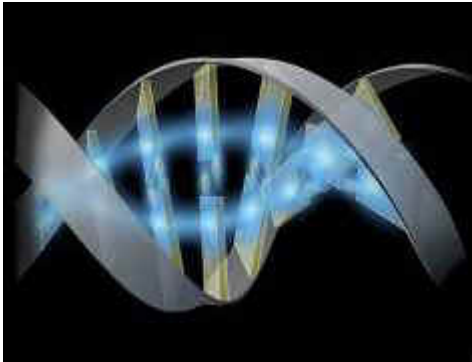


Analysis of Nutrient use during Low, Moderate, and High Intensity Exercise



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Abstract

Fuel utilization during exercise is coordinated through an exquisite array of mechanisms which are carried out through neural, hormonal, and muscular systems. The nervous system's role is to select out and recruit muscle fibers which have the proper enzymatic milieu to accommodate a given intensity. From an endocrine standpoint, hormones are secreted which modulate these transient neural adaptations to specific training protocols. Finally, on a cellular level, the muscle fiber provides the means to perform extraneous work loads, and is equipped with localized and highly responsive machinery which act acutely to absorb needed fuels, even in the absence of outside influence. The purpose of this paper was to review how nutrients are supplied and utilized during low, moderate, and high intensity exercise selections.

Low Intensity Exercise Performed Below 50 % Maximal Oxygen Consumption

Slow Twitch, Type I Oxidative muscle fibers are preferentially recruited during low intensity exercise (Sale, 1987). These cells are characterized by high mitochondrial density, and an extreme array of enzymes conducive to the oxidation of triglycerides (TGs). Evidence suggests that over 80 % of fuels used from Type I cells come from TGs (Romijn et al. 1993). These TGs are supplied both exogenously (from an outside source) from blood plasma as well as endogenously (from an inside source) from a tremendous store house of intramuscular lipids. They are termed slow fibers, due to their so called 'slow' myosin ATPase enzyme, which catalyzes the reaction that breaks down ATP to elicit muscular contraction. The slow myosin ATPase breaks down ATP in a relatively longer time frame than the fast myosin ATPase expressed in Type II fibers (brooke et al. 1970, Pette and Staron,

1999, Hamilton *et al.* 1998, Wilson 2002). Finally, from a neurological standpoint, these fibers are innervated by low threshold moto neurons, and are therefore recruited preferentially for low intensity movements (Sale, 1987, Wilson 2001).

The ability of Slow Twitch fibers to extract peripheral nutrients is uncanny. They are equipped with a tremendous supply of lipoprotein lipase (LPL) (Bey and Hamilton, 2003, Hamilton *et al.* 1998; Ladu *et al.* 1991,) hexokinase (HK) (Saakian *et al.* 1977), and glucose transporters (GLUT) (Slentz 1992, Henriksen *et al.* 1990, Kern *et al.* 1990) . A 7 fold greater concentration of LPL in slow oxidative fibers compared to fast white fibers has generally been found (Bey and Hamilton, 2003, Hamilton *et al.* 1998; Ladu *et al.* 1991). Further, Kern *et al.* (1990) investigated the concentration of GLUT-4 transporters and GLUT-4 mRNA in red and white muscle fibers. It was found that red (type I) muscle fibers had 5 times the concentration of Glut-4 receptors and two times the amount of Glut-4 mRNA than white muscle tissue. Additionally, Saakian (1977) found several times higher concentration of hexokinase in slow twitch than fast twitch fibers. Recall, that in order for glucose to enter the cell and be utilized, HK must first add a phosphate group to the sixth carbon of the molecule. HK is regulated by negative feedback, meaning its product-glucose 6 phosphate inhibits its action. However, during exercise, glycolysis is rapid enough to keep this from happening. Also recall that HK has a low KM, meaning it can take in and phosphorylate glucose at extremely low concentrations, which is needed for exercise. This along with a rich supply of glycogen stores provides the energy needed for slow twitch fibers to resist fatigue.

During exercise at 25 % VO₂ max, over 85 percent of energy is derived from peripheral fatty acids (circulating fatty acids from adipose tissue) (Romijn *et al.* 1993). Other fuels are derived equally from stored lipid droplets, and circulating blood glucose. Fuel use is also time dependent. As time increases, the preferential use for peripheral fatty acids increases. In this context, Ahlborg *et al.* (1974) investigated the effect of duration on substrate utilization during exercise. Participants consisted of six healthy male volunteers, who were analyzed following a continuous bicycle ride for four hours at 30-40% of their VO₂ max. At the onset of the exercise session, 40 % of fuels were derived from peripheral fatty acids; however, at approximately 4 hours time this had shifted to 60 %. It was also found that glucose uptake peaked at 90 minutes, providing approximately 41% of fuels; conversely, this rate steadily declined as exercise continued, dropping to approximately 30% at 4 hours. At 4 hours, hepatic glycogenolysis had provided approximately 75 grams of glucose. Of this, only 15-20 grams had been derived from gluconeogenesis. Therefore peripheral glucose production was dominant from hepatic glycogenolysis. However, the contribution of hepatic gluconeogenesis increased as exercise duration increased. At 40 minutes of exercise, gluconeogenesis accounted for approximately 25% of hepatic glucose release, while at 4 hours, it rose to 45% of total glucose release. These results occurred for several reasons. First, liver glycogen is limited to approximately 75-90 grams. As these stores decline, the body must rely more heavily on gluconeogenic processes to maintain hepatic glucose production. This in large part can be attributed to lowered plasma glucose levels, and subsequent increases in GH, glucagon, and cortisol. Glucagon stimulates the uptake of amino acids by the liver, while cortisol stimulates protein catabolism in muscle tissue (Wilson and Wilson, 2005).

Fuel consumption is also a consequence of hemodynamic (pertaining to blood flow), contractile, and endocrine mechanisms. What is not realized by most is that insulin

under conditions of low intensity, plays a considerable role in a slow twitch fiber's ability to take in and utilize glucose (recall that glucose provides about 7-10 % energy at 25 % V_{O2} max). Slow fibers contain a tremendous supply of capillaries and are very sensitive to insulin's actions (Pette Peuker and Staron, 1999, Henriksen et al. 1990, James et al. 1985, Kern, 1990). James et al. (1985) investigated the effect of insulin administration on glucose uptake and glycogen storage in the soleus which is primarily comprised of slow twitch fibers, the deep aspect of the medial red gastrocnemius which contains primarily type II intermediate or oxidative fast twitch muscle fibers, and the lateral white aspect of the gastrocnemius which contains primarily fast twitch II b muscle fibers in rats. It was found that the lowest levels of insulin were required to stimulate half of the maximal glucose uptake in the soleus, followed by the medial red gastrocnemius. The greatest amount of insulin needed to stimulate half of the maximal glucose uptake was found on the lateral white gastrocnemius. It appeared that the amount of insulin needed to stimulate intermediate fibers was twice that of slow type one fibers. This doubling rate was also found from intermediate to fast twitch type IIb fibers.

Glucose uptake and glycogen storage was highest in the soleus, intermediate in the medial gastrocnemius, and lowest in the lateral gastrocnemius. These findings strongly suggest a relationship between fiber composition and the effect of insulin in muscle tissue. With greater sensitivity being found in slow type one fibers, than fast type II fibers.

Interestingly enough, there appears to be a significant correlation between muscle fiber type and obesity. Those who are obese show a lower percentage of type one fibers than non obese individuals(Hickey, 1995, Tanner et. al 2002). This is attributed to a greater insulin sensitivity and subsequent control of glucose levels by the non obese.

Insulin levels lower proportionally to exercise intensity, as catecholamines depress this hormone at higher thresholds. However, even at lower levels cardiac output has increased. Cardiac output is a measure of how much blood is circulated throughout the body per minute. At higher cardiac outputs, blood transit time (the time blood stays in a certain region) is faster through capillary beds. However, localized metabolic consequences of muscular contraction and higher energy use increase transit time through the stimulation of vasodilatation of capillaries. For example, lowered concentrations of oxygen, and higher concentrations of CO₂ serve as potent stimulators. Therefore slow twitch fibers receive a greater supply of blood. Further, even at lower levels of insulin, a greater blood supply exposes these fibers to enough concentration to allow for several positive energetic insulinogenic effects (this is in large part due to their high sensitivity to the hormone). One such effect is a further increase in capillary transient time by increasing vasodilatation via nitric oxide utilization (Baron, 1995, Lembo, 1997 Steinberg et al. 1994, Scherrer, 1994,). As an illustration, James et al. (1985) found a significant relationship between insulin sensitivity in the musculature and blood flow to the region. A greater blood supply and expansion of the capillaries allows for greater uptake and utilization of nutrients, and oxygen, as well as disposal of metabolic by products. Additionally, Insulin stimulates the expression of GLUT-4 transport proteins in the cell membrane of muscle fibers, while simultaneously up regulating the activity of HK. This action works synergistically with muscular contraction (Nuutila, 2000), which also stimulates the translocation of GLUT-4 receptors(Dela, 1994, Friedman, 1990, .Host, 1998, Rodnick, 1992). During exercise ATP is used for energy at a higher rate.

When this occurs a build up of ADP occurs in the cell. One mechanism which reforms ATP, is to combine two ADPs to form one ATP and one AMP. An increase in AMP, activates a protein kinase, which is responsible for stimulating the translocation of GLUT-4 receptors to the cellular surface. This is known as AMP activated protein kinase (AMPK). It is unique in that it acts as machinery which senses intracellular energy levels. In fact, it has been termed the "fuel gauge" of the mammalian Cell (Paulsen et al. 2001, Hardie et al., 1997). As energy decreases, AMP increases. Increased AMP, activates AMPK, as it is an allosteric enzyme (Cortin, 1994, Hardie et al., 1997 , also see Wilson and Venom 2004, Energetic Transference Occurring in the Biosphere Part I for more on allosteric enzymes). The opposite decreases AMPK. This accounts in large part for the ability of Type I fibers to utilize peripheral glucose. As an illustration, Paulsen et al. (2001) investigated the effect of muscular denervation and Glut-4 expression. A decrease in AMPK activity was found in both the denervated gastrocnemius. Concurrently a 40 percent decrease in Glut-4 levels was found in the gastrocnemius. To test the relationship, AMPK was chemically activated. After AMPK activation, it was found that the decline in GLUT-4 levels was prevented in the denervated gastrocnemius muscles. In another study Kurth-Kraczek et al. (1999) investigated the effect of increasing AMPK activity on GLUT-4 expression in the cell membrane. It was found that as AMPK activity was increased, GLUT-4 translocation increased.

However, as stated the majority of the fuel utilized comes from fat oxidation. Numerous mechanisms are responsible for this. One such mechanism is the suppression of acetyl coenzyme A carboxylase (ACC). ACC is responsible for the formation of malonyl coenzyme A, which blocks carnitine transferase (Merrill et al.1997, Merrill et al. 1999,). Carnitine transferase is responsible for transporting fatty acids into the mitochondria for oxidation (Kudo et al., 1995, Lopaschuk et al., 1994, McGarry et al., 2002, McGarry et. al.,1997, McGarry et al., 1983.) Evidence suggests that muscular contraction inhibits ACC activity (Dean et al., 2000, Rasmussen et al., 1998, Rasmussen et al., 1997, Ruderman et al., 1999, Saha et al., 2000). It appears that AMPK may be responsible for the decrease in activity. Winder and Hardy (1996) investigated AMPK's effect on ACC. It was found that in vitro AMPK added a phosphate group to ACC. As ACC was phosphorylated, its activity decreased. As ACC lowers, its product malonyl coenzyme A decreases. As a consequence, carnitine transferase activity increases, meaning a proportional increase in fatty acid transport and utilization for energy. Muscular contraction also activates hormone sensitive lipase (HSL) (Langfort *et al.* 2000), the enzyme responsible for the breakdown of TGs into fatty acids and glycerol. Donsmark et al. (2003) found that calcium activated protein kinase C, which is activated by an increase in concentration of calcium(as the name indicates) can activate HSL. Calcium concentration increases as muscular contraction increases.

Slow Oxidative fibers contain a vast supply of beta andrenergic receptors. Martin et al.(1989) investigated the concentration of beta receptors in slow red fibers and white fast fibers. This was conducted by analyzing the soleus, which is comprised almost entirely of slow twitch fibers, and the vastus lateralis, which is superficial and comprised of 95 % fast twitch muscle fibers. The tissue concentration in beta receptors was three times greater in the soleus than the vastus lateralis. Therefore, increased transit time of blood flow, combined with an increase in catecholeamine concentration drastically enhances lipolysis. As catecholamines stimulate HSL and LPL in the musculature (Langfort, 1999). The combination of muscular contraction, as well as catecholeamine concentration overrides the antilypolytic action of insulin.

During low intensity exercise, epinephrine levels nearly double, which again acts on the high concentration of beta two receptors in skeletal muscle (Romijn et al. 1993). Further, sympathetic nervous system (SA) activity increases in its innervation of adipose tissue. Sympathetic nerves discharge approximately once per second during low intensity training on adipose tissue, which provides a high lipolytic effect on adipose, yet it is not enough to cause vasoconstriction of the arteries to these regions (Fredholm and Rosell 1967, 1968). Therefore TGs are catalyzed to free fatty acids and glycerol at a higher rate, without inhibition of blood flow. This provides for a greater concentration of plasma TGs.

Cortisol is a hormone which is secreted in response to various stressors. In the case of exercise it is dependent on intensity. In a landmark study Davies and Few (1973) investigated the effect of exercise intensity on plasma cortisol secretion during one hour of treadmill walking/running. They found that at low intensity exercise of less than 50 % $\dot{V}O_2$ max, under normal conditions that cortisol levels actually showed a decrease relative to resting levels. They attributed this to either (a) a decrease in secretion rate, or (b) an increase in plasma clearance rate. It appears that during low intensity exercise, that cortisol plasma concentration is therefore dependent on metabolic need. This also appears to be the case during moderate intensity exercise. Sotsky et al. (1989) investigated the effect of hypoglycemia on moderate intensity exercise, below 60 % $\dot{V}O_2$ max over 50 minutes of cycling in participants with normal blood glucose levels of 87 mg / dl, and in participants with low blood glucose levels of 59 mg / dl. No significant difference in cortisol levels were found in the normal glucose condition, while a 400 % increase was found in the low glucose condition. Therefore it appears that under normal dieting conditions that cortisol secretion may not significantly rise during an hour of low intensity exercise, suggesting that it is an effective tool for fat metabolism, without high catabolic effects. Growth hormone, and glucagon also appear to rise primarily due to metabolic need. For example, in the same study, GH and glucagon did not increase at moderate intensity significantly during the normal glucose level condition. However, they increased by 100 % for glucagon, and 150 % for GH during the low glucose condition. This was in agreement with the Ahlborg et al. (1974) study, who found that counterregulatory hormones rose with metabolic need. It was noted that when the liver was depleted after 4 hours of exercise, that the counter regulatory hormone response was similar to fasting conditions.

As further evidence for the catabolism of training in a depleted state, Bjorkman et al. (1983) reported on the effect of depleting the liver of glycogen stores on glucose output during exercise. It was found that the liver only released 40 % of the glucose that it normally would have, even after a night of fasting! Further, in this state, the output is entirely by gluconeogenesis. Therefore muscle protein catabolism at low intensities is proportional to blood glucose levels, which in large part is proportional to hepatic glycogen stores. Finally, during low intensity exercise, type one fibers are selectively depleted of glycogen, while fast twitch are spared (*Krustrup, 2004*).

Intermediate Intensity exercise

Intermediate intensity exercise (50 to 75 %) $\dot{V}O_2$ max recruit a higher proportion of fast twitch IIa fibers. During this time, more fuel is derived from intramuscular stores than low intensity exercise. At approximately 65 % $\dot{V}O_2$ max, fuel is derived from approximately 50 % fats, and 50 % carbohydrates. Of this, fatty acids are derived in nearly equal measure from peripheral and endogenous (intramuscular)

TGs, while the majority (80%) of glucose is derived from intramuscular fuels, with only 20% from the periphery (Romijn et al. 1993). Of the 20% glucose released by the liver, approximately 15% of it is from gluconeogenesis (Ahlborg et al., 1974, Ahlborg and Felig, 1982,). However, again such fuel use is also time dependent. For example, after two hours of exercise TGs become dominant from peripheral fuels compared to endogenous fuels. Twice the amount of peripheral fatty acids are used relative to intramuscular fatty acids which may be due to depleted intramuscular TG stores. Depletion of glycogen also increases use of peripheral fuels. Ahlborg and Felig (1982) performed a similar study to the Alborg et al. (1974) study, with the exception that exercise was performed at 59% $\dot{V}O_2$ max. Because exercise intensity was higher than low protocols (30-40% performed in Alborg et al. 1974), 75 grams of glucose was released by the liver in 3 instead of four hours. After this amount of time, the level of liver depletion, like low intensity exercise, increases the rate of gluconeogenesis. This is in large part due to increasing cortisol levels due to lowered plasma glucose, as well as increased glucagon levels (see below). Up to

60% of fuels at this time are produced by gluconeogenesis. During this study, plasma glucose levels rose from the onset of exercise and peaked at 90- minutes of exercise. However, by 3.5 hours of cycling, blood glucose levels had decreased to hypoglycemic levels. The decline was most rapid from 120 – 180 minutes, and was associated with the lowest outputs of glucose from the liver, due to the extreme and catabolic reliance on gluconeogenesis. Further, the fall in plasma glucose was 40% lower after 3 hours than it was at low intensity exercise.

Type IIa fibers contain an enzymatic environment which is between slow oxidative and fast glycolytic fibers (Wilson, 2001). That is, they are equipped to utilize both aerobic and anaerobic fuels in almost equal measure, which reflects the above statements. They are rich in glycogen, and are also sensitive to the effects of insulin. During intermediate exercise catecholamine levels rise up to six times resting levels (Romijn et al. 1993). Catecholamines stimulate glycolysis through activation of the enzyme glycogen phosphorylase (Langfort, 2003). This, coupled with their rich supply of glycogen explains the high use of this fuel during exercise. Fast Twitch Oxidative fibers also have a rich supply of LPL, and intramuscular lipids.

Though they are still highly dependent on metabolic needs, it does appear that moderate intensity can elicit an increase in both cortisol and GH. For example, in the study cited earlier, Davies and Few (1973) found a significant increase in cortisol after a 60% threshold in $\dot{V}O_2$ max intensity. During intermediate intensity, catecholamines are also high enough to significantly reduce plasma insulin levels. Insulin antagonizes glucagons (suppresses it). Therefore, glucagon becomes hyper responsive to any drop in plasma glucose levels. Intermediate intensity exercise depletes both type I and type IIa muscle fibers of glycogen stores.

High Intensity Exercise

Exercise above 80 percent $\dot{V}O_2$ max obtains approximately 75% of its energy from carbohydrates, of which 80% comes from intramuscular glycogen stores. The remaining 20% are released by the liver. Though the liver provides 20 percent of CHO, only 1% of the total glucose production is from gluconeogenesis. Intramuscular lipid stores provide 7 percent of energy, while peripheral FFA's provide the remainder of energy (Romijn et al., 1993; Ahlborg et al., 1974). The closer intensity is to 100% $\dot{V}O_2$ max, the greater the recruitment of type IIb, fast glycolytic muscle fibers is

(Wilson, 2002, Muscle Fibers Part Two). Type II b fibers contain low intramuscular triglyceride stores and therefore are not dependent to a large degree on fatty acid utilization (Essen et al., 1975). Further, they are resistant to insulin and catecholamines in that they do not express a great number of receptors for these hormones (Greenhaff et al. 1991). Recall that catecholamines are perhaps the number one lipolytic hormone in the body. Blood flow and nutrient exchange is also lower to these fibers as they have a low capillary density (Saltin et al., 1977; Wilson, 2002, [Muscle Fibers Part Two](#).)

Insulin resistance is strongly correlated to a preponderance of highly glycolytic, relatively insulin-insensitive fast twitch fibers as well as a low density of muscle capillaries. The nature of the relationship between these observations has been attributed in large to small amounts of capillarization in type II fibers (Holmang et al, 1993). Lillioja et al. (1987) investigated this hypothesis. They compared the capillary density and muscle fiber type of the vastus lateralis with in vivo insulin action in 23 Caucasians and 41 Pima Indian non diabetic men. They found a significant correlation between high capillary densities in slow twitch fibers and insulin sensitivity. Conversely, they found that low capillary density in IIB fibers was highly correlated with insulin resistance. Now, as you recall, nutrient exchange only occurs at the capillaries. Thus, the authors hypothesized that these results could be a product of decreased diffusion rates of glucose and insulin to parts of the muscle cell. Additionally, results demonstrate that in obesity, there is an increase in II b fibers, and consequently a decrease in capillarization (Lillioja et al., 1987). They therefore, propose that the slower response of insulin observed in obese subjects is due in part to the increased diffusion distances for glucose and insulin.

Consequently, type IIb cells contain a vast supply of glycogen and enzymes for the anaerobic energy yielding glycolytic pathway (Baldwin et al., 1973). Glycolysis, by definition is an anaerobic process. For this reason, it is scientifically fallacious as well as wholly invalid to use the term 'aerobic glycolysis' as if such a process existed. Moreover, it is tautologous (redundant, a needless repetition of an idea, statement, or word) to say 'anaerobic glycolysis' since glycolysis is always anaerobic. In reality, absolutely no oxygen is used in this pathway (See Bioenergetic transference in The Biosphere Part 3 for an in depth discussion of this fallacy). Further, evidence suggests that lactic acid is the final product of glycolysis to a greater extent than pyruvate. Wilson and Venom (2004) suggest that:

The speed of a reaction is directly correlated to the catalytic rate of the enzyme controlling the process. Lactate Dehydrogenase is the rate-limiting enzyme, which transfers two hydrogens to pyruvate to form Lactic Acid. Its rate of catalytic activity is faster than each of the glycolytic enzymes. Further it also operates at a higher rate than Pyruvate Dehydrogenase. The latter enzyme converts pyruvate to Acetyl Co enzyme A, which enters the aerobic pathways. Therefore, any increase in NADH + H⁺ and pyruvate will inevitably increase the formation of Lactate.

Therefore as glycolysis increases in activity, lactate will increase in its accumulation. It is also fallacious to assume that when lactic acid is not rising in the blood that it is not being produced. In reality, lower blood lactate levels do not indicate that lactic acid is not being produced, but rather that its production rate is balanced with its clearance rate. Fast twitch muscle fibers have a high capacity to utilize glycolysis, without a great ability to clear its by product, lactic acid. This in large part is due to

its low mitochondrial density (Baldwin et al., 1973).

The counter regulator hormones including catecholamines, growth hormone, cortisol and glucagon rise to their highest levels during high intensity exercise (Romijn et al., 1993). For example, catecholamines rise to 20 times resting levels at high intensity exercise protocols (Romijn et al., 1993). These come from the adrenal medulla (endocrine) as well as sympathetic nerve endings (neurological). The sympathetic nerve impulses at this time rise to discharge at a rate of 3 times per second on adipose tissue (Fredholm and Rosell, 1967, 1968)! As a consequence, lipolysis is increased drastically in this tissue. However, the intense rate of discharge also has the effect of activating alpha receptors on arterioles and venules associated with adipose, which shunts blood away from this region (Wilson, 2004, [Exercise Endocrinology Principles and Catecholamines](#)).

Therefore, fatty acid release is inhibited. For instance, to investigate differences between the metabolic effects of light and heavy exercise, Jones et al. (1980) performed an experiment with five healthy male participants, whom exercised for 40 min at 36% of their VO₂ max (light work) and 70% of their VO₂ max (heavy work) on separate days. Results demonstrated that for light and heavy work respectively, the respiratory exchange ratio was 0.89 and 1.01, showing an increase in carbohydrate utilization during high intensity work, and an increase in fat utilization during low intensity work. They noticed that, while, an increase in plasma glycerol was greater in heavy exercise (0.054-0.229 mmol/l) than in light (0.053-0.094 mmol/l); heavy work was associated with falls in the plasma concentrations of all free fatty acids measured, suggesting that lipolysis was occurring rapidly, but did not lead to an influx of free fatty acids into plasma. Plasma lactate concentrations increased over five fold as intensity increased; as mentioned previously, this increase in lactate is a result of an increased reliance on glycolysis; further, there is evidence that lactate decreases fat oxidation. To determine the effect of plasma lactate on fat oxidation, Achten and Jeukendrup (2004) examined blood lactate levels and fat oxidation in thirty-three moderately trained endurance athletes on a cycle-ergometer. Results showed that accumulation of lactate in plasma was strongly correlated to the reduction seen in fatty acid oxidation with increasing exercise intensities.

Now, the reason that blood vessels located near the working musculature are not constricted, but rather dilated, is do to several reasons. First, your body uses a process called 'auto-regulation' to increase vasoconstriction or dilatation according to the needs of a given tissue. Incidentally, oxygen demands are the strongest stimulus for auto regulation. As tissues oxygen needs increase, the supply lowers, causing local arterioles to dilate and allow more blood flow. Additional stimulates are by products of exercise such as CO₂, K⁺, H⁺, LA, increased ATP utilization, or inflammatory chemicals. More potent vasodilators are acetylcholine and adenosine. Thus, these auto regulatory factors override alpha receptor mediated vasoconstriction in working muscles (Farias et al., 2004; Kirsten et al., 2000; Astrid et al, 2002; Thomas et al., 1994; Anderson and Faber, 1991).

Another fascinating mechanism is that by products of exercise may attenuate alpha receptors in the working muscles; and, therefore, promote vasodilatation. These counter regulatory actions have collectively been termed, "functional sympatholysis" (Thomas et al., 1994) Anderson et al. (1991) examined the contraction of rat skeletal muscle to investigate the effect of increased oxygen demand on adrenergic

constriction of arterioles. This was a follow up to his previous study, in which he demonstrated selective attenuation of arteriolar alpha 2 constriction during a reduction in the oxygen supply/demand ratio. Low-frequency skeletal muscle contraction attenuated only alpha 2 constriction; slightly greater contractions attenuated alpha 1 constriction and further reduced alpha 2 constriction. It was found that alpha 2 receptors were ten times more sensitive to these antagonistic effects of contraction. Very potent muscular contractions also were found to decrease sympathetic tone. These results support the hypothesis that increased blood flow and oxygen delivery through decreased alpha receptor stimulation during exercise is in part mediated by elevated oxygen demand of heavily exercising muscles.

Thomas et al. (1994) further investigated this phenomenon. Because alpha 2 adrenergic vasoconstriction has been shown to be attenuated by mild acidosis (Thomas et al., 1994), they hypothesized that alpha 2-mediated sympathetic vasoconstriction would be attenuated in contracting glycolytic muscle, which produces more acidosis than oxidative muscle. They compared the effects of lumbar sympathetic nerve stimulation and alpha-adrenergic agonists on arterial pressure, blood flow, and force output during contractions of oxidative or glycolytic muscles in rats. Results demonstrated that sympathetic vasoconstriction was preserved during contractions of oxidative soleus muscle and during low-intensity contractions of the glycolytic gastrocnemius and plantaris musculatures. This is in accord with their hypothesis, since oxidative fibers would produce very little lactic acid, and therefore, little acidity due to their low glycolytic capacities; further, glycolytic fibers would not be called on maximally during low intensity work. However, they found that maximal contractions of these glycolytic fibers abolished sympathetic vasoconstriction by impairing alpha 2 receptors. Consequently, there was an increase in muscle blood flow, which was a result of both impaired vasoconstriction and increased arterial pressure. This was paralleled by increased force of gastrocnemius-plantaris muscle contraction. Thus, musculature contraction can attenuate alpha receptor mediated vasoconstriction. But this effect is dependent on the muscle fiber type, as well as the intensity of contraction.

When intensity is lowered sympathetic tone lowers proportionally, and a high rise in plasma fatty acids is seen (Romijn et al., 1993.) For this reason, Wilson (2004) suggested that a combination of high intensity and low intensity training protocols may be a highly effective technique for fat metabolism.

The great rise in catecholamines has little effect on type IIb fibers due to their insensitivity to these hormones. Therefore, it does not increase the rate of glycolysis or of lipolysis. For instance, Greenhaff et al. (1991) tested the rate of glycogenolysis in type II, and type I muscle fibers. Muscle samples were obtained before and after 64 seconds of intermittent electrical stimulation. Additionally, the experiment was carried out with and without epinephrine infusion. Before stimulation, it was noted that glycogen content was 11% higher in the fast twitch muscle cells. During electrical stimulation, rapid glycogenolysis occurred in type II fibers with hardly any detectable glycogenolysis in type I fibers. However, the infusion of epinephrine caused a 10 fold (!) increase in glycogenolysis in slow twitch cells, but did not enhance the rate in type II fibers (P greater than 0.05). Glycolysis, which provides the majority of energy at 85 % V_{O2} is, therefore, activated primarily by muscular contraction. To elaborate, muscular contraction increases the enzyme phosphorylase, and therefore, glycogen catabolism; as well as HSL (Langfort et al., 2000). Contraction also stimulates the main rate limiting enzyme of glycolysis known as

phosphofructokinase (PFK). PFK is normally inhibited by citrate, which is higher during exercise (citrate is produced in the krebs cycle); however, muscular contraction appears to attenuate this inhibition (Dyck, et al., 1996). High intensity exercise, not only stimulates glycolysis, it also stimulates a higher production of acetyl coenzyme A (Constantin-Teodosiu et al., 1991). Again, though lactic acid is produced at a high rate, pyruvate production also increases and enters the pyruvate dehydrogenase complex (PDH). PDH removes a carbon dioxide molecule from pyruvate, and adds a coenzyme A to it, to form acetyl coenzyme A. Acetyl coenzyme A, activates the enzyme ACC, which therefore increases malonyl coenzyme A, in turn inhibiting fat oxidation (Sugden et al., 1993).

Conclusion

Low intensity exercise is associated with a 85% reliance on fatty acids for fuel, the remaining coming from carbs; moderate intensity is 50/50; during high intensity, 75% comes from carbohydrates, and 25 percent from lipids. These changes in metabolic fuel use is attributed to a selective recruitment of either slow oxidative, fast oxidative, or fast glycolytic fibers.

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