REVIEW

Cardiopulmonary exercise testing: a review of methods and applications in surgical patients

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Cardiopulmonary exercise (CPX) testing has a number of medical applications, including the assessment of heart failure and the investigation of unexplained breathlessness. Over the past decade, it has become an important preoperative assessment tool to evaluate functional capacity and predict outcomes in patients undergoing both cardiac and noncardiac surgery. A CPX test is an incremental exercise test during which respiratory variables, including oxygen uptake and carbon dioxide excretion are measured and the ECG is monitored. Among the variables reported from a CPX test are oxygen uptake at anaerobic threshold and peak oxygen uptake. A limited functional capacity as indicated by a low anaerobic threshold or VO_{2peak} has been shown to be associated with an increased incidence of perioperative complications in a number of surgical settings. Other reported variables, including the ventilatory equivalents for oxygen (VE/VO_2) and carbon dioxide (VE/VCO_2) and the millilitre of oxygen delivered per heartbeat or oxygen pulse [VO_2/heart rate (HR)] may give indications as to the reasons for exercise limitation. ECG evidence of myocardial ischaemia with increasing workload is also an important indicator of increased perioperative risk. As a noninvasive, low-risk, test of the integrated responses to increasing cardiovascular stress, anaesthesiologists involved in preoperative assessment should have an understanding of its current uses and test outcomes. This review presents the physiological basis for CPX testing, methodology, advantages over other preoperative tests of cardiovascular function and guidance on the interpretation of CPX results in the perioperative setting.

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Introduction

Cardiopulmonary exercise (CPX) testing involves the measurement of physiological variables during incremental exercise in order to assess a patient's functional capacity. 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 noncardiac surgery.[1] Patients who demonstrate inducible myocardial ischaemia, or who have a limited cardiac reserve, are more likely to suffer major perioperative complications. Various tests, including treadmill testing, nuclear cardiology studies and dobutamine stress echocardiography have been used to investigate patients facing major noncardiac surgery to assess perioperative risk.[2] A significant limitation of these tests is that they give information only on response of the cardiovascular system to stress. CPX testing provides a global assessment of the integrated response to increasing aerobic work involving the cardiovascular, respiratory, neurophyschological and skeletal muscle systems, all of which are activated during the neurohumoral stress response to surgery. It is not a new test and has been used in physiological research and in the assessment of patients with cardiac and respiratory disease for many years.[3] Over the past decade, it has found a place in preoperative assessment and its use for this purpose has increased steadily.

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The conduct of a cardiopulmonary exercise test

A CPX 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.[4] In brief, the patient wears a nose clip and breathes through a mouthpiece connected to a pneumotachograph and metabolic cart allowing breath by breath analysis of oxygen uptake and carbon dioxide excretion. 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 (Fig. 1).

Mode of exercise used

There are two commonly used exercise testing modalities: the treadmill and the stationary cycle ergometer. The bicycle ergometer is favoured by some for exercise testing, as work rate can be measured on a bicycle. Treadmill testing only allows an estimate of work rate. However, most patients are familiar with walking and the treadmill walking presents a less threatening form of exercise for the purposes of testing than cycling. As a treadmill provides a constantly moving platform, patients may have difficulty in continually maintaining the required forward momentum. This is supported by the observed difference in walking distances between 6-min shuttle tests and treadmill tests.[5] Determination of an

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Fig. 1

Cardiopulmonary exercise set up in our institution showing a cycle ergometry exercise test. The patient is connected to the metabolic cart via the mouthpiece, with continuous ECG recording.

individual's maximum exercise capacity is influenced by the mode of exercise used.[4]

Due to the utilization of more muscle groups during treadmill walking/running (lower body, core muscles and upper body), oxygen consumption during this form of exercise has generally found to be higher than that on a cycle ergometer. Maximal oxygen uptake on the treadmill has been reported to be 5–20% greater than equivalent cycle ergometer work.[6] In the clinical setting, however, in which testing involves nonathletic individuals, it is often possible to achieve maximal oxygen uptake within the more modest metabolic demands of the bicycle.[7]

The test starts with a rest period to allow patient familiarization with the gas exchange equipment and bicycle and allows for resting HR, blood pressure (BP), ECG and gas exchange values to be established. The proper conduct of this stage of the test is important if valid results are to be obtained when exercise begins. Patients can be anxious prior to the start of the test and hyperventilation often then occurs once the patient is connected to the mouthpiece and other testing equipment. It is important for accurate conduct of the test to establish a regular settled resting breathing pattern before initiation of exercise for the measurement of the baseline respiratory exchange ratio (RER). The RER is the ratio of carbon dioxide output to oxygen uptake. The resting RER should ideally be between 0.7 and 0.95.[8]

When the patient has become used to the equipment, they are asked to start pedalling at a steady cadence of about 60 revolutions per minute. During this initial freewheel stage of the test, no resistance is placed on the cycle ergometer. After a short period, usually 2–3 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 $20\,\mathrm{W\,min^{-1}}$. The aim is to increase the workload at a rate that allows a full test to be completed in less than 10 min. In perioperative practice, both a submaximal or a maximal test may be performed. In a submaximal test, the patient is asked to exercise until it is deemed that the anaerobic threshold 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 to 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 hypotension and syncope if exertion is stopped suddenly.

Test termination

It is important to remain in communication with the patient throughout the test. As the patient cannot talk because of the mouthpiece, they should be instructed to use hand signals (e.g. thumbs up and thumbs down) to respond to questions. In a maximal test, termination of the test occurs either at volitional exhaustion when the patient feels that they have exercised to their limit, when the patient is unable to maintain cadence on the cycle or when the clinician identifies one or more of the indications for test termination as mentioned below (adapted from American Thoracic Society/American College of Chest Physicians Consensus Statement on Cardiopulmonary Exercise Testing).

(1) Chest pain consistent with myocardial ischaemia.
(2) Ischaemic ECG changes (>2 mm ST depression with pain or >3 mm ST-depression without pain).

(3) Complex ectopy, for example, multifocal ventricular ectopics.
(4) Second-degree or third-degree heart block.
(5) Fall in systolic pressure more than 20 mmHg from highest value obtained during test.
(6) Hypertension (>250 mmHg systolic; >120 mmHg diastolic).
(7) Severe desaturations to an $Sp\mathrm{O}_2$ (arterial oxygen saturation as indicated by pulse oximetry) of 80% or less when accompanied by symptoms and signs of severe hypoxaemia.
(8) Sudden pallor.
(9) Loss of coordination.
(10) Mental confusion.
(11) Dizziness or faintness.
(12) Signs of respiratory failure.

Risks of cardiopulmonary exercise testing

CPX testing with a maximal symptom-limited CPX test is a relatively safe procedure, with a quoted risk of death of between two and five per 100 000 clinical exercise tests.[4] It is important, as with all clinical tests, to gain informed consent prior to the testing procedure with appropriate discussion of risks.

Physiological and medical context

CPX testing has had an established role in medical diagnosis and management for many years.[9] Clinical applications of cardiopulmonary exercise testing are listed below:

(1) Assessment of heart failure and of suitability for heart transplantation.
(2) Assessment of chronic obstructive pulmonary disease and of suitability for lung volume reduction surgery.
(3) Assessment of primary pulmonary hypertension and of suitability for lung transplantation.
(4) Assessment of unexplained breathlessness.
(5) Disability evaluation.
(6) To plan and assess progress during an exercise rehabilitation programme.
(7) Preoperative assessment in noncardiac surgery.

CPX testing has had an established role in assessment of patients prior to thoracic surgery and lung resection for many years. It is increasingly being applied to patients undergoing other forms of noncardiac surgery.

Data obtained from cardiopulmonary exercise testing

A large amount of data is obtained from a full CPX test. The commonly used outputs from the test are described below. The reader is referred to other sources for more detailed information.[4,8,10]

Oxygen uptake (VO_2)

Oxygen uptake increases linearly with increasing work rate in normal individuals. The slope of VO_2 versus external work rate reflects the efficiency of metabolic conversion of chemical potential energy to mechanical work and the mechanical efficiency of the musculoskeletal system. The linearity of slope is remarkably consistent between normal individuals. In healthy individuals, there is tight physiological coupling between increase in oxygen requirements and increasing muscle work with a mean value of $10.3\,\mathrm{ml\,min^{-1}\,W^{-1}}$ and 95% confidence limits of $8.3–12.3\,\mathrm{ml\,min^{-1}\,W^{-1}}$.[8]

Exercise intensity is often described in units of metabolic equivalents (METs). One MET equals the resting basal oxygen uptake in a 70-kg man in a sitting position and equals $3.5\,\mathrm{ml\,kg^{-1}\,min^{-1}}$.

Maximum oxygen consumption (VO_{2max})

At VO_{2max}, a participant has achieved their maximum possible oxygen consumption. A plateau in oxygen consumption between the final two work rate increments indicates that maximal oxygen uptake has been achieved and sustained for a brief period. As the work rate increases during exercise, one or more of the determinants of oxygen uptake reaches its maximum limit for that participant. In healthy individuals, oxygen uptake is limited by cardiovascular reserve (HR and stroke volume) rather than by respiratory reserve. A normal resting level for VO_2 is $3.5\,\mathrm{ml\,kg^{-1}\,min^{-1}}$ (one MET). Maximal oxygen uptake is dependent upon the mode of exercise, age, sex and body weight. Increases during exercise vary among individuals depending on training, and oxygen consumption can increase to 15 to over 20 times resting levels (up to $80\,\mathrm{ml\,kg^{-1}\,min^{-1}}$ in an endurance athlete).[11] Formulae for predicted VO_{2max} ($\mathrm{ml\,kg^{-1}\,min^{-1}}$) are:

$$VO_2 = W \times [50.75 - 0.372(A)]\text{(male participants)}$$

$$VO_2 = (W + 43) \times [22.78 - 0.17(A)] \times \text{(female participants)}$$

Where W is weight in kilograms and A is age in years. Values of 85% of predicted or more are considered to be within the normal range.[4]

VO_{2max} can be identified in trained athletes. In most patients, a clear plateau in oxygen uptake is not seen before exercise is limited by fatigue or before symptoms limit exercise. Generally, maximal tests in the clinical setting report the result of peak oxygen uptake.

Peak oxygen uptake (VO_{2peak})

VO_{2peak} is the oxygen consumption at the maximum level of exercise that an individual can attain regardless of whether a plateau in oxygen consumption is seen. As with VO_{2max}, it is reported in $\mathrm{l\,min^{-1}}$ or $\mathrm{ml\,kg^{-1}\,min^{-1}}$. VO_{2peak} has the weakness that it is dependent on volition, that is, on the participants' willingness to exert themselves to their limit. However, it allows peak oxygen consumption to be reported in participants in whom a true VO_{2max} cannot be defined and is an important indicator of exercise capacity in participants in the clinical setting.

The peak VO_2 is widely recognized as a risk stratifying measure in patients with cardiovascular disease.[11] It is a widely used measure in the evaluation of chronic heart failure.[12]

Ventilatory equivalents

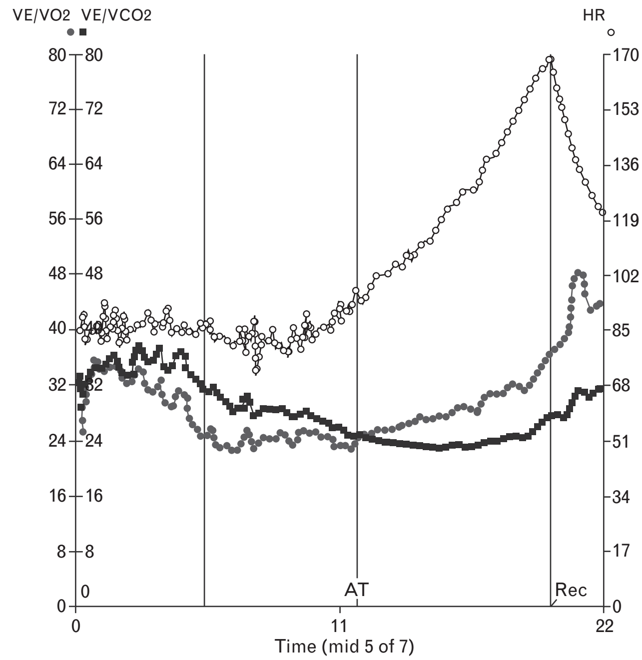
The ventilatory equivalents for oxygen and carbon dioxide are dimensionless ratios. The ventilatory equivalent for oxygen is the ratio of total expired volume to the volume of oxygen taken up at a given point in the test, VE/VO_2. The ventilatory equivalent for carbon dioxide is the ratio of expired volume to the volume of carbon dioxide excreted at a given time point, VE/VCO_2. 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 higher values indicating that more ventilation (a greater minute volume) is required for a given amount of oxygen uptake or carbon dioxide excretion. The normal pattern of change in VE/VO_2 is a decrease in early exercise to a nadir at or close to the anaerobic threshold and then an increase as maximum exercise capacity is approached. The increase in ventilation that causes this increase in VE/VO_2 is caused by the increased carbon dioxide evolution due to the buffering of lactate. The ventilatory equivalent for carbon dioxide also decreases with the start of exercise. The upturn in the equivalent for carbon dioxide occurs after that for oxygen and reflects increasing hyperventilation with a reduction in $p\text{aCO}_2$ to compensate for metabolic acidosis (Fig. 2).

Anaerobic threshold

The anaerobic threshold, also known as the metabolic threshold, identifies the point during an CPX test for the onset of an increase in blood lactate levels during exercise. The rise in circulating lactate during exercise was attributed by Wasserman and McIlroy[13] to the existence of a critical threshold at which the metabolic needs for oxygen in the muscle exceed the capacity of the cardiovascular system to supply them. In recent years, this interpretation has been questioned and alternative explanations for the increase in lactate posited.[14]

Blood lactate levels are not generally measured during a clinical CPX test. The changes seen in respiratory gas analysis are used to identify the point at which the lactic acid concentration in the blood begins to increase. During the initial aerobic part of the CPX test, carbon dioxide production from working muscles increases linearly with oxygen consumption. Blood lactate levels do not change substantially during this period, as muscle lactic acid production does not exceed the body's capacity for removal.[14] Anaerobic threshold is identified during CPX testing by an increase in carbon dioxide excretion

Fig. 2



Determination of the anaerobic threshold by the ventilatory equivalents method. The anaerobic threshold is the VO_2 at which the ventilatory equivalent for O_2 (VE/VO_2 ratio) begins to increase systematically without an immediate increase in the ventilatory equivalent for CO_2 (VE/VCO_2). AT, anaerobic threshold; HR, heart rate.

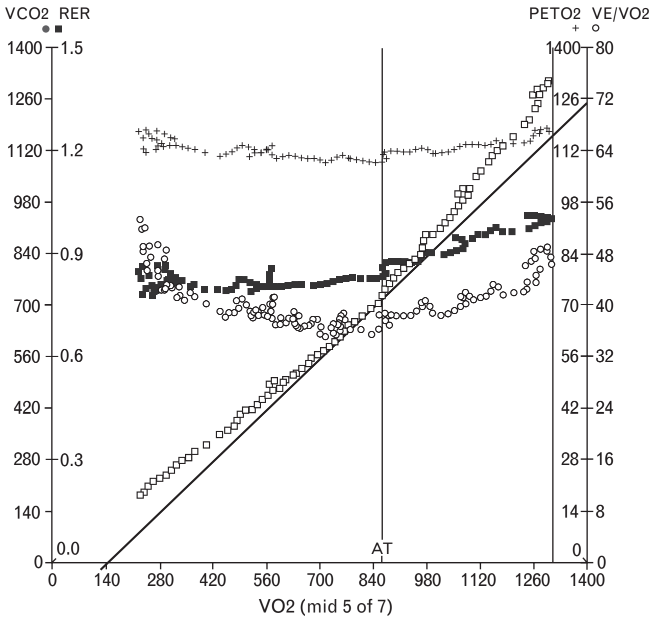
relative to oxygen uptake. The increase in carbon dioxide production above the anaerobic threshold is due to the buffering of lactate by the bicarbonate buffer system giving a rise in carbon dioxide production.

There are several methods of determining the VO_2 at anaerobic threshold from gas exchange data.

(1) The modified V-slope method is based on a graph in which carbon dioxide excretion on the Y-axis is plotted against oxygen uptake on the X-axis (Fig. 3). This produces a straight line (S1) with a gradient of approximately unity as oxygen uptake and carbon dioxide excretion increase with exercise.[15] As exercise intensity increases and the blood lactate concentration begins to rise, there is an increase in the steepness of the slope (S2) as an excess of carbon dioxide is produced by the action of the bicarbonate buffer system. This inflection point identifies the anaerobic threshold. As with VO_{2peak}, anaerobic threshold is reported in $l\,min^{-1}$ or $ml\,kg^{-1}\,min^{-1}$ of oxygen uptake.

(2) The anaerobic threshold can also be identified as the VO_2 at which there is systematic increase in the ventilatory equivalent for oxygen (VE/VO_2) without an increase in the ventilatory equivalent for carbon dioxide (VE/VCO_2)

Fig. 3



Determination of the anaerobic threshold by the V-slope method. The anaerobic threshold is the point at which the slope of the relative rate of increase in VCO_2 is relative to VO_2 changes. Note the slight increase in the $PETO_2$ and increase in the ventilatory equivalent for oxygen after this point. VCO_2 and VO_2 are given in ml kg^{-1} min^{-1}. $PETCO_2$, end-tidal oxygen tension (mmHg); RER, respiratory exchange ratio; VE/VO_2, ventilatory equivalent for oxygen.

(3) The changes in ventilation described in the above paragraph are associated with a rise in end-tidal oxygen pressure occurring with increasing exercise without a decrease in the end-tidal carbon dioxide tension.

Although the V-slope method is widely used, there is no clear advantage of one of the above methods over another.[16] The recommendation from the Joint Guideline of the American Thoracic Society and the American College of Chest Physicians is to use both the V-slope method and ventilatory equivalents method (dual criteria) as the RER approaches unity to minimize errors.[4] Modern exercise testing equipment automatically calculates the anaerobic threshold using one of several published or empirical algorithms. However, computer-generated values should be validated by an experienced reviewer.

The above methods may not be reliable in an anxious individual who has been hyperventilating prior to the start of exercise. Hyperventilation before the start of exercise leads to depletion of body stores of carbon dioxide and may lead to inaccurate estimation of anaerobic threshold with a ‘pseudo-threshold’ being seen before the onset of metabolic acidosis.[17] Such hyperventilation often occurs in stressed patients subjected to any form of testing procedure. To obviate this problem, the respiratory rate, RER and end-tidal carbon dioxide should be allowed to settle to normal values before the start of exercise. If this cannot be achieved, the anaerobic threshold as determined by noninvasive testing has to be regarded as unreliable.

The anaerobic threshold represents the exercise intensity that can be sustained indefinitely. Anaerobic threshold is dependent on exercise modality. Values from cycle ergometry are 5–10% less than those obtained from treadmill testing. Exercise intensities above anaerobic threshold are associated with a limited exercise tolerance. Anaerobic threshold expressed as a percentage of VO_{2max} increases with age. Anaerobic threshold generally occurs at 50–60% of VO_{2max}, but there is a wide range of values between 40 and 85% of VO_{2max} that are considered to be within normal range. Values of anaerobic threshold below 40% of predicted VO_{2max} are indicative of significant exercise limitation.[4]

Heart rate

Healthy individuals are generally subject to cardiovascular rather than respiratory limitation at maximum exercise and a HR at or close to peak predicted HR is often taken as an indication that the participant is close to peak exercise intensity. There is an approximately linear relationship between VO_2 and HR with increasing work, though the relationship is often nonlinear at lower exercise intensities. Two equations are commonly used to estimate maximum predicted HR:[4]

$$220 - \text{age}$$

$$210 - (age \times 0.65)$$

The first of these two equations tends to underestimate maximum predicted HR in older individuals. Both this uncertainty in prediction and the considerable interindividual variability in HR between participants of a similar age mitigate against the use of maximum HR as an indicator that maximum exercise has been attained.

Oxygen pulse

The ratio of HR to oxygen uptake (VO_2/HR) is termed the oxygen pulse and is a measure of oxygen extraction per heartbeat. In healthy individuals, oxygen uptake increases steadily with increasing work at lower exercise intensities. At higher intensities, the rate of increase slows. Failure of the oxygen pulse to increase can be an indicator of poor left ventricular function and is often viewed as an indicator of myocardial ischaemia. However, caution is required. The oxygen pulse may also fail to increase because of failure of oxygen uptake to increase because of respiratory constraints or deconditioning, leading to failure of muscle oxygen extraction to increase.

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 (>2 mm ST depression with pain or >3 mm ST-depression without pain) 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.

Limitations of cardiopulmonary exercise testing

CPX testing is not suitable for determination of functional capacity in all groups of patients. Those severely limited by musculoskeletal or neuromuscular diseases will find any sort of exercise difficult. In patients with lower limb weakness, it can be possible to gain an estimate of functional capacity using a hand cycle ergometer. However, VO_{2peak} values obtained from arm ergometry are only about 70% of those obtained from leg exercise and an increase in lactate is often seen early in exercise.[18,19]

Comparison with other methods of estimating exercise tolerance

A detailed comparison of CPX testing with other modalities of exercise testing is beyond the scope of the current review, but it is important that CPX testing is considered in the context of current recommendations on preoperative assessment. Both the European Society of Cardiology (ESC) and the American College of Cardiology/American Heart Association (ACC/AHA) guidelines on cardiac assessment for noncardiac surgery highlight the importance of estimating exercise capacity in assessing perioperative risk.[2,20] Both recommend estimating functional capacity in METS using questions derived from the Duke Activity Status Index. (As already discussed, one MET is equivalent to an oxygen consumption of $3.5\,ml\,kg^{-1}\,min^{-1}$.) The Duke Activity Status Index questionnaire relies on patients answering 12 questions from which a weighted score is calculated. An estimate of VO_{2peak} can be obtained from this weighted score.[21] This is not practical tool for routine preoperative assessment. In practice, clinical assessment often relies on asking whether a patient is able to climb one flight of stairs (equivalent to four METs). The reliability of estimating exercise capacity from individual questions within the questionnaire is not clear. Although the inability to climb two flights of stairs was shown by Reilly *et al.*[22] to be associated with perioperative complications, relying on this question alone has the weakness that patients have different perceptions of the work involved in the task relating it to an uncertain number of steps that may be climbed quickly or slowly.

The incremental shuttle walk test offers an alternative means of estimating exercise capacity. The test involves walking incremental 'shuttles' of 10 m between 'beeps'. As the test progresses, the time allowed for walking the shuttle between beeps decreases. That the test continues until exhaustion means that the patient is unable to complete one shuttle between the given beeps.[23] The total distance walked is then recorded. It has been shown to be of benefit in the assessment of medical patients with cardiac failure and pulmonary diseases. The test has been used to assess perioperative fitness in surgical patients undergoing major surgery.[24] Along with CPX testing, it forms part of the British Thoracic Society algorithm for the preoperative work-up of patients presenting for lung cancer reduction surgery.[25] A distance of 400 m on the shuttle test has been shown to correlate with a peak oxygen consumption of at least $15\,ml\,kg^{-1}\,min^{-1}$ on formal exercise testing.[26] However, a recent study comparing the incremental shuttle walk test with both the Duke Activity Status Index Questionnaire and CPX testing in the assessment of preoperative fitness of general surgical patients found that many patients with poor scores or shuttle distances had acceptable levels of oxygen consumption with reasonable anaerobic thresholds (anaerobic threshold greater than $11\,ml\,kg^{-1}\,min^{-1}$).[27] They concluded that the objectivity of both Duke Activity Status Index and incremental shuttle walk test to discriminate between high-risk and low-risk patients is questionable in a surgical population.

Cardiopulmonary exercise testing in thoracic surgery

A recent meta-analysis by Benzo *et al.*[28] confirmed a significant association between VO_{2max} or VO_{2peak} and an increased risk of complications following lung resection surgery. Guidelines such as those issued by the British Thoracic Society recommend preoperative CPX testing as part of an investigative pathway for patients presenting for lung resection.[25] Preoperative CPX testing is not necessary for all patients, but is considered to have value in patients who after lung resection are expected to have a forced expiratory volume in one second (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_{2peak} of less than $15\,ml\,kg^{-1}\,min^{-1}$ on preoperative testing are considered to be at high risk of complications following lung resection.

Cardiopulmonary exercise testing in other noncardiac surgery

In work published in 1993, Older *et al.*[29] demonstrated an association between cardiovascular mortality and anaerobic threshold as determined by CPX testing in 187 elderly patients undergoing major intraabdominal surgery. Patients who had an anaerobic threshold of less than $11\,ml\,kg^{-1}\,min^{-1}$ were identified as being at a higher risk of postoperative death. In a subsequent study, the same group examined risk stratification of patients presenting for major noncardiac surgery and postoperative outcome.[30] Five hundred and forty-eight patients over the age of 60 (or younger if they had existing cardiorespiratory impairment) were triaged to receive different levels of care based on anaerobic threshold, the presence or otherwise of induced myocardial ischaemia on exercise testing and the ventilatory equivalent for oxygen at anaerobic threshold. Patients with an anaerobic threshold of greater than $11\,ml\,kg^{-1}\,min^{-1}$ 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 the ward after 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 $11\,ml\,kg^{-1}\,min^{-1}$ were cared for in intensive care after their surgery. The overall mortality was 3.9%. Forty-three percent of deaths were attributable to poor cardiopulmonary function and CPX testing was effective in predicting these deaths.. The authors point out the value of CPX testing for identifying patients at low risk of complications who are candidates for ward care after surgery. The corollary is that, even with the benefits of intensive or high dependency care, patients who performed less well on CPX testing were at increased risk of perioperative complications.

A review by Smith *et al.*[31] examined the value of CPX in predicting perioperative complications in noncardiopulmonary surgery. They reviewed all studies comparing the predictive value of maximum oxygen consumption ($VO_{2max}/_{peak}$) or anaerobic threshold and analysed nine studies in further detail. They concluded that the majority of studies demonstrate that CPX variables, especially VO_{2peak}, are associated with perioperative morbidity and mortality in noncardiopulmonary surgery. Six out of the seven studies which reported sufficiently detailed findings on peak oxygen consumption[32–37] and four out of six reporting anaerobic threshold[29,32,33,37] found these variables to be associated with perioperative complications.

An association between poor performance during CPX testing and mid-term outcome has also been reported for aortic surgery. Carlisle and Swart[32] found reduced 30-day survival and mid-term (2 years) survival in patients who performed less well on preoperative CPX testing. On multivariable analysis, greater values of the ventilatory equivalent for $CO_2\,(VE/VCO_2)$ at anaerobic threshold were found to be associated with both 30-day mortality and worse mid-term survival. More recently, Swart and Carlisle[38] have conducted a randomized controlled trial of risk stratification based on CPX criteria in patients undergoing major noncardiac surgery. Patients with an anaerobic threshold of less than $11\,ml\,kg^{-1}\,min^{-1}$ were randomly allocated to receive either high dependency care or normal ward postoperative care. Patients with an anaerobic threshold greater than $10.9\,ml\,kg^{-1}\,min^{-1}$ were sent back to the ward for their postoperative care. The number of cardiac events (acute left ventricular failure and acute coronary syndromes) and length of hospital stay was measured in each group of patients: no cardiac events and lowest hospital stay occurring in the patients with an anaerobic threshold of greater than $10.9\,ml\,kg^{-1}\,min^{-1}$ sent straight back to the ward or in patients with an anaerobic threshold less than $10.9\,ml\,kg^{-1}\,min^{-1}$ nursed on the high dependency unit, whereas six perioperative cardiac events were observed in patients with an anaerobic threshold less than $10.9\,ml\,kg^{-1}\,min^{-1}$ nursed on the ward.

In their review, Smith *et al.* speculate that adverse outcomes following different types of surgery may be associated with different CPX variables, that the strength of the association between exercise capacity and perioperative risk may be different for different types of surgery and that the levels of preexisting morbidity accepted for surgery may affect the predictive value of CPX results. They conclude that CPX needs to be validated for each surgical procedure.

Using the results of cardiopulmonary exercise testing

The value of CPX testing lies in the insights about cardiopulmonary function offered by the data obtained. The test may be used to direct the patient to the appropriate level of postoperative care. It may also be used to direct the preoperative preparation 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. Elevated ventilatory equivalents throughout a test may represent respiratory insufficiency and suggest a need for preoperative medication changes and for vigorous physiotherapy in the postoperative period.

The future

At present, the evidence supporting preoperative CPX testing as a useful test to aid patient's and clinician's decision in terms of guiding surgical risk is incomplete. There have been a number of small-sized and medium-sized studies on a limited range of surgical patients. 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 the preoperative risk stratification of patients.[39] The logical next stage in the development of preoperative risk stratification is the development of tools which integrate the results of preoperative stress testing, preoperative risk scoring and biomarkers such as brain natriuretic peptide to give a comprehensive tool for preoperative risk stratification.[40]

This will require the prospective study and follow-up of a large number of patients, but has the potential to offer better tools for preoperative risk prediction than either risk scoring or exercise testing alone. In the meantime, preoperative CPX can reasonably be supported on the basis of an established relationship between exercise capacity and outcome and plausible scientific arguments to support its validity.

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