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BUFFERS AND THEIR ROLE IN THE NUTRITIONAL PREPARATION OF ATHLETES

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KEY POINTS

- Performance during continuous or intermittent high-intensity exercise can be limited, at least in part, by the accumulation of hydrogen ions (H^+) which reduce muscle pH and interfere with muscle contractile and metabolic processes.
- H^+ accumulation in the muscle cells and blood can be buffered in many different ways, but few of these can be altered by nutrition. The exceptions are the intracellular buffer, carnosine, and the extracellular buffer, bicarbonate. Nutritional interventions with carnosine and bicarbonate might therefore enhance fatigue resistance and improve performance during high-intensity exercise.
- Muscle carnosine concentration can be increased by dietary supplementation with ß-alanine (approximately 3–6 g of ß-alanine per day for 4–8 wk) whereas extracellular bicarbonate concentration can be increased by about 20% following ingestion of sodium bicarbonate (~0.3 g per kg body mass 1-2 h before exercise).
- There is evidence that both ß-alanine and sodium bicarbonate ingestion can enhance exercise performance during single or repeated bouts of high-intensity exercise in which energy is supplied predominantly through anaerobic glycolysis.
- Sodium bicarbonate supplementation can produce gastrointestinal disturbances. ß-alanine supplementation in doses greater than 10 mg/kg BM can lead to a short period of paresthesia (flushing and a prickling sensation on the skin) although recent "slow-release" supplements have largely overcome these unpleasant side effects.
- To ensure that the potential benefit of supplementation with bicarbonate or ß-alanine outweigh any negative side effects, it is important for athletes to practice their supplementation strategy prior to competition.

INTRODUCTION

Exercise performance in "middle-distance" sports events (lasting between ~1 and 8 min) is related to energy supply through both oxidative and non-oxidative metabolic processes. Because the energy demand in these sports is close to or in excess of the maximal rate of O_2 consumption, there will be an appreciable contribution to the energy supply from anaerobic glycolysis, resulting in a significant production of lactate and hydrogen (H^+) ions. These large increases in [H^+] may reduce muscle pH from ~ 7.1 at rest to as low as 6.4 at the point of exhaustion. Although fatigue is clearly multi-factorial in these (and other) sports events, performance limitation appears to be related to the extent of the muscular acidosis which is developed along with associated ionic disturbances which may affect muscle excitation (Chin & Allen, 1998; Fitts, 1994). Metabolic acidosis can impair performance through direct interference with the muscle contraction process and by limiting the resynthesis of high-energy phosphates and inhibiting the rate of anaerobic glycolysis (Fitts, 1994).

During high-intensity exercise, several systems contribute to both intracellular and extracellular buffering in attempts to maintain pH homeostasis, with intramuscular carnosine and plasma bicarbonate both having important roles (Juel, 2008; Harris and Sale, 2012). Accordingly, there are two nutritional supplements that middle-distance athletes may be able to use to enhance buffering capacity with a view to enhancing performance. The first of these is the most established and involves the acute supplementation of sodium bicarbonate to increase extracellular buffering capacity. The second approach has been less extensively researched but may involve longer-term supplementation with the non-essential amino acid, ß-alanine, to increase muscle carnosine content and enhance intracellular buffering capacity.

EXTRACELLULAR BUFFERING: SODIUM BICARBONATE

A high rate of anaerobic glycolysis in skeletal muscle during high-intensity exercise can produce hydrogen ions (H^+) in excess of the intracellular buffering capacity. Increasing the bicarbonate concentration and elevating pH in the extracellular space, however, increases the efflux of H^+ from the muscle (Juel, 1996). Because of the negative consequences of H^+ accumulation within muscle cells, this greater H^+ efflux may reduce the fall in muscle cell pH and therefore retard the rate of muscle fatigue development and enhance performance by facilitating enhanced energy supply through anaerobic glycolysis (Hollidge-Horvat et al., 2000).

Bicarbonate plays an important role in maintaining pH and electrolyte gradients between intracellular and extracellular environments. The rationale for "bicarbonate loading" is that consumption of dietary bicarbonate can temporarily increase blood bicarbonate concentrations and pH, thereby enhancing the buffering capacity of the extracellular space. The bicarbonate concentration in the extracellular fluid is normally around 25 mmol/L at rest, but may be increased to around 30 mmol/L after the ingestion of 0.3 g/kg body mass (BM) sodium bicarbonate. H^+ and bicarbonate combine to form carbonic acid which in turn dissociates to form carbon dioxide and water. For reasons outlined earlier, bicarbonate loading may be most effective in sporting events which are heavily dependent on the generation of energy through anaerobic glycolysis with consequent challenges to acid-base homeostasis which may contribute to performance limitation.

BICARBONATE LOADING

Most often, bicarbonate loading involves the acute ingestion of bicarbonate shortly before the targeted training session or competition. Typically, 0.3 g per kg of the athlete's BM is consumed (i.e. about 20 g for a 70 kg athlete), 1-2 h prior to exercise, usually in the form of sodium bicarbonate. Citrate has also been used as a buffering agent but does not seem to be as effective in enhancing performance (Carr et al., 2011a).

The major potential side-effect of bicarbonate supplementation is the possibility of gastro-intestinal (GI) problems including stomach pain, diarrhea, nausea and vomiting. These side-effects clearly have the potential to present significant problems for athletes in a competition setting. The best strategy to increase blood alkalosis and to reduce GI symptoms may be to spread out the consumption of bicarbonate, commencing 120-150 min before the start of exercise, and consuming it alongside a small carbohydrate-based meal and some fluid. It is recommended that athletes wishing to use bicarbonate experiment to find which loading protocol suits them best (i.e., optimises performance while minimising GI disturbance).

Another potential side effect of sodium bicarbonate ingestion is that large quantities of sodium are ingested, which can lead to a temporary fluid retention. While this may be useful in some sports involving high sweat rates over long periods, the increased body mass gain may be a disadvantage in many other situations.

EFFECTS OF BICARBONATE ON PERFORMANCE

As outlined earlier, bicarbonate loading could theoretically enhance sporting events which rely on high rates of energy generation through anaerobic glycolysis. Events involving sustained high-intensity exercise lasting between ~1 and 8 min, such as many swimming, running, track, cycling and rowing events, are obvious candidates. However, it is possible that performance in longer events of 30-60 min may also be enhanced by bicarbonate loading by enabling the athlete to fatigue less or to produce more power during pace surges within the event or in a final sprint finish. A study by Berger et al. (2006) found that bicarbonate ingestion reduced the VO_2 'slow component,' which reflects a progressive loss of muscle efficiency, during constant-work-rate exercise at an intensity corresponding to about 80% VO_2max. There was a significantly lower O_2 cost of exercise after 6 min which, in this situation, may reflect reduced fatigue development (perhaps due to a reduced fall in pH) and a blunted recruitment of fast-twitch muscle fibres as exercise proceeds. Also, bicarbonate supplementation may potentially enhance performance during sports which involve intermittent high-intensity exercise such as many team sports, racquet sports and combat sports (Bishop et al., 2010). Bishop et al. (2004) reported a significant 5% increase in total work done during five 6-s sprints separated by 30-s recovery periods, although Parry-Billings and MacLaren (1986) found no performance improvement in repeated 30-s sprints.

The potential for bicarbonate to enhance sports performance has been extensively investigated in both laboratory and field settings. With some notable exceptions (Parry-Billings and MacLaren, 1986; Stephens et al., 2002; Vanhatalo et al., 2010), these studies generally support the benefits of bicarbonate loading for the sporting scenarios listed earlier (Costill et al., 1984; Jones et al., 1977). A review of the literature by Requena et al. (2005) concluded that athletes competing in high-intensity sports where a relatively large muscle mass is recruited (athletics events, cycling, rowing, swimming and many team sports) could benefit from bicarbonate loading. An early meta-analysis concluded that the ingestion of sodium bicarbonate has a moderate positive effect on exercise lasting between 30 s and 7 min (Matson & Tran, 1993). Positive performance effects were related to the degree of metabolic acidosis achieved during the exercise, suggesting that the benefit of bicarbonate supplementation may be related to an interaction between the accumulation of intracellular H^+ and the extracellular alkalosis brought about by the intervention. Another meta-analysis concluded that a bicarbonate dose of 0.3 g/kg body mass resulted in a mean performance enhancement of 1.7% in a single 1-min sprint in male athletes (Carr et al. 2011b). The benefits of bicarbonate were modified by effects such as: loading dose (0.5% mean improvement in performance for each 0.1 mg/kg BM increase in dose; number of sprint bouts (0.6% mean improvement with five extra sprint bouts); exercise duration (0.6% reduction in performance when test duration was increased from 1 min to 10 min); training status (1.1% reduction of effectiveness with non-athletes); and sex (0.7% less effectiveness in females compared to males) (Carr et al. 2011b).

Rather than take a relatively large acute dose of bicarbonate, an alternative approach is to load bicarbonate in small doses over several days prior to competition. This approach enhances muscle extracellular buffering capacity but with reduced risk of GI problems. A typical approach is to take 100-150 mg/kg BM sodium bicarbonate in 3-4 doses over the day for 3-5 d prior to the competition. Several days of such dosing increases blood bicarbonate concentration and enable this to be maintained for at least 24 h after the last dose (McNaughton & Thompson, 2001). This may therefore be a useful approach if the goal is to enhance performance during multiple events on the same day or where a competition runs over several days. There are also clear advantages to this approach in avoiding GI disturbances in the hours surrounding competition. However, there is relatively little information on the effectiveness of this longer-term approach to bicarbonate loading on sports performance.

Given that bicarbonate might allow more work to be done within a single exercise bout or a series of exercise bouts, it is reasonable to consider whether the chronic use of bicarbonate might support the training process. Edge et al. (2006) studied the effects of chronic bicarbonate loading prior to interval training sessions in moderately trained females. The subjects consumed 400 mg/kg BM bicarbonate on three occasions per wk (prior to intense training sessions) over an 8 wk period. There were significantly greater improvements in time to exhaustion (164% vs. 123%) for the bicarbonate supplemented group compared to a group which consumed a placebo. The authors concluded that while training process itself is important in increasing muscle buffering capacity, bicarbonate supplementation may enhance training intensity and augment the gains in buffering capacity brought about by training.

INTRACELLULAR BUFFERING: CARNOSINE

Carnosine, a potent intramuscular buffer, is a dipeptide found at high concentrations in the cytosol of skeletal muscle and especially concentrated in fast-twitch muscle fibres (Artioli et al., 2010; Derave et al., 2010). Animal species who rely on anaerobic energy production and exercise for survival (e.g. horses and greyhounds) or who have adapted to cope with bouts of hypoxia (e.g., diving whales) have particularly high muscle carnosine concentrations (Harris et al., 1990). Moreover, higher concentrations have been found in sprinters than in marathon runners (Parkhouse & McKenzie, 1984) and sprint training increases muscle carnosine concentration (Suzuki et al., 2004). These natural differences in muscle carnosine concentrations provide a rationale for nutritional interventions to increase intracellular buffering capacity and performance. The contribution of muscle carnosine to total intracellular muscle buffering capacity has been suggested to be approximately 7% under normal conditions but this may be increased to 15% following dietary supplementation with ß-alanine (Harris et al., 2006). ß-alanine is a naturally occurring amino acid that, along with L-histidine, is one of the precursors to carnosine. Because L-histidine is more abundant in muscle cells than ß-alanine, the latter is considered the rate-limiting amino acid for carnosine formation.

INCREASING MUSCLE CARNOSINE

There is now good evidence that muscle carnosine can be increased substantially (40-50%) after prolonged ß-alanine supplementation (~3–6 g of ß-alanine per day for 4–8 wk; Derave et al., 2010; Harris et al. 2006). Moreover, the subsequent loss of skeletal muscle carnosine following ß-alanine supplementation is very slow, with studies suggesting that it may take 10-15 wk to return to baseline levels after cessation of successful supplementation (Baguet et al., 2009; Stellingwerff et al., 2012). ß-alanine supplementation in doses greater than 10 mg/kg BM can lead to a short period of paraesthesia (flushing and a prickling sensation on the skin) but recent 'slow-release' supplements have largely overcome these unpleasant side-effects.

EFFECTS OF INCREASING MUSCLE CARNOSINE ON PERFORMANCE

In one of the earlier studies in this field, Suzuki et al. (2002) reported that 30-s Wingate test performance was correlated with initial muscle carnosine content. A later study showed that 4 weeks of ß-alanine supplementation reduced the decline of blood pH during intense exercise (Baguet et al., 2010). Although not a universal finding, some studies have demonstrated significant benefits of ß-alanine supplementation for high-intensity performance during cycling, rowing and knee-extension exercise (Artioli et al., 2010; Derave et al., 2010). However, in one of the few studies which investigated the effects on actual athletic performance, Derave et al. (2007) found no difference in 400 m sprint performance following ß-alanine compared to placebo supplementation. Also, a recent study found that ß-alanine supplementation alone did not enhance performance in a cycle time trial compared to combined supplementation with ß-alanine and sodium bicarbonate (Bellinger et al., 2012). Overall, however, it appears that dietary supplementation with 3–6 g ß-alanine day for between 4-8 wk will increase muscle carnosine by about 40–50% and that the associated enhancement of intracellular buffering may improve high-intensity exercise performance in events lasting 1-6 min. A recent meta-analysis concluded that supplementation with a total of 179 g ß-alanine (the median across the studies considered) would result in a median improvement in performance of 2.85% compared to a placebo (Hobson et al., 2012). The meta-analysis also showed that ß-alanine was not significantly performance-enhancing for events lasting less than 60 s, but was ergogenic in events lasting 60-240 s with effects being less pronounced for exercise of durations longer than 240 s. Further research is required to ascertain whether ß-alanine might enhance performance in shorter sprint/power events, longer-term endurance events or intermittent exercise.

PRACTICAL RECOMMENDATIONS

Athletes wishing to explore the ergogenic potential of sodium bicarbonate supplementation may be advised to consume 300 mg per kg body mass (i.e., approximately 20 g sodium bicarbonate for an athlete weighing 70 kg) 1-2 hours prior to exercise.

Spreading the bicarbonate load over a period of 30-60 min, with plenty of fluids and perhaps a light carbohydrate-based meal, may ameliorate the likelihood of adverse gastrointestinal effects.

Athletes wishing to explore the ergogenic potential of ß-alanine supplementation may be advised to consume 4-6 g per day of ß-alanine, divided into 6–8 equal doses throughout the day, for 4-6 weeks

SUMMARY

There is reasonable evidence that bicarbonate supplementation can enhance performance in a variety of sports events. However, it is incumbent on athletes who are interested in exploring the ergogenic potential of bicarbonate to practice with it in order to maximise benefit and minimise risk. There is also evidence that ß-alanine supplementation can increase muscle carnosine and improve performance during high-intensity exercise. Since bicarbonate and ß-alanine enhance extracellular and intracellular buffering capacity, respectively, the physiological and performance benefits should theoretically be additive. It is important to recognise that, in the 'real-world', athletes may combine supplements and it is presently not known whether bicarbonate or ß-alanine supplementation is effective when combined with, for example, caffeine, nitrate, or creatine. There is a need for future studies to examine the extent to which these supplements interact in affecting performance.

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