Maximal Oxygen Consumption- The VO_2max

If you walk into the locker room of a bunch of American Football players, bragging rights are reserved for the man with the heaviest bench press. Similarly, talk to a group of endurance athletes that are "in the know", and conversation will eventually turn to "What is your VO_2 max?" A high maximal oxygen consumption is indeed **one** of the hallmark characteristics of great endurance performers in running, cycling, rowing and cross-country skiing, so it must be pretty important. *What is it and how is it measured?*

VO_2max defined

VO_2 max is the maximum volume of oxygen that by the body can consume during intense, whole-body exercise, while breathing air at sea level. This volume is expressed as a rate, either liters per minute (L/min) or millilitres per kg bodyweight per minute (ml/kg/min). Because oxygen consumption is linearly related to energy expenditure, when we measure oxygen consumption, we are indirectly measuring an individual's maximal capacity to do work aerobically.

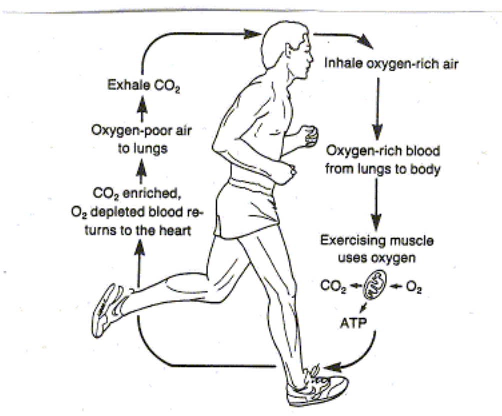


Figure 2.1 The pathways by which oxygen is transported from atmospheric air to the active muscles.

Why is his bigger than mine?

To rephrase, we might start by asking "what are the physiological determinants of VO_2 max?" Every cell consumes oxygen in order to convert food energy to usable ATP for cellular work. However, it is muscle that has the greatest range in oxygen consumption. At rest, muscle uses little energy. However, muscle cells that are contracting have high demands for ATP. So it follows that they will consume more oxygen during exercise. The sum total of billions of cells throughout the body consuming oxygen, and generating carbon dioxide, can be measured at the breath using a combination of ventilation volume-measuring and O_2/CO_2-sensing equipment. The figure to the left, borrowed from Prof. Frank Katch, summarizes this process of moving O_2 to the muscle and delivering CO_2 back to the lungs. So, if we measure a greater consumption of oxygen during exercise, we know that the working muscle is working at a higher intensity. To receive this oxygen and use it to make ATP for muscle contraction, our muscle fibers are absolutely dependent on 2 things: 1) an external delivery system to bring oxygen from the atmosphere to the working muscle cells, and 2) mitochondria to carry out the process of aerobic energy transfer. Endurance athletes are characterized by both a very good cardiovascular system, and well developed oxidative capacity in their skeletal muscles. We need a big and efficient pump to deliver oxygen rich blood to the muscles, and we need mitochondria-rich muscles to use the oxygen and support high rates of exercise. Which variable is the limiting factor in VO2 max, oxygen delivery or oxygen utilization? This is a central question that has created considerable debate among exercise physiologists over the years, but for most the jury is now out.

In the well-trained, oxygen delivery limits VO_2 max

Several experiments of different types support the concept that, in trained individuals, it is oxygen **delivery**, not oxygen **utilization** that limits VO_2 max. By performing exercise with one leg and directly measuring muscle oxygen consumption of a small mass of muscle (using arterial catheterisation) it has been shown that the capacity of skeletal muscle to use oxygen exceeds the heart's capacity for delivery. Thus although the average male has about 30 to 35 kg of muscle, only a portion of this muscle can be well perfused with blood at any one time. The heart can't deliver a high blood flow to all skeletal muscle, and still maintain adequate blood pressure. This limitation is analogous to the water pressure in your house. If you turn all the faucets on while trying to take a shower, the shower pressure will be inadequate because there is not enough driving pressure. Without getting in to deep on the hemodynamics, it seems that blood pressure is a centrally controlled variable; the body will not "open the valves" to more muscle than can be perfused without compromising central pressure, and blood flow to the brain. The bigger the pumping capacity of the heart, the more muscle can be perfused while maintaining all-important blood pressure.

As further evidence for a delivery limitation, long-term endurance training can result in a 300% increase in muscle oxidative capacity, but only about a 15 to 25% increase in VO_2 max. VO_2 max can be altered artificially by changing the oxygen concentration in the air. VO_2 max also increases in previously untrained subjects before a change in skeletal muscle aerobic capacity occurs. All of these observations demonstrate that VO_2 max can be dissociated from skeletal muscle characteristics.

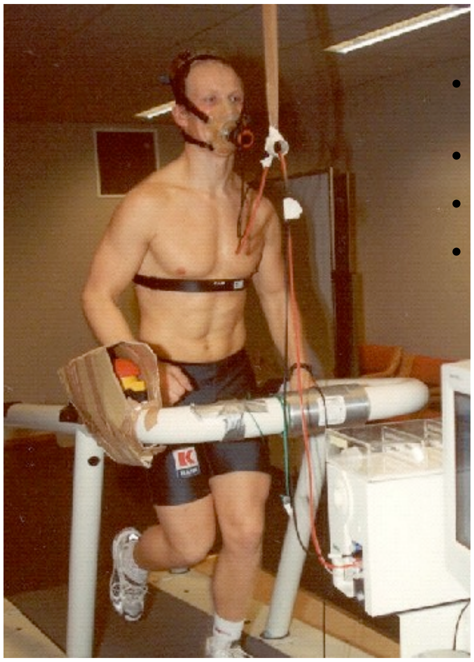
Stroke volume, in contrast, is linearly related to VO2 max. Training results in an increase in stroke volume and therefore, an increase in maximal cardiac output. Greater capacity for oxygen delivery is the result. More muscle can be supplied with oxygen simultaneously while still maintaining necessary blood pressure levels.

In the untrained, skeletal muscle capacity can be limiting

Now, having convinced you that heart performance dictates VO_2 max, it is important to also explain the contributing, or accepting, role of muscle oxidative capacity. Measured directly, Oxygen consumption= Cardiac output x arterial-venous oxygen difference (a-v O2 diff). As the oxygen rich blood passes through the capillary network of a working skeletal muscle, oxygen diffuses out of the capillaries and to the mitochondria (following the concentration gradient). The higher the oxygen consumption rate by the mitochondria, the greater the oxygen **extraction**, and the higher the a-v O2 difference at any given blood flow rate. Delivery is the limiting factor because even the best-trained muscle cannot use oxygen that isn't delivered. But, if the blood is delivered to muscles that are poorly trained for endurance, VO_2 max will be lower despite a high delivery capacity. When we perform VO_2 max tests on untrained persons, we often see that they stop at a at a time point in the test when their VO_2 max seems to still be on the way up. The problem is that they just do not have the aerobic capacity in their working muscles and become fatigued locally prior to fully exploiting their cardiovascular capacity. In contrast, when we test athletes, they will usually show a nice flattening out of VO_2 despite increasing intensity towards the end of the test. Heart rate peaks out, VO2 maxes out, and even though some of the best trained can hold out at VO_2 max for several minutes, max is max and they eventually hit a wall due to the accumulation of protons and other changes at the muscular level that inhibit muscular force production and bring on exhaustion.

How is VO_2 max measured?

In order to determine an athlete's true maximal aerobic capacity, exercise conditions must be created that maximally stress the blood delivery capacity of the heart.

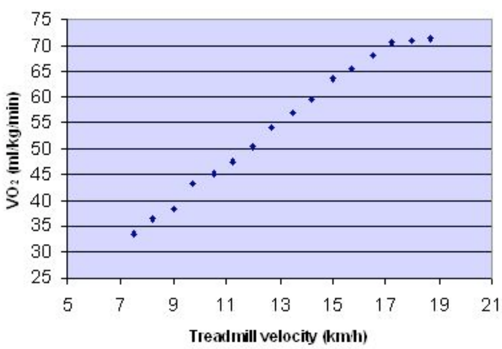


A physical test that meets this requirement must:

- * Employ at least 50% of the total muscle mass. Activities which meet this requirement include running, cycling, and rowing. The most common laboratory method is the treadmill running test. A motorized treadmill with variable speed and variable incline is employed.
- * Be independent of strength, speed, body size, and skill. The exception to this rule is specialized tests for swimmers, rowers, skaters, etc.
- * Be of sufficient duration for cardiovascular responses to be maximized. Generally, maximal tests using continuous exercise protocols are completed in 6 to 12 minutes.
- * Be performed by someone who is highly motivated! VO_2 max tests are very tough, but they don't last too long.

If we use a treadmill test as an example, here is what will happen. You will go to a good laboratory at a University fitness program, performance testing lab, or hospital wellness center. After a medical exam, and after being hooked up to an ECG machine to monitor cardiac electrical activity, you might start the test by walking on the treadmill at low speed and zero grade. If your fitness level is quite high, the test might be initiated at a running speed. Then, depending on the exact protocol, speed or inclination (or both) of the treadmill will increase at regular intervals (30 sec to 2 minutes). While running, you will be breathing through a 2-way valve system. Air will come in from the room, but will be expired through sensors that measure both volume and oxygen concentration. Using these values and some math, your oxygen uptake will be calculated by a computer at each stage. With each increase in speed or incline, more muscle mass will be employed at a greater intensity. Oxygen consumption will increase linearly with increasing workload. However, at some point, an increase in intensity will not result in an “appropriate” increase in oxygen consumption. Ideally, the oxygen consumption will completely flatten out despite ever-increasing workload. This is the true indication of achieving VO_2 max.

In the figure below, we see the results of actual test on a well trained runner performed in our lab with the treadmill incline a constant 5% and velocity increased 0.75km/h each minute. Even well trained athletes cannot stay at their VO2 max very long due to concurrent skeletal muscle fatigue. Other indications of max VO_2 are extreme hyperventilation, and a heart rate of very near 220 minus age that does not increase further with increased workload.



The value you are given by the test administrator will be in one of two forms. The first is called your **absolute** VO_2 max. This value will be in liters/min and will probably be between 3.0 and 6.0 liters/min if you're a man and between 2.5 and 4.5 l/min if you’re a woman. This absolute value does not take into account differences in body size, so a second way of expressing VO_2 max is common. This is called your **relative** VO_2 max. It will be expressed in milliliters per min per kg bodyweight (ml/min/kg). So if your absolute VO_2 max was 4.0 liters/min and you weighed 75 kg, then your relative VO_2 max would be 4000 divided by 75, or 53.3 ml/min/kg. In general, absolute VO_2 max favors the large endurance athlete, while relative VO_2 tends to be higher in smaller athletes. Click here to read why.

For comparison, the average maximal oxygen consumption of an untrained male in his mid 30s is about 40-45 ml/min/kg, and decreases with age. The same person who undergoes a regular endurance exercise program might increase to 50-55 ml/min/kg. A champion male masters runner age 50 will probably have a value of over 60 ml/min/kg. An Olympic champion 10,000-meter runner will probably have a VO_2 max over 80 ml/min/kg! What about females? I talk about gender differences in performance in another section. The underlying physiology is the same, however specific differences result in lower population values for VO_2 max in untrained, trained and champion females when compared to men at a similar relative capacity.

Genetics play a big role

I grew up being told that I could do anything and be anything I set my mind to. I think that was nice of my mother to encourage me that way. However, the biological reality is that there is a significant genetic component to most of the underlying physical qualities that limit just how *“Citius, altius, fortius”* we can be with training. VO_2 max is no exception. The reality is that if an adult male with a natural, untrained VO_2 max of 45 ml/min/kg trains optimally for 5 years, they **might** see their VO_2 max climb to around 60-65 ml/min/kg. This is a huge improvement. Yet, the best runners have a VO_2 max of 75 to 85 ml/kg so our hard training normal guy is still going to come up way short against the likes of these guys. If they were to stop training for a year, their VO_2 max might fall to about where the average guy’s topped out after years of optimal training. The bottom line is that Olympic champions are born with unique genetic potential that is transformed into performance capacity with years of hard training. Recent studies focusing on the genetics of exercise adaptation have also demonstrated that not only is our starting point genetically determined, but our adaptability to training (how much we improve) is also quite variable and genetically influenced. While the typical person will show a substantial increasing in VO_2 max with 6 months of exercise, carefully controlled research studies have shown that a small percentage of people will hardly show an increase in VO_2 max at all.

One more thing. Just to put things in perspective, the VO_2 of a typical thoroughbred horse is about 600 liters/min or 150 ml/min/kg! So compared to a horse, even an Olympic endurance champion human comes out looking like a couch potato.

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