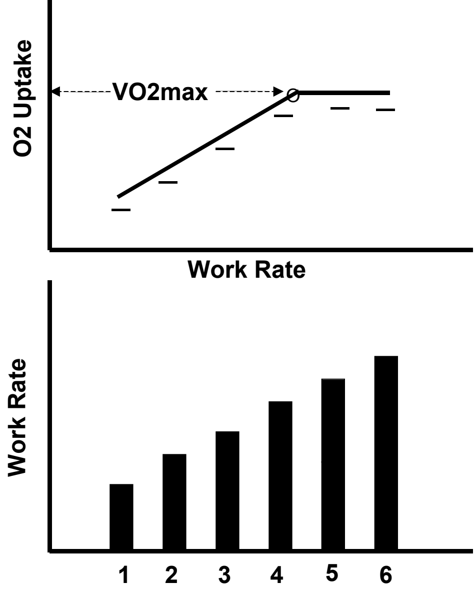
THE PEAK VERSUS MAXIMUM OXYGEN UPTAKE ISSUE

By Professor Brian Whipp

The terms peak and maximum oxygen uptake ($V'O_2$ peak and $V'O_2$ max, respectively) are often used as though they are synonymous. But there are important distinctions to be made between them. While the $V'O_2$ peak is the easier to define and determine, its relevance to physiological and patho-physiological functioning is less secure. It is, simply, the highest value of $V'O_2$ attained on the particular test, most commonly an incremental or other high-intensity test, designed to bring the subject to the limit of tolerance – neglecting, for the moment, considerations of what time, or breath-number, frame of reference is chosen for the determination. Unfortunately, it is the highest value achieved regardless of the subject's effort. And so while it defines the highest $V'O_2$ that was *attained* during the test it does not necessarily define the highest $V'O_2$ *attainable* by the subject. The latter value is termed the $V'O_2$ max and its rigorous determination depends on a particular criterion having being met. This being the demonstration that $V'O_2$ does not continue to increase, or only to increase by a trivially-small amount, despite further increases in work rate (WR) "involving a large proportion of the muscle mass" i.e. a $V'O_2$ "plateau" results when $V'O_2$ is plotted as a function of work rate.

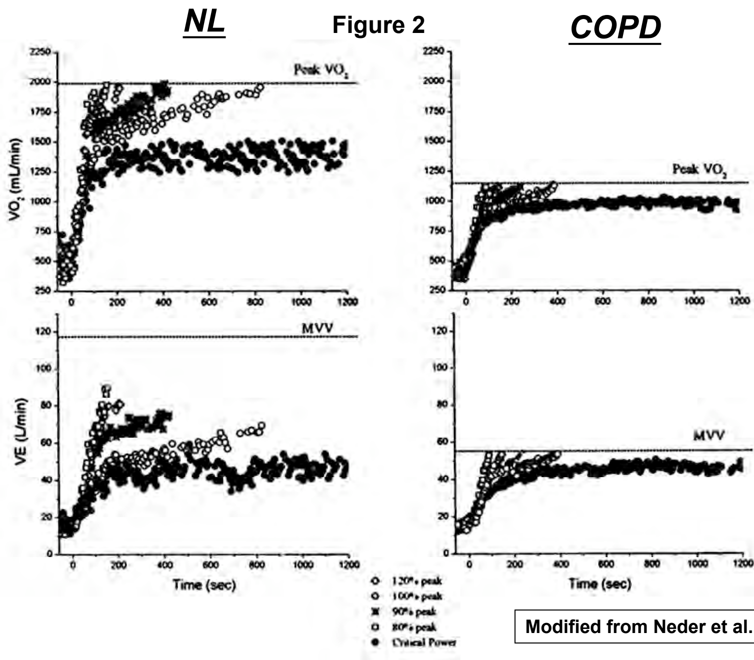
As originally designed in the 1950's the determination of the $V'O_2$ max utilised a series of non-continuous, progressively-increasing, constant-work-rate tests performed on separate days, or at different times of the day. Naturally the range of work rates that can be utilised by the investigator, and their consequent O_2 demands, is greater than the body's ability to transport and utilise the necessary oxygen. And so, when the tests are performed with this format, a plateau becomes apparent in every subject, as schematised in Figure 1

Figure 1



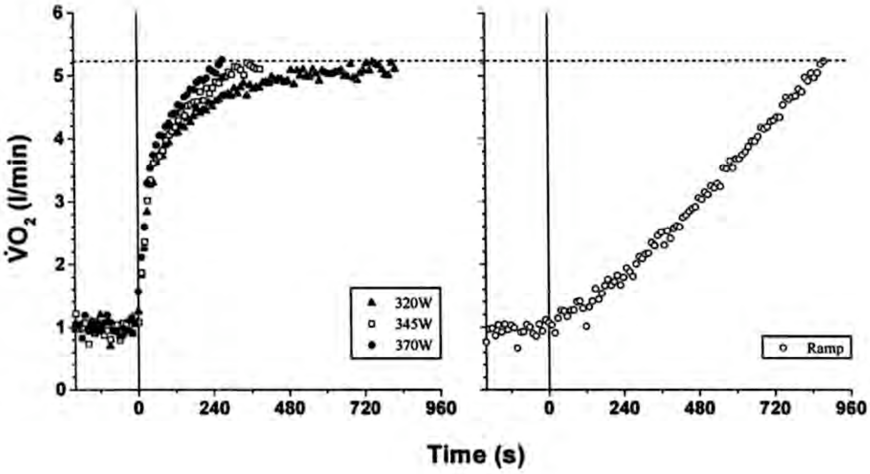
and demonstrated experimentally in Figs 2 and 3.

Figure 2



Modified from Neder et al., 2000

Figure 3



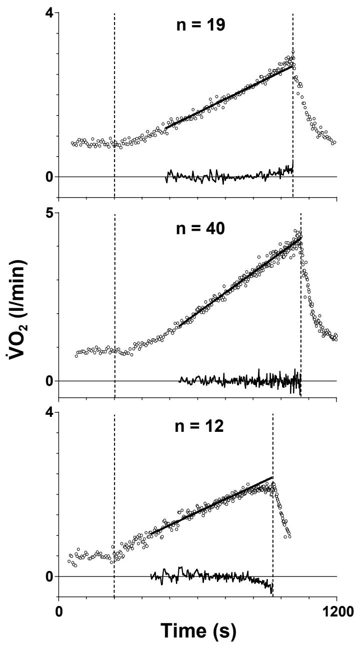
While the demonstrable plateauing of the V'O_2 justifies the use of the term V'O_2 max. it should be noted that were the subject in Fig 1 to have ended the test at the work rate and V'O_2 depicted by the open symbol then the value should only be characterized as the V'O_2 peak – despite, in this case, actually being the subjects V'O_2 max. But of course the investigator doesn't know this without the subsequent supporting criterion of the plateau.

As stated above, the presence of a V'O_2 "plateau" requires a demonstration that the V'O_2 *not* continue to increase, or only to increase by *a trivially-small amount*, despite further increases in WR. But what constitutes an appropriate criterion of the V'O_2 as a "trivially-small amount"? Naturally this depends on the expected increase over the work rate increment. As originally proposed by Taylor et al., in order to meet the criterion of a V'O_2 max the V'O_2 was stipulated not to increase by more than 2.1 ml/kg/min, or approximately 150 ml/min for a "typical" subject. But this was for an increment of 2.5% on the treadmill at a speed of 7 mph – clearly not relevant for clinical exercise testing. This value was slightly different in the subsequent study of Mitchell et al., but these authors used the lower speed of 6 mph. In both cases, however, the “trivially-small” criterion amounted to approximately 50% of the *expected* increase in $V'O_2$ for that work rate increment. Unfortunately, the 150 ml/min criterion somehow became commonplace as a criterion of adequacy for justifying that a $V'O_2$ max had been obtained, independent of the work rate increment over which it was determined – even, in many instances, when that work rate increment actually required a $V'O_2$ of less than 150 ml/min. The original, and importantly experimentally determined, value of less than 50% of the expected increase in $V'O_2$ for that work rate increment can therefore be considered appropriate as an adequate criterion that a $V'O_2$ max has been obtained. But while this can apparently be justified independent of the work-rate profile it is most appropriately applied to incremental testing. To meet that criterion for a single constant-load test the investigator would have to discriminate the 50% discrepancy in the expected kinetic profile of the $V'O_2$ response in the final period of the test; there is, to date, no general agreement of what that is for different subjects performing very heavy exercise to the limit of tolerance. The issue can be resolved with a series of additional tests, where the plateau criterion for establishing the subject’s $V'O_2$ max is met *between* tests - whether or not there was a demonstrable plateau *within* a test e.g. Figs 2 and 3 (left panel). But note that, as shown in the right panel of Fig 3, the same and limiting value of $V'O_2$ resulting from a single ramp-incremental protocol should only be reported as the subject’s $V'O_2$ peak.

The issue of “involving a large proportion of the muscle mass” also justifies consideration. Using the multi constant work rate format described above the V'O_2 plateau achieved for arm exercise will be appreciably less than for leg exercise and will be less using conventional cycle compared with treadmill ergometry. And if arm exercise is added to leg exercise the V'O_2 max can be even greater – as demonstrated in the classic 1955 study by Taylor et al. And so, even with a demonstrable plateau of V'O_2 the consequent V'O_2 max may not be that of "the body" but rather of the muscle mass recruited to perform the task – unless, of course adding the additional arm work does not further increase the maximum value obtained in the limiting leg test. This has been shown to be the case in some highly elite endurance athletes.

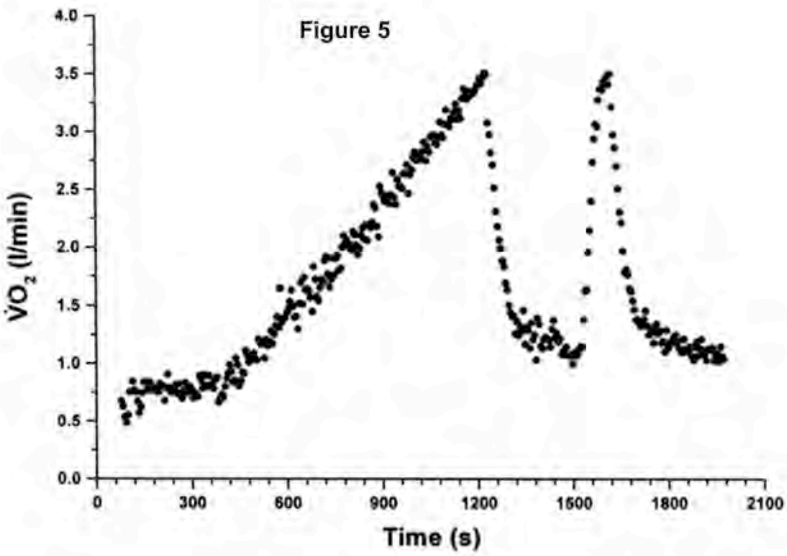
During the more clinically relevant ramp-type cycle ergometer exercise, it has been reported that plateaus of V'O_2 are evident in only a small fraction of normal subjects as shown in Fig 4.

Figure 4



But with sufficiently good effort the final value attained on the ramp, even without plateauing, does not differ significantly from that attained with the demonstrable plateau criterion from a series of high intensity constant load tests (see, for example, Figs 2 and 3). This has recently supported in a large group of subjects by Snell et al. – although in this instance the authors did report a consistent plateauing of V'O_2 in their subjects. These, however, were highly trained distance runners undergoing a treadmill exercise protocol that utilized 2.5% increases in grade each 2 mins at running speeds of 9 mph for men and 8 mph – an unlikely protocol for clinical exercise testing.

In those instances in which the investigator has chosen the ramp protocol (for the wide range of additional physiologically-relevant information it provides) and there is concern that a sufficiently discernable plateau of V'O_2 is evident at the limit of tolerance then performing a subsequent constant work rate test, after a short recovery period e.g. 5 mins, at a work rate slightly higher than that attained on the ramp can provide incontrovertible evidence of the V'O_2 max, as shown in Fig. 5.

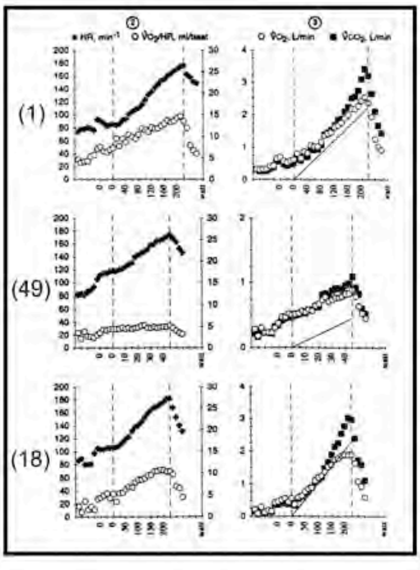


This, however, has been shown to be the case in normal subjects; whether this physically challenging protocol is appropriate to patient populations is another matter.

The $V'O_2$ "plateau" value that is achieved is taken to reflect the attainment of a limitation at some point(s) in the O_2 conductance pathway from the lungs to the site of the mitochondrial O_2 consumption - the convective flows of O_2 into the lungs and through the vasculature, and the diffusive O_2 flows across the pulmonary and muscle capillary beds. In normal subjects this is thought to be determined by a limit being reached in the cardiac output – at least for *large* muscle group dynamic exercise. But, of course, this is not necessarily the case in patients with impaired systemic functioning i.e. where "premature" termination of the test is a consequence of unusually potent perceptual influences, such as dyspnea, angina or claudicating pain. This may, therefore, reflect as good an effort as that given by subject who does attain a $V'O_2$ "plateau"; just that the source of the limiting perception differs. But again, without wishing to belabor the point, the investigator doesn't (in fact cannot) know that this is the case without supporting criteria.

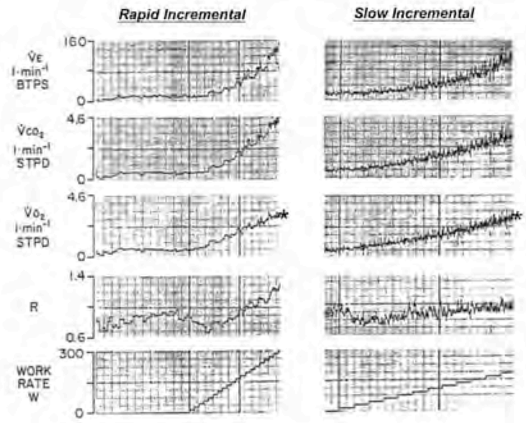
In an effort to circumvent the problem of whether the subject gave sufficiently-good effort other, presumably corroborative, indices of have been utilized. These include: a maximum heart rate of more than 90% predicted; a respiratory exchange ratio greater than 1.15; and a peak post-exercise lactate of greater than 8mM. Clearly, none of these provide adequate assurance that the subject actually gave a maximum effort, even in normal subjects, because: in the first instance the predicted maximum heart rate has a standard deviation of approximately 10 beats per minute; in the second the maximum respiratory exchange ratio (R) is highly work-rate profile dependent: and in the third many subjects achieve peak post-exercise lactates that are appreciably greater than 8mM. Furthermore, in those subjects with chronic obstructive lung disease none of these criteria typically are approached even when the subject gives his/her maximum effort. For example, the clear evidence of the $V'O_2$ plateau exemplified by the patient with chronic obstructive lung disease in the right panel of Fig. 2 is consistent with a pulmonary-mechanical determinant of $V'O_2$ max rather than a cardiovascular, and particularly cardiac output, limitation. The peak heart rate is typically low at the limit of tolerance (as is peak lactate and R); the normal-to-high heart rate at a given sub-maximal $V'O_2$ being inconsistent with chronotropic incompetence being the cause. As in normal subjects, a plateau in the $V'O_2$ response to ramp-type incremental test is not consistently seen in patients with pulmonary-mechanical abnormalities; it is much more common in patients with cardio-vascular disease (see Fig 6).

Figure 6



We mentioned above that maximum respiratory exchange ratio (R) is a poor index of subject effort as it is, unlike V'O_2, highly work-rate profile dependent (see Fig. 7).

Figure 7



This is because the *rate* at which CO_2 is produced from the bicarbonate-linked proton buffering (associated with the increased lactate ions) is a function of the *rate* of the bicarbonate decrease i.e. molecules of CO_2 per unit time being the yield from molecules of bicarbonate change per unit time. And as the bicarbonate decreases more rapidly during faster incremental tests the CO_2 yield is greater. But not only is maximum R highly work-rate profile dependent but so is maximum work rate (Fig. 7). The consequence is that care should be taken in assigning a constant work rate test as a fraction of the maximum work rate attained on a ramp test.

The normalcy (or otherwise) of the V'O_2 max or peak should considered with respect to the subject's age, gender, height and body mass. Although it is most common to normalize the V'O_2 for body mass (ml/min/kg) there are advantages to normalizing to whole-body (or even leg) fat-free mass, especially perhaps in obese subjects or those with muscle wasting (e.g. subjects with COPD or the frail elderly) – or even scaling to the subject's height rather than weight. The normal value for $V'O_2$ max or peak in young healthy adults is averages approximately 30-40 ml/min/kg; this, however, is typically considerably lower in chronically sedentary or elderly subjects but in elite endurance athletes it can exceed 80 ml/min/kg]. It has also been demonstrated that the mass-specific $V'O_2$ max is higher in small than in large subjects - suggesting that $V'O_2$ max scaled to $mass^{0.67}$ is more appropriate. This is not currently in widespread use, however, and its value and benefits for clinical exercise testing remains to be determined.

While the conventional mass-specific $V'O_2$ peak values of less than 14 ml/min/kg has been shown to be reflective of poor prognosis for patients with chronic heart failure (with the value also being used as a discriminator of the appropriateness of a subject to undergo cardiac transplantation and other major surgery) there must be some doubt as to the extent to which the $V'O_2$ peak achieved really is indicative of maximum effort either given by the subject or demanded by the investigator. But perhaps the value is useful in being reflective of the "real" peak $V'O_2$ being "at least that". The lactate threshold in contrast, either determined from appropriate blood sampling or estimated from pulmonary gas exchange indices, is not effort dependent in this sense. It may therefore prove to be a "firmer" index of the functional status of the subject.