Understanding the Ventilation Threshold

Historically, the blood lactate response to incremental or multiple bouts of steady state exercise was used to detect the change in muscle metabolism from steady state to non-steady state exercise. This transition, or threshold change in metabolism, has been repeatedly shown to be a major determinant of endurance exercise performance. The higher this metabolic threshold (expressed as exercise intensity or absolute VO_2), the faster an endurance athlete can complete a given distance event. A large volume of research has shown that measures obtained from expired gas analysis indirect calorimetry are equally as sensitive, and perhaps more sensitive, to detecting this metabolic threshold than blood lactate. If you think about for a bit, this makes sense. We can now collect respiratory-based data of whole body metabolism every breath, and therefore have high temporal precision in the capability to detect a response such as a change in pulmonary indices of muscle metabolism. When the added benefits from respiratory measures being non-invasive and immediate display on the computer screen during the exercise test are also considered, it is logical that ventilation measures of the metabolic threshold are now the preferred method.

Figure 1 shows the breath-by-breath **expired ventilation** (V_E) response to **incremental exercise**. The exercise intensity coincident with the initial break point or deviation select pulmonary variables to increasing exercise intensity is termed the **ventilation threshold** (VT). The data of Figure 1 show three clear linear segmental responses. The first segment occurs between approximately 5 to 9.3 min, the second from 9.3 to 10.9 min, and third is the remainder of the test data. As will be explained in this Topic, threshold changes in ventilation are not as easily observed in some subjects, and there are more sensitive variables that can be used to detect the VT.

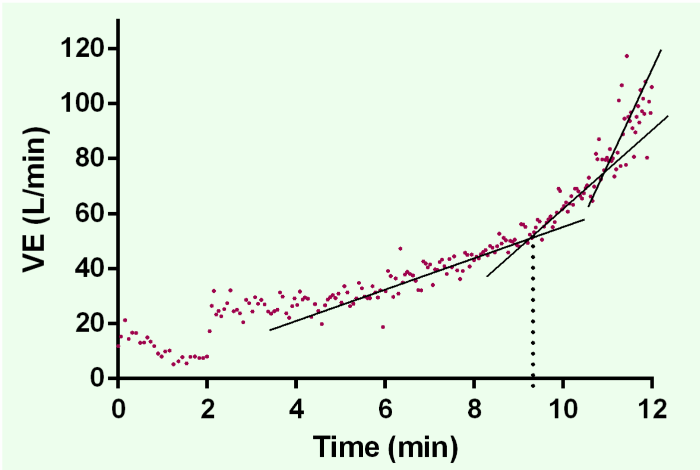
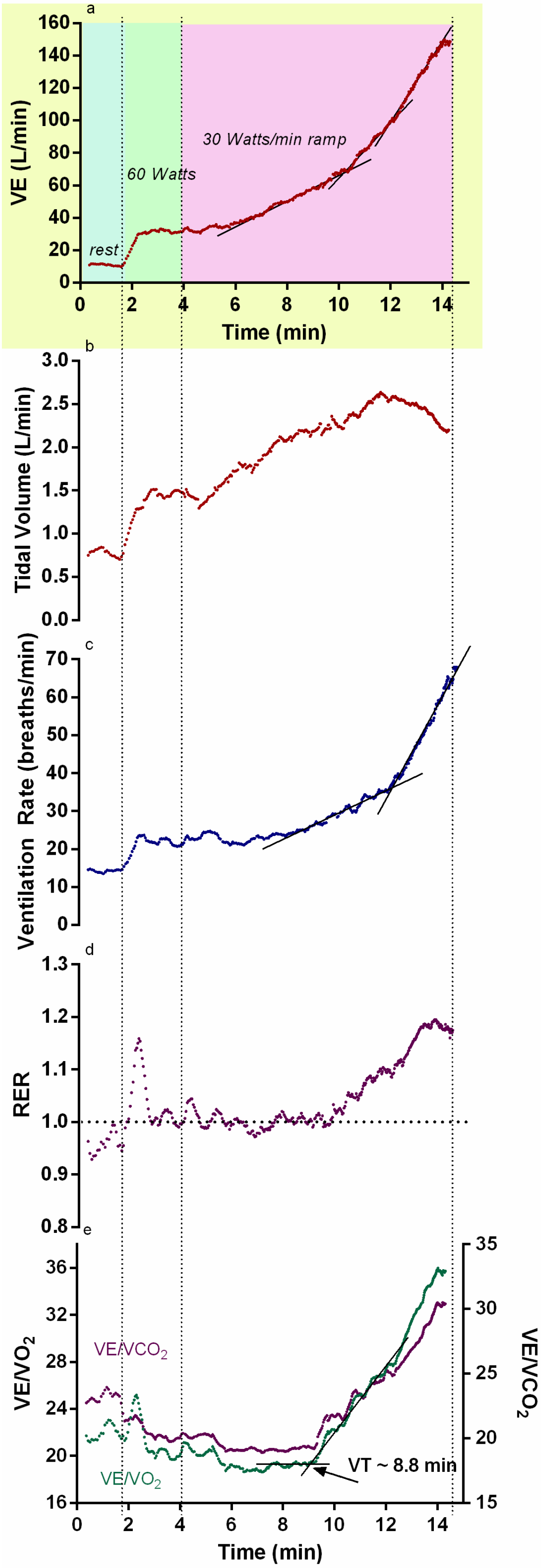


Figure 1. The ventilation response to 2 min of rest followed by a 35 Watt/min ramp protocol in a highly endurance trained male cyclist.

The Ventilatory Equivalents

Figure 2 is a stack plot of the main variables (V_E, **tidal volume** (Vtidal), ventilation rate, RER and V_E/VO_2 and V_E/VCO_2) that show the VT response during a cycle ergometer **ramp protocol** for a highly endurance trained subject (different subject to Figure 1). The data have been processed with a 7 breath average. You will notice that all variables show a deviation from linearity, but all at very different intensities. This data set is a classic example of the inability for ventilation alone to detect the VT. Let's review each variable to assess the physiology occurring during incremental exercise.



Tidal volume increases abruptly at the start of exercise. In other words, our depth of breathing increases rapidly during exercise, and far more so than the rate of ventilation. In fact, there is very little increase in the rate of ventilation once exercise has started between 2.5 and 8 min! After 8 min, both tidal volume and the rate of ventilation increase. At close to 12 min, there is a tremendous change with the rate of ventilation increasing precipitously, causing decreases in tidal volume. However, the combined rate and depth of ventilation continue to cause a rapid increase in ventilation in these last minutes of incremental exercise.

The variable that most clearly detects the deviation in V_E from VO_2 is the variable V_E/VO_2. Both **VE/VO_2** and **VE/VCO_2** are called **ventilatory equivalents**, with each one being termed the ventilatory equivalent for oxygen (V_E/VO_2) and carbon dioxide (V_E/VCO_2), respectively. As indicated by the abbreviations, the ventilatory equivalents are simple ratios of expired ventilation to either of VO_2 and VCO_2.

It is important you understand why V_E/VO_2 is the superior variable for detecting the VT, and why V_E/VCO_2 lags behind in this detection by anywhere from 1 to 3 min. First of all, we know that for most subjects, the VO_2 response is mostly linear to near the end of an incremental protocol. Depending on the subject, VO_2 can then either level off, such as in a true plateau response, remain linear, or actually begin

Figure 2. A stack plot of the main variables of interest to the ventilation threshold (VT). a) expired ventilation (VE), b) tidal volume, c) ventilation rate, d) the respiratory exchange ratio (RER), and e) the ventilatory equivalents for oxygen (VE/VO_2) and carbon dioxide (VE/VO_2).

to increase at a greater rate. However, such deflections in the VO_2-time or VO_2-intensity profile occur near the end of the protocol. Thus, as a metabolic threshold occurs anywhere from 60 to 90% of the VO_2max, most thresholds occur in the linear region of the VO_2-time curve. Thus, if VO_2 is increasing linearly, and V_E initially remains linear, then the ratio between VO_2 and V_E should remain at a near constant value. As V_E begins to increase more abruptly, deviating from this linear profile, yet VO_2 continues on a linear profile, then the ratio between the two (V_E/VO_2) will start to increase. This then defines the onset of the VT, where there is the first sustained increase in V_E/VO_2.

Why does V_E/VO_2 decrease during the early phase of an incremental protocol? This occurs due to the exaggerated initial ventilatory response to exercise. Figure 1 presented the VE data for an incremental exercise test. The ventilation occurring during the first 2 min is at rest and is a profound **hyperventilation**, most likely due to increasing anxiety prior to the start of the exercise protocol. As VO_2 is low at rest, regardless of anxiety, the net result is to increase the V_E/VO_2 variable. The commencement of exercise sees a further increase in ventilation, but as VO_2 now starts to increase, the V_E/VO_2 variable value begins to decrease. Such a decrease continues, but clearly levels off as exercise intensity increases from light to moderate. At this phase of the protocol there is a consistent increase in V_E and VO_2, and hence the $_EVO_2$ variable stabilizes.

The influence of ventilation to metabolic demand is best shown by the expired gas fractions, and these are presented in Figure 3. The data clearly reveal that the increased ventilation occurring after approximately 8.8 min exceeds metabolic demand, as **$\%_EO_2$** increases, and **$\%_ECO_2$** decreases. Interestingly, this time coincides with the detected VT from the ventilator equivalents of Figure 2.

The subject for the Figure 2 data set was unusual in that he was highly trained, but a sprint cyclist and not an endurance trained cyclist. The profile of his V_EVO_2 and V_EVCO_2 responses is a little unusual in that the increase in both occurs near simultaneously. Thus, the ventilatory equivalent data for the subject of Figure 1 is presented in Figure 4.

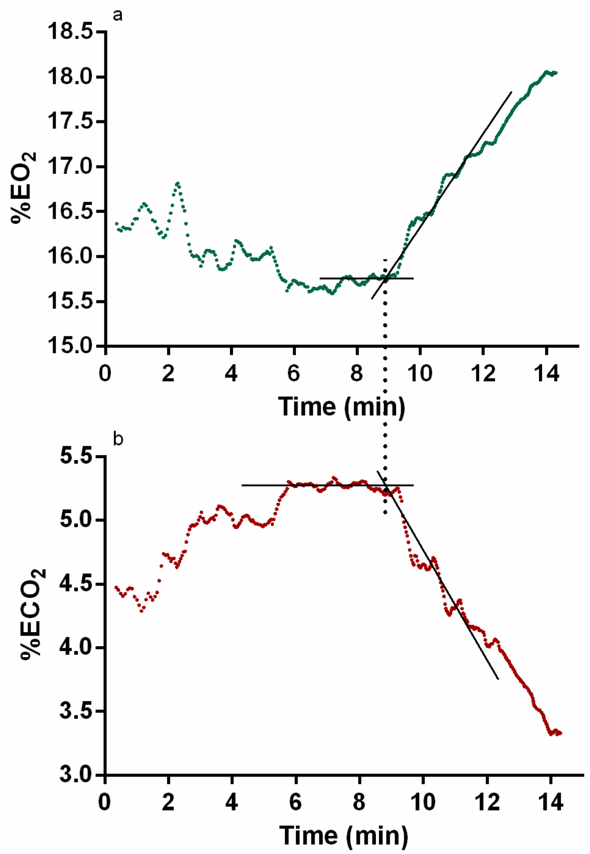


Figure 3. The change in a) expired O_2 %, and b) expired CO_2 % for the same subject as Figure 2.

The data of Figure 4 show that the initial hyperventilation to exercise is

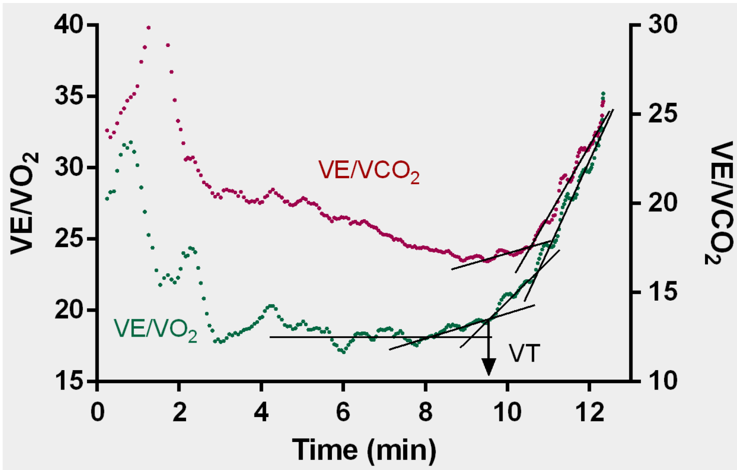


Figure 4. The data for the ventilatory equivalents for the same endurance trained cyclist of Figure 1. Note the ~1.1 min delay in the threshold change in V_E/VCO_2 compared to V_E/VO_2.

more exaggerated for V_E/VCO_2. This is because the initial hyperventilation has removed CO_2 stores from the blood and additional body fluids, thereby blunting the increase in VCO_2. In addition, low intensity exercise produces less CO_2 due to a high proportion of fat oxidation. The ratio decreases because of a greater production of CO_2 per rate of ventilation caused by increasing carbohydrate oxidation (decreasing proportion of fat oxidation), as well as the restoration of more normal body fluid CO_2 stores.

Why Is There a Delayed Increase in V_E/VCO_2?

Another important criterion for using ventilatory equivalents for detecting the VT is to combine the V_E/VO_2 criterion with a 1 to 2 min delayed threshold change in V_E/VCO_2. This is an important part of the VT detection method. For example, look at Figure 4 again. There are three threshold responses within the V_E/VO_2 data set. Obviously, a question arises regarding which is the true VT? This is where the V_E/VCO_2 criterion fits into the joint method. As the V_E/VCO_2 threshold should occur after the V_E/VO_2 threshold, with a time delay between 1 to 2 min, the first V_E/VO_2 threshold does not fit this feature as it occurs almost 3 min prior to the V_E/VCO_2 threshold. The second threshold occurs at ~9.5 min, and the third at ~10.7 min. As the third threshold occurs after the V_E/VCO_2 threshold at ~10.5 min, the second V_E/VO_2 threshold is the VT.

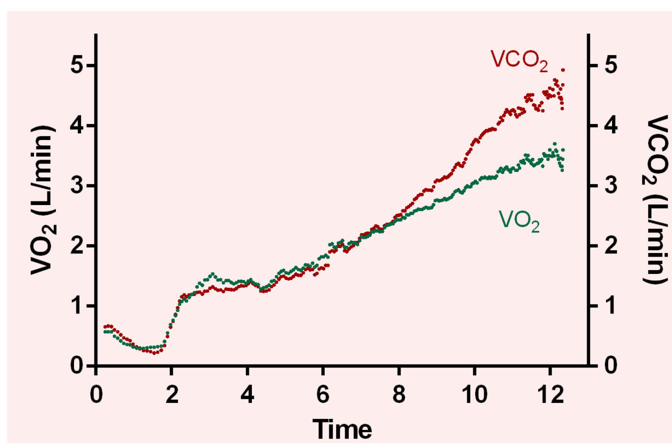


Figure 5. The VO_2 and VCO_2 data for the same subject of Figures 1 and 4. Note the more rapid increase in VCO_2 after ~8 min.

There is a delay in the V_E/VCO_2 threshold due to the similar onset of the threshold changes in both V_E and VCO_2 at the VT, as shown in Figure 5. It is not until metabolic acidosis develops that ventilation is stimulated to a greater extent and increases out of proportion to VCO_2, and these events occur at an RER above 1.0 (Figure 2d). Interestingly, this also means that unlike explained in past textbooks, the VT does not represent the transition from steady state to non-steady state exercise intensities. Nor does it represent the transition into **metabolic acidosis**. The VT is a trait of incremental exercise protocols that is proportional to and predictive of long duration endurance exercise performance potential, is responsive to training, and as such can be used in exercise prescription. However, as any experienced exercise physiologist who has worked with elite athletes will tell you, the VT represents an intensity that can be as much as 60 Watts below an athlete's true maximal steady state as measured from performance times or other laboratory exercise testing methodologies.

Glossary Words

expired ventilation (V_E) refers to the rate of expired air that leave the lungs, and is typically expressed in L/min.

incremental exercise is a type of exercise characterized by a gradual increase in metabolic demand until the subject cannot continue to exercise (volitional exhaustion).

ventilation threshold (VT) refers to the exercise intensity coincident to an abrupt increase in ventilation above whole body oxygen consumption (VO_2). The VT is best detected by graphing each of V_E/VO_2, V_E/VCO_2, $\%_EO_2$ and $\%_ECO_2$. The intensity (or time) when V_E/VO_2 first reveals a sustained increase, followed 1-2 min thereafter by an increase in V_E/VCO_2, is used as the VT. This threshold also coincides with threshold changes in each of $\%_EO_2$ (increase) and $\%_ECO_2$ (decrease).

tidal volume is the volume of air breathed each breathe.

ramp protocol is a sequence of frequent small increments in metabolic demand during incremental exercise. The name implies that the increment in intensity is a continuous function, but in reality it is not. The frequency of change for ramp protocols is constrained by equipment electronics, with most cycle ergometers exerting a 0.5 to 1.0 Hz increment function.

VE/VO_2 refers to the ventilator equivalent for oxygen, which is the ratio between V_E and VO_2.

VE/VCO_2 refers to the ventilatory equivalent for carbon dioxide, which is the ratio between V_E and VCO_2.

ventilatory equivalents, as explained above, refers to the ratio of expired ventilation (V_E) and either of VO_2 or VCO_2.

hyperventilation is an exaggerated state of ventilation, being above that of metabolic demand.

$\%_EO_2$ is the % fraction of expired O_2.

$\%_ECO_2$ is the % fraction of expired CO_2.

metabolic acidosis is the condition of the body characterized by a decrease in body fluid pH and bicarbonate ([HCO_3^-]), and is caused by an increased cellular metabolic release of protons (H^+).