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Cardiopulmonary exercise testing

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Introduction

It is well established that there is an association between the patient's response to cardiovascular stress such as exercise or inotropic drugs and the risk of complications following non-cardiac surgery. Patients who demonstrate inducible myocardial ischaemia or who have a limited cardiac reserve are more likely to suffer major complications. Various tests, including treadmill testing, nuclear cardiology studies, and dobutamine stress echocardiography have been used to investigate patients facing major non-cardiac surgery [1]. A significant limitation of these tests is that they give information only on response of the heart to stress. Cardiopulmonary exercise (CPX) testing examines the integrated response of both the cardiac and the respiratory systems to increasing exercise. It is not a new test but its value in pre-operative assessment has been increasingly recognised over the past decade.

What is cardiopulmonary exercise testing?

The cardiopulmonary exercise test is an incremental exercise test in which the patient's ECG and respiratory function are monitored. Detailed protocols and guidelines are available for CPX testing [2]. In brief, the patient is connected to an ECG during the test. Ideally a 12-lead ECG is used and the software used should allow ST-segment analysis in real time and full disclosure of all leads if required. The patient wears a nose clip and breathes through a mouth-piece connected to a pneumotachograph and metabolic cart allowing breath by breath analysis of oxygen uptake and carbon dioxide excretion. The test may be performed using either a treadmill or a stationary bicycle (cycle ergometer). Many centres undertaking pre-operative testing use a cycle ergometer as this allows testing of many patients with arthritis or claudication who are unable to walk a significant distance but often prove able to pedal a bicycle.

Initially the patient sits quietly at rest on the bicycle whilst the ECG and gas exchange are monitored. The proper conduct of this stage of the test is important if valid results are to be obtained when exercise begins. The patient must be allowed to become used to the equipment and settle to a normal respiratory pattern. Patients are often anxious at the outset and may display both tachycardia and hyperventilation. Hyperventilation early in a test causing the patient to 'blow-off' carbon dioxide may lead to inaccurate estimation of the aerobic threshold later in the test. When it is deemed that the patient has become used to the equipment they are asked to start pedalling at a steady rate of about 60 revolutions per minute. During this initial free wheel stage of the test no resistance is placed on the cycle ergometer. After a short period, usually 2 to 3 min, the ramping stage of the test begins. The workload against which the patient must pedal is gradually increased. Formulae are available to calculate the ideal rate of increase but this is often set on the basis of clinical judgement at a rate of increase of between 10 and 20 Watts per minute. The aim is to increase the work load at a rate that allows a full test to be completed in less than 10 min. Either a sub-maximal or a maximal test may be performed. In a sub-maximal test the patient is asked to exercise until it is deemed that aerobic threshold (see below) has been passed. In a maximal test the patient is asked to exercise until they can no longer maintain the prescribed rate of peddling or they are walking or running as fast as they are able on the treadmill. Symptoms of chest pain, dizziness or feeling unwell are reasons for early termination of the test, as are evidence of myocardial ischaemia or significant arrhythmias on the ECG. Exercise finishes with a cool down stage in which the patient pedals the bicycle for a brief period against zero resistance or the treadmill is slowed to a walking pace. This is to prevent collapse due to cerebral hypoperfusion if exertion is stopped suddenly.

Data obtained from cardiopulmonary exercise testing

A large amount of data is obtained from a full cardiopulmonary exercise test. The main outputs are described below.

VO₂peak

The VO₂peak is the oxygen consumption at maximal exercise. This may be reported in litres per minute or ml per kilogram per minute. It is often confused with the VO₂max. The VO₂max is identified by a brief plateau in oxygen consumption before the subject has to stop exercising and identifies a level of exercise at which the subject has achieved their maximum possible oxygen consumption. It can be identified in trained athletes but few patients presenting for surgery are likely to be able to achieve a true VO₂max. VO₂peak is the oxygen consumption at the maximum level of exercise that a subject can attain. It has the weakness that it is dependant on volition, that is on the subjects' willingness to exert themselves to their limit, but its strength is that it can be defined in subject in who the anaerobic threshold is not clear.

Anaerobic threshold

The anaerobic threshold identifies the point in which the subjects blood lactate levels start to rise during exercise. It is identified during CPX testing by an increase in carbon dioxide excretion relative to oxygen uptake. (The increase in carbon dioxide production is due to the buffering of lactate by the bicarbonate buffer system). There are a number of methods of identifying this point from the data produced by a CPX test. The most widely used is the 'V-slope' method. In this method a graph is produced in which carbon dioxide excretion on the y-axis is plotted against oxygen uptake on the x-axis. This produces a straight line as oxygen uptake and carbon dioxide excretion increase with exercise. At the anaerobic threshold there is a change of gradient and a break in the line as carbon dioxide excretion increases. As with VO₂peak, anaerobic threshold is reported in litres per minute or ml per kilogram per minute of oxygen uptake.

Ventilatory equivalents

The ventilatory equivalents for oxygen and carbon dioxide are dimensionless ratios as measures of respiratory efficiency. The ventilatory equivalent for oxygen is the ratio of minute volume to oxygen uptake at a given point in the test. The ventilatory equivalent for carbon dioxide is the ratio of minute ventilation through carbon dioxide excretion. These numbers give an indication of the amount of ventilation that is required to take up oxygen and to eliminate carbon dioxide. That is to say, they are measures of respiratory efficiency with greater values indicating that more ventilation (a greater minute volume) is required for a given amount of oxygen uptake or carbon dioxide excretion.

Myocardial ischaemia

Clinical or ECG evidence of myocardial ischaemia during the test is an important abnormal outcome. The patient should be instructed to report any dizziness, chest pain or arm pain during the test. ST-segment depression in the limb leads or in contiguous chest leads should be noted. A positive test on ECG criteria (horizontal or downsloping ST-segment depression or elevation 1 mm or more at 80 ms after the J-point in two or more contiguous leads) is a reason for stopping the patient from exercising further.

Arrhythmia

Significant arrhythmias including rapid atrial fibrillation, supraventricular tachycardia or ventricular arrhythmias (including frequent or multifocal ventricular ectopics with increasing exercise) are again indications of an abnormal test and reasons for test termination.

Physiological and medical context

Cardiopulmonary exercise testing has had an established role in medical diagnosis and management for many years [3]. Applications include:

- assessment of heart failure and of suitability for heart transplantation
- assessment of chronic obstructive pulmonary disease and of suitability for lung volume reduction surgery
- assessment of primary pulmonary hypertension and of suitability for lung transplantation
- assessment of unexplained breathlessness
- disability evaluation
- to plan and assess progress during an exercise rehabilitation programme

Cardiopulmonary exercise testing has had an established role in assessment for thoracic surgery and lung resection for many years and is increasingly being applied to patients undergoing other forms of non-cardiac surgery.

Cardiopulmonary exercise testing in thoracic surgery

A recent meta-analysis by Benzo and colleagues has confirmed a clear association between VO_2 max or VO_2 peak and an increased risk of complications following lung resection surgery [4]. Guidelines such as those issued by the British Thoracic Society recommend pre-operative cardiopulmonary exercise testing as part of an investigative pathway for patients presenting for lung resection [5]. Pre-operative CPX testing is not considered necessary for all patients but is considered to have value in patients who after lung resection are expected to have a FEV_1 or transfer factor (T_{LCO}) of less than 40% predicted for their age, height and sex. Patients who prove to have a VO_2 peak of less than $15 \text{ ml.kg}^{-1}.\text{min}^{-1}$ on pre-operative testing are considered to be at high risk of complications.

Cardiopulmonary exercise testing in other non-cardiac surgery

In work published in 1993 Older and colleagues demonstrated an association between cardiovascular mortality and anaerobic threshold in patients undergoing major intra-abdominal surgery [6]. Patients who had an anaerobic threshold of less than $11 \text{ ml.kg}^{-1}.\text{min}^{-1}$ were identified as being at a greater risk of postoperative death. On the basis of these findings, this group of patients presenting for major non-cardiac surgery can be risk stratified on the basis of anaerobic threshold, the presence or otherwise of induced myocardial ischaemia on exercise testing and the ventilatory equivalent for oxygen at the anaerobic threshold. Patients with an anaerobic threshold of greater than $11 \text{ ml.kg}^{-1}.\text{min}^{-1}$, with no inducible ischaemia and a ventilatory equivalent for oxygen of less than 35 were considered to be at low risk of complications and were managed on a surgical ward after major surgery. Patients with an adequate anaerobic threshold but with an elevated ventilatory equivalent for oxygen or evidence of myocardial ischaemia received high dependency care in the postoperative period. Those with an anaerobic threshold of less than $11 \text{ ml.kg}^{-1}.\text{min}^{-1}$ were cared for in ICU after major non-cardiac surgery. This strategy resulted in a significant reduction in postoperative cardiovascular mortality when compared with historical data from the same unit [7].

An association between poor performance during CPX testing and adverse outcome has also been demonstrated for aortic surgery. Patients who died in the six months following surgery tended to have a lower anaerobic threshold and a higher ventilatory equivalent for carbon dioxide at their anaerobic threshold than survivors [8].

More recently Swart and Carlisle conducted a randomised control trial of risk stratification based on CPX criteria in patients undergoing major non-cardiac surgery [8]. Whilst small, this study confirms the findings of Older et al and indicates that the results of CPX testing are a valuable tool for pre-operative risk stratification.

Using the results of cardiopulmonary exercise testing

Part of the value of CPX testing lies in the insights about cardiopulmonary function offered by the data obtained. As described above, the test may be used to direct the patient to the appropriate level of postoperative care. It may also be used to direct the peri-operative care of the patient. The presence of inducible myocardial ischaemia may indicate the need for appropriate cardiac medications and further cardiological investigation. Poor cardiac function may be manifest by a low oxygen pulse (the amount of oxygen delivered per heart beat) and may indicate the presence of heart failure.

Again this can be used to direct the patient to appropriate investigation and treatment. An elevated ventilatory equivalent for oxygen at anaerobic threshold may represent respiratory insufficiency and suggest a need for pre-operative medication changes and for vigorous physiotherapy in the postoperative period.

The future

It is well established that there is an association between a limited exercise capacity and the risk of postoperative complications. Various risk scores such as the revised cardiac risk index are also available for pre-operative risk stratification [9]. The logical next stage in the development of pre-operative risk stratification is the development of tools which integrate the results of pre-operative stress testing and pre-operative risk scoring to give a comprehensive tool for pre-operative risk stratification. This will require the prospective study and follow-up of large numbers of patients, but has the potential to offer better tools for pre-operative risk prediction than either risk scoring or exercise testing alone.

Key Learning Points

- A cardiopulmonary exercise (CPX) test is an incremental exercise test during which gas exchange and the ECG are monitored.
- The exercise capacity of a patient as measured by CPX testing is expressed in terms of their oxygen uptake at anaerobic threshold or at peak exercise VO_{2peak} .
- Patients presenting for lung resection who have a $VO_{2peak} < 15 \text{ ml.kg}^{-1}.\text{min}^{-1}$ are considered to be at significantly increased risk of postoperative complications.
- In patients undergoing abdominal surgery an anaerobic threshold $< 11 \text{ ml.kg}^{-1}.\text{min}^{-1}$ and the presence of inducible myocardial ischaemia on exercise have been shown to be associated with an increased risk of peri-operative death.
- Studies in which the results of CPX testing have been used to risk stratify patients undergoing intra-abdominal surgery and to direct those identified as being at increased risk of major complications to high dependency or intensive care have shown improved outcomes from this strategy.

References

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