The Efficiency of Energy Conseravation in Aerobic and Anaerobic Metabolism - and - The Creatine-Phosphate System•

I. More Comparisons Between Aerobic and Anaerobic Metabolism:

A. **Review**: Lets compare aerobic and anaerobic glycolysis:
Per 6C:

1. ATP Production: 2 or 3 ATP in (anaerobic glycolysis vs. 36 or 37 ATP in aerobic glycolysis + Krebs cycle/ETS. Thus, **about 18X more ATP in aerobic.** Put another way you use **18X less fuel to do the same work**.

2. Waste Products:

a. Anaerobic yields 2 molecules of lactic acid. This is about 1 acdi molecule per ATP.

b. Aerobic yields 6 moleucles of CO_2 which gives 6 H_2CO_3 -- however this is only about 1 molecule of acid to 6 ATP. Furthermore, unlike lactic acid, CO_2 is easily eliminated.

c. Both produce heat as a by product and in most cases this is a waste.

3. Flexibility: The processes in the mitochondria (Krebs Cycle and something called β-oxidation) can also burn fatty acids and the derivatives of a number of types of amino acids. (Note aerobic metabolism utilizing these fuels is not glycolysis).

B. **Efficiency**:

1. **General Definition of Efficiency** the proportion of the totoal energy available for some process that it either turned into useful work or is conserved. All of the energy that does not turn into useful work or is not conserved is lost as heat (again remember the First Law of Thermodynamics).

2. Thus, in comparising aerobic and anaerobic metabolism, we are interested in seeing how efficient the amount of energy available in a fuel molecule such as 6C is conserved in ATP. So:

Efficiency (%) = conserved energy / total available energy * 100

` = Energy conserved as ATP / total available energy

3. How much energy is saved in ATP? If we break it down:

 Please note that if you don't know much about chemical reactions and catalysts, you may find the chemical reactions reference material useful.

ATP -----> ADP + Pi + **7 Kcal**

4. How much energy is available in 6C? From the bomb calorimeter:

Glucose + 6 O_2 ----> 6 H_2O + 6 CO_2 + 686 Kcal

5. How efficiently does the body conserve energy for other uses by putting itt into ATP during the aerobic breakdown of glucose to CO_2 and H_2O?

Efficiency = Energy conserved as ATP / total available energy *100

= (36 ATP * 7 Kcal/ATP) / energy in 6C (glucose) * 100

= **259 / 686 * 100 =38%**

6. How efficient is anaerobic glycolysis? This one is a bit tougher. Like a lot of things, there are several ways to calculate it. Each method makes a different point.

a. First, let's see how much energy we conserve. Assume that we start with glucose (as in the example above). We net 2 ATP with 7 Kcal conserved in each ATP. Thus 2 * 7 = 14 Kcal conserved.

b. How much energy was available. Here is where the rub comes in. There are two ways to calculate available energy.

(1) One is to assume that the available energy is what was in the glucose, as in the example with aerobic processes above. There is excellent logic to this since a muscle using anaerobic glycolysis potentially has the energy available in the glucose. With this assumption, we find:

= 2 * 7 Kcal / 686 Kcal * 100 = 2%

(2) the other way is to look only at the energy that was actually released in going from 6C to 2 lactic acid molecules. Here the assumption is that all of the energy remaining in the lactic acid molecule was unavailable to the muscle (since it was forced to use anaerobic metabolism). Further, as far as the body is concerned, we know that the lactic acid is not a waste. So, the energy available in lactic acid:

2 (lactate (C3H6O3)) + 6 O2 --> 6 H2O + 6 CO2 + **619 Kcal**

and recall that the energy available in glucose was:

Glucose + 6 O_2 ----> 6 H_2O + 6 CO_2 + 686 Kcal

Thus, the energy liberated in going from glucose to 2 lactic acid is the difference between the energy contained in the glucose (686 Kcal) and the energy contained in the lactic acid (619 Kcal):

Energy released in anaerobic glycolysis = 686 - 619 = 67 Kcal

Using this number, the efficiency is:

E = Energy Conserved in ATP / Energy Released in Anaerobic Metabolism

Efficiency = 2 * 7 / 67 * 100 = 14/ 67 * 100 = 21%

This calculation emphasizes the efficiency with which a specfic process (anaerobic glycolysis) removes and conserves energy when going from a 6C fuel to two 3 C waste molecules. The former calcuation emphsizes the efficiency with which anaerobic glycolysis uses the eneryg that was theoretically available . However, the take home message in either case is that anaerobic glycolysis is not very good at conserving energy when compared to aerobic metabolism.

C. **Why not always rely on aerobic metabolism?**

1. The evolutionary reason is that aerobic metabolism is an expensive system to create and maintain compared to the anaerobic system.

a. Not only does it require lots of mitochondria and many more enzyme molecules within each muscle cell but it also requires:

b. a strong heart,

c. an effective circulation,

d. and the ability to exchange large amounts of CO_2 and O_2 with the environment.

All of this for an abiility to produce ATP tthat will not be needed most of the time (when the individual is resting).

2. So, instead we have two systems.

a. The aerobic one is maintained at a level that will deal with the expected typical demands for sustained actiivity.

b. Although it will also contribute to the operation of the system when large amounts of energy are required, aerobic metabolism is not able to meet these demans by itself. Instead, the anaerobic system is in place as a stopgap to handle those other situations.

c. Thus, for short periods of time it can provide an additional large boost of ATP synthesis to meet high energy demands.

II. **<u>The Creatine Phosphate "Buffer"</u>:**

A. Creatine phosphate is a compound that has a single high energy phosphate.

1. This phosphate is exactly like the high energy phosphate found in ATP.

2. We often write the initials of creatine phosphate as C~P to emphasize this, much as we write the two terminal phosphates in ATP as ~P (*e.g.*, A-P~P~P -- see earlier notes on ATP).

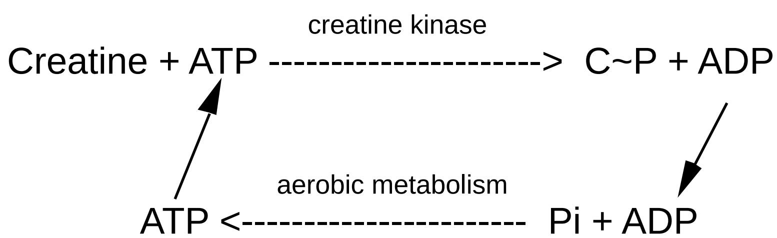
3. Another term used for creatine phosphate is **<u>phosphagen.</u>**

B. Creatine phosphate is formed in <u>resting muscles</u> when ATP transfers its outer-most high energy phosphate to the compound creatine (see the appendix to these notes that deals with creatine supplements to see creatine's structure).

1. The enzyme required to do this is **<u>creatine kinase</u>**:

creatine kinase
creatine + ATP ----------------------------------> C~P + ADP

2. Notice that t**his reaction only occurs when the muscle is resting -- that is, when its demand for ATP is low**. As soon as the reaction is complete, the ADP created by the process will get a new high energy phosphate from aerobic metabolism (this will be true in both type I and II b fibers -- remember that even type IIb fibers have some aerobic capacity. It is just that it is small. So, think about the process like this:



3. The build-up process will continue until nearly all of the creatine in the cell is converted to C~P, at which point it stops.

a. At this point, the C~P just sits around and waits for exercise.

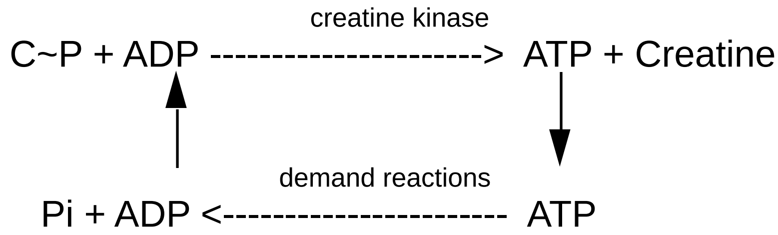
b. T**hink of C~P as money in the bank.** The reaction just shown is the process of filling the bank account with money.

4. In a resting muscle that is fully "charged" with C~P, there is typically between **3 and 5X as much C~P as ATP.**

C. **When exercise starts, the demand reactions (myosin and Ca^{++} ATPase to name a few) quickly start breaking down ATP to ADP and Pi**.

1. Now, the **stored C~P begins to react with ADP (the reverse of the synthesis reaction above)** and gives the ~P back to ADP, making more

ATP. Creatine begins to incresae again, but **the important result is that the concentration of ATP does not fall very much**:



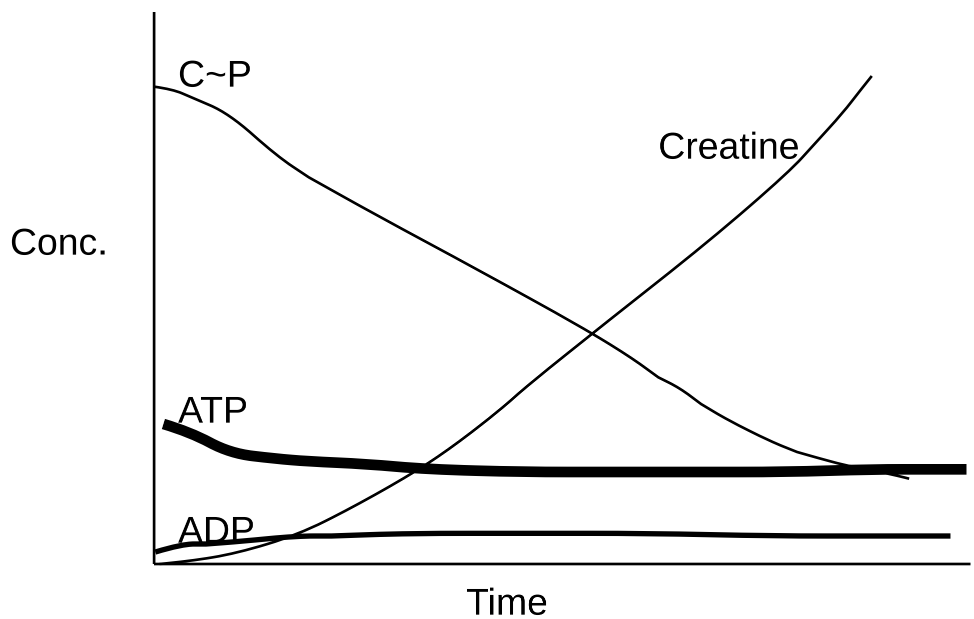
2. We say that the C~P **<u>buffers</u>** the stores of ATP -- that is, it prevents them from changing as rapidly as they would if the C~P stores had not been there. The result is that [ATP] does not change nearly as much as it would have during the time that glycolysis and aerobic metabolism are being activated.

3. Notice that the same enzyme (creatine kinase, CK) is used in both reactions (synthesis and breakdown of C~P).

a. Muscles tend to have very large amounts of CK.

b. This is important during exercise because it ensures that C~P will rapidly transfer ~P to ADP -- no waiting time to find an enzyme molecule as would be the case if there was less CK.

4. Here is a graph that summarizes what happens to ATP, ADP, C~P and C during the first couple of seconds of an activity transition (this one is for going from rest to exericse):



Notice that although the [ATP] does drop a bit and the [ADP] does increase a bit, the changes are very small. What really changes is the [C~P] and [C] -- the decrease in C~P is what prevents large changes in [ATP] and [ADP].

Important Note: We will see in the next set of notes, that **a little bit of a change in [ATP] and [ADP] is actually good**.

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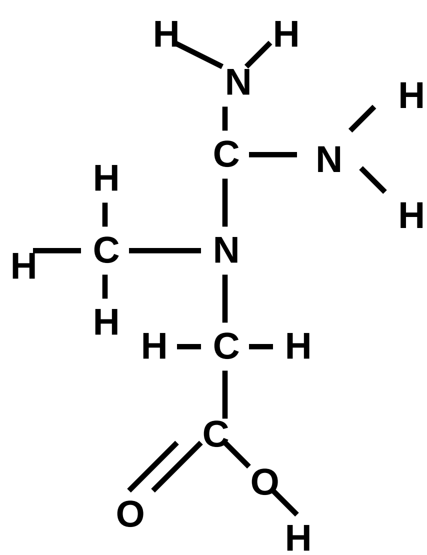
Appendix: About C~P: Training and Creatine Supplements

Training (increased use) of any group of muscle fibers will result in increases in the concentration of both C~P and ATP. The result is especially important for maximal, all-out exercises whose total duration is kept to about 6 to 8 s. (the time that would normally be required to deplete C~P). Repeating such exercise after a short rest will increase the concentrations of both ATP and phosphagen. However, the increase is limited. No matter how much you train, you will not double the concentrations of these substances in your muscles. Thus, there are physiological capacities that your cells possess.

Creatine supplements are increasingly popular. Probably most of their use is not justified. What do such supplements do? The provide the substance creatine which the body can use (as we learned earlier) to synthesize C~P. Here is the structure fo creatine:

Creatine



Notice that it is a highly polar compound that easily dissolves in cellular solutions and makes its way to the tissues.

Creatine has now been shown to be useful in certain types of training. The only documented benefits are in extreme strength training. What I mean by that is strength training that involves many sets of lifting weights that can only be lifted a few times at most per set. The maximum number of times that a subject can lift a certain weight is referred to as the repetition maximum (**RM**). Creatine will benefit those engaging in lifting weights so large that the RM is low -- the entire set would be completed in 4 to 8 s. followed by a rest before the next set. Notice that this time frame is roughly the time it takes to deplete C~P in a muscle at maximal exercise. Besides strength, the limiting factor in these types of exercise is the ability to fuel the activity without incurring large enough amounts of lactic acid to cause fatigue. Any factor that will increase the C~P concentration will stave off the point where fatigue is reached. The athlete will be able to lift a larger weight (requiring more force and more ~P), perhaps a few more times, before lactic acid build up starts to induce weakness. Also, the athlete will be able to do the next set sooner since C~P is resynthesized rapidly after exercise. Since increase in strength is proportional to overload, obviously higher concentrations of C~P will allow a greater overload to be handled and more of an increase in strength. Creatine supplement and training will result in an increase in C~P.

If all of this is true, then why did I say that most people do not benefit from creatine supplements? The simple answer is that most people who are trying to increase their strength do not work at a high enough overload to benefit. The C~P already in their bodies is more than enough for what they are doing and more than enough to help them to increase strength.

Moreover, even individuals who might benefit from creatine supplements commonly take far more than is required. The usual reasoning, if it can be called such, is that if a little helps, more is better. The same sort of reasoning is often applied to protein intake. The fact is that every study has shown that cells will only tolerate a certain maximal amount of C~P. This amount is less than 2X what is normally found in muscle cells. Recommended doses of supplements, combined with heavy training, are more than adequete to reach these levels. Addiitional creatine is turned into piss, pure and simple. Likewise, the money invested in the additional creatine goes to line some salesperson's and company's pockets while giving the athlete no gain.

The susceptibiility of many individuals to pitches for supplements such as creatine is easy to understand. There are real benefits in some cases. However, what is unsaid by the sales types is that the benefits generally do not accure to most individuals using them. These people are deluded by the idea that they are getting some sort of training edge when in fact they are getting none.

As to dangers, besides wasting money some have suggested that creatine supplements might lead to kidney or liver damage. I would have to say that the evdience is very weak in both cases. Those most likely to sustain such damage would be those who use the supplements heavily for long periods of time -- competitive weightlifters and body builders.

I would argue that anyone considering using such a supplement should ask whether or not they are truly likely to benefit and ask the question of whether or not such a practice is ethical.