Anaerobic Metabolic Conditioning

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An innovative strategy incorporated by many personal trainers is the inclusion of anaerobically oriented training workouts for interested clients. Utilized for years with competitive athletes, these types of programs appear to offer a combination of challenge, variety and unique physiological adaptations for recreational exercise enthusiasts. Anaerobic conditioning is a complex fitness component that involves motor unit activity (nerve and muscles innervated by the nerve), metabolic factors (e.g., phosphocreatine recovery and hydrogen ion buffering), substrate use (e.g., the rate of phosphagen, glucose and glycogen liberation of ATP), and force-speed patterns that affect muscle activation and recruitment (Bishop, Girard, and Mendez-Villanueva, 2011, Plisk, 1991). Thus, anaerobic training workouts result in specific neurological, metabolic and muscular adaptations. These programs involve intervals, sprints, repeated sprints and multiple-sequence exercise combinations that are preformed at higher intensities with shorter duration (Bishop, Girard, and Mendez-Villanueva). This article will provide an overview of the scientific theory and physiology underlying the bioenergetic systems emphasized in this type of conditioning and will introduce some training design guidelines and ideas for implementation of anaerobic training programs.

What Biological Energy is utilized for Anaerobic Training?

All exercise programs, and life for that matter, require the capability of the cells' to provide sufficient energy for the demands placed upon them. It is important to emphasize that the breakdown of the foods we eat does not directly release cellular energy for life and physiological work. It is the breaking of the chemical bonds in foods that releases the energy to produce and utilize the high-energy molecule known as adenosine triphosphate (ATP). All living organisms use ATP as their primary energy currency. Cells metabolically split a phosphate group from ATP molecules (as needed), which release the energy that is used for life functions and exercise needs (see Figure 1). The energy released from ATP occurs when one or both of the two terminal phosphate-oxygen molecules attached to the ATP are detached. Each phosphate group is separated from the ATP in the presence of water (called hydrolysis), and approximately 7.3 kilocalories of usable energy are immediately liberated to the cell to do work. Interestingly, the energy level ATP carries is just the right amount for most biological reactions.

$$\text{ATP} \rightarrow \text{ADP} + \text{P}_i + \text{energy for work} + \text{heat}$$

Figure 1. Diagram Showing Breakdown of ATP and Release of Energy and Heat
A phosphate group is split off from the ATP molecule, yielding ADP + P_i and energy for work. This splitting of ATP also liberates some heat energy, which is vital for maintaining body temperature. This splitting of ATP process occurs in the presence of water, and thus is referred to as the hydrolysis of ATP.

It is essential to emphasize that there is a limited stored quantity of ATP in each muscle cell, which demand a lot of energy to perform muscular work. Thus, ATP is constantly being regenerated from two anaerobic systems and one aerobic energy pathway. The anaerobic energy systems include the phosphagen system and anaerobic glycolysis (partial breakdown of glucose and glycogen in the absence of sufficient oxygen), and are the energy systems of focus for this article.

The Phosphagen System: Providing Immediate Energy to Drive Anaerobic Conditioning

Phosphocreatine (PC) stored in muscle cells has a lot of energy, just like ATP. However, when the phosphate group is broken off in PC (see Figure 2), the energy liberated is used to synthesize ATP in a coupled reaction in the presence of adenosine diphosphate (ADP).

$$\text{PC} \rightarrow \text{P}_i + \text{C} + \text{Energy}$$
$$\downarrow$$
$$\text{Energy} + \text{ADP} + \text{P}_i \rightarrow \text{ATP}$$

Figure 2. Diagram Showing Synthesis of ATP from PC and ADP
The breakdown of PC into P_i, creatine (C) and energy released is coupled with the reaction that synthesizes ATP with energy, ADP and inorganic phosphate (P_i). Creatine remains in the cell to be bound with P_i to form another PC.

Because PC and ATP contain phosphate groups, they are referred to as the phosphagen energy system. The phosphagen system is associated with energy production needs lasting several seconds in duration, but at high levels of intensity such as in sprints or near-maximal muscle contractions done in anaerobic exercise conditioning. PC is reformed from inorganic phosphate (Pi) and creatine from the energy released from ATP. This reformation of phosphocreatine occurs during the recovery of exercise. Thus, during high-intensity exercise a limitation to the amount of high-intensity (energy demanding) exercise work that can be accomplished is due to the limited supplies of PC in the muscle. The intensity of exercise is too high and rapid for PC to be regenerated during the exercise bout. In summary, three reasons the phosphagen energy system is referred to as the most rapid source of ATP are the following: 1) it does not require oxygen for any of the reactions, 2) ATP and PC are stored (in limited amounts) within the contractile proteins of muscle, and 3) few chemical reactions are needed to break off the phosphate groups from PC and ATP for energy needs in the cell.

The Anaerobic Glycolytic Energy System: Breaking Down Glucose for Rapid Energy

Carbohydrates eaten in the diet are converted to glucose for immediate energy needs or stored in the liver and muscle as glycogen. Glycogen is actually the linkage of many glucose molecules by chemical bonds called glycosidic bonds. With the help of a specialized enzyme, glycogen phosphorylase, sequential glucose molecules may be removed from the glycogen and sent to the active muscles for further breakdown to produce ATP in a process called glycolysis (See Figure 3).

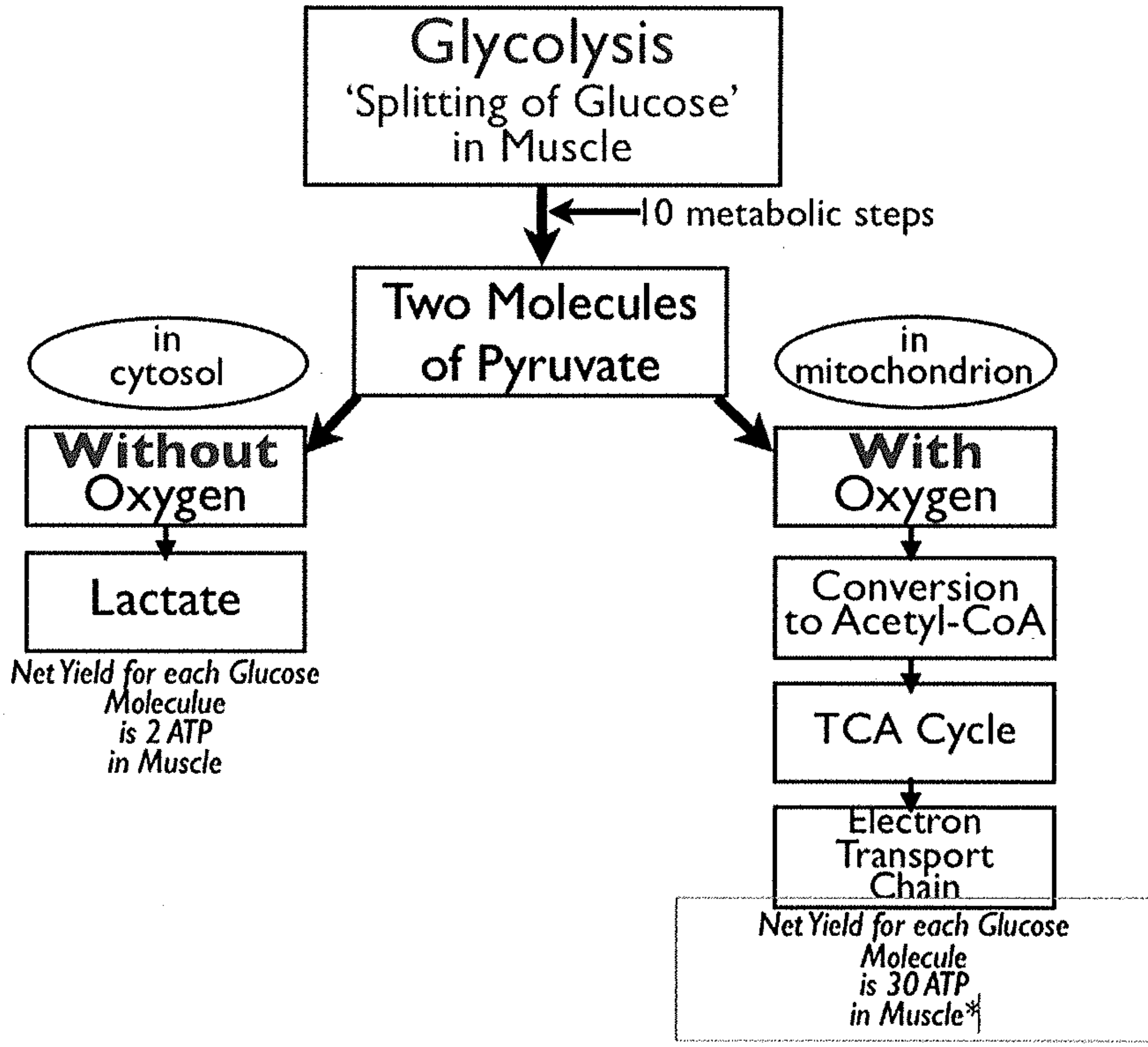

Figure 3. Comparison of Glycolysis Pathways With or Without Sufficient Oxygen Present
Anaerobic glycolysis yields much less ATP (2) versus the complete oxidation (with sufficient oxygen present) of glucose. *The total number (30) of ATP liberated with oxygen present assumes the current concept that each NADH and $FADH_2$ yields an average of 2.5 ATP and 1.5 ATP, respectively (Plowman & Smith, 2011).

As the name implies, anaerobic glycolysis is the splitting of glucose in the absence of oxygen during any of the breakdown reactions. Glycolysis, which begins with glucose or glycogen (called glycogenolysis), occurs in the cytosol (cellular fluid) of the muscle cell. Anaerobic glycolysis provides ATP at a very rapid rate in near maximal-to-maximal exertion lasting up to 2 minutes. Pyruvate is the final product of glycolysis, and in the absence of oxygen it is converted to lactate. Although once considered a 'dead-end' metabolite, it is now understood that lactate is a valuable fuel substrate for heart muscle and skeletal muscle. The production of lactate coincides with the release of hydrogen ions (protons released from the splitting of ATP), which make the muscle cells' environment more acidic. This cellular acidosis will inhibit energy production and contribute to muscular fatigue. So, lactate production does not cause acidosis, it just **accompanies** the acidosis. Aerobic metabolism (see Figure 3) of carbohydrate involves the complete breakdown of glucose and glycogen with oxygen present in the mitochondrion of the cell. The pathways involved are the conversion of pyruvate to acetyl-coenzyme A, the citric acid cycle (TCA or Krebs cycle; a series of chemical reactions in the mitochondrion that breaks down all organic fuel molecules), and the electron transport chain (a sequence of electron carrier proteins that shuttle electrons from the organic fuel molecules to make ATP). Oxidative glycolytic pathways largely support endurance-type exercise.

How Do You Design Anaerobic Training Programs?

Remarkably, little research has been published to summarize the best training methods for the spectrum of anaerobic fitness components. Researchers, coaches and exercise professionals have consistently targeted specific muscles or movement patterns for the athletic race or event and designed progressively increasing training strategies (i.e., overload principle). Fortunately, one of the most comprehensive practical application evidence-based articles on anaerobic metabolic conditioning by Plisk (1991) provides splendid guidance and theory-driven direction for overall anaerobic training program design. Key areas of attention presented by Plisk are repetition intensity-duration, exercise-to-relief ratio, total exercise volume, program duration, value of resistance training design, and training progression.

Repetition intensity-duration: Intensity of exercise is considered a primary stimulus for anaerobic conditioning. Plisk (1991) notes that the phosphagen energy system and glycolytic-glycogenolytic pathways are best trained with exercises that increase intensity or speed (without compromising technique) as opposed to longer duration exercises. These energy systems dominate the first 120 seconds of exercise. With cardiovascular exercise the personal trainer is able to able to use heart rate as a relative intensity guideline for how hard an exercise bout is being performed. Contrariwise, with anaerobic conditioning heart rate is a poor indicator of exercise intensity, as neurological factors elevate heart rate disproportionately with anaerobic exercise. Exercises are often performed over a continuum of somewhat hard, near-maximal and maximal intensities. Plisk suggests that the trainer needs to focus on exercise quality (not quantity) and sufficient intensity for eliciting the optimal training responses and adaptations.

Exercise-to-relief ratio: With repeated bouts, such as repeated sprints, Bishop, Girard, and Mendez-Villanueva (2011) assert the restoration (or resynthesis) of phosphocreatine is of great concern because it is the most rapid supplier of ATP for the contracting muscle proteins during anaerobic training. The authors affirm that compete phosphocreatine resynthesis takes up to 3 minutes after bouts of high-intensity exercise. For repeated bursts of high-intensity exercise, Plisk (1991) suggests to initially use a 1-to-4 exercise-to-relief ratio and then, over a period of weeks, taper to a 1-to-2 or 1-to-1.5 exercise-to-relief ratio for repeated bouts. So, if a bout of exercise takes 30 seconds to complete, initially the 1-to-4 exercise relief ratio indicates the relief should be at least 120 seconds, and then the exercise burst is repeated. Athletes may perform multiple sets of exercise-to-relief bouts. For this training strategy, Plisk suggests at minimum of 2 minutes should be allowed between sets for near complete phosphagen resynthesis. Interestingly, Bishop, Girard, and Mendez-Villanueva note an active recovery, such as walking or jogging, is optimal to enhance phosphocreatine resynthesis and clearance of the build-up of hydrogen ions (from the splitting of ATP). In addition Bishop, Girard, and Mendez-Villanueva explain that persons with higher aerobic fitness are able to resynthesize phosphocreatine more effectively, thus emphasizing a unique benefit of cardiovascular exercise (for improving anaerobic performance).

Total Exercise Volume. Evidence-based guidelines for total workout volume (i.e., how many repetitions, sets and circuits) with anaerobic conditioning have yet to be elucidated. Coaches and researchers have explored parameters for competitive athletes (for specific events), yet general guidelines are currently not established. Plisk (1991) summaries that "until more information is available, manipulation of this variable is best left to the discretion of the practitioner."

Training Frequency: The training frequency for athletes may be quite different as compared to incorporating anaerobic conditioning for a recreational client. In view of previously established parameters to train for quality and not quantity, Plisk (1991) suggests that two to three days per week for trained individuals should provide sufficient recovery between workouts while avoiding overtraining.

Program duration: Consistent anaerobic conditioning has been shown to meaningfully improve several physiological components including oxidative capacity, phosphocreatine recovery, hydrogen ion buffering, muscle activation and recruitment is as little as 5 weeks (Bishop, Girard, and Mendez-Villanueva, 2011). This information is useful to personal trainers educating their clients how long it will take to start realizing some changes from anaerobic training.

Value of resistance training: For clients desiring to improve anaerobic performance in recreational activities such as short races, improvement in maximal strength is less favorable with resistance training programs. Studies indicate that resistance training that includes a high metabolic load; such as sets of 10 to 20 repetitions maximum (a 20RM means a person can complete 20 repetitions but not 21 repetitions) are most optimal (Bishop, Girard, and Mendez-Villanueva, 2011). Plisk (1991) also highlights that many sprint-type and explosive competition sports involve a lot a ballistic stretch-shortening eccentric contractions. Therefore, resistance training involving controlled eccentric contractions is recommended (Plisk).

Training progression: The concept of periodized training has been around for ½ a century in research and training programs. This type of training is a sequential, structured development of exercises that varies several meaningful training variables (load, rest, repetitions, sets, recovery, exercise choice, exercise order, etc.) into blocks of training times. Periodized programs can last several weeks to months and even up to a year of training. Typically with athletes, the training progression follows an off-season, preseason and in-season progression. With off-season, the goal is to build a physiological foundation that helps to develop endurance, strength and power for the target athletic goals. The preseason is usually 8 to 12 weeks of training prior to competition where athletes attempt to maximize anaerobic conditioning specific to the competition event. In-season training usually emphasizes skill development and competition preparation. Plisk (1991) notes that due to individual goals and differences, these training phases may have overlapping characteristics as the practitioner is always concerned with finding the ideal training stimulus, while avoiding overtraining and undertraining the client.

From Theory to Practice

Applying the research and physiological understandings of the metabolic, neural and muscular aspects of this type of training, the following recommendations are as follows:

1) Perform all exercises 20 to 30 seconds at a controlled exercise pace.
2) Progress from exercise to exercise as opposed to resting and repeating each exercise.
3) Choose an exercise intensity appropriate to the fitness level and goals of a client from a somewhat hard, to hard, to near maximal and even maximal intensities.
4) After completion of a circuit do an active recovery of brisk walking, light cycling or jogging for 2 to 3 minutes and repeat the circuit again. The total number of circuits should be individualized for each client.
5) Regularly change the order of the exercises and incorporate other exercises to offer a variety of neuromuscular stimuli to the anaerobic training sessions.
6) To make each circuit an aerobic circuit training bout add 2:30 min of walking, jogging or cycling (at 65% to 75% of a client's estimated heart rate maximum {220-age = Estimated heart rate maximum}) after each exercise.
7) To make the circuit a 'circuit weight-interval training' workout incorporate 30 seconds of high-intensity (i.e., hard to very hard intensity on a ratings of perceived exertion of client)

treadmill running/walking (depending on fitness level of client) or cycling, followed by 3 minutes of active recovery on the same mode at a self-selected intensity. Complete these 30-second bursts after the 2nd and 4th exercise in the circuit.

8) Intersperse the anaerobic training with the client's regular training programs.
9) Complete some type of anaerobic training 2 to 3 times a week.

Side Bar 1. New Circuit Training Study Offers Innovative Insights on Anaerobic Conditioning

Circuit weight training, a form of anaerobic conditioning, and interval training have gained popularity because of their approach in maximizing training results in a time-efficient manner. For good reason, this concept is massively attractive to a society of exercisers with time constraints. Traditional circuit weight training (TRAD) typically consists of performing a specific number of weight-lifting exercises with short rest periods between sets. In their research review, Skidmore et al. (2011) observe that TRAD studies have been shown to increase muscular strength and muscular endurance with a mild improvement in aerobic capacity. Aerobic circuit weight training (ACWT) uses a design similar to circuit weight training, but the rest periods involve an aerobic component. Circuit weight-interval training (CWIT) aims to combine TRAD with high-intensity interval training (HIIT). HIIT entails short bouts of high-intensity exercise with pre-determined rest periods and has been shown to improve aerobic capacity very effectively (Zuhl and Kravitz, 2012). With so many promising options, which mode of circuit training is the most effective? Skidmore and colleagues (2012) set out to elucidate more on that question by comparing the traditional circuit weight training (TRAD), aerobic circuit weight training (ACWT), and a combined circuit weight-interval training (CWIT) programs.

Subjects

Eleven women averaging 34 years in age participated in this study. It was required that all of the women had been training aerobically for 30-minutes, three days per week for at least 6 months. Participants who were currently pregnant or had spinal and/or lower limb musculoskeletal injuries within the past 6 months were excluded.

Circuit Training Programs

Prior to measuring the impact of each circuit-training program, participants completed each of the programs on separate days in order to familiarize themselves with protocols and tempo of each program. Each participant then completed the TRAD, ACWT, and CWIT protocols (see Table 1.) on different days separated by at least 72 hours between sessions to ensure adequate recovery time. Each of the circuit weight training programs consisted of a 5-minute cycle warm-up at 60-70% of maximum heart rate (HRmax) followed by the same resistance training exercise stations, labeled as A[1], B[2], and C[3] (see Table 2.). Participants completed three sets of 13 repetitions for each resistance training exercise in the station. The TRAD protocol involved 30-seconds of weight lifting and 30-seconds of rest between each set, the ACWT protocol involved the same amount of time lifting weight but shortened the rest periods to 15-seconds and added 2:30 minute cycling bouts at 65-75% HRmax between stations. The CWIT workout consisted of the same weight lifting and rest period times between sets as the ACWT group but performed a 30-second max effort cycle sprint followed by a 3-minute cool-down (pedaling with no resistance on bike) between each station. Each program ended with a five minute cool-down of easy pedaling on a cycle. The total time to complete each workout was approximately 40 minutes.

Table 1. Circuit Training Workouts

Aerobic CT	CT	HIIT-CT
(30-second lift: 15-second rest between sets)	*(30-second lift: 30-second rest between sets)*	*(30-second lift: 15-second rest between sets)*
5-minute cycle warm-up @ 60-70% HRmax	5-minute cycle warm-up @ 60-70% HRmax	5-minute cycle warm-up @ 60-70% HRmax
Bike 2:30 min @ 65-75% HRmax	Station A[1]	Station A[1]
Station A[1]	Station B[2]	30-second max cycle sprint 3-minute cool-down
Bike 2:30 min @ 65-75% HRmax	Station C[3]	Station B[2]
Station B[2]	5-minute cycle cool-down	30-second max cycle sprint 3-minute cool-down
Bike 2:30 min @ 65-75% HRmax		Station C[3]
Station C[3]		30-second max cycle sprint 3-minute cool-down
Bike 2:30 min @ 65-75% HRmax 5-minute cycle cool-down		5-minute cycle cool-down

Adapted from Skidmore et al., 2011

Table 2. Resistance Training Stations

Station A[1] (3 set of 13 repetitions)	**Station B[2]** (3 set of 13 repetitions)	**Station C[3]** (3 set of 13 repetitions)
Triceps bench dips	Standing biceps curl	Standing dumbbell lateral raise
Hip lifts	Dumbbell squats	Dumbbell split squat L leg
Prone planks (30-second hold)	Pushups	Dumbbell split squat R leg
		Standing dumbbell bent-over row

Adapted from Skidmore et al., 2011

Variables Measured and Results

The three different variables of exercise intensity measured in this study were the following: blood lactate (BLA), rating of perceived exertion (RPE), and heart rate (HR). Variables were measured upon the completion of each resistance training station (A[1], B[2], and C[3]) during the TRAD workout and after completing the cycling bout (2:30 min or 30-sec sprint) for ACWT and CWIT groups. The results showed that BLA increased over the course of each workout, however these concentrations were significantly greater at each of the time points during the CWIT workout compared to the TRAD and ACWT workouts. It should be noted that BLA was significantly greater in ACWT compared to TRAD after the final time point (C^3) of the workout. At the end of the workout, BLA in CWIT was 132% greater than TRAD and 60% above ACWT. Similar to the response in BLA, HR rose throughout each protocol but the CWIT workout elicited significantly greater HR than ACWT and TRAD at each point during the exercise session. The ACWT workout HR was significantly greater than TRAD after the first time point (A^1). After completion of the workout, HR in CWIT was 14% greater than that of ACWT and TRAD. Finally, RPE increased throughout the course of each circuit weight training protocol, but the RPE during the CWIT workout was significantly greater at all time points compared to TRAD and ACWT. Interestingly, RPE was also greater at all time points during ACWT compared to TRAD. RPE measures after completing the CWIT workout were 38% and 8% greater than TRAD and ACWT, respectively.

Summary Thoughts

Clearly, any of the aforementioned circuit weight training protocols follow a pattern of increasing exercise intensity throughout the course of the workout. However, for recreationally active and healthy populations seeking to achieve the greatest amount of work in an efficient time frame, CWIT appears to be superior to TRAD and ACWT programs. If performing maximal sprints cannot be completed due to physical limitations or personal choice, ACWT would be an effective option, as it provides an aerobic and anaerobic stimulus.

Bios:

Len Kravitz, PhD, is the program coordinator of exercise science and a researcher at the University of New Mexico, Albuquerque, where he won the Outstanding Teacher of the Year award. He has received the prestigious Can-Fit-Pro Lifetime Achievement Award and American Council on Exercise Fitness Educator of the Year.

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