged” within the Arterial-Venous O$_2$ content difference (AVO2D) term?

VO$_2$ = CO x (A-V) O$_2$ content = CO x (CaO$_2$-CvO$_2$)
\[
CO \times [(SaO_2 - MvO_2) \times Hgb \times 1.34] \text{ (we’re ignoring dissolved } O_2)\]

Therefore, the quantity AVO2D captures effects of anemia/hemoglobinopathy, gas exchange function of the lungs, distribution of blood flow to the periphery, and utilization of oxygen by muscles.

Note that the lungs are only directly represented in the equation by the SaO2 component. No other parameters related to lung function (e.g., PFT parameters) appear here.

**Question 5: What does the \( \text{V}_E/\text{VCO}_2 \) represent conceptually?**

\( \text{V}_E/\text{VCO}_2 \), or “ventilatory equivalents for CO\(_2\),” reflects the degree of ventilatory efficiency, or how much minute ventilation is occurring per liter of CO\(_2\) production. (\( \text{V}_E/\text{VO}_2 \) is also a marker of efficiency, but because regulation of minute ventilation is more tightly linked with CO\(_2\), \( \text{V}_E/\text{VCO}_2 \) makes more sense as the best marker).

Mathematically it is proportional to the dead space fraction and inversely proportional to PaCO\(_2\). Therefore, an elevated \( \text{V}_E/\text{VCO}_2 \) is due to either elevated dead space or a reduced PaCO\(_2\) (Hyperventilation). Hyperventilation may be “appropriate” (respiratory compensation in setting of chronic metabolic acidosis, respiratory compensation for severe/early onset of exercise-induced lactic acidosis, or hypoxemia), or “inappropriate” (psychogenic hyperventilation/dysfunctional breathing). Normal range for \( \text{V}_E/\text{VCO}_2 \) is 25-30. Slight elevation above 30 can be normal variant in but elevation of > 34 is considered clinically significant. (**though it is age-dependent**)

**Question 6: What CPET parameters suggest a primary cardiac limitation?**

CPET parameters indicating an abnormal cardiac limitation to exercise include\(^9\)

- Reduced peak VO\(_2\)
- Early-onset anaerobic threshold (AT), reduced \( \Delta \text{VO}_2/\Delta \text{WR} \) (both indirect indicators of adequacy of oxygen delivery/utilization)
- Reduced peak "O\(_2\) pulse" (\( \text{VO}_2/\text{HR} \)) (as a reflection of reduced maximal stroke volume)
- Rapid rise in HR relative to VO\(_2\)
- Low reserve between maximum HR achieved and predicted max HR (heart rate reserve)

**Question 7: Which parameters suggest a pulmonary vascular limitation to exercise?**

A pulmonary vascular pattern of exercise limitation is like a cardiac limitation; however, a few parameters are notably different in the setting of pulmonary vascular disease. First, patients with pulmonary vascular disease typically exhibit an abnormally elevated Vd/Vt during exercise. This can be manifested as ventilatory inefficiency (high \( \text{V}_E/\text{VCO}_2 \)). Assuming the patient isn’t hyperventilating, a high \( \text{V}_E/\text{VCO}_2 \) is attributed to abnormally elevated Vd/Vt. Vd/Vt can also be calculated using values for expired and arterial CO\(_2\) using the Bohr equation. In addition to elevated Vd/Vt, patients with a pulmonary vascular limitation also frequently experience arterial desaturate during exercise.

Note that the computer-generated estimated of Vd/Vt values based on end-tidal CO\(_2\) measurements are NOT ACCURATE and should be IGNORED, particularly when disease is present. This is because end-tidal values for CO\(_2\) do not correlate with arterial values in disease states, particularly when the pulmonary circulation is affected). As a result, the computer will tend to underestimate abnormal dead space in disease (and overestimate it in health).
Question 8: CPET was performed for our patient. Values and graphs are listed below.

Selected CPET variables (exercised to 156 Watts):

<table>
<thead>
<tr>
<th></th>
<th>Patient’s Value</th>
<th>Predicted Value</th>
<th>%-Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak VO₂</strong></td>
<td>1,857 ml/min</td>
<td>3,172 ml/min</td>
<td>59</td>
</tr>
<tr>
<td><strong>Heart rate</strong></td>
<td>144</td>
<td>174</td>
<td>83</td>
</tr>
<tr>
<td><strong>Oxygen pulse</strong></td>
<td>13 ml/beat</td>
<td>18 ml/beat</td>
<td>71</td>
</tr>
<tr>
<td><strong>Anaerobic threshold</strong> (as % of predict VO₂max)**</td>
<td>42%</td>
<td>&gt;44%</td>
<td>-</td>
</tr>
<tr>
<td><strong>Peak oxygen saturation</strong></td>
<td>80%</td>
<td>&gt;95%</td>
<td>-</td>
</tr>
<tr>
<td><strong>Breathing reserve</strong></td>
<td>47%</td>
<td>&gt;15%</td>
<td>-</td>
</tr>
<tr>
<td><strong>End-tidal CO₂ at AT</strong></td>
<td>32</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td><strong>Ve/VCO₂ slope</strong></td>
<td>36</td>
<td>&lt;33</td>
<td>-</td>
</tr>
<tr>
<td><strong>Calculated rest Vd/Vt</strong> (Computer’s value)**</td>
<td>0.32 (0.29)</td>
<td>&lt;0.4</td>
<td>-</td>
</tr>
<tr>
<td><strong>Calculated peak Vd/Vt</strong> (Computer’s value)**</td>
<td>0.4 (0.24)</td>
<td>&lt;0.25</td>
<td>-</td>
</tr>
</tbody>
</table>
Which pattern of exercise limitation is present in this patient?

Our patient’s CPET shows all the hallmarks of a pulmonary vascular limitation to exercise including a low peak VO₂, elevated VeVCO₂, elevated Vd/Vt at peak exercise, and arterial desaturation. Note the discrepancy between the computer reported Vd/Vt (seemingly normal) and the calculated Vd/Vt using transcutaneous CO₂ values (normal at rest, but abnormal at peak exercise).
Scenario, continued:

The patient undergoes both V/Q and CTA scanning, which reveal complete occlusion of both lower lobe pulmonary artery branches.

<table>
<thead>
<tr>
<th>Resting Right Heart Hemodynamics:</th>
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<tbody>
<tr>
<td>RA</td>
</tr>
<tr>
<td>PA</td>
</tr>
<tr>
<td>PCWP</td>
</tr>
<tr>
<td>tCO</td>
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<tr>
<td>PVR</td>
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</tbody>
</table>

**Question 9: Interpret the hemodynamics. Does he have CTEPH?**

The resting hemodynamics are normal. Since he does not have pulmonary hypertension as demonstrated by his mPAP <20 mmHg, he doesn’t have CTEPH. This, by definition, does not exclude CTED, as his radiology studies clearly show perfusion deficits. Given the remarkable reserve with recruitability and distensibility of the pulmonary circulation, there may be significant reductions in cross-sectional area of the pulmonary vascular bed without resting hemodynamic perturbation. Provoking the system, as with exercise, can unmask functionally relevant changes that are not apparent at rest. And, of course, this is when many patients’ manifest symptoms.

**The patient is exercised in a near-supine position, using an ergometer device to 100 Watts, with a peak HR of 112**

<table>
<thead>
<tr>
<th>Exercise Right Heart Hemodynamics:</th>
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</thead>
<tbody>
<tr>
<td>RA</td>
</tr>
<tr>
<td>PA</td>
</tr>
<tr>
<td>PCWP</td>
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<tr>
<td>tCO</td>
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<tr>
<td>PVR</td>
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<tr>
<td>TPR</td>
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<tr>
<td>Lactate</td>
</tr>
</tbody>
</table>

**Question 10: Describe the normal hemodynamic response to exercise and contrast it to this patient.**

Due to distensibility and recruitability of pulmonary vessels, as well as dynamic changes in left ventricular function and relaxation characteristics, the following observations can be made regarding hemodynamic changes with exercise:

- During progressive exercise, the following occur in normal individuals:
  - Steady increase in CO, mPAP, and wedge
  - Mild decrease in PVR
  - Modest decrease in TPR
In contrast to the expected normal changes described above, our patient’s exercise hemodynamics are notable for an exaggerated rise in mPAP and an increase in PVR and TPR.

Over the preceding decades, there has been ongoing debate about defining the normal pulmonary vascular responses to exercise. However, there is now some emerging consensus, with publication of a European-based, ERS task force statement in 2017. Historical definitions of exercise-induced PH (eiPH) often used a single mPAP cut-off (e.g., >30 mmHg at peak). However, cumulative appraisal of literature has indicated, perhaps not surprisingly, that the degree of increase in mPAP is correlated with the degree of increase in cardiac output, and thus determining whether a certain pressure response is abnormal should take into account the level of flow achieved.

- The mPAP/CO slope (or a single value measured at peak, i.e. the peak TPR) can define normal vs an abnormal pulmonary vascular response to exercise. An upper limit of normal of 3 mmHg/L/min is reasonable (noting that healthy younger patients likely should have lower values than this). This translates to an upper limit of normal (ULN) of mPAP of 30 at CO <10 L/min

Recall that Ohm’s law is used to approximate the relationship between flow, pressure, and resistance in the pulmonary circulation, given by:

\[ \text{mPAP} = (\text{CO} \times \text{PVR}) + \text{PCWP} \]
\[ \text{TPR} = \text{mPAP} / \text{CO} \]

Our patient’s exercise hemodynamics revealed a TPR of 3.7, which is above the upper limit of normal, consistent with eiPH.

However, an abnormal mPAP/CO slope alone does not pinpoint the clinical pathophysiology (need to tease out whether it is due to rise in wedge vs PVR problem)

- The rise in wedge pressure in healthy patients is also dependent on cardiac output. An absolute peak wedge cutoff of 20 mmHg is used in most studies by reference labs. Thus eiPH can be defined as an elevated mPAP or TPR with an exercise PCWP <20.
  - There is some interest in the wedge/CO relationship, using an ULN of 2 mmHg/L/min, but this is not in use clinically.

Scenario conclusion:
The patient was diagnosed with exercise-induced PH based on chronic thromboembolic disease (CTED). Given the functional limitations as documented by CPET, with complete obstruction of blood flow to his bilateral lower lobe pulmonary arteries, he was referred for multidisciplinary discussion in consideration of pulmonary thromboendarterectomy. There is scant evidence to guide this decision, however. In overt CTEPH, a prospective observational study suggested better survival in appropriate candidates who underwent thromboendarterectomy compared to non-operative therapy. He was deemed to be a good candidate and is slated for surgery in the near future.
References:

13. Delcroix M, Lang I, Pepke-Zaba J, et al. Long-Term Outcome of Patients With Chronic Thromboembolic Pulmonary Hypertension: Results From an International Prospective Registry. *Circulation.* 2016;133(9):859-871.