Sports Nutrition

"The possible effects of caffeine supplementation on health and exercise performance capacity"

Coaches have always looked at ways to improve performance capacity such as new training techniques. However, the increasing demands of sport and the decreasing distance between winning and losing has led to them looking at ways to get that extra competitive advantage over their competitors. Coaches aided by scientists have looked at the use of supplements that effect energy utilisation and these methods are termed ergogenic aids. Mottram (1996, pg xvi) defined an ergogenic aids as 'agents, which are used in an attempt to increase the capacity to work'. Caffeine is one of these said ergogenic aids and can be further defined as a pharmacological ergogenic aid. The associated benefits of caffeine have been the subject of a number of scientific investigations however the information provided has proven to be unclear and often contradictory. Therefore the true ergogenic effects of caffeine on exercise and performance are unknown.

Caffeine: What is it?

Caffeine is regarded as a psychoactive drug and has been used as a stimulant since the Stone Age (Mottram, 1996). It is a natural substance that is found in coca beans, coffee beans and tealeaves and is the most casually and widely used drug throughout the world. The evidence that suggests associated ergogenic effects has stimulated widespread interest because its availability is extensive, found legally in most soft drinks and over the counter medicines (Van Handel, 1983). Applegate (1999) stated that caffeine is a widely used ergogenic aid consumed by a wide variety of athletes ranging from the elite competitor to the weekend warrior.

Caffeine is a drug that belongs to a family of compounds known as methylxanthines. Chemically it is known as 1, 3, 7 – trimethylxanthine (Figure 1) and is one of the most active biosynthesised methylxanthines.

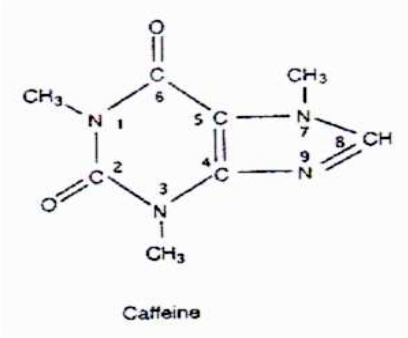

Figure 1. Structure of 1, 3, 7 – trimethylxanthine
(Taken from Graham et al., 1994)

The associated ergogenic effects of caffeine have forced the International Olympic Committee (IOC) to restrict its use but defining an appropriate legal limit for sports performers has been difficult. The IOC placed the drug on the doping list but later removed it because of the equivocal results on its role as an ergogenic aid. However, they have presently banned high levels and have set a maximum permitted urine content level of 12 ug/ml (Spriet, 1995). Although, reports have suggested that the beneficial effects of caffeine can also be witnessed at levels below this legal limit.

Health Risks and Adverse Effects

Before the effects of caffeine supplementation are examined and the relationship with exercise performance is established it is important to highlight any associated health risks. This is an important aspect as the ergogenic benefits of caffeine ingestion may be outweighed by the possible detrimental (ergolytic) effects to performance (Tarnopolsky, 1994). Most studies tend to agree that the side effects associated with caffeine use are dependent on several factors and that the responses vary greatly between individuals. A mild health risk is insomnia however this is only significant if caffeine ingestion is 1hr before sleep. Therefore this could be negative if caffeine is taken the night prior to competition. Other health risks associated with caffeine are irritability, anxiety and in some cases muscle tension. More severe chronic side effects are delirium, seizures and heart arrhythmias but these are only reported after high caffeine doses (Mottram, 1996). Although the mild effects of caffeine supplementation on health are not dangerous it is apparent that the adverse risks could limit sports performance is taken prior to competition.

Actions of Caffeine

In order to investigate into the effects of caffeine supplementation on exercise capacity it is essential to consider the major mechanisms responsible for the changes. Nehlig and Debry (1994) revealed three main mechanisms at a cellular level that seem to mediate the ergogenic responses related to caffeine.

The first proposed mechanism is that caffeine lowers the excitability threshold of the muscle and therefore prolongs the duration of active contraction. An increased release of calcium from the sarcoplasmic reticulum and conversely an inhibited uptake result in prolonged activity. The Ca^{2+} release channel contains cytoplasmic orientated receptor regions for modulating the channel state and caffeine can bind to these receptors. The effect of caffeine is to hold the channel in an open state, which allows large amounts of calcium to pass through into the cytoplasm. These actions result in additional calcium being available for muscular contraction. Collomp et al. (1991) examined caffeine during maximal performance and concluded that the coupling of excitation and contraction in striated muscle is apparent due to increased levels of intracellular calcium mediated by caffeine.

The second major mechanism involves cyclic nucleotide phosphodiesterase, which is an important enzyme in relation to the levels of cyclic AMP. It is responsible for the breakdown of cyclic-3', 5'- adenosine monophosphate (cAMP) and caffeine has been found to alter its activity. Research has shown inhibiting properties caffeine by decreasing the activity of these cellular enzymes and thus increasing the action of cyclic AMP. In conjunction with this caffeine is shown to elevate catecholamine levels in humans. Van Soeren and Graham (1998) examined catecholamine response to caffeine ingestion (6 mg/kg) in recreational athletes (n = 6) that were habitual caffeine users. The findings showed that there was a significant increase in both plasma adrenalin and noradrenalin concentrations resulting in the activation of adenylate cyclase, which is responsible for catalysing cAMP formation from ATP. An elevation in cAMP levels from enzyme inhibition and adenylate cyclase activation results in muscle glycogen sparing due to activation of enzyme sensitive lipases that promote lipolysis.

However the relevance of these actions is questionable, as the doses needed to achieve the actions described above would require extremely high doses. For example Fryer and Neering (1989) measuring the effects of caffeine on fast and slow twitch fibres found that caffeine concentrations potentiate twitch and titanic force in mammalian skeletal muscles. However the doses being specified in this study were concentrations of around 5 mmol/l, which is extremely high. Several comprehensive reviews of *in vitro* investigations (Dodd et al., 1993; Tarnopolsky, 1994; Nehlig and Debry, 1994; Graham et al., 1994; Spriet, 1995; Sinclair and Geiger, 2000) stated that the likelihood that caffeine will result in significant phosphodiesterase inhibition is only probable when using supraphysiological concentrations. Such levels are rarely found *in situ* and are considered toxic in such high levels (1mmol) and so it was concluded that the pharmacological properties of caffeine in concentrations found in circulating blood concentrations have limited effects on phosphodiesterase inhibition.

The final mechanism, adenosine receptor antagonism, is currently the most prevalent proposed mechanism for the ergogenic actions associated with caffeine (Sinclair and Geiger, 2000). The molecule adenosine either inhibits or stimulates adenylate cyclase and because caffeine has a similar structure it is recognised as a competitive antagonist. Adenosine stimulates A_1 receptors, which inhibit adenylate cyclase and consequently suppress fat metabolism (Daly et al., 1981). However caffeine exerts antagonist actions on the type A_1 and A_2 receptors and therefore regulates physiological functions resulting in increased lipolysis. Zhang and Wells (1990) examined the effects of chronic caffeine administration on peripheral adenosine receptors and reported significant adaptations. The results showed an increased number of A_1 receptors (37%) in fat cell membranes after caffeine treatment. However increased A_1-adenosine receptor-mediated inhibition of lipolysis and adenylate cyclase was not apparent. Importantly Tarnopolsky (1994) stated that unlike the other mechanisms evidence has suggested that antagonism occurs at moderate caffeine doses that are not harmful to the user. Therefore this is the most likely mechanism to consider, as the doses needed to elicit this response are more representative of concentrations found in the body.

Caffeine and Exercise Performance Capacity

The professionalism of sport and the fact that the IOC has placed restrictions on the drug has increased research into the area of ergogenic aids in general. Costill et al. (1978) conducted the first conclusive investigation into this relationship and stimulated the interest that followed. The study required the subjects to exercise on cycle ergometer at 80% VO_2 max until exhaustion under caffeine and placebo conditions. The results generated were significant and showed that time to exhaustion was 19.5% greater when the subjects ingested caffeine rather than decaffeinated (placebo trial). The subjects were able to cycle for approximately 90 mins (caffeine trial) compared to 75 mins (placebo trial) thus highlighting the possible effect on endurance performance in particular. Further analysis of the results suggested that the reasons behind such a significant increase could be accounted to a higher fat oxidation ($p<0.05$) during the caffeine trial, with a 50 to 100% increase in plasma free fatty acids.

The findings of this study and the significant data generated stimulated further investigation a year later by the same laboratory. Ivy et al. (1979) looked at the influence of caffeine ingestion on endurance performance since the previous study seemed to favour prolonged activity. Rather than cycling to exhaustion the subjects were required to perform continuous prolonged exercise i.e. 2hrs at 80rpm. The results provided further evidence that caffeine ingestion prior to endurance exercise increased performance significantly, stressing the elevated fat oxidation (31%) during the last 70 mins as the principal factor.

These initial studies highlighted that caffeine produced a consistent improvement in performance when the exercise is prolonged and involves mechanisms such as glycogen sparing and lipid metabolism. Therefore the majority of research has concentrated on the influence of caffeine ingestion on endurance performance.

Caffeine and Endurance Exercise

A key study by Graham and Spriet (1991) provided strong evidence in favour of the benefits of caffeine. The experimental protocol consisted of 2 running and 2 cycling bouts of exercise to exhaustion. The four testing occasions were randomised and double blind and was therefore well designed and controlled. The data generated showed increases in the time to exhaustion during the caffeine trial in both modes of exercise therefore eliminating modality as a key factor. Furthermore, the increases were significant; approximately 49.2 $\pm$ 7.2 min to 71 $\pm$ 11 min (treadmill) and 39.2 $\pm$ 6.5 min to 59.3 $\pm$ 9.9 min (cycling). The study also highlighted that the dose of 9-mg/kg-body weight elicited the benefits to endurance performance whilst remaining below the legal limit in the urine. A later study by Spriet et al. (1992) used the same dose but this time concentrated on cycling to exhaustion at 80% VO_2 max. Again the results showed that the subjects cycled significantly longer during the caffeine trial than the placebo trial (96.2 $\pm$ 8.8 min compared to 75.8 $\pm$ 4.8 min, respectively). However, comparison of the cycling trial in the study by Graham and Spriet (1991) and this later study shows that the increase is greater in the earlier study. This may be attributed to the differing fitness levels of the subjects used in both studies. The first study used competitive runners whereas the later used endurance-trained athletes. This factor is clearly highlighted by looking at the times

to exhaustion, with them being much higher at a similar intensity in the later study. Therefore the improvement is expected to be less because the trained subjects are close to their peak performance. However, the improvement in both studies reinforces the strong evidence that suggests that the performers can achieve the beneficial effects of a high dose of caffeine (9mg/kg) without exceeding the allowed limit (IOC).

The benefit to endurance performance was also examined with lower doses to see if they elicited the same response. A double blind study by Sasaki et al. (1987b) looked at a smaller dose of 6.6mg/kg of caffeine and its influence on strenuous prolonged exercise. Despite the differing dose the results follow the trend of the previous mentioned studies with the authors reporting an increase in the duration of treadmill running by 33%. An earlier report by Cadarette et al. (1983) applying the same exercise protocol i.e. treadmill run to exhaustion at 80% VO_2 max used an even lower dose of 4.4mg/kg body weight. Again the results showed an increased time to fatigue in the caffeine trial.

The results of these studies seem to indicate that there is an increase in time to exhaustion post caffeine ingestion and that it applies to varying doses. However, not all the research into this area has produced favourable results and has created some uncertainty. Graham and Spriet (1995) found that there was no significant effect with 9mg/kg of caffeine, which completely contradicts the previous studies (Graham and Spriet, 1991; Spriet et al., 1992). These earlier studies provided significant evidence of the ergogenic potential of caffeine (9mg/kg) on endurance performance. Whereas the later study compared various doses of caffeine and found that endurance was enhanced significantly with both 3 and 6 mg/kg caffeine but not for the 9mg/kg dose. Comparison of the studies suggests that the level of fitness of the subjects could again be a factor in the contrasting results. Graham and Spriet (1991) examined competitive runners whilst the later study used well-trained endurance athletes. This therefore may be further evidence to suggest that the ergogenic effects of caffeine are only significant in non-endurance trained athletes.

Further contradiction was found by Sasaki et al. (1987a) with no significant difference in time to exhaustion during caffeine and placebo trials. This may be explained by examining the exercise intensity. Previously in this assignment it was stated that caffeine was proved to be beneficial to endurance performance when glycogen depletion is a limiting factor. This would be at exercise intensities of around 65% to 85% VO_2 max. However on inspection of this study it is apparent that the subjects were running at around 62% VO_2 max and so glycogen depletion may not play a role especially if the subjects were familiar to graded testing and prolonged submaximal running at was the case in their study.

Caffeine and Short Term Exercise

Further research has been conducted after these initial studies to determine whether caffeine had a similar affect on activities of varying intensity and duration. The evidence is unclear when considering the effects of caffeine on anaerobic maximal power. Collomp et al. (1991) were particularly interested in this area but their findings showed no significant improvements in power performance. Williams et al. (1988) confirmed this conclusion in a study that examined maximal power output during 15 s maximal exercise bouts on a cycle ergometer. The results generated showed that caffeine

ingestion (7mg/kg) did not increase maximal ability to generate power. Contradictory to this, more recent research (Anselme et al., 1992) found that 250mg of caffeine ingested significantly increased 6 s sprint performance by increasing maximal power output by 7%. The action behind this was suggested to be direct stimulation of the muscle or central nervous system rather than glycogen sparing. The contradictions in the above investigations may be explained by the exercise duration. With the first study employing exercise bouts of almost double in duration than that of the later. Collomp et al. (1992) generated further conflicting results in a later study stating that caffeine ingestion (4.3mg/kg) significantly increased swimming sprint performance (100m) in trained athletes. This could suggest that mode of exercise during sprint performance is also a key factor and may explain why the literature above provides contrasting results.
Further evidence to support this trend is in a more recent study by Doherty (1998) found that caffeine was an effective ergogenic aid for short-term running performance using normal doses of 5mg/kg. This ambiguity could be attributed to the differing intensities, with the later study exercising at 125% VO_2 max, producing varying times to exhaustion. In this later study the exercise duration was 3-4 mins whereas in the earlier study by Williams et al. (1988) that exercise period was significantly shorter (15s).

Caffeine and Resistance Exercise

The research into the area of caffeine and resistance exercise is limited because as shown the mechanisms such as glycogen sparing seem to favour more prolonged activity. Jacobson and Edwards (1991) conducted a study to examine the effects of two doses of caffeine on maximal strength and endurance of the knee extensors and flexors. The subjects were randomly assigned to a low caffeine (200mg), high caffeine (600mg) and a placebo group. The results generated showed no significant differences in peak torque and joint angle throughout the testing conditions and therefore concluded that maximal strength and endurance was not significantly affected by caffeine supplementation. However a later study by Jacobson et al. (1992) found conflicting evidence. The investigation found that caffeine supplementation (7mg/kg) had significant effects on knee extension and power tests with increases reported at several angular velocities. Furthermore significant changes were recorded in the caffeine trial for knee flexion. More importantly this increase was not reported for the placebo trial. The conflicting results generated may be explained by the training status of the subjects analysed. The later study tested elite male athletes whereas in the earlier study the subjects were considered naïve to resistance training. Therefore the benefits associated with caffeine ingestion on resistance exercise may only be present in subjects who are familiar to resistance work.

Caffeine and Training

The fact that training may effect the significance of the associated benfits of caffeine on individuals has stimulated several investigations into the area. LeBlanc et al. (1985) compared the responses to caffeine supplementation in trained and non-trained individuals. The results found that resting metabolic rate was higher in the trained subjects due to a greater increase in the availability of free fatty acids. Furthermore it was

recorded that although caffeine induced significant decreases in plasma noradrenalin and increases in plasma adrenalin in both groups, the changes were significantly greater in the trained subjects. Further evidence to support this finding was generated in an investigation by Poehlman et al. (1985). Again the study reported a significantly greater increase in the resting metabolic rate (RMR) in the caffeine group when compared to the placebo. However an interesting finding is that the study did not find any differences between the trained and untrained subjects for free fatty acids. This contradicts the previous study, which stated that a major factor for the greater increase in RMR was the increase in free fatty acids in the trained subjects. The discrepancy highlighted may be down to the fact that the control subjects in the first study were inactive. The subjects in the second study were untrained but not inactive and therefore the increase in FFA reported in the first study may be because the difference in the level of training between the control and the trained group is greater.

Conclusions and Recommendations

It is clear from the studies highlighted that the evidence for the ergogenic benefits of caffeine is somewhat indefinite. When considering the effects on short-term intense exercise and maximal anaerobic power the findings suggest no apparent actions unless the duration was more than a few seconds. The most interesting area that has produced significant data seems to be endurance activity but again the there has been some contradictions in the results concerning doses. The reason behind theses variable results could be attributed to differing experimental protocol adopted by each study. Another factor may be the fact that the actual mechanism of caffeine is not truly known. Three principal cellular mechanisms highlighted in this assignment have all been proposed and it is unsure which one is the definite answer. However research by Fredholm et al. (1999) has provided sound evidence that adenosine receptor inhibition is the most important mechanism based on the high doses required to elicit the other two. The benefits towards exercise also seem to be without severe detriments to health with studies highlighting only mild side effects using the doses needed to produce the reported ergogenic effects.

Examination of the past literature has highlighted certain limitations to the work. Review of the studies suggests that the exact ergogenic effects are unclear and equivocal and may be because the studies have been largely poorly designed and controlled. Many have failed to address that response to caffeine will vary greatly between subjects and that there is a dose response effect. It must also be noted that limited research has been performed on resistance training, which must be addressed.

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