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REVIEW ARTICLE

Dietary Nitrate Supplementation and Exercise Performance: Implications for Taekwondo Athletes

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Abstract

Presently, very little is known about the potential beneficial effects of dietary supplements on Taekwondo performance. Research into this area should focus on supplements that can potentiate the function of those physiological systems that optimize peak performance during Taekwondo competition (e.g., anaerobic and aerobic metabolism, power production, and O_2 delivery). One candidate that may meet these criteria is dietary nitrate (NO_3^-). In general, NO_3^- supplements (consumed acutely or chronically) have been shown to decrease the O_2 cost of exercise, prolong the onset of fatigue, increase O_2 delivery, reduce the work of the heart, enhance blood flow to contracting muscle, improve neuromuscular efficiency, and improve peak force production in healthy humans. However, the effects of NO_3^- on performance in elite athletes have been less obvious. Reasons for these differential responses are unclear, but factors such as dose, duration of supplementation, intensity and duration of training, and exercise mode may be intervening factors.

KEYWORDS
nitrite, nitric oxide (NO), beetroot juice, elite athletes, healthy individuals

Introduction

A dietary supplement has been defined by the US Dietary Supplement Health and Education Act of 1994 as a product (other than tobacco) intended to supplement the diet and contains one or more of the following dietary ingredients: 1) a vitamin, 2) a mineral, 3) an herb or other botanical, 4) an amino acid, 5) a dietary substance intended to supplement the diet by increasing the total dietary intake; or 6) a concentrate, metabolite, constituent, extract or combination of the substances listed in categories 1-6 (18).

There is a long history of using these substances to enhance sports performance, improve fatigue resistance, and/or expedite recovery (15, 51). Surprisingly, research focused on the effects of dietary supplements on Taekwondo performance, per se, has been limited. In fact, a search of the literature uncovered only two such studies (i.e., effects caused by acute administration of caffeine [36, 45]). Consequently, more research into the usefulness of dietary supplements in Taekwondo athletes may be worthwhile and should focus on the potential of these substances to meet the overall functional demands of the sport. That being said, it is first necessary to be aware of the physiological systems and characteristics that are conducive to optimal Taekwondo performance, so supplements that are most likely to enhance the capacity of those systems can be utilized.

Major systems of importance in

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competitive Taekwondo appear to be those involved with aerobic and anaerobic metabolism, O_2 delivery, skeletal muscle blood flow, as well as generation of skeletal muscle strength, power, and speed (10). An overview of these factors is provided below.

Metabolism

Metabolic responses that occur during Taekwondo competition have recently been described. In general, brief bursts of activity (i.e., attack and defense) are dispersed within longer periods of non-activity (i.e., pauses) and primarily rely on phosphocreatine (PC) and anaerobic glycolysis as energy sources (10). On the other hand, the aerobic metabolism of fats and carbohydrates supports energy demands during individual rounds of competition and expedites recovery between sessions (10). A recent study assessed the relative contribution of specific energy systems to the total cost of simulated Taekwondo combat in young males (12). Combat was designed in accordance with the World Taekwondo Federation Rules of Competition. Thus, each subject simulated 3 two min rounds of Taekwondo fighting with 1 min of recovery provided between rounds. The aerobic component of the overall activity was assessed by subtracting the O_2 uptake (VO_2) at rest from VO_2 during the individual rounds. The anaerobic component was estimated by calculating the lactate concentration after combat, while the alactic component (i.e., energy component supplied by adenosine triphosphate [ATP] and PC) was approximated by assessing VO_2 during the intervals between rounds and the excess O_2 consumption after exercise. Somewhat surprisingly, results revealed that the major component of the total energy supply under these conditions was met by aerobic metabolism (66 ± 6%) followed by contributions from the anaerobic alactic and lactic energy systems (30 ± 6 % and 4 ± 2%, respectively). The authors attributed this pattern of response to a high-intensity to low-intensity movement ratio of approximately 1:7. They concluded that high intensity activity is sustained by anaerobic alactic metabolism, while resynthesis of substrates (e.g., PC) and other metabolic activities that occur during the remaining active recovery period are supported by aerobic metabolism.

Cardiorespiratory function

Due to a major dependence on aerobic metabolism during high level Taekwondo competition (see above), it is not surprising that these individuals demonstrate a relatively high level of cardiorespiratory fitness. In this regard, values of maximal O_2 uptake (VO_2max) (determined by treadmill testing) in elite national and international level Taekwondo athletes have been reported to be in the general range of 56 to 63 ml/kg/min for males and 47 to 51 ml/kg/min for women (10). While not at the level of elite endurance athletes (e.g., long distance runners, cross country skiers, and cyclists), the aerobic capacity of Taekwondo athletes is comparable to elite soccer, basketball, and hockey players (2). Thus, the cardiovascular and respiratory systems likely play an important role in providing adequate O_2 delivery to skeletal muscle during Taekwondo competition in order to meet increases in O_2 demand. Unfortunately, studies confirming this likelihood have not been conducted.

Skeletal muscle function

A hallmark of successful Taekwondo performance is the ability to perform fast, high kicks that require ample muscle power (21). The leg muscles are instrumental in this regard, specifically in relation to explosive kicking and jumping as well as stance maintenance (10). Thus, high levels of mus-

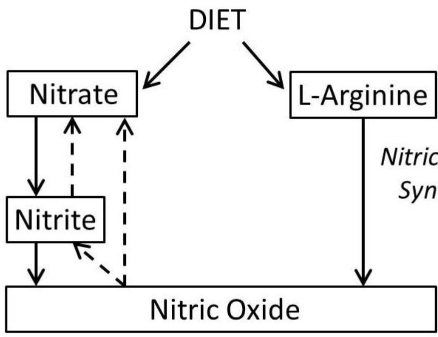

Figure 1: Overview of nitric oxide (NO) pathways. NO can be produced via the action of the enzyme NO synthase on the amino acid L-arginine and then be metabolized to nitrite and/or nitrate. Alternatively, dietary nitrate (NO3-) can be reduced to nitrite via anaerobic bacteria in the oral cavity. In turn, nitrite can then be reduced to NO. This latter process suggests that nitrate can serve as a storage reservoir for nitric oxide (modified from [2]).

cle strength, power, and speed appear to be important attributes that contribute to and predict success in Taekwondo competition. Actual data supporting this contention is limited. However, results of two studies of

Taekwondo athletes provide evidence that this may indeed be the case. One study, using a 30 m sprint field test as an index of muscle speed, found that male medal winners in the Polish Senior Championships had faster times than those who had never won a medal (44). Medal winners also performed better on field tests of explosive power and muscle endurance. A second study found that dynamic muscle strength (assessed via maximal bench and leg press performance) was greater in both experienced male and female Taekwondo athletes (i.e., black belts) compared to novice competitors (47).

The observations above suggest that coaches, trainers, and athletes interested in using dietary supplements to improve competitive Taekwondo performance should consider supplements that are capable of enhancing, at least in part, anaerobic and aerobic metabolism; cardiovascular and respiratory function; skeletal muscle blood flow; and/or muscle strength, power, and endurance. In this regard, one potential candidate that may meet many of these criteria is dietary nitrate (NO_3^-).

Relationship between NO_3^- and Nitric Oxide (NO)

Nitric Oxide (NO) is an important signaling molecule that has numerous functions in the human body, including blood flow regulation, neurotransmission, glucose and calcium homeostasis, muscle contractility, and mitochondrial respiration (16, 17, 46). It is well established that NO is synthesized via oxidation of the amino acid L-arginine in a reaction catalyzed by the NO synthases (41) (Figure 1). NO can also be generated from NO_3^- via the NO_3^--nitrite (NO_2^-)-NO pathway (Figure 1).

NO_3^- is found in many vegetables, such as mustard leaf, lettuce, spinach, rucola, and, in particular, beetroot (27). Following dietary intake, NO_3^- can be reduced to NO_2^- by commensal bacteria in the oral cavity and then converted to NO in the acidic environment of the stomach (Figure 2) (37). As such, NO_3^- and NO_2^- have been suggested to represent a storage reservoir for NO (11).

Physiological Actions of NO_{3-} on Physical Performance

As far as physiological actions of NO_3^- are concerned, one of its first reported effects in healthy humans was the ability to reduce resting blood pressure (33, 49). More recently, a small number of studies have focused on potential effects of this supplement on blood pressure and other cardiovascular responses to exercise. Acute administration of beetroot juice, containing ~750 mg of NO_3^-, reduced systolic blood pressure, vascular resistance, and rate X blood pressure product (an index of the work of the heart) during graded submaximal cy-

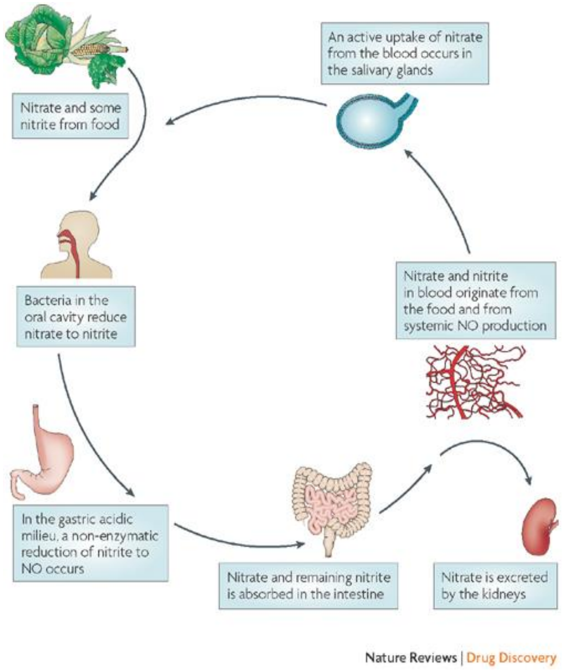

Figure 2: The small intestine quickly absorbs dietary NO_3-. While abundant amounts of circulating NO_3- are eliminated via the urine, ~25% is extracted by the salivary glands. Subsequently, this NO_3- is reduced to NO_2- by commensal bacteria in the oral cavity. NO_2- is then converted to NO and other nitrogen oxides in the acidic environment of the stomach. The remaining NO_3- and NO_2- are absorbed into the blood from the intestine where they can be converted to NO under various physiological conditions. (Reproduced with permission [37].)

cling exercise in young, overweight women (8). In another study, NO_3^- modified hemodynamics at rest and during exercise in young, healthy male subjects (35). In this case, 15 days of supplementation with beetroot juice (400 mg NO_3^-/day) attenuated systolic, diastolic, and mean arterial pressure and vascular resistance at rest and during 3 submaximal workloads of cycling. Furthermore, rate X blood pressure product was decreased during exercise. Cardiac output was also increased, but only at rest and during the lower workloads. Interestingly, endothelial function was enhanced, as characterized by increases in flow mediated dilation of the brachial artery. Thus, increases in endothelial function in concert with elevations in cardiac output may be representative of enhanced skeletal muscle blood flow during contraction. While there is presently no data to support this contention in humans, a study of rats found that, compared to control conditions, 5 days of NO_3^- supplementation (6.25 mg [0.1 mm]/kg/day) enhanced blood flow in predominantly type II fast-twitch muscles (i.e., those that primarily contribute to muscle speed and power) during submaximal treadmill exercise (19). Consequently, it may be that NO_3^- can improve exercise performance in humans via enhancing O_2 delivery to contracting skeletal muscle at a given work intensity (20).

Several other studies have investigated the actions of NO_3^- supplementation on respiratory responses to exercise. For example, in healthy individuals, doses of NO_3^- ranging from 40-500 mg/day (administered as beetroot juice or sodium nitrate and given acutely over 2-6 days) have been reported to reduce O_2 uptake during submaximal and/or maximal exercise at a given workload (3, 4, 31, 34, 49, 52). For the most part, O_2 uptake was reduced by ~3%. However, one of these studies did see relatively large reductions (11-14%) (4). These outcomes provide support for the hypothesis that NO_3^- decreases the O_2 cost of exercise. Acute NO_3^- can also prolong the onset of fatigue (defined as the inability to maintain a given work intensity [52] or as the onset of exhaustion during cycling exercise [3]). Taken together these cardiovascular and respiratory effects suggest that NO_3^- can reduce the O_2 cost of exercise and delay the onset of fatigue. These effects would likely be beneficial to Taekwondo competitors, especially when they participate in multiple matches in a given day.

Two primary mechanisms have been proposed to explain the attenuating effects of NO_3^- on O_2 graded submaximal cycling exercise in young, uptake during exercise. One is linked to changes in skeletal muscle metabolism associated with NO induced increases in the efficacy of ATP production in the mitochondria of skeletal muscle cells (1). A second proposed mechanism is a reduction in the ATP cost of power production; an effect that could be due to the action of NO on the handling of calcium by the sarcoplasmic reticulum that, in turn, affect contractile state (4, 28). In this vein, a study of mice that received a 7-day regimen of sodium NO_3^- demonstrated increases in tetanic force and myoplasmic calcium in response to electrically-induced contractions of type II fast-twitch muscles (24).

Effects of NO_3^- on skeletal muscle contractile function in humans have also been observed. In untrained men, 7 days of beetroot ingestion (~600 mg/day) improved both peak force production during low frequencies of electrical stimulation of the knee extensor muscles and generation of explosive force during high frequencies (23). In male subjects with some resistance training experience, 3 days of supplementation with concentrated beetroot extract (~110 mg NO_3^-) improved neuromuscular efficiency during a heavy resistance paradigm (characterized by lower mean and maximal electromyogram amplitudes at the same workloads). The authors did not see any effects on voluntary force production (i.e., in response to knee extension), which was consistent with what has been reported previously (22). However, in the that study, even though force production was not enhanced by NO_3^- supplementation, the PC cost of force production was reduced; suggesting an increase in muscle efficiency related to ATP utilization.

There is further direct and indirect evidence that NO_3^- may alter other aspects of muscle metabolism. NO has been shown to contribute to glucose uptake in contracting skeletal muscle in humans (38, 40). Alternatively, a high dose of NO_3^- can enhance both glucose uptake and force generation in skeletal muscle of frogs (25). In humans, acute administration of beetroot juice has been shown to reduce plasma glucose concentrations during high-intensity intermittent exercise (53), while no effects were seen on glucose kinetics during 60 min of submaximal cycling exercise (6).

Effects of NO_3^- on Performance in Elite Athletes

An important question that has arisen from previous studies is whether or not established effects of NO_3^- supplementation on performance can be translated to elite athletes. In other words, are the effects of nitrates contingent on the level of training (30)? It has been argued that elite athletes may be less sensitive to the ergogenic actions of NO_3^- treatment than lesser trained recreational competitors (29, 50). While a number of investigations have demonstrated that supple-mentation with NO_3^- can improve time trial performance and/or prolong the onset of fatigue in well-trained athletes such as rowers, cyclists, runners, and kayakers (7, 13, 32, 43, 53), others have failed to demonstrate these effects (5, 9, 14, 42).

Several explanations have been offered for these differential observations in well-trained athletes. Jones (29) pointed out that the high levels of exercise training undertaken by these individuals greatly increases energy expenditure compared to less trained recreational athletes and, in turn, results in a 50-100% increase in caloric intake. Assuming a well-balanced diet, it is reasonable to expect that dietary intake of NO_3^- would also be higher (30). Consequently, additional NO_3^- intake via dietary supplementation may be less effective. It is also possible that other intervening factors such as dose, duration of supplementation, intensity and duration of training, and exercise mode may play a role.

Methodological differences may also skew results of previous studies. To date, research in elite athletes has focused primarily on performance of submaximal endurance activities; conditions that would not be expected to constrain O_2 demand or delivery. Thus, detection of potential performance benefits derived from NO_3^- supplementation in this group of athletes may be more obvious when responses to higher intensity workloads are assessed (50). It is also important to note that even small improvements in performance in elite athletes may have major consequences on competitive outcomes. For example, variations in performance of less than 1% between competitors have been shown to be highly beneficial in elite swimmers and track and field athletes at major competitions (26, 48) and can even determine the difference between first and fourth place (48). Thus, in elite Taekwondo athletes, small or even undetectable effects of NO_3^- supplementation on factors such as skeletal muscle efficiency and/or endurance could play a major role in determining the ultimate outcome of a given match.

In order to assess small, but possibly important effects of NO_3^- on elite athletes such as high level Taekwondo competitors, it may be necessary to adopt a more focused research paradigm. Accordingly, it has been proposed that such a paradigm would involve repeated assessment of specific performance factors in a given competitor instead of analysis in the context of group based comparisons (30).

Practical Considerations

The preponderance of evidence suggests that doses of NO_3^- ranging from 300 to 500 mg (5-8 mmol) are necessary to induce improvements in exercise performance associated with cardiorespiratory and skeletal muscle function. These doses can be attained by ingestion of ~500 ml of beetroot juice. Since increases in plasma concentrations of NO_3^- evoked by these doses tend to peak in 2-4 hr and do not return to base line levels for another 6-9 hr (52), it appears that beetroot juice should be taken approximately 3 hr before competition. On the other hand, chronic supplementation (i.e., with similar doses) would likely maintain elevated levels of NO_3^-; an intervention that could be beneficial to Taekwondo athletes in competitions where multiple matches are staged over several hours.

As addressed previously, bacteria in the oral cavity play an important role in the conversion of NO_3^- to NO_2^- (Figure 1). Disturbance of oral microflora reduces the production of NO_2^-, which is essential for the production of NO via the NO_3^- NO_2^-NO pathway (Figures 1 and 2). Accordingly, treatment with mouthwash containing antibacterial agents such as chlorhexidine has been shown to diminish increases in NO_2^- and to attenuate reductions in exercise blood pressure caused by ingesting beetroot juice (39). Thus, use of mouthwash should be avoided when taking beetroot juice/nitrate supplements.

Conclusion

NO_2^- is a dietary supplement that can have acute and chronic effects on exercise performance. Supplementation has been shown to decrease the O_2 cost of exercise, prolong the onset of fatigue, increase O_2 delivery, reduce the work of the heart, enhance blood flow to contracting skeletal muscle, improve neuromuscular efficiency, and improve peak force production in healthy humans. Since physiological systems critical to peak Taekwondo performance include anaerobic and aerobic metabolism, skeletal muscle power production, and O_2 delivery, administration of NO_2^- may enhance the function of these systems in a manner that enhances competitive outcomes in Taekwondo athletes. However, studies of elite athletes have revealed inconsistent effects on performance, and those that have reported beneficial outcomes found only small improvements. On the other hand, in competition among elite athletes, small differences in performance may make the difference between winning and losing. Thus, studies designed to assess the effects of NO_3^- on Taekwondo performance seem to be justified and should be conducted. In order to delineate potentially small differences in performance, it may be necessary to conduct studies that involve repeated evaluation of specific performance related factors in an individual athlete (e.g., aerobic and anaerobic power, fatigability, glucose uptake, and O_2 utilization) instead of conducting group based comparisons.

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