

RECOVERY FROM EXERCISE: ROLE OF CARBOHYDRATE NUTRITION

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INTRODUCTION

Every training programme is based on three cardinal principles namely (i) intensity (ii) frequency and (iii) duration. Of these three principles, frequency is probably the most important because repeated stimulation promotes the adaptation process. Elite and professional athletes train more than they compete therefore in order to cope with their training loads it is essential that they recover quickly. It is also important that those who play recreational sport or exercise for health recover quickly so that they avoid residual fatigue and its negative impact on their vitality and enthusiasm for physical activity.

Strategies for optimizing recovery from exercise depend on the specific sport or type of exercise, its intensity and duration, and the time between training sessions or competitions. Successful recovery involves many physiological and metabolic processes that act in concert to prepare the athlete for the next bout of exercise. However, the essential requirements for successful short-term recovery are (1) resynthesis of the body's carbohydrate stores (2) rehydration, and (3) adequate rest. A return of performance is the clear measure of successful recovery. Therefore, this brief review will address only those studies that have assessed the influences of carbohydrate nutrition on performance following medium (24 hours) and short (4-5 hours) recoveries after endurance running and after variable speed running that are common in multiple sprint sports.

Role of Muscle Glycogen in Metabolism during Intense Exercise

During prolonged constant-paced cycling or running at a moderate intensity, e.g., ~ 70% VO_2max , carbohydrate and fat are the main fuels for energy production. The carbohydrate contribution is mainly from glycogen stores in skeletal muscle and, to a lesser extent, from hepatic glucose. The contribution of fat to energy metabolism is a consequence of the oxidation of fatty acids from adipose tissue cells as well as from the pool of intramuscular triglycerides. During sprinting for several seconds the rapid replacement of high energy ATP is provided by the degradation of both muscle glycogen and phosphocreatine (PCr). As exercise continues fatty acid oxidation increases in an attempt to ensure the continued rapid production ATP. However this up-regulation of fat metabolism is inadequate to cover the required high rate of ATP production for intense exercise. The contribution of blood glucose to muscle metabolism increases, but is also inadequate to sustain high-intensity exercise, even when high concentrations of blood glucose are maintained throughout exercise by glucose infusion (Claassen et al. 2005).

As a consequence of a decreased rate of ATP production, the athletes can no longer run at their optimum running speeds (Hargreaves, 2005). Reducing running speed enables fatty acid and glucose oxidation to fuel the resynthesis of ATP that allows athletes to continue to run. However, even low speed running cannot continue indefinitely because of the reduction in blood glucose and the onset of hypoglycemic. Blood glucose is the main fuel for the brain and central nervous system. Therefore, it is not surprising that the brain will invoke actions that protect this essential fuel supply. Inhibiting the continued recruitment of motor units during exercise is one action that helps protect blood glucose concentrations (Matsui et al. 2011). There are probably other ways in which the brain regulates exercise capacity to protect its essential fuel supply from an irretrievable reduction.

Restoration of Muscle Glycogen: Carbohydrate Feedings in the Early Phase of Recovery

Glycogen resynthesis begins immediately after exercise and is most rapid during the first 5-6 h of recovery (Goforth et al. 2003; Piehl 1974), so it is not surprising that eating carbohydrate immediately after exercise accelerates this process. After reviewing early studies on glycogen resynthesis Ivy (1991) suggested that the consuming about 1 to 1.5 g of carbohydrate/kg body weight, consumed immediately after exercise and at 2-h intervals until the next meal maximizes glycogen resynthesis. Timing of carbohydrate intake is important because immediately after exercise glycogen resynthesis is most rapid.

Contractile activity of skeletal muscle lowers glycogen stores and as a consequence stimulates the release of glucose transporter proteins (GLUT 4) from their intra-fibre storage sites and up-regulates the activity of the enzyme glycogen synthase. The translocation of GLUT4 transporters to the membrane accelerates the transport of glucose into the muscle fibres where it goes through the anabolic process of glycogen resynthesis. The activation of GLUT4 transporters is extended when carbohydrate is consumed after exercise because of the rise in plasma insulin concentration. Insulin receptors on the fibre membrane lead to a signaling process that prolongs the activation of GLUT4 transporters and so glucose uptake is extended for many more hours after exercise. The consequence is that resynthesis continues to replete glycogen stores. This is the reason why eating carbohydrate immediately after exercise is so strongly recommended (Jensen and Richter 2011).

Most studies on glycogen storage after exercise have used men as subjects. Earlier studies on carbohydrate loading in women suggested that they were unable to increase the concentration of muscle glycogen (Tarnopolsky et al. 1990), or at least not to the same extent as occurs in men (Walker et al. 2000). However, subsequent research demonstrated that when the carbohydrate intakes of men and women are carefully matched, both genders increase their glycogen stores to similar supra-normal values (James et al. 2001).

It is also important to note that the rate of glycogen resynthesis depends not only on the amount of carbohydrate consumed after exercise but more importantly on the intensity and duration of the exercise (Price et al. 2000). The lower the post-exercise glycogen stores the greater the need to consume the larger amounts of carbohydrate. However when exercise is neither prolonged nor intense then there is no need to consume large amounts of carbohydrate during the recovery period.

Adding protein and some amino acids to carbohydrate increases insulin concentrations to values that are higher than those achieved by consuming an equal amount of carbohydrate (van Loon et al. 2000a; Zawadzki et al. 1992). Ivy and colleagues were among the first to report that consuming a

carbohydrate-protein mixture immediately after exercise increased the rate of post-exercise muscle glycogen resynthesis beyond that which occurs with carbohydrate alone (Fogt and Ivy 2000; Ivy et al. 2002; Zawadzki et al. 1992). However, these early studies did not match the total energy intake when comparing the rates of glycogen resynthesis between post-exercise consumption of carbohydrate alone, carbohydrate plus protein and a placebo. A similar failure to match energy intake during recovery undermines their conclusions that exercise capacity is greater when ingesting a carbohydrate-protein mixture compared with a carbohydrate sports drink (Williams et al. 2003).

Not all authors report that glycogen resynthesis following the ingestion of carbohydrate-protein mixtures immediately after exercise is any better than after consuming energy-equivalent amounts of carbohydrate (Carrithers et al. 2000; Jentjens et al. 2001; van Hall et al. 2000; van Loon et al. 2000b). In a more recent study Bangsbo and colleagues examined whether or not ingesting carbohydrate and whey protein mixture improves muscle glycogen resynthesis forty-eight hours after a competitive soccer match (Gunnarsson et al. 2013). They were unable to confirm a greater glycogen resynthesis when the normal recovery diets of football players contained additional whey protein and carbohydrate compared with an increase in carbohydrate alone. Early studies that promoted the benefits of adding protein to carbohydrate during recovery from exercise used improvements in subsequent exercise capacity as indirect evidence of greater glycogen resynthesis. However, these findings have not been widely supported (Betts and Williams 2010; McLellan et al. 2014).

The available evidence does not support the performance benefits of consuming carbohydrate-protein mixtures after exercise however some authors suggest they will decrease the level of muscle soreness after exercise. Nevertheless, the weight of the available evidence does not support this proposed benefit (Pasiakos et al. 2014).

After strength training the dynamic balance between protein synthesis and degradation is tipped in favor of protein synthesis. Consuming a protein after strength training provides substrate for the accelerated synthesis process (Phillips 2011). The benefits of increased protein synthesis are not seen over a short recovery period because of the very long time course required for the formation new proteins that serve a wide range of biological functions. Nevertheless, consuming a carbohydrate-protein mixture (4:1) provides substrate to cover the glycogen used during exercise as well as for protein synthesis.

Recovery of Exercise Performance

Athletes do not readily change their dietary behaviour or food choices. Therefore it is essential to base recommendations for dietary changes that are based on evidence for improved performance. Several laboratory studies methods have been used to investigated the restoration of performance following a carbohydrate diet.. The most commonly used protocol requires participants to cycle or run at constant intensity to exhaustion because endurance capacity is largely dependent on skeletal muscle glycogen stores. In contrast is the protocol that requires participants to cycle or run a pre-determined distance or work load as quickly as possible. These protocols attempt to simulate the time trial performances that reflect real-world competitions. Exercise protocols that mimic the activity pattern of the multiple-sprint sports such as soccer, field hockey, rugby and basketball are also used to study the impact of carbohydrate nutrition on performance (Bendiksen et al. 2012; Nicholas et al. 2000).

Carbohydrate supplementation during 24 hours of recovery: endurance running.

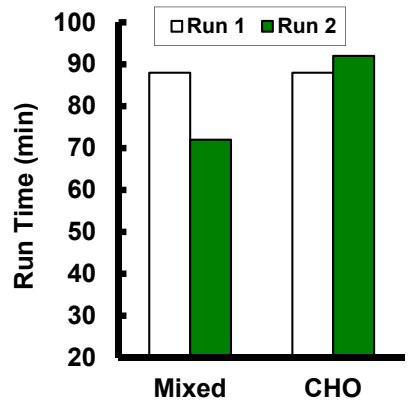
Consuming a high-carbohydrate diet during the first 24 h after prolonged strenuous exercise restores muscle glycogen concentrations to normal values (Goforth et al. 2003; Keizer et al. 1987). Interestingly, Keizer and colleagues noted that when some of their subjects were allowed to eat whatever they wished, they failed to restore their muscle glycogen concentrations after 22 h (Keizer et al. 1987). Therefore, to maximize glycogen recovery, it is essential to prescribe and carefully monitor the amount of carbohydrate that athletes consume during the recovery period.

Unfortunately, there are only a few studies that have considered the impact of carbohydrate-loading on performance 24 h later. In one such study, successful recovery of endurance running capacity 22 hours after prolonged exercise was reported by Fallowfield and Williams (1993). When their subjects ran on a treadmill at 70% $\text{VO}_{2\text{max}}$ for 90 min or to fatigue (whichever occurred first) and were then fed either a high-carbohydrate diet (9 g/kg) or an isoenergetic mixed diet that included 6 g of carbohydrate/kg during a 22-h recovery period, only those runners on the high-carbohydrate diet were able to match their previous day's run time of 90 min. Runners who consumed the mixed diet could only manage to complete 78% of their previous day's exercise, even though their recovery diet contained their normal carbohydrate intake (Fallowfield and Williams 1993).

Table 1 Examples of Common Foods Providing 50g of Carbohydrate

Food	Approximate Weights		Kitchen Measures
Porridge	500g	20 oz.	2 large bowls
Cornflakes	50 g	2 oz	1 large bowl
Potato			
Boiled	300g	12 oz.	5 egg size potatoes
Jacket	175g	7 oz.	1 medium potato with skin
Rice (cooked)	175	7 oz	4 tablespoons
Pasta			
White or wholemeal (cooked)	225g	9 oz	8 tablespoons
White Bread	100g	4 oz.	3 to 4 slices
Bagel	75g	3 oz.	1
Malt Loaf	75g	4 oz.	2 to 3 slices
Jaffa Cakes	75g	3 oz.	6
Fruit Juice	550 ml	22 fl.oz	1 pint
Milk	1000 ml	40 fl.oz	2 pints
Cola (not diet)	500 ml	20 fl oz	1.5 cans
Fruit			
Apples	425g	17 oz	4 medium
Oranges (peeled)	625g	25 oz	4 medium
Bananas	225g	9 oz	2 large

Figure 1 Recovery of endurance running capacity 22 hours after the first run, which was treadmill running at 70% VO_2max for 90 min or to fatigue, whichever occurred first. The high-carbohydrate (9 g/kg/d) and mixed recovery diets were isoenergetic Fallowfield et al 1993)



The type of carbohydrate consumed during recovery may also have an influence on the rate of muscle glycogen resynthesis and subsequent performance. Burke and colleagues (1993) reported that muscle glycogen resynthesis after recovering for 24 h from prolonged exercise was greater when their subjects consumed a recovery diet containing a high-glycemic-index carbohydrate (HGI) when compared to a low-glycemic-index carbohydrate (LGI). Although they did not assess the exercise capacity of their subjects after the 24-h recovery period, it is reasonable to expect that a greater endurance capacity would have been achieved with the greater glycogen stores following the HGI diet (Burke et al. 1993).

In contrast to the results of Burke et al. (1993), Stevenson et al. (2005a) found that treadmill run time to exhaustion was 12 min longer and fat oxidation was higher after a LGI recovery diet than after a HGI diet (Stevenson et al. 2005a). The greater rate of fat oxidation during the run to exhaustion after the LGI recovery diet presumably compensated for the lower pre-exercise glycogen stores. It is also interesting to note that the runners reported that they never felt hungry on the LGI diet, even after the overnight fast prior to the run to exhaustion the following day. But they were hungry when they consumed the HGI recovery diet that was matched for energy and macronutrient composition with the LGI diet. Therefore, it may be more effective to consume HGI carbohydrates for the first few hours after exercise and then switch to LGI carbohydrate meals for the remainder of the recovery period. In this way, the HGI carbohydrate may better contribute to the most rapid early period of glycogen resynthesis, whereas the LGI carbohydrate may continue to provide energy as well as the sensation of satiety. In addition, an evening meal containing LGI carbohydrate depresses the spike in blood glucose in response to a standard HGI breakfast the following morning and so may enhance fat oxidation during subsequent exercise (Stevenson et al. 2005b). Additional research is needed to determine the mix of carbohydrates that maximizes glycogen restoration and performance.

Carbohydrate supplementation during 24 hours of recovery: multiple-sprint sports

Prolonged, intermittent, high-intensity running is the common activity pattern of multiple-sprint sports. Even though each sprint last no more than 3 or 4 seconds collectively they reduce muscle glycogen stores to low values (Balsom et al. 1999a; Mohr et al. 2005; Nicholas et al. 1999). For example, the muscle glycogen concentrations of professional soccer players are severely reduced after 90 min of match play (Bangsbo et al. 2006; Bendiksen et al. 2012; Jacobs et al. 1982; Saltin

1973). It is well established that those players who begin match play with modest or low glycogen concentrations in their muscles cannot fully engage in the game because of the early onset of fatigue.

In a study on nutrition and soccer-specific fitness, Bangsbo and colleagues (1992) showed that when players consumed a high-carbohydrate diet for 48 h before a series of soccer-specific tests, their endurance capacity during prolonged, intermittent, high-intensity treadmill running was significantly better than when a normal mixed diet was the nutritional preparation for the test. In a study of soccer players during a 4-aside competitive game changing their pre-game diet from low to high carbohydrate foods improved their running performance (Balsom et al. 1999b).

Using intermittent high-intensity shuttle running as an exercise protocol that mimics the activity patterns common in soccer, Nicholas et al. (1997) examined the influence of different nutritional strategies on exercise capacity during the last 15 min of the 90-min test. All the subjects completed 75 min of the test and then they were required to complete as many 20 metre shuttles while alternating between sprinting and jogging to the point of fatigue. Endurance capacity was assessed as the shuttle run time beyond 75 min. Recovery of shuttle running capacity was restored after 22 h of recovery when the subjects consumed a recovery diet that provided a carbohydrate intake of 10 g/kg/d (Nicholas et al. 1997). However, when the subjects consumed their normal amount of carbohydrate with additional protein and fat to match the energy intake of the carbohydrate-recovery diet, they were unable to run as long as on the previous day.

Although these studies contribute to our understanding of carbohydrate metabolism it is also important to be able to translate the available information into practical recommendations for athletes. For example, the large amounts of carbohydrate used in studies on the maximum rates of glycogen resynthesis after exercise may cause gastro-intestinal discomfort. Therefore, eating smaller amounts of carbohydrate more frequently e.g. the equivalent of 0.6g/kg body weight every 30 min during the first 4 to 5 hours of recovery will also increase the rate of glycogen resynthesis (van Loon et al. 2000b). It is also important to remember that when translating this information into recovery diets that the carbohydrate forms only a part of the energy content of even high carbohydrate containing foods (for examples see Table 1). A post-exercise intake of about 50g of carbohydrate every 2 hours before the main recovery meal appears to be effective in restoring muscle glycogen stores and performance. These recommendations are intended for those athletes who need recover in 24 hours to cope with daily training sessions

Carbohydrate supplementation during 4 hours of recovery: endurance running.

Consuming carbohydrate beverages immediately after exercise accelerates muscle glycogen resynthesis, even during a recovery as short as 4 h, but does it make any difference to performance during subsequent exercise? Fallowfield et al. (1995) attempted to answer this question with a group of endurance runners who initially ran on a treadmill at 70% $\text{VO}_{2\text{max}}$ for 90 min or to fatigue (which ever occurred first). Immediately after the exercise and 2 h later, the subjects drank either a placebo or a sports beverage containing about 1 g of carbohydrate/kg body mass. After a 4-h recovery period, both groups ran to exhaustion at the same treadmill speeds as on the first occasion. The group who drank the sports beverage ran for 22 min longer than the group who drank the placebo (Fallowfield et al. 1995).

Figure 2. Recovery of endurance capacity during intermittent high-intensity shuttle running 24 hours after the same run. The high-carbohydrate (9 g/kg/d) and mixed recovery diets were isoenergetic (Nicholas et al., 1997).

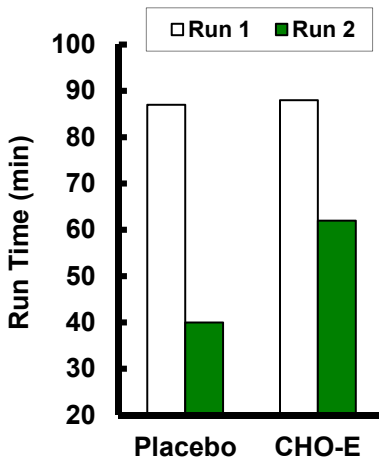
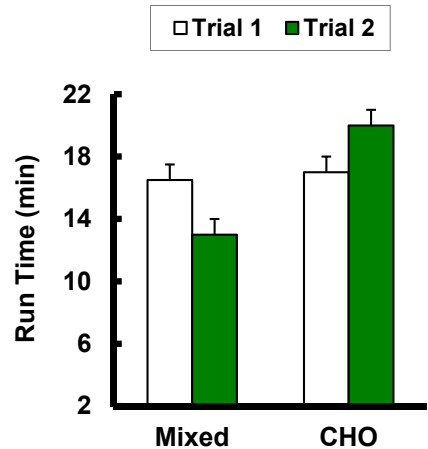


Figure 3. Run time to exhaustion at 70% VO_{2max} 4 h after running at 70% VO_{2max} for 90 min or until fatigue, whichever came first. One group drank a sports beverage (6.9% carbohydrate), whereas the other group drank a placebo beverage (Fallowfield et al., 1995).

Interestingly, ingesting large amounts of carbohydrate immediately after exercise may not be more beneficial than a moderate amount. For example, Wong and Williams (2000) gave a group of runners 50 g of carbohydrate in a 6.5% carbohydrate-electrolyte beverage immediately after 90 min of treadmill running (70% VO_{2max}) and then rehydrated them by providing either water or the carbohydrate beverage in sufficient quantity to cover 150% of the body mass lost during the initial run. Surprisingly there was no difference in run times to exhaustion when the runners consumed 175 g or 50 g of carbohydrate during the 4-h recovery period (Wong and Williams 2000). Yet there was a greater increase in muscle glycogen concentration during the 4 h of recovery when the runners ingested the larger amount of carbohydrate (Tsintzas et al. 2003). These results are somewhat paradoxical because it would be reasonable to expect a greater improvement in exercise capacity after a treatment that causes a greater increase in muscle glycogen stores. Nevertheless, post-exercise ingestion of a well-formulated sports beverage does improve endurance capacity during subsequent exercise, but more information is needed to be able to prescribe the optimal amounts of beverage for each athlete (Bilzon et al. 2002).

Carbohydrate supplementation during 4 hours of recovery: multiple-sprint sports.

In professional multiple-sprint team sports such as football, soccer, rugby, field and ice hockey, and basketball, only one game or match is normally played each day. However, in tournaments or championship competitions in some sports, players may have to compete more than once with only a few hours of recovery between matches. In the absence of studies on the nutritional influences on recovery under these circumstances, it appears reasonable to suggest that athletes should implement the same nutritional recommendations offered to endurance athletes. As mentioned earlier athletes are advised to ingest a well-formulated sports drink immediately after exercise and at 30-min intervals during the recovery period.

However, when recovery is so short then post-exercise recovery merges with pre-exercise nutritional preparation. The recommended pre-exercise meal is an easy to digest high carbohydrate meal that has low fibre content so that it doesn't cause gastro-intestinal disturbances. High glycaemic index (HGI) carbohydrate foods are absorbed and digested more rapidly than low glycaemic index (LGI) carbohydrate foods. For example when skeletal muscle glycogen was assessed three hours after runners ingested either a HGI or LGI carbohydrate breakfast (2.5g/kg body weight) its concentration increased by about 15% whereas there was no measurable increase after the LGI meal (Wee et al. 2005).

Factors That May Delay Recovery

Glycogen repletion after prolonged heavy exercise will obviously be slower when carbohydrate intake is low or is withheld during recovery (Fournier et al. 2004). Recovery of muscle glycogen may also be delayed when prolonged exercise involves a significant amount of eccentric muscle actions because this type of activity damages muscle membranes and results in delayed-onset muscle soreness (Asp et al. 1998; Costill et al. 1990; O'Reilly et al. 1987). (Eccentric actions are those in which the muscle lengthens as it produces force, e.g., the actions of the elbow flexors as a dumbbell is lowered.) Furthermore, Asp et al. (1998) reported that prior eccentric contractions during leg exercise resulted in a greater reduction in muscle glycogen concentration than in the contralateral limb that performed concentric contractions. The lowered glycogen concentrations following eccentric exercise was accompanied by a marked reduction in power output and endurance capacity during subsequent two-legged concentric exercise. This poorer performance was attributed to the reduction in glycogen concentration and a greater rate of glycogen utilization (Asp et al. 1998).

There is an eccentric component to leg muscle actions during running, and this may explain the slower recovery of muscle glycogen after prolonged running such as in marathon races (Sherman et al. 1983). Muscle glycogen resynthesis was reported to be only 70% of pre-race values two days after a competitive marathon race, in spite of the fact that the runners ate a high-carbohydrate diet (7 g/kg). Muscle glycogen stores were restored to their high pre-race values after seven days of recovery (Asp et al. 1997). This information should be used in planning a recovery strategy because athletes who experience delayed-onset muscle soreness may take longer than normal to restore their muscle glycogen stores and endurance fitness.

REHYDRATION

Immediately after exercise most athletes generally prefer to drink fluids rather than to consume solid foods. This choice helps rehydrate the athlete, which is an essential part of the recovery process. The volume, type, and timing of fluid ingested during short recovery periods (e.g., of only a few hours) are important considerations for successful rehydration and subsequent exercise. In order to fully hydrate during short-term recovery, athletes should drink the equivalent of 150% of the volume of body mass lost through sweating (Shirreffs and Maughan 2000) because of the way the kidneys handle the fluid load. The fluid that is most effective in rehydrating athletes after exercise is a well-formulated sports drink rather than water (Gonzalez-Alonso et al. 1992). Drinking a sports beverage immediately after exercise not only provides fluid, but the carbohydrate helps begin the process of glycogen resynthesis and the sodium in the sports drink promotes retention of the fluid in the body.

It appears that when recovery duration is short, e.g., ~4 h, athletes should drink the appropriate amount of a sports drink (150% of body weight lost) in portions allocated throughout the recovery period; they should not simply consume the beverage as fast as possible. When athletes were allowed to drink the required volume of a sports beverage voluntarily, they consumed most of the volume immediately after exercise, and their endurance capacity during a subsequent exercise session was less than when the fluid intake was ingested throughout the 4-h recovery period as prescribed (Wong et al. 1998). Therefore, it is essential to develop a rehydration plan as part of a recovery strategy in order to prepare successfully for the next round of exercise whether it is in training or competition .

SUMMARY

Restoration of muscle glycogen stores underpins the recovery of endurance capacity for moderate-to-high-intensity exercise. Therefore, eating sufficient carbohydrate following prolonged intense exercise is an essential part of any recovery strategy. The carbohydrate intake required to replace large decreases in muscle glycogen within 24 h is approximately 10 g/kg/d (Burke et al. 2011). When the daily carbohydrate intake is less than 4 g/kg/d, it is insufficient to support daily prolonged submaximal exercise (Kirwan et al. 1988; Pascoe et al. 1990). When recovery is of short duration, there is still an advantage to be gained from consuming a sports beverage that can provide the equivalent of 1-1.2 g carbohydrate/kg/h because this will accelerate glycogen resynthesis, help the rehydration process, and benefit performance during subsequent exercise. When athletes experience soreness after exercise, their recovery may be delayed, not only because of the soreness per se, but also because the rate of glycogen resynthesis may be slower.

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