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Editorial

VO_2^{max} makes bridge between aerobic and anaerobic exercise

Shruti Rai and Prof. Dr. Dhrubo Jyoti Sen*
D.Pharm., B.Sc. (Hons), B.Pharm. (Hons), M.Pharm., Ph.D., FICS, CChem FIC (India), CChem FRSC (UK), CSci (UK), AOM (USA)

Professor, Department of Pharmaceutical Chemistry, Shri Sarvajanik Pharmacy College, Gujarat Technological University, Arvind Baug, Mehsana-384001, Gujarat, India
Phone: 00-91-2762-247711 (Ext-307); Fax: 00-91-2762-247712
Website: http://sspcmsn.org/yahoo_site_admin/assets/Facultyprofiles/drdjsen.pdf
Mobile: 09979132823, E-mail: dhrubosen69@yahoo.com

Recipient of K.K. Acharjee Award, Recipient of Jewel of India Award, Recipient of Rashtriya Vidya Saraswati Puraskar, Recipient of Rashtriya Vidya Jyoti Award and Gold Medal, Recipient of Life Time Achievement Gold Medal Award, Recipient of Eminent Educationist Award, Recipient of International Gold Star Award, Recipient of Vidya Ratan Award, Recipient of Gyan Jyoti Gold Medal Award, Recipient of Bharat Excellence Award & Gold Medal, Recipient of India Inspiration Award & Gold Medal, Recipient of Seva Chakra Puraskar, Recipient of American Order of Merit, Recipient of Golden Educationist of India Award, Recipient of NEHS Global Award of Excellence and Gold Medal of Excellence, Recipient of NEHS Jewel of India Award and NEHS Gold Medal of Excellence, Recipient of Academician of the Year Award, Recipient of Outstanding Faculty of the Year Award, Recipient of Award for Special Achievement in Technology

ABSTRACT

The basic definition of VO_2^{max} is the maximum amount of oxygen your body can use during exercise. VO_2^{max} (also maximal oxygen consumption, maximal oxygen uptake, peak oxygen uptake or maximal aerobic capacity) is the maximum rate of oxygen consumption as measured during incremental exercise, most typically on a motorized treadmill. Maximal oxygen consumption reflects the aerobic physical fitness of the individual, and is an important determinant of their endurance capacity during prolonged, sub–maximal exercise. The name is derived from V–volume, O_2 – oxygen, max – maximum. VO_2^{max} is expressed either as an absolute rate in (for example) liters of oxygen per minute (L/min) or as a relative rate in (for example) milliliters of oxygen per kilogram of body mass per minute (e.g., mL/(kg·min)). The latter expression is often used to compare the performance of endurance sports athletes. However, VO_2^{max} generally does not vary linearly with body mass, either among individuals within a species or among species, so comparisons of the performance capacities of individuals or species that differ in body size must be done with appropriate statistical procedures, such as analysis of covariance.

Keywords: Maximal oxygen consumption, Maximal oxygen uptake, Peak oxygen uptake, Maximal aerobic capacity, Aerobic exercise, Anaerobic exercise, VO_2^{max}, Carbohydrate, Lipid and Fat metabolism cycle

INTRODUCTION

Aerobic exercise (also known as **cardio**) is physical exercise of low to high intensity that depends primarily on the aerobic energy-generating process. Aerobic literally means *relating to, involving, or requiring free oxygen* and refers to the use of oxygen to adequately meet energy demands during exercise via aerobic metabolism. Generally, light-to-moderate intensity activities that are sufficiently supported by aerobic metabolism can be performed for extended periods of time. When practiced in this way, examples of cardiovascular/aerobic exercise are medium to long distance running/jogging/swimming/cycling/walking according to the first extensive research on aerobic exercise, conducted in the 1960s on over 5,000 U.S. Air Force personnel by Dr. Kenneth H. Cooper. Aerobic exercise and fitness can be contrasted with anaerobic exercise, of which strength training and short-distance running are the most salient examples. The two types of exercise differ by the duration and intensity of muscular contractions involved, as well as by how energy is generated within the muscle.[1]

New research on the endocrine functions of contracting muscles has shown that both aerobic and anaerobic exercise promote the secretion of myokines, with attendant benefits including growth of new tissue, tissue repair and various anti-inflammatory functions, which in turn reduce the risk of developing various inflammatory diseases. Myokine secretion in turn is dependent on the amount of muscle contracted and the duration and intensity of contraction. As such, both types of exercise produce endocrine benefits. In almost all conditions, anaerobic exercise is accompanied by aerobic exercises because the less efficient anaerobic metabolism must supplement the aerobic system due to energy demands that exceed the aerobic system's capacity. What is generally called aerobic exercise might be better termed "solely aerobic", because it is designed to be low-intensity enough not to generate lactate via pyruvate fermentation, so that all carbohydrate is aerobically turned into energy.[2]

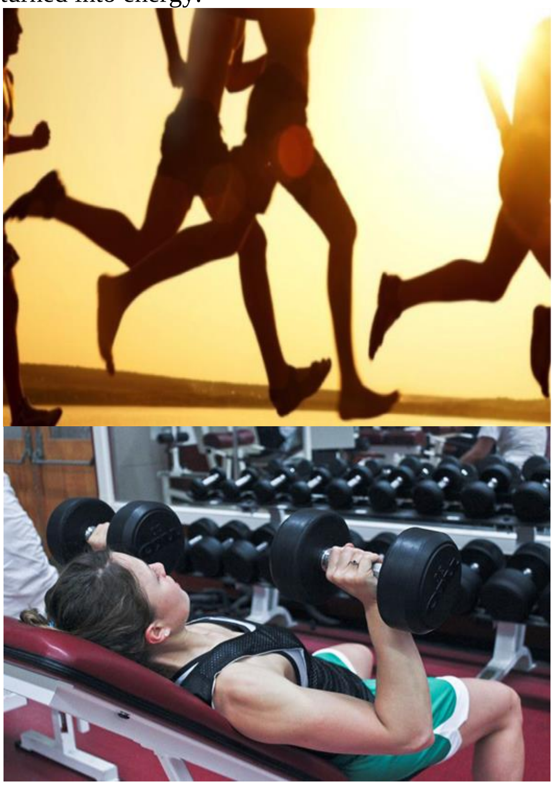


Figure-1: Aerobic and Anaerobic exercise

Initially during increased exertion, muscle glycogen is broken down to produce glucose, which undergoes glycolysis producing pyruvate which then reacts with oxygen (Krebs cycle, Chemiosmosis) to produce carbon dioxide and water and releases energy. If there is a shortage of oxygen (anaerobic exercise, explosive movements), carbohydrate is consumed more rapidly because the pyruvate ferments into lactate. If the intensity of the exercise exceeds the rate with which the cardiovascular system can supply muscles with oxygen, it results in buildup of lactate and quickly makes it impossible to continue the exercise. Unpleasant effects of lactate buildup initially include the burning sensation in the muscles, and may eventually include nausea and even vomiting if the exercise is continued without allowing lactate to clear from the bloodstream.[3]

As glycogen levels in the muscle begin to fall, glucose is released into the bloodstream by the liver and fat metabolism is increased so that it can fuel the aerobic pathways. Aerobic exercise may be fueled by glycogen reserves, fat reserves, or a combination of both, depending on the intensity. Prolonged moderate-level aerobic exercise at 65% VO_2^{max} (the heart rate of 150 beats per minute for a 30-year-old human) results in the maximum contribution of fat to the total energy expenditure. At this level, fat may contribute 40% to 60% of total, depending on the duration of the exercise. Vigorous exercise above 75% VO_2^{max} (160 beats per minute) primarily burns glycogen. Major muscles in a rested, untrained human typically contain enough energy for about 2 hours of vigorous exercise. Exhaustion of glycogen is a major cause of what marathon runners call "hitting the wall". Training, lower intensity levels and carbohydrate loading may allow postponement of the onset of exhaustion beyond 4 hours. Aerobic exercise comprises innumerable forms. In general, it is performed at a moderate level of intensity over a relatively long period of time. For example, running a long distance at a moderate pace is an aerobic exercise, but sprinting is not. Playing singles tennis, with near-continuous motion, is generally considered aerobic activity, while golf or two person team tennis, with brief bursts of activity punctuated by more frequent breaks, may not be predominantly aerobic. Some sports are thus inherently "aerobic", while other aerobic exercises, such as fartlek training or aerobic dance classes, are designed specifically to improve aerobic capacity and fitness. It is most common for aerobic exercises to involve the leg muscles, primarily or exclusively. There are some exceptions. For example, rowing to distances of 2,000 m or more is an aerobic sport that exercises several major muscle groups, including those of the legs, abdominals, chest, and arms. Common kettlebell exercises combine aerobic and anaerobic aspects. Strengthening the muscles involved in respiration, to facilitate the flow of air in and out of the lungs

Strengthening and enlarging the heart muscle, to improve its pumping efficiency and reduce the resting heart rate, known as aerobic conditioning. Among the recognized benefits of doing regular aerobic exercise are: (1) Improving circulation efficiency and reducing blood pressure (2)

Increasing the total number of red blood cells in the body, facilitating transport of oxygen (3) Improved mental health, including reducing stress and lowering the incidence of depression, as well as increased cognitive capacity (4) Reducing the risk for diabetes. One meta-analysis has shown, from multiple conducted studies, that aerobic exercise does help lower Hb A1Clevels for type 2 diabetics.[4]

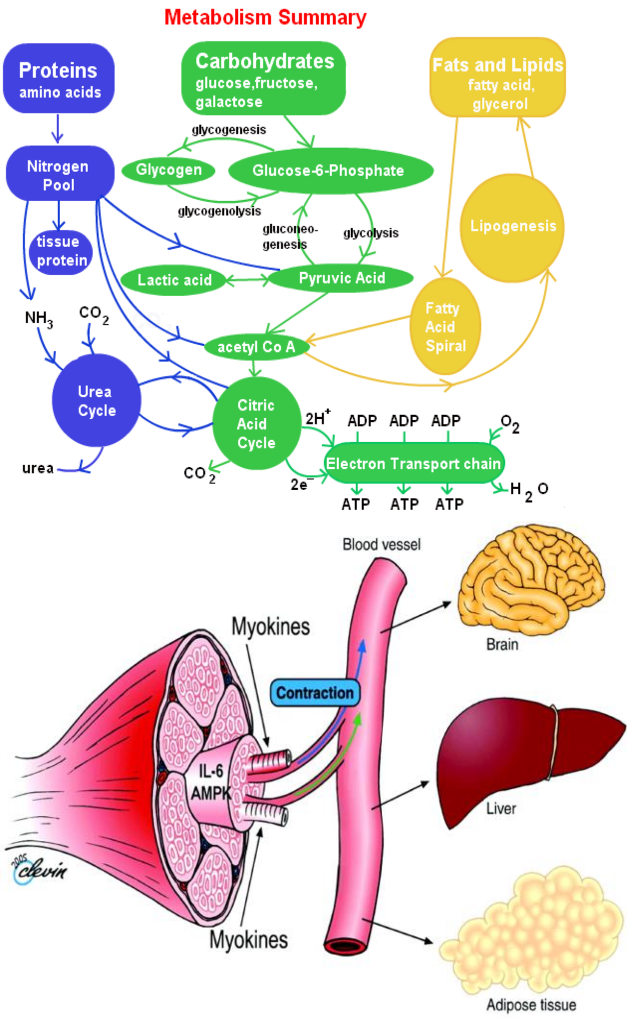


Figure-2: Metabolism cycle

As a result, aerobic exercise can reduce the risk of death due to cardiovascular problems. In addition, high-impact aerobic activities (such as jogging or using a skipping rope) can stimulate bone growth, as well as reduce the risk of osteoporosis for both men and women. In addition to the health benefits of aerobic exercise, there are numerous performance benefits: (1) Increased storage of energy molecules such as fats and carbohydrates within the muscles, allowing for increased endurance (2) Neovascularization of the muscle sarcomeres to increase blood flow through the muscles (3) Increasing speed at which aerobic metabolism is activated within muscles, allowing a greater portion of energy for intense exercise to be generated aerobically (4) Improving the ability of muscles to use fats during exercise, preserving intramuscular glycogen (5) Enhancing the speed at which muscles recover from high intensity exercise (6) Neurobiological effects: improvements in brain structural connections and increased gray matter density, new neuron growth, improved cognitive function (cognitive control and various forms of memory), and improvement or maintenance of mental health.[5]

Some drawbacks of aerobic exercise include: (1) Overuse injuries because of repetitive, high-impact exercise such as distance running (2) Is not an effective approach to building muscle (3) Only effective for fat loss when used consistently.

Both the health benefits and the performance benefits, or "training effect", require a minimum duration and frequency of exercise. Most authorities suggest at least twenty minutes performed at least three times per week. Aerobic capacity describes the functional capacity of the cardio respiratory system, (the heart, lungs and blood vessels). Aerobic capacity refers to the maximum amount of oxygen consumed by the body during intense exercises, in a given time frame. It is a function both of cardio respiratory performance and the maximum ability to remove and utilize oxygen from circulating blood. To measure maximal aerobic capacity, an exercise physiologist or physician will perform a VO_2^{max} test, in which a subject will undergo progressively more strenuous exercise on a treadmill, from an easy walk through to exhaustion. The individual is typically connected to a respirometer to measure oxygen consumption and the speed is increased incrementally over a fixed duration of time. The higher the measured cardio respiratory endurance level, the more oxygen has been transported to and used by exercising muscles, and the higher the level of intensity at which the individual can exercise. More simply put, the higher the aerobic capacity, the higher the level of aerobic fitness. The Cooper and multi-stage fitness tests can also be used to assess functional aerobic capacity for particular jobs or activities. The degree to which aerobic capacity can be improved by exercise varies very widely in the human population: while the average response to training is an approximately 17% increase in VO_2^{max} x, in any population there are "high responders" who may as much as double their capacity, and "low responders" who will see little or no benefit from training. Studies indicate that approximately 10% of otherwise healthy individuals cannot improve their aerobic capacity with exercise at all. The degree of an individual's responsiveness is highly heritable, suggesting that this trait is genetically determined.[6]

Aerobic exercises:
(1) Indoor: Stair climbing, Elliptical trainer, Indoor rower, Stairmaster, Stationary bicycle, Treadmill
Outdoor: Walking, Cycling, Running, Cross-country skiing, Cross-country running, Nordic walking, Inline skating, Rowing
Indoor or outdoor: Swimming, Kickboxing, Skipping rope or jump rope, Circuit training, Jumping jacks, Jogging, Water aerobics

Maximal oxygen uptake norms for men (ml/kg/min)						
Grade	Age (years)					
	18–25	26–35	36–45	46–55	56–65	65+
Excellent	> 60	> 56	> 51	> 45	> 41	> 37
Good	52–60	49–56	43–51	39–45	36–41	33–37
Above average	47–51	43–48	39–42	36–38	32–35	29–32
Average	42–46	40–42	35–38	32–35	30–31	26–28
Below average	37–41	35–39	31–34	29–31	26–29	22–25
Poor	30–36	30–34	26–30	25–28	22–25	20–21
Very poor	< 30	< 30	< 26	< 25	< 22	< 20
Maximal oxygen uptake norms for women (ml/kg/min)						
Grade	Age (years)					
	18–25	26–35	36–45	46–55	56–65	65+
Excellent	> 56	> 52	> 45	> 40	> 37	> 32
Good	47–56	45–52	38–45	34–40	32–37	28–32
Above average	42–46	39–44	34–37	31–33	28–31	25–27
Average	38–41	35–38	31–33	28–30	25–27	22–24
Below average	33–37	31–34	27–30	25–27	22–24	19–21
Poor	28–32	26–30	22–26	20–24	18–21	17–18
Very poor	< 28	< 26	< 22	< 20	< 18	< 17

Table-1: Comparison of VO_2^{max} in male and female

Aerobic exercise may be fueled by glycogen reserves, fat reserves, or a combination of both, depending on the intensity. Prolonged moderate-level aerobic exercise at 65% VO_2^{max} (the heart rate of 150 beats per minute for a 30-year-old human) results in the maximum contribution of fat to the total energy expenditure. At this level, fat may contribute 40-60% of total, depending on the duration of the exercise. Vigorous exercise above 75% VO_2^{max} (160 beats per minute) primarily burns glycogen. VO_2^{max} (also maximal oxygen consumption, maximal oxygen uptake, peak oxygen uptake or maximal aerobic capacity) is the maximum rate of oxygen consumption as measured during incremental exercise, most typically on a motorized treadmill. Maximal oxygen consumption reflects the aerobic physical fitness of the individual, and is an important determinant of their endurance capacity during prolonged, sub-maximal exercise. The name is derived from V - volume, O_2 - oxygen, max - maximum. VO_2^{max} is expressed either as an absolute rate in (for example) litres of oxygen per minute (L/min) or as a relative rate in (for example) millilitres of oxygen per kilogram of body mass per minute (e.g., mL/(kg•min)). The latter expression is often used to compare the performance of endurance sports athletes. However, VO_2^{max} generally does not vary linearly with body mass, either among individuals within a species or among species, so comparisons of the performance capacities of individuals or species that differ in body size must be done with appropriate statistical procedures, such as analysis of covariance.[7]

Accurately measuring VO_2^{max} involves a physical effort sufficient in duration and intensity to fully tax the aerobic energy system. In general clinical and athletic testing, this usually involves a graded exercise test (either on a treadmill or on acycle ergometer) in which exercise intensity is progressively increased while measuring ventilation and oxygen and carbon dioxide concentration of the inhaled and exhaled air. VO_2^{max} is reached when oxygen consumption remains at steady state despite an increase in workload.[8]

Fick equation

VO_2^{max} is properly defined by the Fick equation: $VO_2^{max} = Q \times (CaO_2 - CvO_2)$, when these values are obtained during an exertion at a maximal effort.
where Q is the cardiac output of the heart, CaO_2 is the arterial oxygen content, and CvO_2 is the venous oxygen content.
$(CaO_2 - CvO_2)$ is also known as the arteriovenous oxygen difference.
Estimation of VO_2^{max}: Tests measuring VO_2^{max} can be dangerous in individuals who are not considered normal healthy subjects, as any problems with the

respiratory and cardiovascular systems will be greatly exacerbated in clinically ill patients. Thus, many protocols for estimating VO_2^{max} have been developed for those for whom a traditional VO_2^{max} test would be too risky. These generally are similar to a VO_2^{max} test, but do not reach the maximum of the respiratory and cardiovascular systems and are called sub–maximal tests.[9]

Uth–Sørensen–Overgaard–Pedersen estimation
Another estimate of VO_2^{max} for humans, based on maximum and resting heart rates, was created by a group of researchers from Denmark. It is given by: $VO_2^{max} \approx 15.3 \times HR^{max}/HR_{rest}$
This equation uses the ratio of maximum heart rate (HRmax) to resting heart rate (HR_{rest}) to predict VO_2^{max} and is measured in units of mL/kg/minute.

Figure-3: VO_2^{max} makes bridge between aerobic and anaerobic exercise

Cooper test
Kenneth H. Cooper conducted a study for the United States Air Force in the late 1960s. One of the results of this was the Cooper test in which the distance covered running in 12 minutes is measured. Based on the measured distance, an estimate of VO_2^{max} [in mL/(kg•min)] is: $VO_2^{max} \approx d_{12} – 504.9/44.73$
where d_{12} is distance (in metres) covered in 12 minutes
An alternative equation is: $VO_2^{max} \approx (35.97 \times d_{miles12}) – 11.29$
where d_{12} is distance (in miles) covered in 12 minutes.

Multi–stage fitness test
There are several other reliable tests and VO_2^{max} calculators to estimate VO_2^{max}, most notably the multi–stage fitness test (or beep test), based on the research paper by Leger and Lambert, "A Maximal Multi–Stage 20–m Shuttle Run Test to predict VO_2^{max} ".

Rockport fitness walking test
Estimation of VO_2^{max} from a timed one–mile track walk with duration t, incorporating gender, age, body weight in pounds (BW), and heart rate (HR) at the end of the mile. The factor x is 6.3150 for males, 0 for females. BW is in lbs, time is in minutes.[10]

Factors affecting VO_2^{max}: The factors affecting VO_2 are often divided into supply and demand. Supply is the transport of oxygen from the lungs to the mitochondria (including lung diffusion, stroke volume, blood volume and capillary density of the skeletal muscle) while demand is the rate at which the mitochondria can reduce oxygen in the process of oxidative phosphorylation. Of these, the supply factor is often considered to be the limiting one. However, it has also been argued that while trained subjects probably are supply limited, untrained subjects can indeed have a demand limitation. Cardiac output, pulmonary diffusion capacity, oxygen carrying capacity and other peripheral limitations like muscle diffusion capacity, mitochondrial enzymes, and capillary density are all examples of VO_2^{max} determinants. The body works as a system. If one of these factor is sub–par, then the whole system loses its normal capacity to function properly.. The drug erythropoietin (EPO) can boost VO_2^{max} by a significant amount in both humans and other mammals. This makes EPO attractive to athletes in endurance sports, such as professional cycling.[11]

VO_2 Abbreviation: The V in VO_2 represents volume, but not just as a quantity. It also represents a rate – how much over a certain period of time. The O_2 simply refers to the chemical formula for oxygen. Your body has several VO_2 rates.

One such rate is your resting rate, which is how much oxygen your body uses while at rest. There are then rates for VO_2 during exercise.[12]

Figure–4: VO_2 measurement

VO_2 during Running: As you begin running, your muscles begin working above your VO_2 resting rate. As a result they naturally need more fuel to sustain this increased activity. Part of this increased demand requires more oxygen so your breathing gets progressively faster and deeper as your running pace increases.

What is VO_2^{max}?: As stated above, it is the maximum amount of oxygen your body can use during exercise. It is a combination of how much oxygen your lungs can take in, convert into the bloodstream which is then pumped throughout your body by your heart and finally how efficient your muscles are in consuming and converting that oxygen for use.

Since oxygen is the most critical component to running a fast pace, your VO_2^{max} is the best measure of your running fitness. As you begin running your VO_2 rate will increase and continue to increase until a point it can increase no more. This plateau of where you can no longer utilize oxygen any faster is your VO_2^{max}.[13]
The higher your VO_2^{max}, the better your fitness level. How To Calculate VO_2^{max}: The only method for truly determining your VO_2^{max} accurately is to have it read via a laboratory test. These are expensive and not really necessary except for elite runners striving to make incremental improvements and need that level of precision.

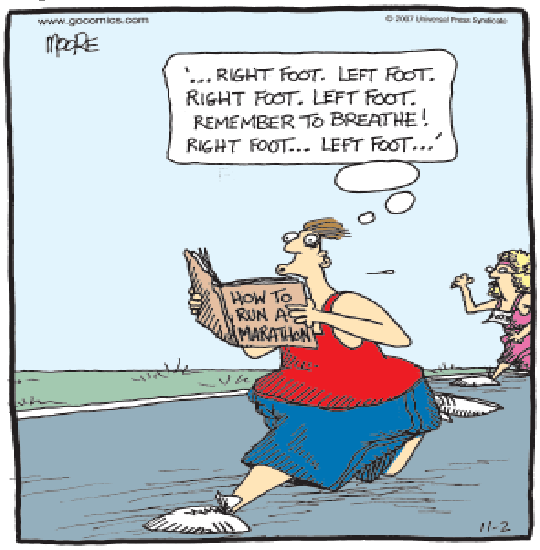
The rest of us can use a simple test called the "**One Mile Walk Test**" to determine our VO_2^{max}. That's right, we are going to walk…well, walk fast. For accuracy we recommend you conduct this test at your local running track. A standard track is 400m for 1 lap, so 4 laps equals 1600m or 1 mile.[14]
Here are the steps for this test:
1. Walk exactly one mile as fast as you can without straining yourself or running. Think Olympic speed walking if you can manage it!
2. Note the time in seconds it takes for you to complete the distance.
3. Immediately upon completion take your pulse for 15 seconds and multiply by 4 to obtain your heart rate.
4. Calculate your VO_2^{max} via the following formula:

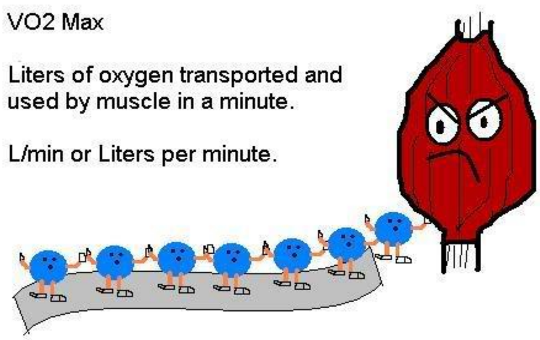
$$VO_2^{max}=132.853–(0.0769×Weight)–(0.3877×Age)+(6.315×Gender)–(3.2649×Time/60)–(0.1565×Heart\ Rate)$$

Interpreting Your VO_2^{max} Results: Take the result from our calculator to interpret your VO_2^{max} results. As a runner you should work towards being in the good to high category and work to improve towards the lower range of the Athletic category for your age group to reach your potential as a runner. The elite level is rarely obtainable except for the most exceptional of athletes. Runners at these levels usually have natural gifts in addition to extensive training although there are some elite runners that do not have a elite level VO_2^{max} and still manage to win based on other factors.[15]

How to Improve Your VO_2^{max} There are several specific running workouts you can use to improve your VO_2^{max}, many of which we have as part of our training inside Runner Academy Membership. Interval type workouts are classic ways to improve. But before you focus on improving your VO_2^{max} as the sole way to get faster as many runners do, you are likely better served focusing on other aspects of your running including: Running form, Running specific strength exercises, Consistency, Building a strong aerobic base. Most runners have advanced their VO_2^{max} through their training to a level that specific workouts to advance it will make marginal improvements to actual performance. Think of it as one piece to the puzzle rather than the entire focus as many commonly do.[16]
Anaerobic exercise is a physical exercise intense enough to cause lactate to form. It is used by athletes in non-endurance sports to promote strength, speed and power and by body builders to build muscle mass. Muscle energy systems trained using anaerobic exercise develop differently compared to aerobic exercise, leading to greater performance in short duration, high intensity

activities, which last from mere seconds to up to about 2 minutes. Any activity lasting longer than about two minutes has a large aerobic metabolic component. Anaerobic exercise, or anaerobic energy expenditure, is a natural part of whole-body metabolic energy expenditure.[17] Fast twitch muscle (as compared to slow twitch muscle) operates using anaerobic metabolic systems, such that any recruitment of fast twitch muscle fibers leads to increased anaerobic energy expenditure. Intense exercise lasting upwards of about four minutes (e.g., a mile race) may still have a considerable anaerobic energy expenditure component.





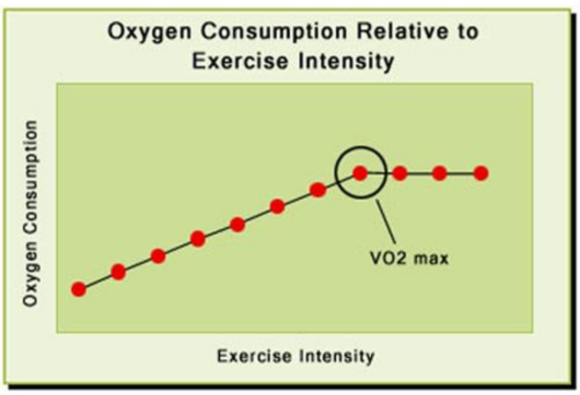


Figure-5: VO_2

High-intensity interval training, although based on aerobic exercises like running, cycling and rowing, effectively becomes anaerobic when performed in excess of 90% maximum heart rate. Anaerobic energy expenditure is difficult to accurately quantify, although several reasonable methods to estimate the anaerobic component to exercise are available. In contrast, aerobic exercise includes lower intensity activities performed for longer periods of time.[18] Activities such as walking, long slow runs, rowing and cycling require a great deal of oxygen to generate the energy needed for prolonged exercise (i.e., aerobic energy expenditure). In sports which require repeated short bursts of exercise however, the anaerobic system enables muscles to recover for the next burst.

Therefore training for many sports demands that both energy producing systems be developed. The two types of anaerobic energy systems are: (1) high energy phosphates, adenosine triphosphate and creatine phosphate and (2) anaerobic glycolysis. The former is called a lactic anaerobic and the latter lactic anaerobic system. High energy phosphates are stored in limited quantities within muscle cells. Anaerobic glycolysis exclusively uses glucose (and glycogen) as a fuel in the absence of oxygen, or more specifically when ATP is needed at rates that exceed those provided by aerobic metabolism. The consequence of such rapid glucose breakdown is the formation of lactic acid (or more appropriately, its conjugate base lactate at biological pH levels). Physical activities that last up to about thirty seconds rely primarily on the former, ATP-CP phosphagen system.[19] Beyond this time both aerobic and anaerobic glycolysis-based metabolic systems begin to predominate. The by-product of anaerobic glycolysis, lactate, has traditionally been thought to be detrimental to muscle function. However, this appears likely only when lactate levels are very high. Elevated lactate levels are only one of many changes that occur within and around muscle cells during intense exercise that can lead to fatigue. Fatigue, that is muscle failure, is a complex subject. Elevated muscle and blood lactate concentrations are a natural consequence of any physical exertion. The effectiveness of anaerobic activity can be improved through training.[20]

Conclusion

VO_2^{max} is defined as the maximal volume of oxygen that the body can deliver to the working muscles per minute. This is an excellent measure of physical fitness because it provides a metric of efficiency. So if we think about the body as a machine, the muscles collectively are the engine. Just like a car engine, the muscles require a constant delivery of fuel (carbohydrates and fats) and oxygen (to aid in "burning" the fuel). One of the functions of blood is to transport the fuel and oxygen to the muscles. The heart acts as a fuel pump, sending oxygen and nutrient rich blood out to the tissues via arteries and bringing back CO_2 and metabolic wastes via veins. So you can see that there are several components involved in the operation of the system. This is reflected in the equation for calculating VO_2^{max}. $VO_2^{max} = HR^{max} \times SV^{max} \times (AO_{xy} – VO_{xy})$. This looks much worse than it really is. HR^{max} is the maximal heart rate at peak exertion. It is measured as beats/minute. SVmax is the volume of blood pumped by the heart out to the muscles after each beat and is measured as liters/beat. If we multiply HRmax and SVmax we get maximal cardiac output (Q^{max}), measured as liters/minute of blood pumped out to the muscles. The last part of the equation is AO_{xy}-VO_{xy}. This is called the A/V oxygen difference and it is a measure of how much oxygen is taken out of the blood as it travels through the exercising muscles. The final unit for VO_2^{max} is liters of oxygen per minute. Aerobic exercise improves VO_2^{max} significantly. Interestingly, much of this improvement results from an increase in the size of the heart. So clearly, VO_2^{max} is a great measure of physical fitness. But it is a poor predictor of athletic performance. If you measured the VO_2^{max} of eight world-class cyclists before a race, you would be hard pressed to predict which of them would win if you only had their respective VO_2^{max} max values. This is where the LT comes into the picture.

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