

Energetic Transference Occurring in the Biosphere Part II

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Abstract

The anaerobic energy pathways govern in large part the capacity for peak performance during supramaximal exercise. Within this framework, capacity, power, and the time continuum will be discussed. Further, each step in the glycolytic pathway will be carefully analyzed, from reactants to products. Additional attention will be partitioned to eleven specific enzymes responsible for the direction and speed of glycolysis. Finally, techniques used to measure anaerobic energy systems will be reviewed.

Introduction

Louis Pasteur is considered a father of the scientific study of glycolysis. This process was first studied through fermentation, which occurs as yeast carries glycolysis extra steps to produce ethyl alcohol, CO₂, and vinegar. This scientist also found a technique that prevented table wine from going the extra steps mentioned. This process is known as pasteurization. Further, Pasteur analyzed glycolysis in yeast and in other single celled organisms in which O₂ was removed, or present. He noted that when O₂ was included glycolysis occurred at a slower rate and resulted in less lactate accumulation. However, when it was not included glycolysis, it was rapid and lactate accumulated. As will be seen in part three of this series, these slow and rapid velocities have much importance in exercise science. Pasteur is also famous for discovering a vaccine for rabies. Moreover, in 1888, the Pasteur Institute was established in Paris to continue the fight against diseases. A further subject studied by this giant was Biogenesis.

Biogenesis explains that living things can be produced only by other living things.

Abiogenesis is the supposed transformation of inanimate matter into living matter; also known as spontaneous generation. Spontaneous generation has never been observed. This has been seen so consistently that it is called the law of biogenesis, which states that life comes only from life, a fundamental law of biology. Louis Agassiz and Louis Pasteur scientifically developed this law in the 1850s, yet science textbooks today still state that abiogenesis happened. Dr Jonathan D. Sarfati (2004) states:

So far, there has not been a single observed exception to the Law of Biogenesis, so it truly stands as a scientific law. Nevertheless, billions of schoolchildren who are taught this law are also taught that 'once upon a time, perhaps in a galaxy far, far away', there was an exception, and possibly many more.

It should be realized that textbooks do take a while to get up to date. But 150 + years are long enough to correct this error.

Professor Dr. Klaus, in "The Origin of Life; More Questions than Answers," states (p. 348):

More than 30 years of experimentation on the origin of life in the fields of chemical and molecular evolution have led to a better perception of the immensity of the problem of the origin of life on earth rather than to its solution. At present all discussions on principal theories and experiments in the field either end in stalemate or in a confession of ignorance.

Simply put, to believe in abiogenesis goes against all logic and scientific support. George Wald, famous for being one of the founders of the Neo Darwinian Religion, states:

One has only to contemplate the magnitude of this task to concede that the spontaneous generation of a living organism is impossible. Yet here we are as a result, I believe, of spontaneous generation.



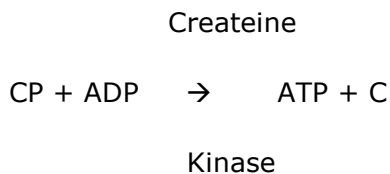
The present writers wholly agree with the impossibility aspect. Moreover, British scientist Sir Fred Hoyle (1981), who won the Nobel Prize for astronomy, can also sympathize. This great scientist calculated the probability of just *one* functioning protein molecule originating from nothing as being equivalent to filling the entire solar system with blind men holding Rubik's cubes, and for each of them to get the right solution at the exact same time! Now if someone would like to believe in spontaneous generation, that is fine. But just understand that this belief goes against all logic, and takes complete blind faith to trust in. However, it would behoove the reader to instead put their trust in the way, the truth, and the life—Jesus Christ.

Jeremiah 17:5-8

5 Thus saith the LORD; Cursed be the man that trusteth in man, and maketh flesh his arm, and whose heart departeth from the LORD. 6 For he shall be like the heath in the desert, and shall not see when good cometh; but shall inhabit the parched places in the wilderness, in a salt land and not inhabited. 7 Blessed is the man that trusteth in the LORD, and whose hope the LORD is. 8 For he shall be as a tree planted by the waters, and that spreadeth out her roots by the river, and shall not see when heat cometh, but her leaf shall be green; and shall not be careful in the year of drought, neither shall cease from yielding fruit. The heart is deceitful above all things, and desperately wicked: who can know it?

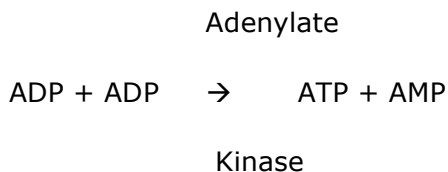
The Phosphagen System

The immediate source of energy in the body comes from three interrelated components (Brooks et al., 2000). Generally, three ounces of adenosine triphosphate (ATP) are stored and broken down by ATPases when needed for an immediate supply of energy. Further, the amount of free energy from ATP hydrolysis is estimated to be $-11 \text{ kcal}\cdot\text{mol}^{-1}$. This phase is quite short, lasting only 1-2 seconds. The byproducts of ATP are adenosine diphosphate (ADP) and inorganic phosphate (Pi). The former molecule is rephosphorylated (has a phosphate attached) by the high-energy compound creatine phosphate (CP). This is the second immediate source of energy. Catalyzed by the enzyme creatine kinase, the inorganic phosphate of CP is transferred to the ADP molecule, forming ATP. CP is more prevalent in muscle cells than ATP—approximately six times the amount. Here is a visual analysis of this reaction:



This newly formed molecule of ATP can now be hydrolyzed for another rapid source of energy while CP is rephosphorylated by mitochondrial creatine kinase.

Lastly, two molecules of ADP can be used to generate ATP. The enzyme adenylate kinase, also known as myokinase in muscle cells, takes two ADP molecules to form ATP; one is dephosphorylated, and the other is phosphorylated by the removed phosphate of the former molecule, resulting in one molecule of ATP and one molecule of Adenosine monophosphate (AMP). Here is an illustration:



In total, this energy system can be maximally sustained for 5-15 seconds.

The Creatine Phosphate shuttle

Adenosine Triphosphate is a very volatile substance. Therefore a problem in exercise physiology was finding how it was transferred from the mitochondria to region of the myofibrils to provide for the initiation of contraction. Enter the Creatine Phosphate Shuttle mechanism. The system can be described as follows (Bessman, 1987):

1. ADP is rephosphorylated by creatine phosphate in the cytoplasm.
2. The free creatine is then rephosphorylated at the inner mitochondrial membrane from ATP that was produced by the electron transport chain.
3. The ADP is then rephosphorylated by Oxidative phosphorylation (ETC).

4. Process continues until ATP and CP stores are filled.
5. Creatine Kinase is responsible for the phosphorylation process.

Glycolysis

Glycolysis can be defined as the dissolution of sugar (Plowman & Smith, 2001). More specifically, it is a concept representing the energy pathway in which the catabolism of glucose in a 10 or 11 step process yields the products pyruvate (10 steps) or lactate (11 steps). The subsequent analysis will focus on the ever-constant molecules present in anaerobic energy production. It should be noted, however, that several molecules can be converted into substrates (a substrate is any molecule acted upon by an enzyme) utilized during glycolysis.

Energy is directly available from glycolysis via substrate-level phosphorylation. That is, the transfer of an inorganic phosphate (Pi) directly from a phosphorylated intermediate. If glucose is utilized, a net total of two ATP molecules are produced; if glycogen, 3 molecules.

Each step is catalyzed by enzymes. For glycolysis to occur in the musculature, glucose must first be absorbed, and transported into the muscle cell. This then crosses the cell membrane by facilitated diffusion. With the help of a protein carrier; this transpires by a concentration gradient; as such, the transport is by passive systems, and energy is not required. For more information on transport systems, refer to Venom (2003. [Sodium - A comprehensive Analysis.](#))

The protein carrier utilized is either GLUT-1 (non-insulin-regulated) or GLUT-4 (insulin-dependent). When blood glucose levels are stable, most glucose enters the cell by GLUT-1 receptors; and contrarily, when insulin is high it enters primarily by GLUT-4 receptors (Wilson, 2003 Pre Contest Preparation Analysis) as well as exercising activities. It is postulated that calcium is a secondary messenger to insulin, which causes activation of GLUT-4 receptors during exercise (Wilson, 2003).

The location of glycolysis is in the cytosol, with the exception of a few glycolytic enzymes such as Lactate dehydrogenase, which exist in organelles such as the mitochondria. Moreover, the process is entirely anaerobic (occurs without utilizing oxygen). For a review of the cell cytoplasm, see Wilson (2002, [The Anatomy of A Muscle.](#))

Additionally, 4 hydrogen atoms are carried of by 2 NAD coenzymes, and potentially taken to the electron transport system for oxidative phosphorylation. Pyruvate, the final product of glycolysis, may also be converted to acetyl coenzyme A, and enter the Tricarboxylic Acid cycle, sustaining the process of cellular respiration.

Glycolysis is said to be controlled primarily by feed forward and feedback controls (Brooks, 2000). Feed forward control factors include stimulation of glucose uptake (i.e. muscular contraction) and glycogenolysis (by epinephrine and contractions). These factors speed glycolysis. Feedback controls refer to changes in levels of metabolites by glycolysis, such as a decline in blood glucose at the end of exercise. These can either speed or slow glycolysis.

Lastly, glycolysis is an exergonic reaction.

The following is a comprehensive 11-step analysis of glycolysis, after glucose or glycogen has entered the cytoplasm of the cell (Brooks, 2000; Plowman & Smith, 2001; Marieb 2001; and Frissel, 1982).

Step 1:

To begin, glucose is phosphorylated by the rate limiting enzyme hexokinase. In the process, adenosine triphosphate (ATP) is de-phosphorylated. This phosphate is then transferred to the sixth carbon of glucose, resulting in glucose-6-phosphate.

If your body instead utilizes glycogen, glycogenolysis occurs; either way, the same product—glucose-6-phosphate—is produced. In this event, the rate limiting enzyme glycogen phosphorylase degrades glycogen into the molecule glucose-1-phosphate, the enzyme phosphoglucomutase, and then transfers the phosphate bond from the first carbon of glucose to the sixth, forming glucose-6-phosphate. The advantage to using glycogen is ATP hydrolysis is not required, effectively sparing energy.

In review, phosphorylation refers to the addition of a phosphate group to a molecule. De-phosphorylation is the exact opposite; a phosphate group is removed from a molecule. Moreover, a rate limiting enzyme literally regulates the speed of a process. As the activity of these enzymes increases, the product increases; likewise, as the activity of these enzymes decreases, the rate of the process decreases.

In muscle cells, the electrical charge added to glucose (or glycogen) by phosphorylation traps the molecule within the cell. The reasons for this are twofold: first, the cell membrane is non-polar (has no charge), thereby prohibiting the charged glucose molecule from crossing the cell member, as the cell lacks transport mechanisms for phosphorylated molecules; secondly, the enzyme which is able to separate this bond does not exist in muscle cells. In the liver, however, (and to some extent, in the kidneys) the enzyme phosphatase is present and able to readily split the glucose-phosphate bond. Subsequently, glucose is de-phosphorylated; it may now leave the cell and enter the blood stream, where it is partitioned by the body to various sites.

This information is vital for the athlete. That is, glycogen depletion and supercompensation are specific to individual muscle groups. Moreover, in order for glycogen to be utilized during exercise, it must be already present within the muscle cell. It follows that depleting muscle glycogen stores must be done by training the specific muscle group. This is especially significant when considering that glycogenolysis (the catabolism of glycogen) is the preferred energy source for glycolysis during exercise.

Step 2:

Glucose-6-phosphate is now rearranged to form fructose-6-phosphate. The enzyme that catalyzes this reaction is called phosphoglucose isomerase.

Throughout this entry the reader will view the term, "isomer". An isomer refers to two or more molecules that have the same chemical formula but different atomic

arrangements. Enzymes, which catalyze these structural changes, are known as isomerases.

Step 3:

Fructose-6-phosphate is phosphorylated on the first carbon of the hexagon molecule, forming fructose 1, 6-diphosphate. The enzyme that catalyzes this is phospho-fructokinase (PFK). Consequently, this is the most essential rate-limiting enzyme in glycolysis. During this procedure, another ATP molecule is de-phosphorylated. To clarify the name of this new molecule, "1, 6" stands for the phosphate bonds attached to the first and sixth carbon of the fructose molecule; "di," meaning two, refers to there being 2 phosphate bonds.

Step 4:

The following event is the namesake of glycolysis, for here, sugar splitting—the meaning of the term "glycolysis"—transpires. Directed by the enzyme aldolase, the 6 carbon molecule, fructose 1,6 diphosphate, is split into 2, 3-carbon sugar molecules. While having identical component atoms, this duo differs in atomic arrangement; hence, two different names are given, these being dihydroxyacetone phosphate (DHAP) and glyceraldehyde 3-phosphate (G3P).

Step 5:

Here the enzyme Triose Phosphate Isomerase rearranges DHAP to form G3P.

Note: From this point on, every reaction occurs *twice*. However, they will only be listed *once* (with reminders given throughout); keep this in mind when calculating the following reactions.

Step 6:

Two conditional reactions occur next. First, G3P is oxidized by the hydrogen carrier nicotinamide adenine dinucleotide (NAD). NAD is subsequently reduced to NADH + H⁺. Following the energy released from the reaction, a second event results. The now oxidized form of G3P is phosphorylated on the first carbon by an inorganic phosphate—ever present in the cytoplasm—forming 1, 3-disphosphoglycerate. As noted above, this reaction occurs twice. And lastly, this reaction is catalyzed by Glyceraldehyde-3-Phosphate Dehydrogenase.

Venom (2003) explains the hydrogen carrier Nad as follows:

Niacin, also known as nicotinic acid nicotinamide and vitamin b 3, is a water-soluble vitamin, and a part of the b-complex.

Digestion

In the human body, niacin is broken down to Nicotinamide adenine dinucleotide phosphate (NADP), and nicotinamide adenine dinucleotide (NAD). These are the primary forms which niacin functions within the body...

Function

Almost 200 enzymes require NAD and NADP to function. To name a few B3 functions, NAD helps glycolysis, oxidation of pyruvate, acetyl CoA by the kreb cycle, and fatty acids. NADP assists with fatty acid synthesis, cholesterol and steroid synthesis, oxidation of glutamate, and DNA synthesis. Some enzymes which require NADP are glutathione reductase, dihydrofolate, and tetrahydrofolate [107,56,43,33].

NAD⁺ is a prime hydrogen carrier in glycolysis. This derivative of Niacin can accept two electrons and protons from two hydrogen atoms. It is composed of the nucleotides adenine and nicotinamide.

The term "oxidation" means the loss of electron atoms. "Reduction" describes a gain of electrons atoms.

Therefore, in the step 5, G3P is oxidized (loses electrons), while NAD is reduced (gains electrons).

It may seem odd that the term reduction is used, but think of it this way: electrons have a negative charge; therefore, by gaining electrons, the molecule effectively *reduces* its charge.

The final destination for the hydrogen atoms taken by NAD is the electron transport system, where oxidative phosphorylation takes place. Here, a multitude of ATP molecules are produced. This vital step of cellular respiration will be discussed in future entries. If the reduced form of NAD is unable to enter the electron transport chain, the result is pyruvic acid, which forms lactic acid.

NAD is often referred to as a taxi cab. It "picks up" hydrogen atoms (passengers; resulting in reduction) from one point, and drops them off (as a taxi cab would; resulting in oxidation) at another, without either participant being permanently changed.

Step 7:

Finally, the high-energy molecule ATP is formed! 1, 3-disphosphoglycerate is de-phosphorylated on the first carbon-phosphate bond by the enzyme Phosphoglycerate Kinase. This phosphate is transferred to an ADP molecule, resulting in ATP. Once again, this reaction occurs twice.

Step 8:

3-phosphoglycerate, the resulting product from the previous step, is rearranged to form 2 phosphoglycerate (G2P). Here the phosphate group is simply transferred from the third carbon to the second. This is catalyzed by phosphoglycerate mutase.

Step 9:

Catalyzed by the enzyme enolase, a water molecule is now removed, resulting in phosphoenolpyruvate. This causes the bond between the phosphate group and the remaining atoms in the molecule to be weakened.

Step 10:

The lone phosphate group is now transferred from phosphoenolpyruvate to an ADP molecule by the rate limiting enzyme pyruvate kinase. The end products are pyruvate and ATP.

Step 11:

Referring back to step six, if the hydrogen atoms picked up by NAD are not able to participate in oxidative phosphorylation, they are instead transferred to pyruvic acid (produced in step 10), resulting in the formation of lactic acid.

Now, glucose, the first molecule in this process, has a chemical formula of $C_6H_{12}O_6$, while pyruvic acid has the structure $2C_3H_4O_3$. The amount of oxygen and hydrogen atoms in these molecules is equivalent; however, pyruvic acid contains two less hydrogen atoms. These are the same atoms that NAD picks up in step six. If lactic acid is formed, then the result is $2C_3H_6O_3$; all original atoms are now accounted for. Additionally, both pyruvic and lactic acid contain carboxyl groups, that is, one of the oxygens is double-bonded to a carbon atom; another oxygen molecule is single bonded to the carbon on one side, and single bonded to the hydrogen on the other; and the remaining bond on the carbon atom is attached to the rest of the molecule.

This is a reversible reaction, which means that lactate can be reconverted to pyruvate. The enzyme which catalyzes step 11 is called lactate dehydrogenase, which is a vital rate limiting enzyme, discussed profoundly further on in this entry, in addition to the final destination of lactic acid.

Lastly, pyruvate can be used for the formation of acetyl coenzyme A, which then enters the Krebs Cycle.

Control of Glycolysis

As previously discussed, feedback and feed forward control systems primarily regulate the rate at which glycolysis runs. This next section will be comprehensive analysis of several of these elements (Brooks, 2000).

Phosphofructokinase

PFK is the most essential rate-limiting enzyme in glycolysis; this falls under the category of feedback control. PFK is a multivalent, allosteric enzyme, which means that numerous metabolites can bind to it and influence its catalytic capacity. High levels of ATP, CP, and citrate slow PFK activity. Citrate is the first product in the Tricarboxylic Acid Cycle (also known as Krebs and citric acid cycle). It therefore follows that aerobic metabolism can lower anaerobic metabolism from the formation of citrate. These modulators are high during rest; however, when exercise starts their activity subsequently decreases, promoting the activation of PFK. Some stimulators of PKF are ADP, AMP, Pi, and elevated Ph and ammonia.

Glycogenolysis

At rest, glycogen catabolism is minimized; contrary to this, anabolism is often prevalent. As such, during rest glycolysis utilizes glucose at a heightened extent. During exercise, however, this is not the case. Glycogen catabolism is immensely accelerated during physical events, and subsequently becomes the dominant source of fuel for glycolysis. In fact, during steady exercise at 65% VO₂ max, glycogenolysis can surpass muscular glucose absorption by 5 times. This again solidifies the importance of having high glycogen stores to maximize exercise performance. Incidentally, glycogen depletion results in extreme muscular fatigue (Wilson, 2003 Precontest Preparatory Strategies).

Lactate Dehydrogenase

LDH is the rate-limiting enzyme responsible for the production of lactic acid from pyruvic acid. The rate of lactic acid production is highly dependent on this enzyme, and its respective isoenzymes. This enzyme and its regulation are discussed in-depth further on.

Pyruvate Dehydrogenase

Along with the aforementioned rate-limiting enzyme, this will be discussed thoroughly later in this entry.

Hexokinase & Pyruvate Kinase

Hexokinase is the first rate-limiting enzyme in glycolysis, and is responsible for the phosphorylation of glucose into glucose-6-phosphate. Consequently, its rate is inhibited by the production of the later molecule, but enhanced by the former. Pyruvate Kinase is responsible for the production of pyruvate and ATP in step 10. Its rate is inhibited by ATP and CP, and increased by the production of phosphoenolpyruvate.

Efficiency of Glycolysis

Many falsely claim that glycolysis is an "inefficient" energy pathway, as only 2-3 molecules of ATP are generated. However, this could not be farther from the truth. Glycolysis is in fact very efficient.

The energy transformation (ΔH) from glucose to lactate is $-47\text{kcal}\cdot\text{mol}^{-1}$. The amount of free energy (ΔG) produced from glycolysis is $11\text{ kcal}\cdot\text{mol}^{-1}$ of ATP. When 2 ATPs are formed, calculations find that:

$$\text{Efficiency} = \frac{2 * -11}{-47} = .47 * 100 = 47\%$$

-47

20% efficiency is considered incredible. Glycolysis has nearly 50% efficiency! This is a great amount of energy conserved. Indeed, glycolysis is a very efficient pathway.

The Time Energy System Continuum

The manufacture and utilization of ATP occurs through three energy systems: the phosphagen system (ATP-PC), glycolysis, and the oxidative system. The sequence at which these energy systems are recruited is known as the "Time Energy Continuum" (Plowman & Smith, 2001). The following section will analyze which systems predominates in a given event; particular emphasis will be placed on anaerobic metabolism.

The first two energy systems discussed—ATP-PC and glycolysis—are known as anaerobic systems, as they do not utilize oxygen. Conversely, the oxidative system does utilize oxygen, and is therefore termed aerobic. When the phrases "aerobic" and "anaerobic" exercise are used, they refer to which energy systems dominates, not which one exclusively is utilized, as all 3 are used for all exercise modalities.



The anaerobic systems are delineated by lactic acid production. The ATP-PC system does not produce lactic acid, while glycolysis does. As such, these pathways are referred to as alactic and lactic anaerobic, respectively.

In addition to these energy pathways, the body stores a small amount of ATP, which can be used for 1-2 seconds of maximal work. Afterwards, the byproduct ADP can be instantaneously phosphorylated by phosphocreatine, effectively reforming ATP. There is roughly triple the amount of PC than ATP in the muscle. Stored ATP is utilized whenever energy demands increase. Be it typewriting, turning a page, or lifting a weight, a portion of the energy provided will be from this stored form of ATP, which subsequently is replenished. This system predominates for approximately 10 seconds of all out exercise, after which glycolysis begins to dominate.

When the need for ATP surpasses the capacity of alactic anaerobic metabolism and the aerobic system, glycolysis becomes the dominant energy supplier. Together, anaerobic metabolism is chiefly utilized for exercise lasting less than 2 minutes.

After 5 minutes of exercise, the oxidative system—consisting of the Krebs cycle and oxidative phosphorylation—becomes dominant. The longer exercise lasts, the more this system is utilized.

Astrand and Rodhal (1977) and Gollnick and Hermansen (1973) have reviewed the time energy continuum at various intensities. Evidence indicates that in the first 10 seconds, the phosphocreatine system is dominant; at 30 seconds, anaerobic metabolism is called upon for 80% of the energy requirements, but glycolysis is now much more prevalent. At this point, 33% of the energy is supplied by the alactic anaerobic system and 47% by glycolysis. At one minute, glycolysis is used at a slightly heightened extent, as well as aerobic metabolism, while the ATP-PC system continues to decrease. At five minutes, aerobic metabolism dominates as much as anaerobic metabolism did at 30 seconds. Now, 80% of the energy utilized is from aerobic work, and approximately 20% is from anaerobic metabolism; 3, and 17% coming from phosphocreatine and glycolysis, respectively. The longer exercise continues the more aerobic metabolism is called upon. It should be noted that these results can and do vary among individuals; however, this is generally an accurate account.

Ergogenic Aid

Supplementation with creatine can change the time energy continuum so that the ATP-PC system is predominantly relied upon for an extended period of time, effectively enhancing athletic performance. For more on the benefits of creatine, refer to Wilson (2001, [Creatine Myths And Facts.](#))

Anaerobic Metabolism

No sufficient procedure exists to directly measure the amount of energy anaerobic metabolism contributes to exercise. Two indirect approaches exist, however. The first estimates how much work was done, or the power produced during a short duration, high intensity activity. The second monitors changes in chemical substances which are produced by glycolysis (lactic acid) and alactic anaerobic metabolism (ATP and PC levels).

Analyzing PC and Lactate levels

The most often used measure of blood lactate levels is taking a blood sample of the participant. This is done by either venipuncture (the puncture of a vein with the purpose of obtaining a blood sample) or finger prick. This method is very cheap, as well as accurate, and easy to use; thus, it is quite popular.

The reason blood tests are used is that lactic acid ($2C_3H_6O$) at normal pH values dissociates in the blood stream into hydrogen ions and lactate ($C_3H_5O_3^-$). Though lactate and lactic acid are different compounds, they are often used interchangeably. Properly though, lactate is the salt of the acid. Consequently, the same logic applies to pyruvic acid, which is also used interchangeably with its respective salt pyruvate (Brooks, 1985).

From here, lactate values are measured from blood samples. It's important to note that it takes a bit for lactate to reach the blood stream from the muscle cell (approximately 5-10 minutes). Therefore, highest levels of lactate must be viewed within several minutes into recovery, rather than during exercise.

The measurement for lactate is usually measured by millimoles per liter. Resting levels of lactate are around 1-2 mmol.L. Eight mmol.L-1 usually represents the maximum work of an individual. However, values up to 32 mmol.L have been reported.

Muscle biopsy (a procedure in which a small amount of muscle is removed for an analysis) is also used to measure ATP-PC and lactate values, but this is a more complicated and costly procedure, and therefore not used as often.

Anaerobic Power and Capacity

When speaking of energy systems, the term "capacity" means the total amount of energy which can be produced by a particular energy pathway. While "power" refers to the maximal amount of energy that can be produced per unit of time. The rank of power from high to low is: ATP-PC, glycolysis, and aerobic. The system with the most capacity, accordingly, is the exact opposite: aerobic, glycolysis, and ATP-PC.

The following is a chart of the capacity and power of the three energy systems in untrained individuals (Bouchard, Taylor, & Dulac, 1991):

Table 1 Time Energy System Continuum Power and Capacity			
Energy Pathway	Capacity	Power	Time
	Kcal	Kcal.min ⁻¹	Hr:min:sec
Aerobic System	359-1268	7-19	2:21:0
ATP-PC	11	72	0:0:10
Glycolysis	48	36	0:1:20

Table 1 illustrates the ATP-PC system has a high power ranking of 72 kcal per minute. However, it can only sustain this for approximately 9-10 seconds, resulting in a capacity of only 11 kcal. This is calculated by dividing 72 (power) by the time span (one minute) resulting in 1.2 kcal per second. Further dividing 11 (capacity) by 1.2 gets the result 9.17 seconds, or 11kcal produced in 9-10 seconds.

Glycolysis has less power, but more capacity than the lactic acid system. In total, it can manufacture 36 kcal per minute; but, it can maintain this power for 1 minute, and 20 seconds, resulting in 48 kcals.

The aerobic system has the lowest power at 7-19 kcal per minute, but by far the highest capacity. When using only carbohydrates, the oxygen system can maintain its power for 2 hours, resulting in 360-1268 kcals. When all fuels are taken into account, this system can potentially last for hours on end.

Measuring Anaerobic Pathways

As stated previously, no experiment exists that can directly measure power and capacity. Instead, indirect tests are performed by 3 means:

1. The time required to perform a given amount of anaerobic work.

2. The total mechanical power produced during high intensity, short duration work.
3. The amount of mechanical work done in an allotted period of time.

Two commonly used tests are the Maragariat-Kalamen Stair Climb, field tests, and the Wingate Anaerobic Test (WAT) (Bouchard, et al., 1982)

Note:

The following section will continue various calculations; whenever you see a “” between numbers, this represents per unit of time.

Maragariat-Kalamen Stair Climb

Lasting for approximately five seconds, the Maragariat-Kalamen Stair Climb is a short, explosive test used primarily to test the ATP-PC system (Bouchard, et al., 1982).

To perform this test, the participant runs for 6 meters on level ground, and then climbs a staircase, taking three steps each time. Power is calculated by kilogram-meters per sec using measurements of the subjects' weight, vertical height between the third and ninth steps, and the amount of time it takes to reach from the third, to the ninth step.

Field Experiments

Vertical jumps, sprints, and short distance runs are sometimes used to test anaerobic power and capacity.

For vertical leaps, several modalities are used. Sometimes the contestants use their arms, or do not. Often the test will be performed on a force platform, and power values are calculated. Also, it may be performed on the field to test work (force*distance). It is important to note that the height of vertical jump and peak power determined by force plate information are highly correlated ($r=.92$). As such, vertical leap height is an acceptable measurement of anaerobic alactic power (Vandewalle, et al., 1987).

Sprints are related to all out activities. Runs cover short time distances, and can therefore be used to test anaerobic metabolism. Sprints under 15 seconds can cover the alactic system, while sprints from 30-120 seconds can indicate LA power and capacity. Faster speeds would indicate enhanced power and/or capacity.

Note:

Though these are generally utilized, because of specificity, anaerobic power is best measured using similar procedures within the criterion task (i.e. power on a bench press, tests power on the bench press).

Wingate Anaerobic Test

The Wingate Anaerobic Test is probably the most well-known and useful modality for testing anaerobic capacity and power. Moreover, many participants claim that this is the cruelest anaerobic test in existence. It consists of a 30 second all out ride on a bicycle ergometer, with resistance according to body weight. It is short, but quite effective for tearing muscle fibers and testing anaerobic energy systems at various levels. Resistance for children, adult females, and adult males are .0075, .086, and .095 kilograms per kilogram of body weight, respectively. Athletes may need as much as .1 kg.kg⁻¹ of body weight. Additionally, the revolutions of the flywheel are counted per second amidst the experiment. Computer-generated results determine 3 distinct variables from the experiment. These are: mean power, fatigue index, and peak power (Plowman & Smith, 2001).

"Mean power" refers to the average power (force*distance/time) exhibited during short (30 seconds) work. "Fatigue Index" means the percentage of peak power drop off amidst high intensity, short duration work. And lastly, the term "peak power" is defined as the maximal power performed during only 5 seconds of work. These variables are calculated accordingly:

1. Mean Power (kgm per 30 sec) = the total amount of revolutions in 30 seconds*distance that the flywheel travels per revolution (m)* force settings (kg). This can also be expressed as $MP = \text{revolutions (total) in 30 sec} * D.REV-1 * F$
2. Fatigue Index (%) = $[1 - (\text{lowest power kgm.5 seconds}^{-1} \%(\text{peak power kgm.5 seconds}^{-1})) * 100$ or $FI = [1 - (LP/PP) * 100$.

Note:

Calculating the lowest power is the same as peak power, except you would use the lowest power during 5 seconds of a 30 second ride instead of the highest power; this would typically be the last 5 seconds of the ride rather than the first 5 or so seconds, as you would use with peak power.

3. Peak Power (kgm.5 seconds⁻¹) = maximal revolutions in 5 sec*distance that the flywheel travels per revolution (m)*force setting (kg) or $PP = \text{rev (max) in 5 sec} * D.rev-1 * F$

Mean Power

Using the samples of 58.45 revolutions per minute, a flywheel distance of 9 meters per revolution, and 7 kg of resistance, here is an example of this method:

$$MP = 58.45 \text{ rev} * 9 \text{ m.rev}^{-1} * 7 \text{ kg} = 3682.35 \text{ kgm.30 seconds}$$

Translated to one minute, this would be:

$$MP = 3682.35 \text{ kgm.30 seconds} * 2 = 7364.7 \text{ kgm.minute}^{-1}$$

According to body weight (using the measurement for athletes; 7kg/.1=70kg) this would be:

$$7364.7 \text{ kgm.minute}^{-1} / 70 \text{ kg} = 105.21 \text{ kgm.min}^{-1} \cdot \text{kg}^{-1}$$

Using a measurement of watts (one watt=6.12 kgm.min⁻¹):

$$105.21 \text{ kgm.min}^{-1} \cdot \text{kg}^{-1} / 6.12 \text{ kgm.min}^{-1} = 17.2 \text{ W.k.g}^{-1}$$

Since the time energy continuum for glycolysis is dominated at 30 seconds, this variable is often used to determine LA anaerobic capacity.

Fatigue Index

With the stats of the 300 kgm of peak power in 5 seconds, and 150 kgm of lowest power per 5 seconds, here is an example of fatigue index:

$$[1 - (150 \text{ kg} \cdot 5 \text{ sec}^{-1} / 300 \text{ kg} \cdot 5 \text{ sec}^{-1})] * 100 = 50\% \text{ FI}$$

The Fatigue index is a measure of the peak power drop of during high intensity, short duration work. This index, in theory, would determine glycolytic power.

Peak Power

Here is an example of Peak Power in 30 seconds, using the numbers given in the aforementioned variables, with the additional statistic of 4.8 maximal revolutions per five seconds:

$$PP = 4.76 \text{ rev} * 9 \text{ m.rev}^{-1} * 7 \text{ kg} = 300$$

To convert this relative to body weight, watts, or to a minute, use the same calculations listed under MP.

Peak power is primarily used to determine alactic capacity. However, results show that a significant amount of lactic acid can be produced with 10 seconds of high intensity work (Bar-Or, 1987). Therefore glycolysis, by necessity, occurs immediately with the alactic acid system. As such, peak power is not solely a determinate of alactic capacity, but is nonetheless a useful methodology.

Note:

Though the Wingate test is primarily a measure of anaerobic power and capacity, the aerobic system does participate (from 13-30%) during this 30 second ride.

It is still an excellent modality, however, and compares favorably with other solidified tests of anaerobic power and capacity (correlations rank above .75) (Patton and Duggan, 1987).

Conclusion

The anaerobic systems are an integral part in supramaximal exercise modalities. A clear understanding of these systems will afford the athlete a needed edge for manipulative and training strategies.

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