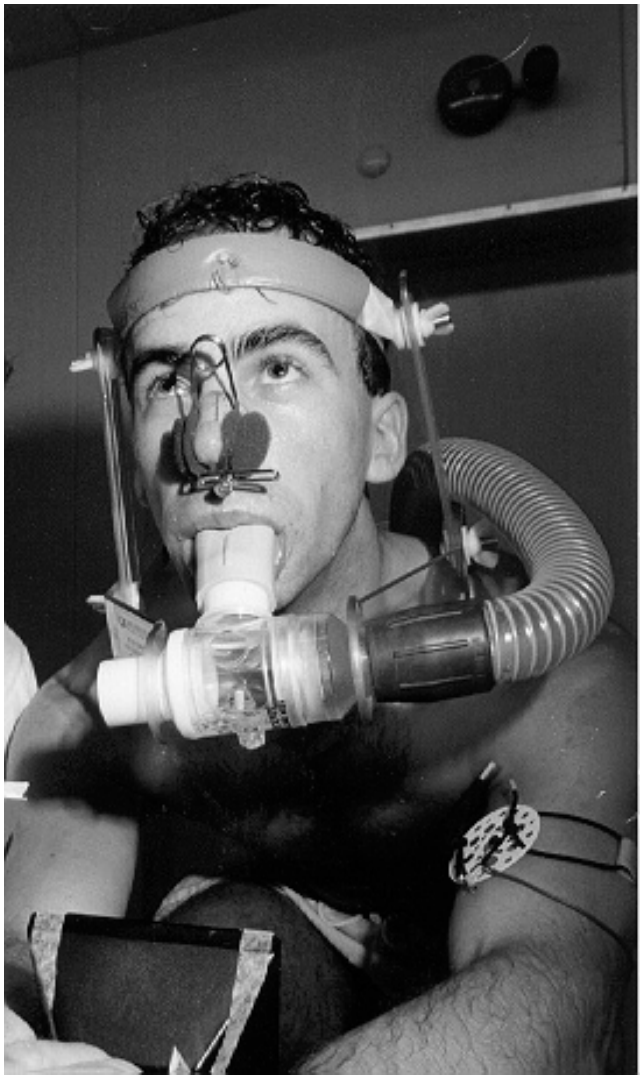
Aerobic Assessment

Gordon Sleivert

Dr Gordon Sleivert, Exercise Physiologist,
School of Physical Education, The University of Otago,
PO Box 56 Dunedin. Phone: (03) 479 9109.
Email: g.sleivert@pooka.otago.ac.nz



Introduction to aerobic assessment of the athlete

"Aerobic fitness" is perhaps the most common of all fitness attributes evaluated in athletes. Endurance athletes rely on high levels of aerobic fitness since their rate of energy supply, or pace, is ultimately determined by their ability to convert fuels into ATP in the presence of oxygen. Athletes involved in intermittent anaerobic sports such as netball, rugby and hockey must also have well developed aerobic systems since recovery from anaerobic efforts is largely an aerobic process. The concept of aerobic fitness is somewhat vague however since their are several facets of aerobic energy supply important to the athlete. These include aerobic power, anaerobic threshold and economy of movement.

Aerobic power, best measured directly in the athlete by determining maximal rate of oxygen consumption (VO_2max), is the single best measure of an athletes maximum ability to take in oxygen from the air, load it into the blood, and transport it to the working muscles to sustain exercise aerobically. It therefore represents our best measure of the current aerobic training status of the cardio-respiratory system.

Anaerobic threshold is a controversial term that is generally agreed to represent an exercise intensity above which energy supply become increasingly reliant on oxygen independent glycolysis or anaerobic metabolism. Exercise above anaerobic threshold intensity cannot be sustained for long due to the accumulation of metabolites such as lactic acid that contribute to fatigue.

Economy of movement is particularly important for endurance athletes that must move as fast as possible for the least amount of energy expenditure. An economical athlete will have a lower oxygen consumption (VO_2) at a given exercise intensity than a less economical athlete and will therefore be able to save energy for the later stages of a race or exercise harder for a similar energy expenditure.

Methodologies of aerobic assessment

Maximal aerobic power (VO_2max)

Nobel Laureate Archibald Vivian Hill was one of the first scientists to describe the concept of maximum aerobic power or VO_2max.

> *"In running the oxygen requirement increases continuously as the speed increases, attaining enormous values at the highest speeds; the actual oxygen intake, however, reaches a maximum beyond which no effort can drive it…owing to the limitations of the circulatory and respiratory system" [1].*

This classical description of VO_2max and those factors that limit VO_2max has changed little over the last 75 years as can be seen by a more recent definition of VO_2max.

> *"…a measure of maximal aerobic power defined as the highest rate of O_2 consumption possible during large muscle mass activity. VO_2max is largely a function of myocardial stroke volume, aerobic enzyme activity, and muscle capillary density" [2]*

There has been intense debate as to whether VO_2max is ultimately limited by central oxygen delivery or peripheral oxygen utilisation at the level of the working muscle [3-6]. Experiments have shown that contrary to expectations, when compared to leg work alone, combining leg and arm work increases VO_2max only to a small extent because of limitations in oxygen delivery due to the inability of the heart to distribute sufficient oxygen to all the working muscle [7]. Additionally, muscle has a very high capacity for blood flow and when a small muscle mass of only 2-3 kg is exercised VO_2 can attain values in excess of 300 ml/kg/min demonstrating that muscle itself does not seem to limit VO_2max [8]. Saltin & Strange [6] conclude that only approximately 10 kg of active muscle mass is required to tax the pump capacity of the heart and reach maximal oxygen uptake. Some individuals with extremely high cardiac outputs also demonstrate pulmonary diffusion limitations since the pulmonary capillary transit time is too short to sufficiently load oxygen onto haemoglobin. Substitution of ambient air (21% oxygen) for hyperoxic air (26% oxygen) has been shown to increase VO_2max in individuals with pulmonary diffusion limitations [9]. Further evidence for a central oxygen delivery limitation on VO_2max has been provided by studies that have infused red blood cells into subjects to increase oxygen carrying capacity of the blood [10] or decreased oxygen carrying capacity through removing a quantity of blood [11]. In each of these cases it was concluded that the more oxygen offered to the muscle the higher the VO_2max.

In light of this evidence most physiologists now agree that oxygen transport is the primary factor limiting VO_2max and VO_2max testing is a measure of the capacity of the cardio-respiratory system to deliver oxygen to the muscle. It has been shown to be a predictor of endurance performance in groups of athletes with heterogenous VO_2max values [12] but in athletes with similar VO_2max levels other factors such as fractional utilisation of VO_2max are better related to performance [13].

Measurement protocols

Direct measurement of VO_2max is primarily obtained using a graded exercise test to exhaustion and open-circuit spirometry. Subjects generally exercise on an appropriate treadmill or ergometer while wearing a noseclip and a mouthpiece equipped with one-way valves (Figure 1). In some cases respiratory masks are used in place of the traditional nose-clip-mouthpiece set-up, although at high ventilation rates they are prone to gas leakage. The low resistance one-way valves allow subjects to breathe ambient air while expired air is either collected into a Douglas bag or meteorological balloon for later analysis, or passed through a gas analyser for on-line measurement

of minute ventilation and fraction of expired O_2 (FeO_2)and CO2 ($FeCO_2$). These measurements along with accurate knowledge of gas temperature, barometric pressure and relative humidity are required for the determination of VO_2. The equations for the calculation of VO_2 are reported in numerous exercise physiology textbooks [14-17].

Figure 1: The mouthpiece and one-way valve system used for open-circuit spirometry.

Equipment specifications

In order to ensure VO_2max tests are both valid and reliable certain equipment specifications are essential. These requirements have previously been outlined by both Davis [14] and Thoden [16]:

1. The system should be air-tight so that no expired air is lost before it is analysed. This should be regularly tested by immersing tubing and gas collection systems underwater and checking for air bubbles.
2. The resistance to inspiration or expiration should be less than 5cm H_2O pressure at any ventilation.
3. The system should be fitted to the subject without restricting movement, adding significant weight, or leaking during maximal exercise (a common problem with face masks).
4. The volume measurement system should not vary as a function of breathing frequency or flow rate.
5. The volume measurement system should provide a reading or recording of gas temperature during volume determination.
6. The volume measurement system should provide a gas volume measurement of less than 1% error but preferably less than 0.05 L error at any volume.
7. The system should provide a method for mixing a minimum of two breaths of gas before any gas samples are taken for analysis.
8. The system should provide for anaerobic collection of gas samples for analysis by ensuring gas spigots have minimal dead space.
9. The system should allow for collection of a minimum of 30s of ventilation during the critical periods of testing.
10. Gas analysers should be able to provide repeated readings within 0.02% oxygen content and 0.04% carbon dioxide content.
11. When collecting the gas sample for analysis contamination should be less than 0.1% volume.

12. Analysers should allow for repeated calibrations before, during and after the test.
13. Equipment should be easily disassembled for cleaning and sterilisation.

Exercise mode

It has long been known that in untrained individuals treadmill testing of VO_2max elicits values approximately 10% higher than cycle ergometry [18]. Athletes however should be tested as sport specifically as possible for VO_2max data to have the most relevance. An obvious example has been demonstrated in swimming research where it has been shown that some elite competitive swimmers can exceed their treadmill VO_2max during swimming tests [19]. Many laboratories will not have access to a swimming flume (Figure 2), but tethered swimming or the use of a swim bench would certainly be improvements over the use of a treadmill. Attention to detail in the simulation of sport specific exercise modes cannot be over-emphasised and a little bit of creativity is invaluable. We regularly test cross-country skiers on a treadmill, but instead of running they use an exaggerated walking movement on a progressively steeper gradient with the addition of arm work using pulleys and weights to simulate the poling action of cross-country skiing. The skiers report that this *ski-walk* test feels like skiing and they certainly achieve VO_2max using this exercise mode. The recent development of valid and reliable portable light weight gas analysis equipment make it increasingly viable to design VO_2max protocols for use in the field. For example a VO_2max test may be utilised in the field by asking athletes to perform progressively faster split times on an athletics track or velodrome while monitoring heart rate and VO_2.

Continuous versus discontinuous protocols

In assessing VO_2max the most common approach is to use a graded exercise test (GXT). In a GXT the subject exercises on an appropriate ergometer and is exposed to progressive increments in exercise intensity, to the point at which they can no longer continue to exercise. This point is usually termed "volitional exhaustion" since the subject decides when they can no longer continue to exercise. The pattern of increasing intensity varies considerably from one protocol to the next but can generally be classified as "continuous" or "discontinuous". A continuous protocol does not allow rest between exercise increments while a discontinuous protocol allows the subjects brief rests between exercise bouts. Continuous protocols may also be classified as "ramp" or "step" protocols. In a ramp protocol intensity is increased continuously while in a step protocol larger increases in exercise intensity are given at set times. For example, in a ramp GXT test power might increase at a rate of 1 W every 2 seconds (30 W every minute), whereas a step protocol would increase power by 30 W instantaneously at the end of each minute. Specialised equipment is required for ramp protocols. Both protocol types have been shown to elicit valid VO_2max values [20]. Most VO_2max tests are continuous since these protocols are generally much less time consuming than discontinuous tests. An advantage of a discontinuous protocol however is that it may facilitate the collection of other data such as blood parameters during the sub-maximal stages of the test.

Figure 2: Testing VO_2max in the swim flume at the Aquatics and Controlled Environment Centre, University of Otago.

Stage increments and test duration

The total duration of a VO_2max test is an important consideration. If the exercise intensity is increased too quickly then neuromuscular limitations may not allow the true expression of VO_2max, due to a lack of leg strength or speed for example. If the increments are too small and test duration is prolonged then the increase in core temperature and redistribution of blood to the skin may limit O_2 supply to the muscle and VO_2max. Peripheral muscle fatigue and motivation may also be a problem in prolonged exercise tests since these protocols are particularly exhausting [14]. In fact, Buchfuhrer et al. [21] found that an intermediate protocol of between 8-12 minutes elicited higher VO_2max values in the same subjects than short (less than 8 minutes) or long protocols (18-26 minutes). It is therefore important that appropriate protocols are used for different levels of athletes. For example, a junior athlete might start at a lower initial work-rate than a senior athlete and work increments might also be smaller. In general the age, gender, body-build and approximate fitness level of the athlete should be examined before a test protocol is decided upon. Thoden [16], suggests that the initial workload be somewhere between 25-40% of estimated VO_2max and progress in steps of approximately 10-15% VO_2max. Examples of different VO_2max protocols are provided in the sport-specific chapters of this book.

Sample intervals

Individuals administering VO_2max tests must decide over which time period to sample respiratory gases for volume and gas concentration measurement. It is clear that the shorter the sampling interval the more variability is observed in VO_2. Myers et al. [22] investigated the influence of sampling intervals on VO_2 variability during breath-by-breath analysis. They examined 60, 30, 20, 15, 10 and 5s intervals, breath-by-breath and 5, 7 and 8 breath averages. They concluded that the shorter sampling intervals increased the variability of VO_2measurement and suggested that sampling intervals should be no shorter than 30s. Our lab uses 60s intervals for VO_2max determination with good success.

VO_2max criteria

A number of criteria are commonly utilised to indicate whether a subject has indeed reached VO_2max. The primary criteria proposed by Hill [23] was a plateau in VO_2 with a further increase in work intensity. This is thought to occur in the region of VO_2max due to the cardio-respiratory system reaching its maximum capability to deliver oxygen to the muscles. Research has shown however that many individuals do not demonstrate a plateau in VO_2 prior to volitional fatigue [22, 24]. For this reason secondary criteria are utilised to indicate that VO_2max has been achieved. These criteria usually include small variations of the following: 1. Blood lactate in excess of 8 mmol/L during the first 5 minutes of recovery, 2. Respiratory exchange ratio > 1.10, 3. attainment of age predicted maximum heart rate [3, 14, 15, 17]. When a plateau in VO_2 has not been observed due to peripheral muscle fatigue or some other factor, or when several of the secondary criteria have not been met the highest VO_2 observed in a test is referred to as Peak VO_2 rather than VO_2max.

Some labs utilise a verification phase in addition to the standard incremental VO_2max test to confirm that VO_2max has been achieved. For example, Thoden [16], recommend that 15 minutes after the completion of a progressive VO_2max test subjects run to exhaustion at one workload higher than the last load reached in the GXT. McKardle, Katch & Katch [15] suggest that several minutes after completion of a GXT a "booster test" started slightly lower than the maximum workload achieved in the first test will provide a slightly higher VO_2max in most cases. Attention should therefore be given to using a verification phase for confirmation of VO_2max, especially in athletes with little experience of maximal exercise testing.

Interpretation

VO_2max is generally expressed as an absolute volume of oxygen consumed per minute (L/min) or as a volume per minute relative to body mass (ml/kg/min) [16]. For exercise modes such as running where body mass must be carried relative VO_2max is most relevant whereas for sports such as rowing that are body mass supported then absolute VO_2max is most relevant. It is possible of course to observe changes in relative VO_2max simply by losing or gaining body mass, therefore when interpreting results both relative and absolute VO_2 must be examined to ascertain the likely cause of VO_2max change. Females generally have VO_2max values 15-30% lower than males. A large portion of this difference disappears when differences in lean body mass and haemoglobin concentrations are accounted for [15].

Using either relative or absolute expressions of VO_2max depending upon whether an activity is weight-bearing or not is of course a gross over-simplification. For example, in swimming the buoyancy of water supports the body mass to some extent but heavier individuals may have greater drag in the water [25] and research has shown that relative VO_2max may be more appropriate for swimmers than absolute VO_2max.[26]. In some cases VO_2max has been allometrically scaled and expressed relative to body mass to the power of 0.67, since evidence suggests that expressing VO_2max relative to body mass may unduly penalise heavier individuals [27]. Allometric scaling of VO_2max may be particularly useful for separating the effects of growth and maturation from training on VO_2max in the young athlete. A discussion of this issue is beyond the scope of this chapter.

As has been previously stated, VO_2max is only a good predictor of performance amongst athletes that are heterogenous in VO_2max. In athletes with well developed cardio-respiratory systems and accompanying high VO_2max values other factors are better predictors of success. This does not indicate that VO_2max is not an important performance factor but rather suggests that it must be developed to a criterion level for membership into the "elite" athlete club. Once that level is achieved then other factors may be focussed upon to a greater extent.

Frequency of testing

How often should athletes undergo VO_2max testing? This depends upon the level of the athlete. It is well known that VO_2max can increase anywhere from 5-25% depending upon the trainability of the individual, which has a large genetic component [28-30]. Certainly the most rapid increases in VO_2max with training occur early, within the first 6 months of beginning training. Athletes that have been training competitively for many years should not expect large changes in VO_2max. Therefore, for the experienced competitive athlete testing should probably be performed at approximately 6 month intervals in order to ensure that no adverse training factors have influenced VO_2max. For the inexperienced or unfit athlete embarking on a new aerobic training programme, testing would be appropriate every 6-8 weeks, depending upon the stage of the fitness programme.

Summary

The measurement of VO_2max is a routine procedure in most exercise physiology laboratories. The purpose of this section was to review some of the key issues surrounding VO_2max testing but not present "canned" protocols. Clearly, each lab and each athlete will have unique requirements that must be considered in the design of any protocol. For maximum interpretability of VO_2max results, similar protocols and identical equipment should be utilised in test-retest situations and when testing teams or large groups of individual athletes from a common sport. Appropriate planning and communication between the coaches, athletes and scientists is essential in this respect.

Ventilatory and lactate thresholds

It has long been known that above certain intensities of exercise lactate begins to accumulate in blood and early on this was attributed to hypoxia in the muscle [23]. Wasserman & McIlroy [31] expanded on this concept and introduced the term "anaerobic threshold". This terminology was used to indicate that above a certain exercise intensity oxygen supply to the working muscle was insufficient to maintain energy supply by aerobic pathways exclusively and anaerobic metabolism was recruited to supplement (but not replace) aerobic energy supply. The non-linear rise in blood lactate at this intensity is commonly known as "lactate threshold".

Lactic acid quickly dissociates to lactate and hydrogen ion (H+) and the hydrogen ion derived from lactic acid is quickly buffered by the bicarbonate system and converted to CO_2. Ventilation responds to two different CO_2 sources, the metabolic CO_2 generated in Krebs cycle and excess CO_2 generated from the buffering of lactic acid. Therefore at the anaerobic threshold a non-linear increase is observed in minute ventilation (Ve) and this is termed the "ventilatory threshold" [32]. Wasserman believed that the ventilatory threshold was integrally linked to the lactate threshold and that either technique could be utilised to estimate anaerobic threshold.

The anaerobic threshold concept has been steeped in controversy over the last 25 years with the primary points of contention being whether a threshold exists at al. (Hughson, Weisiger, and Swanson, 1987), and whether tissue becomes hypoxic at the so called threshold [32, 34]. It is now generally accepted that lactate concentration in the blood is the net result of the balance between production and removal of lactate, regardless of whether increased lactate production is related to tissue hypoxia. Certainly lactate production could also be increased by an increase in recruitment of Type II muscle fibers [15, 17]. Foster et al. [35] among others has recently pointed out that the more important cause of lactate accumulation in blood is probably related to decreased removal of lactate as a result of decreased blood flow to the major lactate removal organs of the liver and kidney as exercise intensity increases. Hence a rise in blood lactate is not necessarily reflective of increased anaerobic metabolism. Despite the controversy surrounding threshold concepts they remain a useful tool for the exercise scientist since the exercise intensity at both ventilatory and lactate threshold has been repeatedly demonstrated to be strongly related to endurance performance even when athletes have homogenous and high VO_2max values [2, 13, 26, 36, 37]. This is likely because the acidosis associated with lactic acid accumulation accelerates fatigue by interfering with calcium binding in the muscle [38, 39].

Measurement protocols

Anaerobic threshold tests are performed in a similar fashion to a VO_2max test, usually using either continuous or discontinuous incremental protocols. Somewhat different protocols are required for reliably detecting ventilatory versus lactate threshold.

Ventilatory threshold

Necessarily ventilatory threshold tests must be completed with the athlete connected to an open-circuit spirometry system. The following respiratory variables are usually monitored: minute ventilation (Ve), volume of carbon dioxide produced per minute (VCO_2), volume of oxygen consumed per minute (VO_2), respiratory exchange ratio ($R=VCO_{2/}VO_2$), breathing frequency (Bf), ventilatory equivalent for oxygen (Ve/VO_2), and ventilatory equivalent for carbon dioxide (VCO_2/VO_2).

Stage increments and test duration

Ventilatory threshold tests are usually continuous in nature and utilise small rapid steps in work increments or ramp protocols, with test duration lasting no longer than 12 minutes. For this reason the testing protocol can often be combined with a VO_2max protocol [40]. A short rapidly incremented

protocol is thought to amplify the ventilatory threshold so that it's identification is simpler than when using longer incremental steps [35]. One minute stages are commonly utilised. It has also been recommended that data should be collected on the athlete during several minutes of rest followed by several minutes of performing unloaded cycling or walking prior to the actual test protocol beginning [35, 40]. This may ensure that the tissues are loaded with CO_2 by the start of the protocol in order that changes in CO_2 production during the test are immediately evident in the respiratory variables being monitored. Similarly, because of the tissues CO_2 capacitance, Beaver et al. [40] suggest that the first minute of incremental test data may also have to be discarded due to the distortion of VCO_2 data.

Sample intervals

Short sampling intervals are usually recommended with Wassermans group recommending breath-by-breath sampling and a 9 s moving average to remove some of the noise attributable to fluctations in ventilation [40]. Others have successfully used mixing chamber data and sampling intervals of 20-30s [41].

Threshold identification

A plethora of methods exist for the detection of ventilatory threshold. Perhaps the most well known method is the V-slope method originally proposed by Beaver et al. [40].

V-slope

The V-slope technique requires that VCO_2 is plotted against VO_2. VO_2 is used as the independent variable since it is a direct index of metabolism. As exercise intensity increases, the relationship between these two variables changes such that a point is reached where VCO_2 increases disproportionately to VO_2. (Figure 3). This transition, thought to be a result of the buffering of lactic acid by bicarbonate, indicates the point of anaerobic threshold. To objectively determine this point, two regression lines are plotted, one using the higher workload points and the other using the lower workload points. The slope of the lower line should be less than 1.0 as VO_2 will be increasing at a rate greater than VCO_2. The slope of the higher line will be greater than 1.0 as VCO_2 is increasing at a rate greater than aerobic metabolism due to bicarbonate buffering. The points included in the regression procedure are manipulated until there is a difference in slope of at least 10% between regression lines. The intersection of these two regression lines is the anaerobic threshold and usually coincides with the first rise of blood lactate above resting levels. This is generally referred to as the "aerobic threshold" and often occurs around 2 mMol/L blood lactate concentration [35].

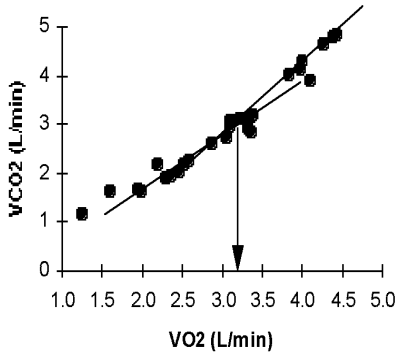


Figure 3: V Slope technique of determining ventilatory threshold

Respiratory compensation point

The respiratory compensation point method requires that Ve is plotted against VCO_2 and divided into two linear segments as above. The intersection of the two segments is the respiratory compensation point [40], and this point generally coincides with a lactate breakpoint or "anaerobic threshold" much more closely than the V-slope method (Figure 4) [35].

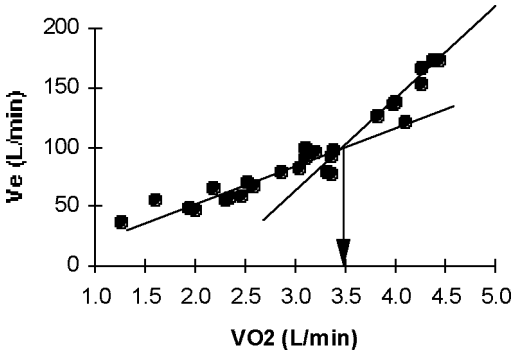


Figure 4: Respiratory Compensation Point method for identifying ventilatory threshold.

Both the V-slope and respiratory compensation methods are rather labour intensive and it can be difficult to judge at which point Ve, or VCO_2 begin to increase more steeply. Davis [32] has suggested that an alternative and better detection point involves the use of the ventilatory equivalents.

Ventilatory equivalent

As exercise intensity increases Ve/VCO_2 usually remains relatively constant since ventilation will usually match the body's need to remove CO_2. Ve/VO2 will also be constant during early increments of exercise indicating that the control systems for breathing are properly matched to the body's need for oxygen. A point is eventually reached however whereVe/VO_2 begins to systematically increase without an increase in Ve/VCO2 indicating that the increase in ventilation required to remove CO_2 is disproportionate to the body's need to provide oxygen (Figure 5). This point is the anaerobic threshold.[32, 42]. Ve/VCO_2 does not increase until after anaerobic threshold because of "isocapnic buffering". That is, the excess CO2 being produced is being buffered by bicarbonate at this time. Isocapnic buffering does not occur when the work increment is long, emphasising the need for a rapid incremental test of ventilatory threshold. This method is attractive since it is easier to judge a break point from a variable that is not continuously increasing (as in the V-slope method) but is relatively constant until the threshold.

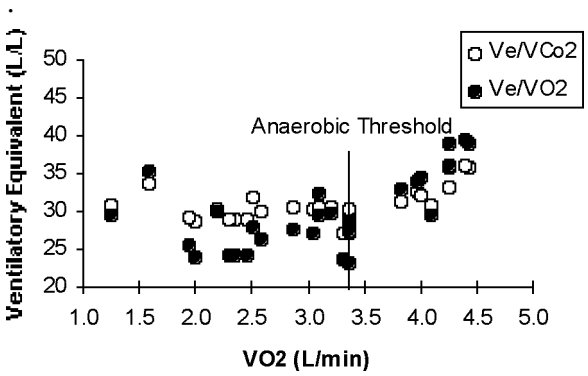


Figure 5: Ventilatory Equivalent method for identifying ventilatory threshold.

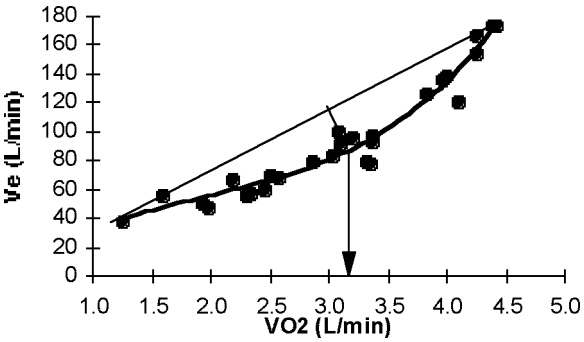


Figure 6: The Dmax method for identifying ventilatory threshold.

Dmax

Cheng et al. [41] developed an alternative threshold detection technique called the Dmax method, that is simple, reliable and can be used with both respiratory and blood lactate data. In the Dmax method the respiratory variables of VCO_2, Ve or Bf are plotted against VO_2. The data is fit with a 3rd order curvilinear regression (available in Microsoft Excel) and a line is drawn between the two end points of the curve (Figure 6). This line indicates the general direction of change (GD) for the variable of interest. The point on the curve that represents the maximal distance from the curve to the line is "Dmax". Below Dmax points get further and further away from GD and above Dmax point get closer and closer to GD. Thus Dmax is the threshold point. Thresholds detected using this technique agree very well with more traditional methods such as the V-slope method and similar threshold values are obtained whether Ve, VCO_2 or Bf is used. Thus the Dmax method is reliable, valid and simple to use. Additionally, since simple variables such as Bf can be used with this procedure it may be particularly useful for field applications.

.

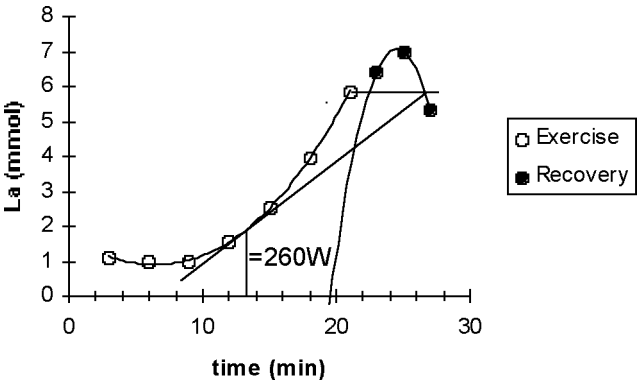


Figure 7: The individual anaerobic threshold method of determining lactate threshold.

Lactate threshold

For lactate threshold testing incremental continuous or discontinuous incremental protocols are utilised. In exercise modes such as cycling where it is easy to take a blood sample while the athlete is exercising continuous protocols are favoured whereas in other modes of exercise such as swimming, rowing, or running, discontinuous protocols are commonly utilised.

Stage increments and test duration

In general lactate testing requires longer stages than ventilatory threshold testing. This is due in part to differences between muscle and blood lactate. Generally blood lactate is always less than muscle lactate, and blood lactate values taken after short exercise stages of less than 4 minutes underestimate

the degree of muscular lactic acidosis [43, 44]. Nevertheless, Foster et al. [35] suggests that blood lactate can reflect intramuscular lactic acidosis, but the exact relationship between blood and muscle lactate is dependent upon the length of the exercise stage and the behaviour of blood lactate following exercise. Several lactate threshold protocols do take into account lactate recovery kinetics [45, 46].

Recently Stockhausen et al. [47] examined the influence of step size and duration on lactate kinetics. They reported that for large versus small increases in workload it took longer for blood lactate to reach a "quasi-steady state" (95% of steady state levels). This is important since if blood lactate values are not allowed to approach steady state during incremental testing then the lactate threshold, or the maximal steady state level of blood lactate that can be sustained during endurance exercise will be overestimated. For cycle ergometry they suggested that for 10, 20, 30, 40 or 50 W steps a minimum of 2:00, 3:00, 4:00, 4:45 and 5:00 minute stages are required to ensure quasi-steady state. This recommendation can be generalised to other exercise modes and simply indicates that for lactate threshold testing to be a valid indicator of maximal lactate steady state longer stages are required for larger steps in workload.

Threshold Identification

Maximal Lactate Steady State (MLSS)

Heck et al. [48] defined MLSS as the highest blood lactate concentration that increases by no more than 1.0 mmol/L during the final 20 minutes of a 30 minute constant workload test. Generally athletes undergo the first test at a workload corresponding to some other index of lactate threshold determined in a previous incremental exercise test. If blood lactate increases by more than 1 mmol/L during the last 20 minutes then the subsequent constant load test is performed at 1 workload lower than the previously identified lactate threshold. If no rise is observed in blood lactate then the subsequent constant load test is performed at 1 workload higher than the previously identified lactate threshold. Constant load tests are performed on separate days and it may take up to 5 - 7 tests to determine MLSS. Therefore, although this procedure is very accurate at determining MLSS, it is very time consuming.

Onset of blood lactate accumulation (OBLA)

The use of fixed blood lactate concentrations to indicate anaerobic threshold is very common since this method removes the complications for detecting a threshold. A blood lactate concentration of 4 mmol/L is commonly used to represent OBLA, an intensity that is representative of maximal lactate steady state [49, 50].

Although this method is attractive because of its simplicity, in practice many athletes have maximal lactate steady states above or below 4 mmol/L. For example a recent paper reported that maximal lactate steady state in rowing averaged 3.1± 0.5 mmol/L, , 5.4 ± 1.0 mmol/L in cycling and 6.6 ± 0.9 mmol/L in speed skating [51]. Additionally, muscle glycogen depletion can influence the intensity at which a fixed blood lactate value occurs [52]. Clearly, reliance on fixed lactate values is an oversimplification. They may be useful to track shifts in a lactate profile within an athlete over time but should not be used for training prescription per se. This is particularly worrisome since many sports utilise lactate zones and absolute lactate values for their training prescription.

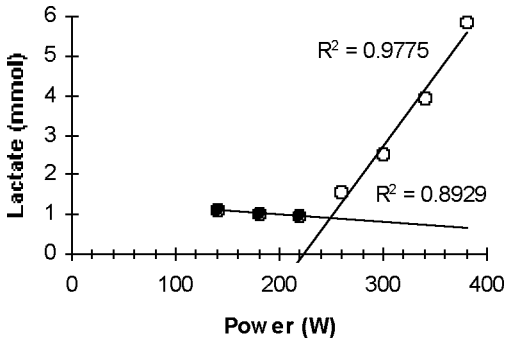
Individual anaerobic threshold

Steggman et al. [45] have proposed a unique method for identifying anaerobic threshold from blood lactate parameters. Their method utilises an incremental protocol and recovery lactates to account for differences between individuals in the diffusion of lactate from muscle to blood, and anaerobic threshold intensities identified using this method have been shown to be useful in prescribing endurance exercise [53].

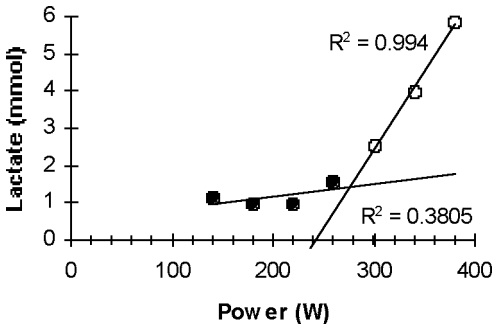
Briefly, exercise lactate values from a standard incremental test are plotted along with recovery lactates values, collected every 2nd minute for approximately 10-15 minutes. The exercise lactates are fitted using a 3rd order polynomial and the recovery lactates are fit separately also using a 3rd order polynomial. The point on the recovery curve where blood lactate is equal to the peak exercise lactate is noted and this point is used as an anchor to draw a tangent to the exercise lactate curve. The intersection of this tangent with the exercise lactate curve is taken as the anaerobic threshold (Figure 7).

Slope method

The slope technique uses the same principles that were outlined in the ventilatory threshold section under the V-slope technique. Essentially, a regression line is fit to the upper data points and one to the lower data points in order that a threshold or breakaway point can be identified. The intersection of these two lines represents the lactate threshold (Figure 8). A problem with technique is that often a continuous function fits the data as well or better than two linear regression lines [33], so there has been a tendency in recent years not to use this approach.



A. Both regression lines fit well as indicated by the R squared values.



The R squared value of the lower line has significantly dropped indicating that the threshold value identified in "A" is better.

Figure 8: The slope method for determining lactate threshold.

1 mmol method

This is a very practical and objective approach of which variations have been advocated by several sport scientists. Thoden [16] suggests that lactate threshold be identified from an incremental test as that exercise intensity just prior to a step eliciting a 1 mmol/L increase in blood lactate, followed by a similar or larger increase in blood lactate on the next step (Figure 9). A limitation that our lab has experienced with the Thoden protocol is that the technique is not sensitive. When testing large groups of competitive athletes many will have thresholds identified at the same workload using the 1 mmol/L criteria. Coyle [2] uses a slightly different technique and fits a regression line to the first

3 points of the exercise lactate data and identifies threshold as a the point that is 1 mmol/L above baseline (Figure 10). This technique may be slightly more sensitive than the Thoden method.

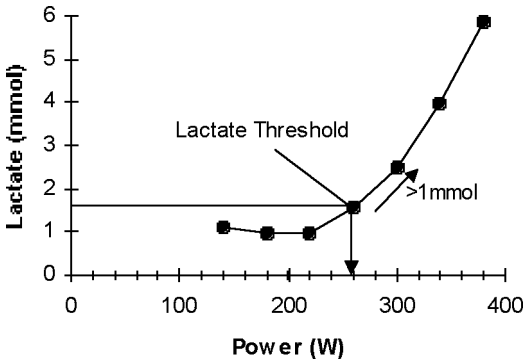


Figure 9: The 1mmol method for determining lactate threshold.

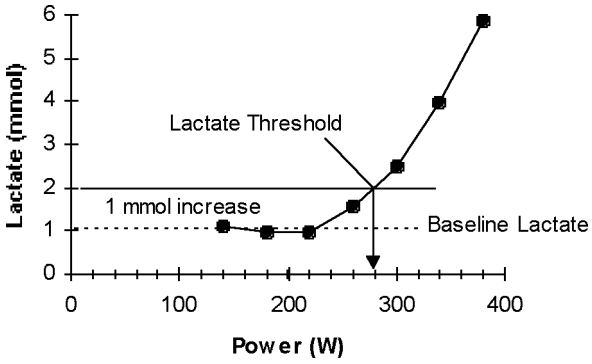


Figure 10: The modified 1 mmol method for determining lactate threshold.

Dmax

The Dmax protocol uses the same curve-fitting strategy as described for identification of ventilatory threshold. Blood lactate is plotted against VO2, power output or velocity and the data is fit with a 3rd order curvilinear regression (available in Microsoft Excel). Our lab utilises a similar continuous function that was suggested by Hughson [33] and we fit the curve using curve fitting software (Tablecurve 2D). A line is drawn between the two end points of the curve (Figure 11). This line indicates the general direction of change (GD) for the variable of interest. The point on the curve that represents the maximal distance from the curve to the line is "Dmax". Below Dmax points get further and further away from GD and above Dmax points get closer and closer to GD. Thus Dmax is the threshold point. As previously discussed a threshold is always detectable using this technique and it has been shown to be both valid and reliable [41].

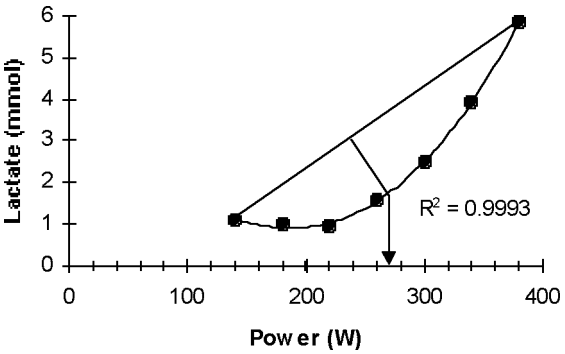


Figure 11: The Dmax method for determining lactate threshold.

Lactate equilibrium

This is a novel approach to detecting a maximal lactate steady state. It uses both exercise and recovery lactate data, and therefore takes into account individual differences in muscle-blood lactate kinetics. It is also possible to measure both VO_2max and lactate threshold using this protocol.

The original protocol was designed by Tegtbur et al. [46] for use on an athletics track. Subjects initially must generate large amounts of lactic acid in their muscles. This is achieved by having the subject perform two successive exhaustive runs with 1 minute recovery bouts between them. Tegtbur et al. [46] used a 300 m run followed by a 200 m run in elite runners and two 200 m runs in basketball players. The end result of either protocol is significant lactic acidosis with values in the range of 14 mmol/L. Our lab has used a rapid incremental VO_2max test as the initial stimulus to generate high amounts of lactic acid. Following the initial exhaustive exercise bouts subjects perform light activity for approximately 8 minutes (walking or cycling at approximately 50W). A blood lactate sample is taken at 7 minutes of recovery and then subjects are exposed to a further incremental lactate threshold type test. Tegtbur et al. [46] used an initial speed of 3.00 m/s for basketball players and increased velocity by 0.33 m/s every step. He concluded that 400 m increments were too short but 800 m or 1200 m increments allowed sufficient time for the attainment of a steady state blood lactate. We have used 4 minute increments of 40 W on the cycle ergometer or 1 km/hr on the treadmill in our lab successfully. Over the course of the first few workload increments blood lactate drops as it is cleared from the muscle. Eventually blood lactate begins to increase again due to lactate production exceeding clearance. The point at which the lactate concentration bottoms out is defined as the lactate minimum or lactate equilibrium, since lactate production should equal lactate clearance at this point (Figure 12). It has been shown to be strongly related to maximal lactate steady state . An advantage of this technique is that glycogen depletion does not move the intensity at which lactate minimum occurs [46].

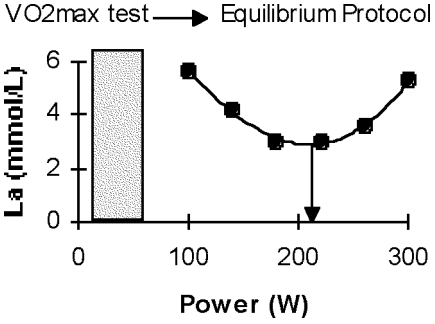


Figure 12: The lactate equilibrium method for determining lactate threshold.

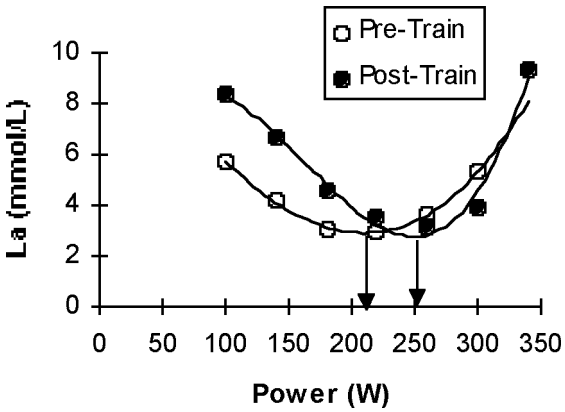


Figure 13: A right shift in the lactate curve (lactate equilibrium method) after 3 weeks of aerobic base training in a cyclist returning from a recovery phase.

Interpretation

The information obtained from a ventilatory or lactate threshold test may be used to track aerobic fitness changes and set appropriate aerobic training intensities. With an improvement in aerobic fitness both lactate and ventilatory threshold will shift to a higher exercise intensity (Figure 13). Using a lactate curve as an example, the shift to the right with training indicates that the athlete is physiologically capable of working at a higher exercise intensity before accumulating lactic acid in the blood.

Threshold values can also be expressed as a percentage of VO_2max. This indicates the fraction of an athletes VO_2max that can be sustained for prolonged periods of time (fractional utilisation of VO_2max). Novice or inexperienced athletes will have threshold values at a much lower percentage of VO_2max. Research has shown that this measure accounts for a large amount of variance in endurance performance and may also help gauge the potential of the athlete to improve their threshold [13, 36]. For example, when comparing novice and elite cyclists who have identical VO_2max values, the lactate threshold may be achieved at 65% and 85% of VO_2max respectively. Therefore the elite rider can perform at a higher intensity despite both riders possessing identical maximum aerobic power. The novice rider has the greatest potential to improve lactate threshold however.

Exercise mode and the amount of muscle mass recruited during exercise can influence the percent of VO_2max that threshold occurs at. In athletes using a large muscle mass, threshold will usually occur at a higher percentage of VO_2max. Therefore, when undertaking threshold testing it is advisable to be aware of the approximate percentage of VO_2max at which threshold will occur. Table 1 suggests some values our lab has observed in different exercise modes for lactate threshold testing.

Table 1: The percentage of VO_2max at which lactate threshold occurs in running, cycling and swimming.

Sport	**Athlete calibre**		
	Novice	***Good***	***Elite***
Running	70	80	>90
Cycling	65	75	>80
Swimming	60	65	>70

Coyle [2] has recently reported that fractional utilisation of VO_2max in cycling may be related to the amount of muscle mass the cyclist is able to recruit. His calculations suggest that experienced cyclists were spreading the power production required for pedalling across approximately 22% more muscle mass than inexperienced cyclists and also had lactate thresholds approximately 24% higher. He hypothesises that with a larger amount of muscle mass to share in the power output, the muscle fibres that are active maintain a lower relative work rate and have a reduced energy requirement for any given power output. Therefore, technique improvement may be a non-physiological mechanism for improving fractional utilisation of VO_2max.

The intensity associated with threshold is also a key training variable. Since lactate and ventilatory threshold represents a maximal intensity that can be sustained for extended duration's without fatigue and lactic acidosis, many exercise physiologists and coaches utilise the heart rate or training pace associated with this index as a key factor in setting training intensities for aerobic development. By training around threshold intensity, fractional utilisation of VO_2max will continue to improve, long after improvements in VO_2max have reached a plateau.

Summary

Mechanisms for both ventilatory and lactate thresholds remain unclear but their utility as a tool for the exercise scientist is undisputed. Both threshold measures have been shown to be related to endurance performance and are more sensitive than VO_2max for the longitudinal monitoring of the endurance athlete. Numerous methods are available for the detection of threshold intensities from an incremental exercise test. The choice of test protocol and threshold detection method are highly individual and should be selected based on objectivity, practicality and fit with other components of a testing battery. As with all physiological testing strict adherence to protocol guidelines and similar equipment should be utilised for test-retest in the longitudinal monitoring of the athlete.

Economy

Economy of movement has been defined by numerous researchers as the oxygen cost of exercising at a standard, pre-determined velocity or power [54-56]. A more economic athlete uses less energy than their less economic counterpart at a standard velocity or power and theoretically is therefore able to move faster or conserve energy for the later stages of an event. Economy has been shown to account for large amounts of variation in 10 km race performance of highly experienced runners with homogenous VO_2max values [57] and others have also shown a significant relationship between running economy and marathon performance [58]. Some researchers have not reported such a relationship between running economy and endurance performance [59, 60], and it has been suggested that homogeneity in running economy may be a factor. Economy has also been shown to be an important determinant of endurance swimming and cycling performance in athletes of heterogeneous ability [2, 61, 62].

Economy has generally been expressed using standard oxygen consumption units (VO_2 expressed as $ml \cdot kg^{-1} \cdot min^{-1}$) but it has recently been shown that the oxygen cost of running does not increase proportionally with body mass, and it may be more valid to express submaximal VO_2 relative to a 3/4 power function of body mass [63]. Expressing running economy as a standard VO_2 also makes comparisons between studies and between laboratories difficult when economy is assessed at different submaximal speeds. Other approaches quantify submaximal steady state aerobic demand at a number of speeds and then calculate the slope of the VO_2-velocity relationship [62] or divide VO_2 by velocity at any given submaximal speed[56]. These methods both provide economy measures in $ml \cdot kg^{-1} \cdot km^{-1}$ or $ml \cdot kg^{-0.75} \cdot km^{-1}$ ($ml \cdot kg^{-1} \cdot m^{-1}$ for swimming) and allow economy comparisons to be achieved between studies and laboratories more readily. It is possible however that a runners economy may change with exercise intensity (% VO_2 max), therefore it has been suggested that running economy

should be assessed at similar relative intensities [56]. In a competitive situation runners are not matched by relative intensities, rather they must compete at identical velocities of running. The argument can therefore be made that the absolute cost of running a given velocity may be the most useful measure of economy for predicting performance. It seems then that there is justification for expressing economy at both relative and absolute velocities and it would be prudent to account for the non-proportional increase in VO_2 with body mass.

Body mass also influences swimming economy since hydrodynamics are influenced by body size. Many early studies presented oxygen cost of swimming data in absolute terms (L/min) because it was widely accepted that the buoyancy forces of water supported body mass. This is a gross over-simplification since body composition, height, weight and surface area all contribute to drag and swimming economy [62]. The best method of factoring out the influence of body size on economy appears to be expressing the data as oxygen cost per unit body mass per metre swum (ml/kg/m) [64].

Measurement protocols

The measurement of economy of movement requires the same open-circuit spirometry set-up as that used for VO_2max testing. Subjects generally exercise on an appropriate ergometer while wearing a noseclip and a mouthpiece equipped with one-way valves. The athlete must be sufficiently accustomed to exercising on the ergometer in order for economy data to be accurate. For example it is recommended that for treadmill exercise between 10-60 minutes of treadmill accommodation are required [65]. Our lab utilises three sessions of fifteen minutes submaximal running for treadmill accommodation. If economy testing is performed prior to this then the VO_2 values may be artificially elevated due to a lack of coordination and the recruitment of extra muscle mass. Similarly, experience testing in the swim flume suggests approximately 20 minutes of familiarisation is required before economy testing swimmers. A standardised warm-up of approximately 15 minutes is also recommended to ensure that the aerobic system is primed and fully recruited during economy testing. It must also be ensured that the subjects are evaluated at the same time of day, footwear and other equipment (eg. cycling cleats) are standardised and the subjects are well rested.

Continuous versus discontinuous protocols

Continuous step protocols are commonly utilised to assess economy at a number of sub-maximal velocities in running. Some labs ask athletes to return on different occasions 3 or 4 times in order to assess economy at a range of velocities and avoid the accumulation of fatigue over a long session. We generally perform economy assessments over 3 or 4 velocities in one session to avoid the inconvenience of athletes having to visit the lab on several occasions. This approach has been shown to be reliable as long as there is adequate control over the range of extraneous variables that can influence economy [66]. For the assessment of swimming economy we use a discontinuous protocol and also test swimmers over 3 to 4 sub-maximal velocities.

Stage increments and durations

It is important that exercise intensities are below anaerobic threshold intensity, since the increased anaerobic contribution to energy supply above this intensity can artificially lower oxygen cost and economy will appear better than it actually may be. The absolute velocities chosen depend on the fitness and skill level of the athlete being tested Stage duration needs to be long enough for athletes to reach an aerobic steady state so that oxygen consumption equals oxygen demand. Once VO_2, Ve and R have stabilised for at least a minute then steady-state has most likely been achieved. In well trained athletes 4 minute stages may be sufficient but less fit athletes may require stages as long as 8 minutes to reach steady state. We have routinely used 5 minute stages in both running and swimming with success.

Sample intervals

Oxygen cost is usually calculated from the last minute or two of a stage. As an example, if a runner has been running at 14 km/h for 5 minutes, the average oxygen consumption between minutes 4 and 5 is used to estimate economy at that velocity. In some cases, if steady state has been achieved early then the last 2 minutes of oxygen consumption data may provide an even better representation of economy.

Interpretation

Economy of movement in running and swimming may vary by up to 25% [2, 56, 67] and it is important that once economy has been assessed appropriate feedback is provided to the athlete and coach. In particular, some classification of "good" or "poor" economy is usually requested. Since procedures and absolute VO_2 values may vary slightly from lab to lab it is useful for laboratories to formulate a database that can be used to help with interpretation. Some economy values extracted from the literature that may aid in interpretation are also shown in Table 2.

Table 2: Typical economy values for freestyle swimming and running reported in the scientific literature.

Classification	Swimming at 1.0 -1.2 m/s (VO_2: ml/kg/m)	Treadmill running (VO_2: ml/kg/km)
Poor	0.75	202.2
Average	0.60	190.5
Good	0.45	181.9

Economy may be related to a number of factors including skill and technique, training status and years experience, percentage of Type I fibre composition and psychological state. In running and cycling very little success has been reported in improving economy through technique training although this may be a successful strategy for uneconomical swimmers. Recently, our lab has demonstrated that training runners in relaxation and biofeedback strategies effectively improved economy by on average 5% [68] and the effect of psychophysiological strategies certainly deserves more attention. Years of training experience also appears to be a key variable for improving running economy [56], a variable that is resistant to change. Little research has been reported on successful strategies for improving economy in other modes of exercise.

Summary

Economy of movement is an important determinant of endurance performance and can vary by up to 20% between athletes exercising at the same intensity. Numerous factors can influence the submaximal oxygen cost of exercise and these factors must be carefully controlled to ensure valid economy measures are obtained. The economy of movement is a difficult variable to improve and seems to be most strongly related to years of training experience. Technique training may improve swimming economy and there is some recent evidence suggesting that relaxation and biofeedback strategies may help improve running economy. Further research is required to refine existing strategies and develop new approaches for improving economy of movement in a variety of exercise modes.

Reference material

1. Hill, A.V. and H. Lupton, *Muscular exercise, lactic acid, and the supply and utilization of oxygen.* Quarterly Journal of Medicine, 1923. **16**: p. 135-171.
2. Coyle, E.F., *Integration of the physiological factors determining endurance performance ability*, in *Exercise and Sport Sciences Reviews*, J.O. Holloszy, Editor. 1995, Williams and Wilkins: Baltimore. p. 25-63.
3. Bassett. Jr, D.R., Howley, E.T., *Maximal oxygen uptake: "classical" versus "contemporary" viewpoints.* Medicine and Science in Sports and Exercise, 1997. **29**(5): p. 591-603.
4. Green, H.P., A.E., *Maximal aerobic power: neuromuscular and metabolic consideration.* Medicine and Science in Sports and Exercise, 1992. 24(1): p. 38-46.
5. Honig, C.R., Connett, R.J. , Gayeski, T.E.J., *O2 transport and its interaction with metabolism; a systems view of aerobic capacity.* Medicine and Science in Sports and Exercise, 1992. 24(1): p. 47-53.
6. Saltin, B., Strange, S., *Maximal oxygen uptake: "old" and "new" arguments for a cardiovascular limitation.* Medicine and Science in Sports and Exercise, 1992. 24(1): p. 30-37.
7. Secher, N.H., Clausen, J.P., Klausen, K, Noer, I., Trapjensen, J., *Central and regional circulatory effects of adding arm exercise to leg exercise.* Acta Physiologica Scandinavica, 1979. **100**: p. 288-297.
8. Saltin, B., *Hemodynamic adaptations to exercise.* American Journal of Cardiology, 1985. **55**: p. 42D-47D.
9. Powers, S.K., Lawler, J., Dempsey, J.A., Dodd, S., Landry, G., *Effects of incomplete pulmonary gas exchange on VO_2max.* Journal of Applied Physiology, 1989. **66**: p. 2491-2495.
10. Spriet, L., *et al.*, *Effect of graded erythrocythemia on cardiovascular and metabolic responses to exercise.* Journal of Applied Physiology, 1986. **61**(5): p. 1942-1948.
11. Ekblom, B., A.N. Goldbarg, and B. Gullbring, *Response to exercise after blood loss and reinfusion.* Journal of Applied Physiology, 1972. **33**: p. 175-180.
12. Karlsson, J., Saltin, B., *Diet, muscle glycogen and endurance performance.* Journal of Applied Physiology, 1971. **31**(2): p. 203-206.
13. Costill, D.L., H. Thomason, and E. Roberts, *Fractional utilisation of aerobic capacity during distance running.* Medicine and Science in Sports, 1973. **5**: p. 248-252.
14. Davis, J.A., *Direct determination of aerobic power*, in *Physiological assessment of human fitness*, P.J.F. Maud, C., Editor. 1995, Human Kinetics: Champaign. p. 9-17.
15. McArdle, W.D., Katch, F.I., Katch, V.L., *Exercise physiology: energy, nutrition and human performance*. 4 ed. 1996, Baltimore: Williams and Wilkins. 849.
16. Thoden, J.S., *Testing aerobic power*, in *Physiological testing of the high performance athlete*, J.D. MacDougall, Wenger, H.A. and Green, H.J., Editor. 1991, Human Kinetics: Champaigne. p. 107-173.
17. Foss, M.L.K., S.J., *Fox's physiological basis for exercise and sport*. 6 ed. 1998, Boston: WCB McGraw Hill.

18. Davis, J.A. and F.W. Kasch, *Aerobic and anaerobic differences between maximal running and cycling in middle aged males.* Australian Journal of Sports Medicine, 1975. **7**: p. 81-84.
19. Magel, J.R.F., J.A., *Maximum oxygen uptake of college swimmers.* Journal of Applied Physiology, 1967. **22**: p. 929.
20. McArdle, W.D., Katch, F.I. and Pechar, G.S., *Comparison of continuous and discontinuous treadmill and bicycle tests for max VO_2.* Medicine and Science in Sports, 1973. **5**: p. 156-160.
21. Buchfuhrer, M.J., Hansen, J.E., Robinson, T.E., Sue, D.Y., Wasserman, K. and Whipp, B.J., *Optimizing the exercise protocol for cardiopulmonary assessment.* Journal of Applied Physiology, 1983. **55**: p. 558-564.
22. Myers, J., *et al.*, *Effect of sampling on variability and plateau in oxygen uptake.* Journal of Applied Physiology, 1984. **68**: p. 404-410.
23. Hill, A.V., C.N.H. Long, and H. Lupton, *Muscular exercise, lactic acid and the supply utilisation of oxygen-parts VII-VIII.* Proceedings of the Royal Society of Britain, 1924. **97**: p. 84-138.
24. Astrand, I., P.-O. Astrand, and K. Rodahl, *Maximal heart rate during work in older men.* Journal of Applied Physiology, 1959. **14**: p. 562-566.
25. Huijjing, P.A., H.M. Toiussant, and R.E.A. Mackay, *Active drag related to body dimensions*, in *Swimming Science V*, B.E. Ungerechts, K. Wilke, and K. Reischle, Editors. 1988, Human Kinetics: Champaigne. p. 219-227.
26. Sleivert, G., and Wenger H.A., *Physiological predictors of short-course triathlon performance.* Medicine and Science in Sports and Exercise, 1993. **25**(7): p. 871-876.
27. Vanderburgh, P.M. and F.I. Katch, *Ratio scaling of VO2max penalizes women with larger percent body fat, not lean body mass.* Medicine and Science in Sports and Exercise, 1996. **28**(9): p. 1204-1208.
28. Bouchard, C., *Genetic determinants of endurance performance*, in *Endurance in Sport*, R.J. Shepard and P.-O. Astrand, Editors. 1992, Blackwell Scientific Publications: Oxford.
29. Dionne, F.T., *et al.*, *Mitochondrial DNA sequence polymorphism, VO2max, and response to endurance training.* Medicine and Science in Sports and Exercise, 1991. **23**(2): p. 177-185.
30. Klissouras, V., *Heritability of adaptive variation.* Journal of Applied Physiology, 1971. **31**(3): p. 338-344.
31. Wasserman, K. and M.B. McIlroy, *Detecting the threshold of anaerobic metabolism in cardiac patients during exercise.* American Journal of Cardiology, 1964. **14**: p. 844-852.
32. Davis, J.A., *Anaerobic threshold: review of the concept and directions for future research.* Medicine and Science in Sports and Exercise, 1985. **17**(1): p. 6-18.
33. Hughson, R.K., K.H. Weisiger, and G.D. Swanson, *Blood lactate concentration increases as a continuous function in progressive exercise.* Journal of Applied Physiology, 1987. **62**: p. 1975-1981.
34. Brooks, G.A., *Anaerobic threshold: review of the concept and directions for future research.* Medicine and Science in Sports and Exercise, 1985. **17**(1): p. 22-31.

35. Foster, C., M. Schrager, and A.C. Snyder, *Blood lactate and respiratory measurement of the capacity for sustained exercise*, in *Physiological assessment of human fitness*, P.J. Maud and C. Foster, Editors. 1993, Human Kinetics: Champaign. p. 57-72.
36. Sleivert, G. and D. Rowlands, *Physical and physiological factors associated with success in the triathlon.* Sports Medicine, 1996. **22**(1): p. 8-18.
37. Tanaka, K., *et al.*, *A longitudinal assessment of anaerobic threshold and distance running performance.* Medicine and Science in Sports and Exercise, 1984. **16**(3): p. 278-282.
38. Fuchs, F., V. Reddy, and F.N. Briggs, *The interaction of cations with the calcium binding site of troponin.* Biochemical Biophysics Acta, 1970. **221**: p. 407-409.
39. Nakumura, Y. and S. Schwartz, *The influence of hydrogen ion concentration on calcium binding and release by skeletal muscle sarcoplasmic reticulum.* Journal of General Physiology, 1972. **59**: p. 22-32.
40. Beaver, W.L., K. Wasserman, and B.J. Whipp, *A new method for detecting anaerobic threshold by gas exchange.* Journal of Applied Physiology, 1986. **60**(6): p. 2020-2027.
41. Cheng, B., *et al.*, *A new approach for the determination of ventilatory and lactate thresholds.* International Journal of Sports Medicine, 1992. **13**(7): p. 518-522.
42. Wilmore, J.H. and D.L. Costill, *Physiology of Sport and Exercise*. 1994, Champaign: Human Kinetics. 549.
43. Jacobs, I., *Lactate, muscle glycogen and exercise performance in man.* Acta Physiologica Scandinavica, 1981. **Suppl. 495**: p. 1-35.
44. Green, H.J., *et al.*, *Anaerobic threshold, blood lactate and muscle metabolites in progressive exercise.* Journal of Applied Physiology, 1983. **54**: p. 1032-1038.
45. Stegmann, H., W. Kindermann, and A. Schnabel, *Lactate kinetics and individual anaerobic threshold.* International Journal of Sports Medicine, 1981. **3**: p. 105-110.
46. Tegtbur, U., M.W. Busse, and K.L. Braumann, *Estimation of an individual equilibrium between lactate production and catabolism during exercise.* Medicine and Science in Sports and Exercise, 1993. **25**(5): p. 620-627.
47. Stockhausen, W., *et al.*, *Stage duration and increase of work load in incremental testing on a cycle ergometer.* European Journal of Applied Physiology, 1997. **76**: p. 295-301.
48. Heck, H., *et al.*, *Justification of the 4mmol/L lactate threshold.* International Journal of Sports Medicine, 1985. **6**: p. 117-130.
49. Karlsson, J. and I. Jacobs, *Onset of blood lactate accumulation during exercise as a threshold concept: Theoretical considerations.* International Journal of Sports Medicine, 1982. **3**(190-201).
50. Mader, A. and H. Heck, *Theory of the metabolic origin of anaerobic threshold.* International Journal of Sports Medicine, 1986. **7**: p. 45-65.
51. Beneke, R. and S.P. von Duvillard, *Determination of maximal lactate steady state response in selected sports events.* Medicine and Science in Sports and Exercise, 1996. **28**(2): p. 241-246.
52. Maasen, N. and M.W. Busse, *The relationship between lactic acid and workload-a measure for endurance capacity or an indicator of carbohydrate deficiency.* European Journal of Applied Physiology, 1989. **58**: p. 728-737.

53. Coen, B., *et al.*, *Control of training in middle and long distance running by means of the individual anaerobic threshold.* International Journal of Sports Medicine, 1991. **12**: p. 519-524.

54. Daniels, J., *et al.*, *Aerobic responses of female distance runners to submaximal and maximal exercise.* Annals of The New York Academy of Science, 1977. **301**: p. 726-733.

55. Farrell, P., *et al.*, *Plasma lactate accumulation and distance running performance.* Medicine and Science in Sports, 1979. **11**: p. 338-344.

56. Morgan, D., *et al.*, *Variation in the aerobic demand of running among trained and untrained subjects.* Medicine and Science in Sports and Exercise, 1995. **27**(3): p. 404-409.

57. Conley, D.L. and G.S. Krahenbuhl, *Running economy and distance running performance of highly trained athletes.* Medicine and Science in Sports and Exercise, 1980. **12**(5): p. 357-360.

58. Sjodin, B. and J. Svedenhag, *Applied physiology of marathon running.* Sports Medicine, 1985. **2**: p. 83-99.

59. Conley, D.L., G.S. Krahenbuhl, and L.N. Burkett, *Physiological correlates of female road racing performance.* Research Quartely in Exercise and Sport, 1981. **52**: p. 441-448.

60. Bulbalian, R., A.R. Wilcox, and B.L. Darabos, *Anaerobic contribution to distance running performance of trained cross-country athletes.* Medicine and Science in Sports and Exercise, 1986. **18**(1): p. 107-113.

61. Montpetit, R.R., H. Smith, and G. Boie, *Swimming economy: How to standardize the data to compare swimming proficiency.* Journal of Swimming Research, 1988. **4**(1): p. 5-8.

62. Kearney, J.T. and P.J. Van Handel, *Economy: a physiologic perspective*, in *Advances in Sports Medicine and Fitness*, B.J. Sharkey, Editor. 1989, Year Book Medical Publishers: Chicago. p. 57-90.

63. Bergh, U., *et al.*, *The relationship between body mass and oxygen uptake during running in humans.* Medicine and Science in Sports and Exercise, 1991. **23**: p. 205-211.

64. Pendergast, D.R., *et al.*, *Quantitative analysis of the front crawl in men and women.* Journal of Applied Physiology, 1977. **43**: p. 475-479.

65. Morgan, D.W. and M. Craib, *Physiological aspects of running economy.* Medicine and Science in Sports and Exercise, 1992. **24**(2): p. 456-461.

66. Morgan, D., *et al.*, *Variability in running economy and mechanics among trained male runners.* Medicine and Science in Sports and Exercise, 1991. **23**: p. 378-383.

67. Costill, D.L., *et al.*, *Energy expenditure during front crawl swimming: Predicting success in middle distance events.* International Journal of Sports Medicine, 1985. **6**: p. 266-270.

68. Caird, S., A. Mckenzie, and G. Sleivert, *Relaxation and biofeedback strategies improve running economy in recreational runners.* Medicine and Science in Sport and Exercise, In press.