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CAFFEINE AND EXERCISE PERFORMANCE

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KEY POINTS

1. Recent, well-controlled studies have established that moderate doses of caffeine ingested 1 h prior to exercise enhance the performance of certain types of endurance exercise in the laboratory. Moderate caffeine doses produce urinary caffeine levels well below the allowable limit, as determined by the International Olympic Committee. The results are specific to well-trained elite or recreational athletes. It is not known if these findings will improve performance in competitions because controlled field studies of the effects of caffeine are lacking.
2. The mechanisms responsible for improved exercise endurance in prolonged exercise remain elusive. A metabolic mechanism appears to contribute early in exercise, when caffeine ingestion increases plasma free-fatty acid concentrations and muscle triglyceride use and spares muscle glycogen. However, it is not clear if increased fat oxidation causes the glycogen sparing in muscle. Increases in plasma epinephrine concentrations usually occur following caffeine ingestion but are not essential for the accompanying metabolic changes. When studying caffeine effects in the human it is difficult to identify the primary source of the "stimulus" because caffeine usually increases epinephrine secretion and is also rapidly metabolized in the liver to three dimethylxanthines (paraxanthine, theophylline and theobromine). The dimethylxanthines can remain in the circulation longer than caffeine and may be metabolic signals in their own right.
3. Caffeine appears to enhance performance during short-term, intense cycling lasting ~5 min in the laboratory and in simulated 1500 m race time. However, positive ergogenic effects of caffeine are much less frequent during sprint exercise lasting less than 90 s and in incremental exercise tests lasting 8-20 min.
4. Potential mechanisms for improving performance during intense exercise lasting 5-20 min include direct effects of caffeine on the central nervous system and/or excitation-contraction coupling and increased anaerobic energy provision in skeletal muscle.

INTRODUCTION

Caffeine is a "controlled or restricted drug" in the athletic world, because urinary levels of greater than 12 µg/mL following competitions are considered illegal by the International Olympic Committee (IOC). However, most athletes that consume caffeine beverages prior to exercise would never approach the illegal limit following a competition. Therefore, caffeine occupies a unique position in the sports world. It is an inherent part of the diet of many athletes although it has no nutritional value and also has the potential to be a "legal" ergogenic aid in many exercise situations. While it is common to equate caffeine with coffee, it should be noted that rarely is coffee the vehicle of administration in research studies. Therefore, it may be misleading to equate the two because coffee contains hundreds of additional chemicals.

In a 1990 Sport Science Exchange article, Wilcox concluded that few well-controlled studies had examined the effects of caffeine on endurance performance and that the results were inconsistent. Since 1990, the research examining caffeine and exercise performance increased and demonstrated the ergogenic effect of caffeine during prolonged endurance exercise (Graham & Spriet, 1991, 1995; Pasman et al., 1995). In addition, investigations examining the effects of caffeine on exercise performance during sprinting (<90 s), intense exercise of short (~5 min) and long duration (~20 min)(Collomp et al., 1990, 1991; Jackman et al., 1996; MacIntosh & Wright, 1995) have appeared.

There has been general improvement in the quality of the investigations because researchers have attempted to control several factors that may confound the caffeine results. Conlee summarized these factors in a 1991 review article. Three factors relate to the nature of the experimental design, i.e., the exercise modality, the power output, and the caffeine dose, whereas four others relate to the status of the subjects prior to the experiment, i.e., nutritional status, training status, previous caffeine use, and individual variability. An additional factor is the ability to reliably measure exercise performance. This reliability is greater in highly trained subjects than it is in the less well-trained.

Caffeine appears to be taken up by of all tissues of the body, making it difficult to independently study the effects of caffeine on the central nervous system, the muscles, and fat tissue in the exercising human. It is also apparent that different mechanisms are probably responsible for performance enhancement in different types of exercise. However, it is important to note that the mechanism(s) may not be entirely due to caffeine. For example, caffeine ingestion usually increases the plasma concentration of epinephrine, a hormone with widespread effects, and the

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liver rapidly metabolizes the caffeine, a trimethylxanthine, into three dimethylxanthines, i.e., paraxanthine, theophylline, and theobromine. The concentrations of these metabolites increase in the plasma as the caffeine concentration declines, and paraxanthine and theophylline especially are potential metabolic stimuli. Thus, it is difficult to resolve which tissues are directly or indirectly affected by which compound. Due to this uncertainty, when the term "caffeine" is used in this report, the reader should note that it could be any of the methylxanthines.

THEORIES OF ERGOGENICITY

There are three major theories for the ergogenic effect of caffeine during exercise. The first theory suggests a direct effect on some portion of the central nervous system that affects the perception of effort and/or the neural activation of muscle contraction. The second theory proposes a direct effect of caffeine on skeletal muscle performance. This may involve ion transport (including Ca^{2+} transport) and direct effects on key regulatory enzymes, including those controlling glycogen breakdown. Support for these suggestions is largely derived from *in vitro* investigations in which high pharmacological concentrations of caffeine are used to demonstrate effects. If these "test-tube" results have any relevance during exercise, the most likely candidates for contributing to an ergogenic effect of caffeine are changes in calcium activity and in the ability of the muscle to pump potassium from the extracellular fluid to the interior of the muscle fibers; caffeine levels during exercise are similar to the lowest concentrations of caffeine used *in vitro* that can affect these processes.

The third theory is the classic or "metabolic" explanation that involves an increase in fat oxidation and a reduction in carbohydrate oxidation. In this scheme, caffeine directly enhances the activity of enzymes that break down fat into fatty acids or caffeine increases circulating levels of epinephrine (EPI), which in turn mobilize free-fatty acids from triglyceride (TG) stores in fat or muscle tissue. The increased fatty acid availability increases muscle fat oxidation and reduces carbohydrate oxidation, thereby improving the performance of exercise that becomes exhausting when carbohydrate stores reach low levels.

The following sections address the ergogenic potential of caffeine during varying types of exercise that are categorized according to power output and time to exhaustion or to completion of a race.

CAFFEINE AND ENDURANCE PERFORMANCE

The interest in caffeine as an endurance ergogenic aid was initially stimulated by work from Costill's laboratory. They examined the effect of ingesting 330 mg of caffeine 1 h prior to cycling to exhaustion at 80% of maximal oxygen consumption (VO_2max) (Costill et al., 1978). The trained cyclists improved performance from 75 min in the placebo condition to 96 min following caffeine ingestion. A second study demonstrated that 250 mg of caffeine was associated with a 20% increase in the amount of work performed in 2 h (Ivy et al., 1979). These studies suggested that utilization of fat for energy increased by ~30% in the caffeine trials. A third study examined exercise muscle metabolism and reported that ingestion of 5 mg of caffeine/kg body weight spared muscle glycogen and increased the use of muscle TG (Essig et al., 1980). In the 1980's, few investigations actually tested the ergogenic effects of caffeine during endurance exercise; most examined only how metabolism was affected by caffeine. Furthermore, conclusions regarding the metabolic effects of caffeine were often based on indirect indicators of fat metabolism, i.e., increases in plasma free-fatty acids (FFA) and/or decreases in the ratio of carbon dioxide production to oxygen consumption (such decreases indicate that more fat is being utilized for energy). This work has recently been reviewed (Graham et al., 1994; Spriet, 1995; Tarnopolsky, 1994, Wilcox, 1990).

RECENT STUDIES OF CAFFEINE EFFECTS ON ENDURANCE PERFORMANCE AND METABOLISM

Several recent studies have carefully examined the performance and metabolism effects of caffeine in well-trained athletes who are accustomed to exhaustive exercise and race conditions. Most confounding factors were well controlled, and performance assessments were chosen to simulate competitive conditions. The studies examined the effects of a caffeine dose of 9 mg/kg body mass on running and cycling time to exhaustion at 80-85% VO_2max (Graham & Spriet, 1991: Spriet et al., 1992), the effects of varying doses (3-13 mg/kg) of caffeine on cycling performance (Graham & Spriet, 1995; Pasman et al., 1995) and the effects of a moderate caffeine dose (5 mg/kg) on performance of repeated 30 min bouts of cycling (5 min rest between bouts) at 85-90% VO_2max (Trice & Haymes, 1995).

Collectively, this work produced several important findings. Endurance performance was improved by ~20-50% compared to the placebo trial ~20-50% following ingestion of varying doses of caffeine (3-13 mg/kg) in elite and recreationally trained athletes who ran or cycled at ~80-90% VO_2max. Without exception, the 3, 5, and 6 mg/kg doses produced an ergogenic effect with urinary caffeine levels that were below the IOC acceptable limit. Three of four experiments using a 9 mg/kg dose reported performance increases, while 6/22 athletes tested in these studies had urinary caffeine levels at or above 12 µg/mL. Performance was enhanced with a 13 mg/kg dose, but 6/9 athletes had urinary caffeine levels well above 12 µg/mL. The side effects of caffeine ingestion (dizziness, headache, insomnia and gastrointestinal distress) were rare with doses at or below 6 mg/kg, but prevalent at higher doses (9-13 mg/kg). Such side effects were associated with decreased performance in some athletes at 9 mg/kg.

Caffeine generally produced a two-fold increase in venous plasma EPI at rest and during exercise and in venous plasma FFA at rest. The elevated FFA with caffeine was no longer apparent within 15-20 min of exercise. At the lowest caffeine dose (3 mg/kg), performance was increased without significant increases in plasma venous EPI and FFA. Muscle glycogen utilization was reduced following caffeine ingestion, but the "sparing" was limited to the initial 15 min of exercise at ~80% VO_2max.

There is little information on the performance and metabolic effects of caffeine in recreationally active or untrained subjects because performance in these groups is difficult to measure accurately. Chesley et al (1994) reported a variable glycogen sparing response to a high caffeine dose (9 mg/kg) in untrained males. Only 4/8 subjects demonstrated glycogen sparing during 15 min of cycling at 80-85% VO_2max. These results suggest that the metabolic responses to caffeine ingestion in untrained subjects are more variable than in aerobically trained populations.

Recently there was a preliminary report (Graham et al., 1995) comparing the effects of caffeine (4.5 mg/kg) in "pure" tablet form to the same amount of caffeine in a coffee beverage (~two mugs of strong coffee ingested in 10 min). Caffeine as a tablet resulted in the usual metabolic and performance effects, but when ingested as a beverage there was less of a response in plasma epinephrine and little or no effect on performance, even though the plasma caffeine concentrations were identical. Presumably the wide variety of compounds in coffee negated the usual ergogenic benefit.

MECHANISMS FOR IMPROVED ENDURANCE

It seems likely that a metabolic mechanism is part of the explanation for the improvement in endurance with caffeine, except at the low caffeine doses for which this hypothesis has not been fully examined. The increased FFA at the onset of exercise, the glycogen sparing in the initial 15 min, and the report of increased intramuscular TG use during the first 30 min of exercise suggest a greater role for fat metabolism early in exercise following caffeine doses of 5 mg/kg and above. However, these metabolic findings do not preclude other factors contributing to enhanced endurance performance. For example, caffeine appears to stimulate transport of potassium into inactive tissues, leading to an attenuation of the rise in plasma potassium concentration during exercise. It has been postulated that the lower plasma potassium helps maintain the excitability of the cell membranes in contracting muscles and contributes to caffeine's ergogenic effect during endurance exercise (Lindinger et al., 1993).

It is also noteworthy that EPI does not appear to play a major role in metabolic changes occurring with caffeine ingestion. Performance was enhanced with a caffeine dose of 3 mg/kg without significant increases in plasma EPI and FFA during exercise. In addition, an infusion of EPI that was designed to produce exercise EPI concentrations similar to those induced by caffeine had no effect on plasma FFA or on the rate of glycogen breakdown (Chesley et al., 1995). Also, Van Soeren et al. (1996) gave caffeine to spinal-cord injured subjects and reported increased plasma FFA without changes in EPI. Therefore, the known alterations in muscle metabolism alone cannot presently explain the ergogenic effect of caffeine during endurance exercise in all situations.

CAFFEINE AND PERFORMANCE OF GRADED EXERCISE TESTS

Several studies reported no effect of moderate doses of caffeine ingestion on time to exhaustion and VO_2max during graded exercise protocols lasting 8-20 min (see Dodd et al., 1993) However, two studies from the same laboratory reported prolonged exercise times when high doses of caffeine were given (Flinn et al., 1990; McNaughton, 1987). The first study used 10 and 15 mg/kg caffeine doses and reported a small, significant increase in performance. However, the control trial always preceded the caffeine trials, leading to the possibility of an order effect. The second study used a 10 mg/kg caffeine dose 3 h prior to cycling exercise and reported an increased time to exhaustion. The subjects completed control, placebo and caffeine trials with the control trial always first, and the remaining two trials randomized. It appears that the high caffeine dose is the most likely factor that separates these positive findings from the studies reporting no effect. Unfortunately, no mechanistic information presently exists to explain the ergogenic effects.

CAFFEINE AND PERFORMANCE OF INTENSE AEROBIC EXERCISE

Competitive races lasting ~20 min require athletes to exercise at power outputs at or above 90% of VO_2max. Recently, MacIntosh and Wright (1995) examined the effect of 6 mg caffeine/kg on performance in 1500 m swim trials in trained distance swimmers. Caffeine significantly reduced swim trial time from 21:22 to 20:59 (min:sec). The authors reported lower pre-exercise plasma potassium levels and higher post-exercise blood glucose concentrations with caffeine and suggested that electrolyte balance and glucose availability may be related to the ergogenic effects of caffeine.

CAFFEINE AND PERFORMANCE OF SHORT-TERM INTENSE EXERCISE

There has been recent interest in the effects of caffeine on performance during short-term intense exercise (~100% VO_2max) lasting ~5 min; near-maximal provision of energy from both aerobic and anaerobic sources is required for such activities.

Collomp et al. (1991) reported that 250 mg of caffeine increased cycle time to exhaustion at 100% VO_2max from 5:20 with placebo to 5:49, although the increase was not significant. A third trial, in which subjects received 250 mg caffeine daily for 5 d also increased exhaustion time non-significantly (5:40). Wiles et al. (1992) reported that drinking coffee containing ~150-200 mg of caffeine improved 1500 m time on a treadmill in well-trained runners by 4.2 s compared to placebo (4:46.0 vs. 4:50.2). In a second protocol subjects drank either coffee or a placebo, ran for 1100 m at a predetermined pace, and then ran 400 m as fast as possible. The average speed of the final 400 was 23.5 km/h with coffee and 22.9 km/h without. Following coffee, all subjects ran faster, and the mean VO_2 during the final 400 m was also higher.

A recent study by Jackman et al. (1996) examined the effects of caffeine ingestion (6 mg/kg) on the performance and metabolic responses to repeated bouts of cycling at 100% VO_2max in 14 subjects. Three bouts of exercise were performed with intervening rest periods of 6 min each. The first two cycling bouts at a controlled power output lasted 2 min, and the third continued to exhaustion. Cycle time to exhaustion was improved with caffeine (4.93 + 0.60 min vs. placebo, 4.12 + 0.36 min). Muscle and blood lactate measurements throughout the protocol suggested a higher production of lactate in the caffeine trial, even in the initial two bouts when power output was controlled. The net rate of glycogen breakdown was not different during the initial two bouts, and less than 50% of the muscle glycogen store was used in either trial during the protocol. The authors concluded that the ergogenic effect of caffeine during short-term intense exercise was not associated with glycogen sparing and may be caused either by a direct action on the muscle or by altered function of the central nervous system.

In conclusion, the mechanisms contributing to the performance improvement in short-term, intense exercise are not known but may include enhanced anaerobic energy provision, direct effects of caffeine on the transport of ions in muscles, and central nervous system effects on the sensation of effort and/or activation of muscle contraction in appropriate muscle fibers.

CAFFEINE AND SPRINT PERFORMANCE

Sprint performance is defined as fatiguing exercise at power outputs 1.5- to 3-fold greater than that required to elicit VO_2max or maximal efforts in sporting events lasting less than 90 s. The amount of energy derived from anaerobic processes would be ~75-80% of the total in the first 30 s, ~65-70% over 60 s, and ~55-60% over 90 s.

Williams et al. (1988) reported that caffeine ingestion had no effect on maximal power output or muscular endurance during short, maximal bouts of cycling. Collomp et al. (1992) found that ingestion of caffeine at a dose of 5 mg/kg did not increase peak power or total work completed in six subjects performing a 30-s Wingate test. However, the same group later reported that 250 mg of caffeine produced a significant 7% improvement in the maximal power output that could be generated during a series of 6-s sprints at varying force-velocity relationships (Anselme et al., 1992)). The same authors also examined the effects of 250 mg of caffeine on two 100-m freestyle swims that were separated by 20 min (Collomp et al., 1990). In well-trained swimmers, the velocity during the first and second swims was improved by 2% and 4%, respectively but performance times were not given.

Therefore, given the present information, it is not possible to conclude whether or not caffeine has an ergogenic effect on sprint performance. The brief and intense nature of sprint exercise makes it very difficult to study and to demonstrate significant effects of caffeine.

FIELD STUDIES

Performance in most laboratory studies examining endurance exercise is measured as the time taken to reach exhaustion at a given power output. However, in the field, performance is measured as the time taken to complete a certain distance. Consequently, extrapolations from the laboratory to field settings may not be valid. Occasionally, laboratory studies simulate race conditions by allowing the subject to control speed on a treadmill or cadence and resistance on a cycle ergometer in order to complete a distance or a given amount of work in the shortest possible time. Other studies have measured performance on the track or in the swimming pool not under actual race conditions but in time trials. However, these studies still do not entirely simulate real competitions.

In field studies that do simulate race conditions, it is often impossible to employ the controls required to generate conclusive results. For example, Berglund and Hemmingsson (5) performed the only field study examining the effects of caffeine ingestion on performance during endurance exercise. Cross-country ski performance in a race lasting 1-1.5 h was improved by 1-2.5 min compared to a control condition. Oddly, this improvement occurred during a race at high altitude but not at sea level. Unfortunately, the weather and snow conditions were variable in both locations, requiring mathematical "normalization" of the performance times in order to make comparisons. These problems raise questions about the validity of the results and indicate how difficult it is to perform well-controlled and meaningful field trials. There is a tremendous need for more field studies examining caffeine and endurance performance.

PRACTICAL CONSIDERATIONS OF INGESTING CAFFEINE

Caffeine Dose

Caffeine is a "controlled or restricted substance" with respect to the IOC. Athletes are allowed up to 12 µg caffeine/mL urine before it is considered illegal. This permits athletes who normally consume caffeine in their diets to continue this practice prior to competition. An athlete can consume a very large amount of caffeine before reaching the "illegal limit". A 70 kg person could drink about three or four mugs or six regular size cups of drip-percolated coffee ~1 h before exercise, exercise for 1-1.5 h and produce a subsequent urine sample that would only approach the urinary caffeine limit. It is not easy to reach the limit by ingesting coffee. A caffeine level above 12 µg/mL suggests that an individual has deliberately taken caffeine in the form of tablets or suppositories in an attempt to improve performance. Not surprisingly, only a few athletes have been caught with illegal caffeine levels during competitions, although formal reports of the frequency of caffeine abuse are rare. One older study reported that 26/775 cyclists had illegal urinary caffeine levels when tested following competition (Delbecke & Debachere, 1984).

Urinary Caffeine and Doping

The use of urinary caffeine levels to determine caffeine abuse in sport has been criticized. Only 0.5-3% of orally ingested caffeine actually reaches the urine because most of the caffeine is metabolized in the liver. The caffeine byproducts that are excreted are not measured in doping tests. Other factors also affect the amount of caffeine that reaches the urine, including body weight, gender, and hydration status of the athlete. The time elapsed between caffeine ingestion and urine sample collection is important and will be affected by the exercise duration and environmental conditions. Sport governing bodies may not regard these concerns as problems because most people caught with illegal levels of caffeine will have used caffeine in a doping manner. However, it is possible that someone who metabolizes caffeine slowly or who excretes 3% of the ingested dose rather than 0.5% could produce IOC-illegal amounts of urinary caffeine following ingestion of a moderate dose of caffeine.

Variability of Caffeine Responses

The variability of most performance and metabolic responses to caffeine is large. This appears to be true for all groups studied, including those who routinely ingest small and large amounts of caffeine, users who have withdrawn from caffeine, and non-users. The variability of muscle glycogen sparing following caffeine ingestion is greater in samples of untrained males than in trained males (Chesley et al., 1994; Spriet et al., 1992). Few females have been studied to determine if the variability in response to caffeine ingestion is similar to that in males. Menstrual status needs to be controlled for in these studies because estrogen may affect the half-life of caffeine. Therefore, although mean results in a group of athletes may predict an improved athletic performance, it is impossible to reliably predict that the performance of a given individual will improve.

Habitual Caffeine Consumption

As reviewed by Graham et al. (1994), several recent studies suggest that chronic caffeine use dampens the EPI response to exercise and to caffeine but does not affect indirect markers of fat metabolism during exercise (Bangsbo et al., 1992; Van Soeren et al., 1993). However, these changes do not appear to dampen the ergogenic effect of 9 mg/kg caffeine. Endurance performance increased in all subjects in two studies in which both users and non-users of caffeine were examined; users abstained from caffeine for 48-72 h prior to experiments (Graham & Spriet, 1991; Spriet et al., 1992). However, the performance results were more variable in a subsequent study with more non-users (Graham & Spriet, 1995). In addition, Van Soeren et al. (1993) recently reported that prior caffeine withdrawal for up to 4 d did not affect exercise-induced changes in hormones and metabolism in subjects who acutely ingested caffeine doses of 6 or 9 mg/kg. Performance times in the recreational cyclists riding to exhaustion at 80-85% VO$_2$max were improved by caffeine, and this was unaffected by 0-4 d of caffeine withdrawal.

Caffeine and High Carbohydrate Diets

It was reported that a high-carbohydrate diet and a pre-race carbohydrate meal negated the expected increase in plasma FFA following caffeine ingestion during 2 h of exercise at ~75% VO$_2$max (Weir et al., 1987). These results were interpreted to imply that high-carbohydrate diets would negate the ergogenic effects of caffeine, although endurance performance was not measured. However, a high-carbohydrate diet and a pre-trial carbohydrate meal did not prevent caffeine-induced increases in performance in a number of recent studies using well-trained/recreational runners and cyclists (see Spriet, 1995).

Diuretic Effect of Caffeine

Because caffeine is a diuretic, it has been suggested that caffeine ingestion may lead to poor hydration status prior to and during exercise. However, two studies reported no changes in core temperature, sweat loss, or plasma volume during exercise following caffeine ingestion (Falk et al., 1990; Gordon et al., 1982). A recent report also demonstrated that urine volumes and body hydration status during exercise were unaffected by caffeine ingested in a fluid replacement drink (Wemple et al., 1994).

Ethical Considerations

Since ergogenic effects of caffeine have been reported with doses of 3-6 mg/kg, it is easy for endurance athletes to enhance performance "legally" with caffeine. We suggested on the basis of our work that caffeine should be banned prior to competitions in endurance athletes. This would ensure that no athlete had an unfair advantage on race day but would not prevent caffeine use in training. Athletes would have to abstain from caffeine ~48-72 h prior to competition to achieve this goal. However, in the present climate, what should athletes do? Should they use caffeine in moderate amounts to make sure they are not missing out on a potential beneficial effect, or should they avoid this tactic because it could be considered doping? The former point of view may be popular because caffeine use is prevalent in society, and athletes will not have "illegal" amounts in their urine. Others argue that caffeine use in moderation is a trivial issue; other drugs with more serious side effects require greater attention. Nevertheless, the potential ergogenic effect of caffeine is impressive. On the other hand, discouraging caffeine use counteracts the "win-at-all-costs" mentality and sets the proper example for youth. The Canadian Center for Drug Free Sport reported in 1993 that over 25% of youths aged 11-18 reported using caffeine in the prior year to help them do better in sports.

SUMMARY

Caffeine ingestion (3-13 mg/kg body weight) prior to exercise often increases performance during prolonged endurance cycling and running in a laboratory setting. Caffeine doses below 9 mg/kg generally produce urine caffeine levels below the IOC-allowable limit of 12 mg/mL. Moderate caffeine doses (5-6 mg/kg) also increase short-term intense cycling (~5 min) in the laboratory and decrease swim time for 1500 m (~20 min). These results are generally reported in well-trained elite or recreational athletes, but field studies are lacking to confirm the ergogenic effects of caffeine in the athletic world. The mechanisms for the improved endurance have not been clearly established, but they may involve metabolic, hormonal, or direct effects of caffeine on muscles and/or on the nervous system.

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