

## Ergogenic Aids

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It is human nature for individuals to cultivate and bring out the best within themselves. Inherently, we strive to understand and shape our physical world to aid us in our endeavors. The optimization of physical performance is no exception to this rule.

By far, the most effective method for improving physical performance is through systematic exercise training over prolonged periods. Improvements in muscular strength or the velocity at which prolonged running can be maintained routinely exceed 50 per cent following the appropriate training of previously sedentary individuals. "Ergogenic aids" present another potential means by which physical performance can be enhanced. These substances, in theory, allow an individual to perform more work (Greek "ergon") than he or she would be capable of performing otherwise. As will be discussed, a wide variety of substances can be categorized as ergogenic aids. Generally, however, these substances do not result in more than a 7 per cent enhancement of work output. By comparison, therefore, the efficacy of ergogenic aids for improving physical performance is minor relative to what can be accomplished through training. This is particularly true in athletes who are not training at levels close to the upper limits of their tolerance. Serious competitive athletes, however, often train at levels close to their tolerance limits and require relatively large increases in training effort in order to promote small improvements in performance. Additionally, small variations in performance among elite athletes often make the difference between finishing first compared with finishing far back in the field of competitors. In this regard it is understandable why athletes and trainers use substances that they believe to be ergogenic aids to physical performance.

As mentioned, many substances have theoretical ergogenic properties, and they range in their degree of acceptability from a cold drink of water consumed by a marathon runner to dangerous drugs that act as psychomotor stimulants. It is not the purpose of this review to address the ethical considerations that should be evaluated before the recommended use of

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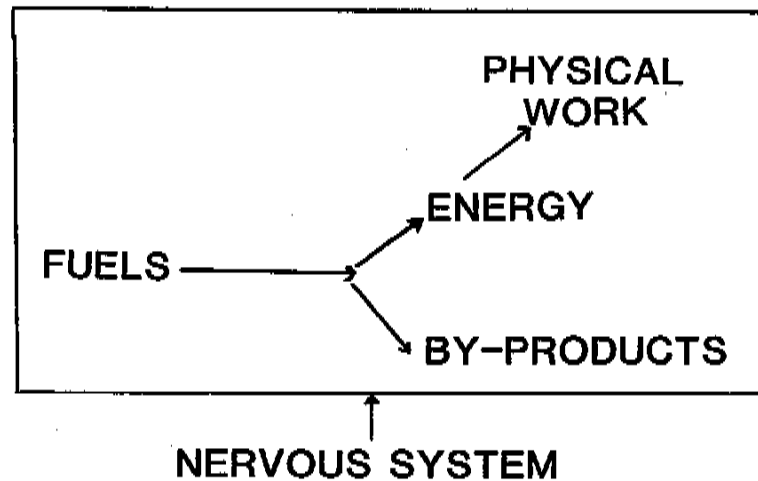


Figure 1. Fuel catabolism is schematically depicted.

these substances is considered. This article will discuss the physiological basis of various ergogenic aids and the scientific evidence currently available regarding their effectiveness.

#### BASIC FRAMEWORK OF ERGOGENICS

For a substance to enhance physical work output it must act upon one of the basic pathways by which the energy for work is generated. Figure 1 presents the basic scheme. The food we consume is stored within the body and provides the fuel that is broken down (that is, catabolized), thus releasing energy, some of which is harnessed in the form of a chemical (that is, adenosine triphosphate, or ATP) and used for muscular contraction. Theoretically, an ergogenic aid can act at four places in this scheme of energy transformation, as follows:

1. It can act as a supplementary source of fuel. The efficacy of carbohydrate and fat ingestion will be discussed.
2. An increase in the catabolism of fuel might increase the rate of energy flux and thus work output. Certain drugs (such as caffeine or amphetamines) have the potential to affect fuel metabolism.
3. By-products of fuel catabolism can cause fatigue; therefore, substances that minimize their accumulation could theoretically enhance performance. The role of fluid ingestion in reducing hyperthermia during prolonged exercise will be discussed, as will the ingestion of bicarbonate, which theoretically can act as a buffer to the acid produced during intense exercise.
4. The nervous system exerts a marked influence on work output by coordinating the recruitment of muscle fibers. Numerous treatments affect neurologic function, including placebos and psychomotor stimulants.

## FUELS

If the fuel reserves that provide the energy for exercise become depleted and cause a reduction in work output, it is reasonable to hypothesize that a treatment that provides additional amounts of the fuel would be an effective ergogenic aid. An important consideration is that supplementation will be of benefit when the body's endogenous stores are inadequate to fuel the energy requirements of a particular activity, as will be discussed regarding carbohydrate supplementation. Another consideration is that increases in the delivery of fat and blood glucose for energy catabolism may delay fatigue by sparing muscle glycogen.

### Chemical Energy

Although all bodily fuels can be considered chemicals, there is a small amount of readily available energy stored in the chemical bonds of ATP and creatine phosphate (CP). These substances are the final link between fuel catabolism, energy liberation, and physical work. Their concentration in the working musculature is lowered after just a few seconds of all-out exercise, and at one time it was theorized that performance might be improved by ingesting these substances or by injecting them into the belly of a muscle. Neither treatment is effective. First, there is no practical method for increasing the concentration of these substances within the many fibers of a muscle. Second, the levels of ATP decline during activity, yet the muscle will not become depleted because a reduction in ATP concentration will stimulate a rapid breakdown of carbohydrates to resynthesize ATP and thus maintain an adequate supply for exercise.

### Carbohydrate

The paramount importance of carbohydrate as a fuel for intense and prolonged exercise is discussed in another article in this volume. Basically, carbohydrate is stored in the form of glycogen within the muscle so that it is available to quickly resynthesize ATP. Additional smaller amounts of carbohydrate can be presented to the muscle in the form of blood glucose. Normally, during moderate to intense endurance exercise (such as running or cycling), muscle glycogen stores will not become sufficiently low so as to affect performance until approximately two hours of exercise have been completed. There is certainly sufficient glycogen present in a rested, well-fed individual to provide the energy required by sprinting or playing a few sets of tennis or most other recreational sports that are completed within an hour or two. Carbohydrate ingestion will not be of benefit during short duration activities since our bodily stores are adequate. The popular image of a sprinter having a candy bar prior to competition, so as to have more energy, has no physiologic basis.

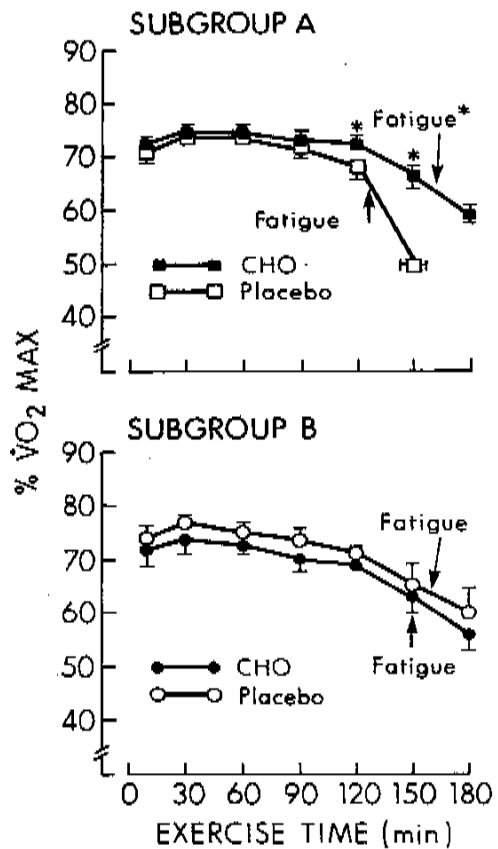
Recently, evidence has been accumulating that carbohydrate ingestion may benefit endurance exercise of longer duration. Carbohydrate ingestion during exercise results in an increase in blood glucose levels, and the glucose is taken up and used as a fuel by the muscle. The rate at which the muscle can catabolize blood glucose is too slow to provide the energy required to maintain intense exercise when muscle glycogen stores are

depleted.<sup>4</sup> Elevations of blood glucose levels, however, appear to spare the use of the muscle's endogenous stores of glycogen.<sup>1</sup> Therefore, since fatigue during moderate exercise occurs as a result of glycogen depletion, if the rate of glycogen usage is reduced, fatigue during prolonged intense exercise can be delayed. The delay of fatigue with carbohydrate feedings is particularly evident in subjects whose blood glucose levels are normally lowered during exercise without feedings.<sup>8</sup> These subjects are denoted as subgroup A in Figure 2. When fed a placebo during exercise at an intensity of 74 per cent of maximal oxygen uptake, they become fatigued (that is, drop work rate by 10 per cent) after 126 minutes. When fed carbohydrates (beginning after 20 minutes of exercise), their fatigue was delayed by 33 minutes, and they were able to perform 6.6 per cent more work during the first two and one-half hours of exercise. It should be realized that carbohydrate ingestion did not allow these subjects to exercise more intensely during the first two hours of exercise, it simply delayed, yet did not prevent, a reduction in work rate. Subjects whose blood glucose levels were not lowered during exercise in the fasting state (Figure 2, subgroup B) became fatigued at a similar time with and without carbohydrate feedings. It therefore appears that carbohydrate feedings can delay fatigue during prolonged and intense exercise that is performed for two hours or more and that this beneficial effect is particularly noticeable in subjects who normally exhibit lower blood glucose levels during exercise when fasting. Fatigue was associated with symptoms of hypoglycemia (nausea, disorientation) in fewer than 30 per cent of the subjects studied. Therefore, for the most part, the beneficial effect of feedings is not mediated by protection against hypoglycemia; instead, it appears to be related to a slowing of muscle glycogen depletion.

It is important that glucose, sucrose, or starch feedings not be given during the period immediately prior (30 to 60 minutes) to endurance exercise. This will result in an increase in insulin levels during early exercise, which appears to lower blood glucose levels while increasing glycogen depletion, resulting in premature fatigue.<sup>5,12</sup> Glucose feedings should be taken after exercise has begun, or at the earliest, immediately prior to exercise. A reasonable amount of carbohydrate to be consumed per feeding would be 0.5 to 1.0 gm per kilogram of body weight taken every 20 to 30 minutes.

Fructose ingestion during the hour immediately prior to exercise causes only a modest increase in plasma insulin levels and it does not result in a lowering of blood glucose below basal levels when exercise is begun.<sup>18</sup> Therefore, it is the preferred form of carbohydrate for ingestion during the two hours prior to the beginning of an exercise bout during which blood glucose will be presumed to decline. The majority of the ingested fructose will be taken up by the liver, converted to glucose, and either stored or released into the blood.<sup>9</sup> Since the majority of the fructose ingested prior to exercise is metabolized in the form of glucose, it probably is of no additional benefit to ingest fructose instead of glucose or sucrose during exercise, although this point has not been investigated. To my knowledge, the ergogenic potential of fructose ingestion prior to or during prolonged

Figure 2. Work intensity (per cent,  $\dot{V}O_2$ max) that could be maintained during exercise with (CHO) and without (Placebo) carbohydrate feeding is shown in subjects who displayed a decline in blood glucose concentration during exercise without carbohydrate feeding (subgroup A) and in subjects who did not (subgroup B). ↓ = The mean time to fatigue (that is reduction in work rate by 10 per cent of  $\dot{V}O_2$ ). \* = Significantly different from placebo,  $p < 0.01$ .



exercise has yet to be directly studied. Its ingestion prior to exercise may promote a sparing of muscle glycogen during the early stages of exercise.<sup>20</sup>

Glycerol is another form of carbohydrate that when ingested does not elevate insulin and theoretically can be converted to glucose and metabolized by skeletal muscle.<sup>26</sup> Glycerol is normally produced by the body in small quantities as a by-product of the breakdown of triglycerides. Glycerol feedings in rats improve running performance because rats can convert glycerol to blood glucose at high rates, which is particularly beneficial to rats because of their heavy reliance upon blood glucose as a carbohydrate source.<sup>26</sup> Glycerol feedings are ineffective in humans, however, because humans do not appear to be capable of converting glycerol to glucose at a fast enough rate to be of practical value during moderate exercise.<sup>22</sup> Glycerol feedings should also be avoided because they cause cerebral dehydration.

#### Fats

As discussed in another article, fats are an important fuel source for endurance exercise. Increases in the rate of fat oxidation during prolonged exercise reduce the rate of glycogen usage, thus sparing the limited stores of glycogen and potentially delaying fatigue. Fats are used for energy in the form of free fatty acids (FFA), which circulate through the blood and are taken up by muscle or are generated in the muscle through the breakdown of intracellular stores or triglycerides. Treatments that increase blood levels of FFA, and probably muscle tissue levels, result in a greater rate of fat oxidation.<sup>5</sup> The chemical reactions involved in fat catabolism appear to be driven faster. Numerous methods have been employed to increase FFA levels in blood, but they are generally not practical or safe. It should also be mentioned that only limited amounts of FFA can be carried in the blood. Also, high concentrations of FFA become toxic to various tissues.

The ingestion of medium chain triglycerides prior to exercise has been used in an attempt to increase FFA levels.<sup>16</sup> These substances were found to be highly unpalatable and required the simultaneous ingestion of carbohydrate, which causes hyperinsulinemia and a lowering of blood glucose during exercise. Their ergogenic effectiveness has yet to be directly evaluated.

FFAs are naturally increased in the blood through the breakdown of triglycerides in adipocytes. Various drugs that stimulate the central nervous system or adrenergic receptors can increase the release of FFAs from adipocytes (that is, lipolysis). Catecholamines (such as epinephrine and norepinephrine), commonly called the "fight or flight" hormones, are naturally released by the body and act as potent stimulators of lipolysis. In this regard it is interesting that a competitor's nervousness prior to an endurance bout may serve a useful purpose by promoting an increase in FFA levels, which may reduce muscle glycogen usage.

### FUEL CATABOLISM

#### Caffeine

Another means of increasing energy transfer and work production, in addition to augmenting the delivery of fuel to the muscle, is by employing

nonmetabolizable substances that favorably alter the pattern of fuel metabolism. Caffeine is one such substance that has been found to improve endurance performance. As a xanthine derivative, caffeine affects numerous bodily systems, including muscle, adipocytes, and the nervous system. It stimulates the sympathetic nervous system (that is, catecholamines) while also increasing the release of FFA from adipocytes and thus providing more fat for oxidation. In muscle, it may indirectly slow the breakdown of muscle glycogen while allowing more fat to be processed for energy.<sup>10</sup>

Of the half-dozen investigations that have examined caffeine's effectiveness during exercise of 1 to 2 hours' duration, two have stimulated competitive racing conditions. In one study, trained cyclists performed 7 per cent more work in two hours when ingesting caffeine compared with their performance when fed a placebo.<sup>15</sup> In another study, cross-country skiers completed 23 km (approximately 50 minutes' duration) in a time that was 2 to 3 per cent faster after ingesting caffeine compared with times after a placebo treatment.<sup>2</sup> Both of these recent studies found that the competitors choose to exercise at a higher intensity with caffeine. The exact mechanism by which caffeine appears to increase the highest tolerable intensity during prolonged exercise is not known, but it could be related to the effect of caffeine upon fat metabolism and/or the nervous system. The competition pace chosen during steady state exercise is usually an intensity just below that which will elicit a rapid consumption of muscle glycogen, an increased lactic acid accumulation, and rapid fatigue. This intensity corresponds to the lactate threshold.<sup>21</sup> By increasing fat utilization and possibly by suppressing reliance upon muscle glycogen as a fuel, it is possible that caffeine alters the lactate threshold intensity, although this needs to be investigated in further detail.<sup>10, 15</sup> Since caffeine also acts as a general stimulant to the central nervous system, it is also possible that it reduces the perception of fatigue or even affects neuromuscular efficiency.

Although caffeine appears to improve performance in steady state endurance activities, it has not been found to be effective during short-term (less than 10 minutes) high intensity exercise (such as sprint swimming or running).<sup>24</sup> These activities do not rely upon fat for fuel, thus the actions of caffeine upon fat metabolism would not be applicable.

#### Amphetamines

Amphetamines are potent sympathomimetic stimulators of the central nervous system. These are potentially dangerous substances that can lead to addiction and result in damage to numerous bodily tissues. They have been used during athletic competition to provide "psych" (that is, self-confidence and a "winning" frame of mind) or to diminish weariness. Investigations into their effectiveness for improving physical performance during various activities have produced diverse results, which need to be considered collectively. Ivy has recently completed a comprehensive review of the literature, and concluded that "the evidence overwhelmingly suggests that amphetamines extend aerobic endurance and hasten recovery from fatigue."<sup>14</sup> He also indicated that the mechanism by which amphetamines yield such effects has not been established. It is difficult to distinguish between their direct physiologic effectiveness as opposed to their psycho-

logical influences, which allow an individual to push himself or herself harder.

The studies that have reported improved aerobic endurance (large muscle mass activity of ½ to 5 hours' duration) have generally not provided information regarding fuel utilization during exercise.<sup>14</sup> It is possible, however, that amphetamines act to increase fat usage in a manner similar to that of caffeine, since both agents increase sympathetic activity. As with caffeine ingestion, amphetamines do not seem to be particularly effective during short-term high intensity exercise.

It is common knowledge that amphetamines have been routinely used by some professional athletes. Although amphetamines do not appear to improve reaction time or diligence in rested motivated subjects, they do appear capable of restoring reaction time in participants who are weary.<sup>19</sup>

Amphetamines can also increase muscular strength, as do numerous substances, including placebos, that affect the nervous system. The implications of these observations will be discussed later in this article.

### REDUCING ACCUMULATION OF BY-PRODUCTS

Fuel catabolism generates the energy for work, but it also produces by-products that must be removed from the muscle and body so that fuel catabolism can proceed. Activities that are limited because of by-product accumulation might benefit from treatments that counteract such accumulation. During all-out exercise of up to 30 seconds' duration, the actual amount of energy catabolized is small and by-product accumulation does not hinder performance. When a subject attempts to maximize work output during bouts lasting from 1 to 30 minutes, fatigue is associated with muscular acidosis, which is thought to contribute to a failure of the muscle's contractile ability. Sodium bicarbonate ingestion has been employed in an attempt to buffer the acid formed during exercise.

During performance bouts that last 30 minutes or more, an appreciable amount of fuel is catabolized, with a large percentage of the liberated energy being transformed into heat. This heat must be dissipated. The effectiveness of water ingestion under thermally stressing conditions will be discussed.

#### Sodium Bicarbonate

Sodium bicarbonate ingestion prior to exercise induces alkalosis, and this creates a "sink" for the hydrogen ions produced during intense exercise. The tissue most affected is blood. The effectiveness of blood alkalizers has been investigated numerous times during the last 50 years, and generally these substances have not improved short-term high intensity exercise, despite the fact that fatigue in this type of exercise is thought to result from acidosis within the muscle.<sup>9, 21</sup> It is possible that the rate of lactate and hydrogen ion build-up during all-out bouts of less than two minutes' duration is too rapid for appreciable amounts of hydrogen ion to be buffered in the blood. When the exercise intensity is reduced somewhat so that fatigue is still associated with acidosis, yet it does not occur until 4

to 15 minutes of exercise have been completed, sodium bicarbonate ingestion appears to be of benefit.<sup>9,17</sup> One possibility is that with the reduced exercise intensity and rate of hydrogen ion accumulation, the blood perfusing the musculature can buffer an appreciable amount of the metabolic by-products. Recently, sodium bicarbonate ingestion prior to exercise has been found to improve performance during high intensity interval exercise.<sup>8</sup> Although the exercise was high intensity, it was interrupted with rest periods, thus allowing a perfusion or "wash-out" of the muscle prior to the next bout. The present findings support the concept that sodium bicarbonate can delay fatigue during bouts of exercise that are limited by acidosis if the blood flow can accommodate the by-product accumulation.

#### Water

Ingested water does not directly enter into the metabolic pathways for exercise metabolism to a significant extent. Instead, its primary role is to help maintain blood volume and sweating rate during prolonged exercise, especially in hot environments. The heat that is produced as a by-product of fuel catabolism must be transported from the active musculature to the skin, which is cooled as a result of the evaporation of sweat. Fluid losses that exceed 3 per cent of body weight impair cardiovascular function during exercise while additionally compromising an individual's heat dissipating ability. Dehydration and hyperthermia are not only detrimental to performance, but they also pose serious health risks.

During prolonged exercise in a thermally stressing environment, it is not uncommon for sweating rates to exceed 3 liters per hour. The upper limit for the rate of fluid replacement is approximated 1 to 1.5 liters per hour, being controlled by the rate of gastric emptying. Although it is difficult to completely replace the water lost during exercise in the heat, it is important that dehydration be minimized by adhering to a feeding schedule that maximizes fluid replacement. Some guidelines to follow are (1) the drink should be low in simple sugars (less than 2.5 per cent), (2) it should be consumed cold (45°F), and (3) approximately 200 ml should be ingested every 10 to 15 minutes.

#### NEUROMUSCULAR ACTIVATION

The nervous system exerts a marked influence on work output by coordinating the recruitment of muscle fibers. This is particularly true during activities that require an individual to generate maximal muscular tension (such as weightlifting, field events, and the like). A muscle's maximal force-generating capability will be expressed when the nervous system activates all of the fibers within a muscle and does so in a highly coordinated manner so that forces are added together. It appears that, normally, we are not capable of maximal neuromuscular activation. One possible reason is that we have not learned how to synchronously recruit a large percentage of our muscle fibers (or motor units). Another reason is that neurologic

pathways exist that normally inhibit maximal contractions. Physical training appears to promote neuromuscular learning while also reducing inhibition.

Numerous treatments acutely increase muscular strength. They include treatments that exert psychological effects, such as placebos and hypnosis, as well as substances that have a known physiologic action, such as adrenaline and amphetamine.<sup>7, 13, 14</sup> Since muscular strength can be increased through psychological interventions that provide a suggestion of improved strength, it is difficult to determine if the effectiveness of pharmacologic agents are primarily physiologic as opposed to being a means of providing the suggestion of improved strength. Morgan and Brown have recently reviewed the theoretical considerations involved in the power of suggestion, or hypnosis, as an ergogenic aid.<sup>23</sup>

#### Amphetamines

A number of studies have demonstrated an increase in maximal muscular strength following the ingestion of a proper dose of amphetamine.<sup>14</sup> For the most part, these investigations tested normal men under laboratory conditions, which does not simulate competition. Amphetamines may provide a substitute form of "psych" during the laboratory experiment, similar to what athletes would otherwise experience during competition. Although amphetamines improve laboratory performance in athletes, they do not appear to allow an athlete to exceed his or her competitive effort.<sup>25</sup> Similar observations have been made with hypnosis.<sup>13</sup>

There are few data presently available regarding the actual effectiveness of numerous substances, which range in their physiologic action from innocuous herbs sold in health food stores to extremely complex psychomotor stimulants. When evaluating these substances, it is even more difficult to distinguish between their direct physiologic effect and their psychological effect.

#### SUMMARY AND CONCLUSIONS

The catabolism of bodily fuels provides the energy for muscular work. Work output can be limited by the size of fuel reserves, the rate of their catabolism, the build-up of by-products, or the neurologic activation of muscle. A substance that favorably affects a step that is normally limiting, and thus increases work output, can be considered an ergogenic aid.

The maximal amount of muscular force generated during brief contractions can be acutely increased during hypnosis and with the ingestion of a placebo or psychomotor stimulant. This effect is most obvious in subjects under laboratory conditions and is less evident in athletes who are highly motivated prior to competition.

Fatigue is associated with acidosis in the working musculature when attempts are made to maximize work output during a 4 to 15-minute period. Sodium bicarbonate ingestion may act to buffer the acid produced, provided that blood flow to the muscle is adequate.

Prolonged intense exercise can be maintained for approximately two hours before carbohydrate stores become depleted. Carbohydrate feedings

delay fatigue during prolonged exercise, especially in subjects who display a decline in blood glucose during exercise in the fasting state.

Caffeine ingestion prior to an endurance bout has been reported to allow an individual to exercise somewhat more intensely than he or she would otherwise. Its effect may be mediated by augmenting fat metabolism or by altering the perception of effort. Amphetamines may act in a similar manner.

Water ingestion during prolonged exercise that results in dehydration and hyperthermia can offset fluid losses and allow an individual to better maintain work output while substantially reducing the risk of heat-related injuries.

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