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REVIEW ARTICLE

Impact of Dietary Antioxidants on Sport Performance: A Review

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Abstract Many athletes supplement with antioxidants in the belief this will reduce muscle damage, immune dysfunction and fatigue, and will thus improve performance, while some evidence suggests it impairs training adaptations. Here we review the effect of a range of dietary antioxidants and their effects on sport performance, including vitamin E, quercetin, resveratrol, beetroot juice, other food-derived polyphenols, spirulina and *N*-acetylcysteine (NAC). Older studies suggest vitamin E improves performance at altitude, with possible harmful effects on sea-level performance. Acute intake of vitamin E is worthy of further consideration, if plasma levels can be elevated sufficiently. Quercetin has a small beneficial effect for exercise of longer duration (>100 min), but it is unclear whether this benefits athletes. Resveratrol benefits trained rodents; more research is needed in athletes. Meta-analysis of beetroot juice studies has revealed that the nitrate component of beetroot juice had a substantial but unclear effect on performance when averaged across athletes, non-athletes and modes of exercise (single dose 1.4 ± 2.0 %, double dose 0.5 ± 1.9 %). The effect of addition of polyphenols and other components to beetroot juice was trivial but unclear (single dose 0.4 ± 3.2 %, double dose −0.5 ± 3.3 %). Other food-derived polyphenols indicate a range of performance outcomes from a large improvement to moderate impairment. Limited evidence suggests spirulina enhances endurance performance. Intravenous NAC improved endurance cycling performance and reduced muscle fatigue. On the basis of vitamin E and NAC studies, acute intake of antioxidants is likely to be beneficial. However, chronic intakes of most antioxidants have a harmful effect on performance.

Key Points

Chronic consumption of dietary antioxidants is likely harmful.

An exception is chronic consumption of polyphenols such as epicatechin and resveratrol, which in combination with training appear beneficial.

Acute intake of vitamin E and *N*-acetylcysteine may offer athletes a performance benefit around competition time.

1 Introduction

During exercise, metabolism increases and oxygen utilization is elevated, leading to leakage of highly reactive oxygen species from mitochondria [1]. Aside from mitochondrial leakage, contraction itself activates phospholipase A2, initiating a cascade of enzymes and thereby increasing reactive species [2]. Reactive oxygen species alter cell structure and function, and contribute to muscle damage, immune dysfunction and fatigue [3]. Other consequences of the release of exercise-induced reactive

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species are beneficial; they are involved in stimulating glycogen resynthesis [4], reducing susceptibility to the risk of infection [5], and they may even enhance athletic performance by initiating and promoting adaptive responses to training [6–9]. The extent to which reactive species are damaging or helpful depends on the exercise duration, intensity, fitness attributes and nutritional status of the individual [10].

Various endogenous antioxidant defence mechanisms exist to cope with oxidative stress, but dietary antioxidants make an important contribution [11]. Research to date has focused more on the effect of dietary antioxidants on exercise-induced markers of oxidative stress and muscle damage than on performance [12, 13]. Some authors have found antioxidant supplements are an effective countermeasure to exercise-induced oxidative stress and muscle damage [14, 15]. There have also been many studies on the impact dietary antioxidants have on the muscle fatigue and damage that follow a substantial bout of unaccustomed exercise [16, 17]. Although not relevant to high-performance sport, these studies have reported beneficial effects that are consistent with the possibility that antioxidants are beneficial in tournaments or competitions with elimination rounds or heats; indeed, one such study has been reported and is included in this review in the section on *N*-acetylcysteine (NAC) [18].

A narrative review on vitamin C and performance has been published elsewhere [19] and highlights the potential issues with chronic consumption. Reactive oxygen species may mediate beneficial training adaptations that vitamin C attenuates; indeed, from a total of 12 studies, vitamin C in doses of 1 g or more daily impaired sport performance substantially in four studies, possibly by reducing mitochondrial biogenesis, while a further four studies demonstrated impairments that were not statistically significant. Four studies reported performance improvements, of which three provided vitamin C acutely or for up to 1 week [19]. In this review, the conclusion was that lower doses of vitamin C consumed through fruit and vegetables (up to 250 mg daily) may be sufficient to reduce oxidative stress and provide other health benefits without impairing training adaptations.

Notwithstanding the potential negative effects of vitamin C on performance, previous researchers have suggested mechanisms by which other antioxidants could enhance athletic performance. Vitamin E may assist in the maintenance of red blood cell structure during exercise at altitude [20]. Results from limited research suggest that polyphenols, including quercetin, can induce mitochondrial adaptation and improve peripheral circulation, in much the same way as exercise [21–23]. High doses of some polyphenols, such as quercetin and resveratrol, induce mitochondrial biogenesis by adenosine monophosphate-activated protein kinase activation of peroxisome proliferator-activated receptor gamma coactivator 1-alpha, which has subsequently been shown to enhance endurance capacity [24, 25]. Polyphenols increase nitric oxide synthesis in the endothelium (via nitric oxide synthase), improving blood flow. These physiological effects of polyphenols have been discussed in detail by other researchers [26]. Beetroot juice contains polyphenols and also has a high content of inorganic nitrate, which affects oxygen utilization and blood flow [27]. Spirulina contains various antioxidants, such as tocopherol, β-carotene, polyphenols and phytocyanins, all of which reduce levels of exercise-induced reactive oxygen species. NAC directly scavenges reactive species and supplies cysteine for synthesis of glutathione, which is an important intracellular antioxidant [28, 29]. In the present review, we have focused on performance outcomes rather than the mechanisms of action of these antioxidants; we have also paid close attention to acute versus chronic effects. Because the effects of vitamin C have been reviewed recently, it is not included here [18].

2 Methods

The studies included in this review were sourced via Medline, Google Scholar and SPORTDiscus, using the initial search terms antioxidant and exercise. A follow-up Web search used the terms vitamin E, exercise, vitamin E, athletes for each antioxidant (antioxidant search terms included vitamin E, quercetin, resveratrol, beetroot, polyphenol, spirulina, *N*-acetylcysteine and NAC). Additional studies were sourced from reference lists in related articles, books on the topic and conference abstracts from the annual American College of Sports Medicine conference (2008–2014). To minimize bias, only those studies with a randomized control or crossover design were included. All studies included in this review were written in English, were not restricted by year of publication (up to June 2014) and had antioxidant supplementation periods from acute (minutes to hours prior to the performance test) to 5 months. To be included, studies were required to report effects of a maximal performance test and include clear performance outcome measures (typically, the time to fatigue or time-trial time). Studies using a submaximal or set intensity for a fixed period of time were not included unless they were followed by a maximal performance test. We excluded studies that reported maximal oxygen consumption (VO_2 max) as the only performance measure, given the large error of measurement inherent in testing [30]. Animal and human studies were included. Several human controlled trials were excluded because of a lack of a pre-supplementation performance test or because of

failure to report the pre-supplement test results [31–38]; these studies are valuable for elucidating antioxidant status, the mechanistic role of supplements or effects on recovery, but they were not adequate for determining performance outcomes. Despite the lack of pre-tests, three animal studies were included, three included a dose–response design [39–41] and others investigated sedentary and trained rats; only trained rat data are shown [6, 42]. The quality of all remaining studies was deemed acceptable for inclusion in this review. Studies that excluded slow and fast participants were excluded, to minimize bias due to selective reporting [43]. The literature review includes the tabulation and discussion of 71 studies.

The studies have been grouped into tables according to the antioxidant investigated: vitamin E, quercetin, resveratrol, beetroot juice, other food-derived polyphenols, spirulina and NAC. We have included the timing of the last dose of the antioxidant in the tables summarizing the studies, in an attempt to address the question of acute versus chronic effects. Within each table, we have shown the percentage effects on the measure of performance in each study, and shown in square brackets, where necessary, is the percentage effect on mean power output in a time trial of a duration equivalent to that of the performance test. The studies have been sorted by the magnitude of this effect. Thresholds for small, moderate, large, very large and extremely large effects on performance were respectively set at 0.3, 0.9, 1.6, 2.5 and 4.0 of the between-competition variation in the performance of elite athletes [44]. We chose 0.5 % as the smallest worthwhile effect for all exercise protocols, as previously described [45]. The corresponding thresholds used to evaluate the magnitude of the effect on mean power were 0.5, 1.5, 2.7, 4.2 and 6.7 % for small, moderate, large, very large and extremely large effects, respectively. Effects on performance in animal studies were not evaluated qualitatively in this manner. If the performance test was a time to fatigue at constant power, the percentage effect was divided by 15 to convert it to the effect on mean power in a time trial. Performance in a time trial was also converted by multiplying the percentage effect by the following: running, 1; cycling on a Monark ergometer: 1, swimming; 2, cycling on Kingcycle and Velotron ergometers; 2.5, rowing and kayaking; 3, Hopkins [44] did not provide a conversion factor for performance in the Yo-Yo Recovery Test; we therefore used data relating distance travelled to peak speed in the test from a website (http://www.topendsports.com/testing/yo-yo-intermittent-levels.htm) to determine that a 1 % change in distance around the typical speed of 16 km/h would be equivalent to a 0.13 % change in peak speed, which we have assumed to be equivalent to the change in peak power. Converted performance effects for incremental tests to fatigue were calculated as a fraction of the power output at which the test started; for example, if the test started at 30 %, the percentage effect was reduced by a factor of 0.7. Conversions of time to exhaustion were based on assumptions of the same power relationship in animals as in humans.

Data from the beetroot juice studies were of sufficient number and quality to warrant meta-analysis. A meta-analytic review of the effects of nitrate on performance has been published recently by Hoon and colleagues [46], but they did not address the question of the independent effect of the antioxidants in beetroot juice. Furthermore, they conducted separate meta-analyses on each of the performance test types, after standardization of the effect in each study. Standardization before meta-analysis is not a recommended approach for measures of performance [42]. Standardization is particularly problematic in time-to-exhaustion tests, where each athlete is given a different workload in an attempt to achieve a similar time to exhaustion: the between-subject standard deviations are thereby biased low and effects are thereby biased high compared with those from time trials and incremental tests. Here we meta-analysed the estimated percentage effects on mean power, and we included a covariate to estimate the effect where the control treatments were beetroot juice depleted of nitrate (for the effect of nitrate only) and non-beetroot juice (for the effect of nitrate and any extra effect of antioxidants). The meta-analysis included fixed effects to estimate the effects for athletes versus non-athletes, arms or legs versus the whole body, and non-beetroot versus beetroot control (the effect of the non-nitrate components in beetroot juice). Dose was included as a linear covariate in a separate meta-analysis (1, 70 mL of concentrated beetroot juice or 500 mL of non-concentrated juice; 2, 140 mL of concentrated beetroot juice; 3, 280 mL of concentrated beetroot juice). Random effects were included for real differences within and between studies. The weighting factor for each effect was the inverse of the square of the standard error (SE), which was derived by assuming that the standard error of measurement for all estimates of mean power was 2.5 %; the SE was therefore $2.5\sqrt{2}/\sqrt{n}$, where n was the sample size in the crossover studies and $n/4$ in the only controlled trial [47].

3 Results and Discussion

3.1 Vitamin E

Vitamin E is an effective fat-soluble antioxidant and is capable of protecting cells from oxidative damage of membrane lipids. At altitude, red blood cell lysis occurs, against which vitamin E may be protective. Table 1 summarizes the studies investigating the effect of vitamin E on

Table 1 Details of studies investigating effects of vitamin E alone or in combination with other antioxidants on exercise performance

References	Vitamin E treatment	Timing of final dose	Subjects; design	Performance protocol[a]	Performance outcome[b]
Simon-Schnass and Pabst [20]	363 mg day^{-1} for 4 weeks @ altitude of 5100 m	Unknown	12 highly trained climbers; controlled trial	Anaerobic threshold power during cycle incremental test @5100 m (10 min)	↑18 %, $p < 0.01$ [↑18 %]
Novelli et al. [48]	300 mg kg^{-1} (IM)	10 min prior to trial	92 male mice (24 on vitamin E); controlled trial	Swim time to fatigue in pool (5 min)	↑139 %, $p < 0.0001$ [↑9.3 %[c]]
Kobayashi [60]	400 mg day^{-1} for 6 weeks @ altitude of 1525 m	Unknown	12 trained males; controlled trial	Anaerobic threshold power during cycle incremental test @1525 m and 4,750 m (10 min)	↑8.9 %, p value not reported [↑8.9 %]; ↑14.2 %, p value not reported [↑14.2 %]
Yfanti et al. [51]	363 mg day^{-1}, vitamin C 500 mg day^{-1} for 16 weeks	Unknown	21 untrained males (11 treatment, 10 placebo); controlled trial	Maximal power during an incremental cycle test (9 min)	↑4.0 %, $p > 0.05$ [↑4.0 %]
Devi et al. [52]	45 mg kg^{-1} day^{-1} for 60 days	Unknown	12 male rats; controlled trial	Swim time to fatigue in 4-month-old rats in pool (70 min)	↑26 %, $p > 0.05$ [↑1.7 %]
Snider et al. [53]	545 mg day^{-1}, coenzyme Q10 300 mg day^{-1}, cytochrome C 1,500 mg day^{-1}, inosine 300 mg day^{-1} for 4 weeks	Unknown	11 highly trained male triathletes; crossover	Run time to fatigue @70 % VO_2max (1.5 h)	↑7.3 %, $p = 0.57$ [↑0.5 %]
Keong et al. [54]	60 mg day^{-1} for 6 weeks	Unknown (plasma levels of vitamin E were higher in intervention group on trial day)	18 trained males; crossover	Run time to fatigue @70 % VO_2 max in the heat (80 min)	↑5.2 %, $p > 0.05$ [↑0.3 %]
Romano-Ely et al. [49]	Vitamin E and C (doses not stated)	During exercise only	14 male cyclists; crossover	Cycle time to fatigue during a 70 % VO_2 max test (1.5 h)	↑2.0 %, $p > 0.05$ [↑0.1 %]
Oostenbrug et al. [55]	300 mg day^{-1}, fish oil 6 g day^{-1} for 3 weeks	Unknown	24 trained male cyclists; controlled trial	Cycle time to fatigue @70 % maximal watts (1 h)	↑0.3 %, $p > 0.8$ [0.0 %]
Kang et al. [56]	1200 IU day^{-1} of vitamin E and 800 mg day^{-1} of vitamin C for 30 days	Unknown	46 trained males and females; controlled trial	Run time to fatigue @80 % VO_2 max (28 min)	↓1.0 %, $p = 0.2$ [0.0 %]
Lawrence et al. [57]	300 mg day^{-1} for 6 months	Unknown	43 trained swimmers; controlled trial	Time to swim repetitions (best of 3 daily repeats), 100 yards × 10 with 10 s of recovery	↓0.7 %, $p > 0.05$ [↓1.4 %]
Paulsen et al. [8]	235 mg day^{-1}, vitamin C 1000 mg day^{-1} for 11 weeks	Unknown	54 trained and untrained men and women; controlled trial	Distance covered in an incremental run test (10 min)	↓4.0 %, $p > 0.05$ [↓4.0 %]
Teixeira et al. [58]	136 mg day^{-1}, vitamin C 200 mg day^{-1}, β-carotene 15 mg day^{-1}, lutein 1 mg day^{-1}, Zn 15 mg day^{-1}, Se 200 μg day^{-1}, Mg 300 mg day^{-1} for 1 month	12 h before trial	20 trained kayakers (14 males, 6 females); crossover	Time to kayak 1000 m (4.5 min)	↓1.5 %, $p > 0.05$ [↓4.5 %]

Table 1 continued

References	Vitamin E treatment	Timing of final dose	Subjects; design	Performance protocol[a]	Performance outcome[b]
Larcombe et al. [59]	Vitamin E, β-carotene, lutein, zeaxanthin (dose not stated) for 1 month	Unknown	Captive adult budgerigars (flight birds); crossover	Flight speed (10 s)	↓1.8 %, $p > 0.05$ [↓5.4 %[c]]

IM intramuscular injection, VO_2 *max* maximal oxygen consumption

[a] The approximate duration of the equivalent time trial is shown in parentheses

[b] ↑ denotes performance improvement versus control; ↓ denotes performance impairment versus control; square brackets denote a performance outcome converted to a change in mean power in an equivalent time trial shown in parentheses

[c] Data using animals or an unusual performance test requiring an educated estimate of the adjustment factor

performance. Two of the 14 vitamin E studies used acute supplement protocols: one in mice [48] and one in humans [49]. The human study showed trivial, if any, performance effects, but there were clear improvements in endurance performance in mice when the vitamin was delivered by intramuscular injection. Acute intake of vitamin E could potentially confer performance benefits if levels can be sufficiently elevated. A likely explanation for the conflicting outcomes of these two studies is that levels of vitamin E are difficult to increase acutely via oral administration, because of the buffering effect of a liver-based salvage mechanism and urinary excretion [50]. It would appear that acute intake parentally could therefore confer performance benefits in athletes. All remaining studies investigated chronic intake of vitamin E in humans and typically did not report the timing of the final dose; overall the majority of effects were clear, with a tendency towards impairment rather than benefit [8, 51–59]. In some of these studies, there may have been an acute enhancement of performance from the final dose of vitamin E, so the chronic effects are all the more likely to be harmful. We conclude that chronic intake of vitamin E, either alone or in combination with other nutrients, is best avoided by athletes.

In contrast to studies completed at sea level, two older studies in Table 1 were performed at altitude and suggested chronic vitamin E intake has an extremely large benefit for athletes [20, 60]. Altitude exposure has been shown to induce oxidative stress, which reduces red blood cell deformability, with proposed performance impairments in acclimatized climbers [61]. Vitamin E may offset the impairment by maintaining red blood cell deformability [62], although this is not a consistent finding in all studies [56]. While vitamin E appears promising for athletes training and competing at altitude, more studies are needed.

3.2 Quercetin

Quercetin is an antioxidant classed as a flavonoid and is found in foods such as red onion, dill, apples and capers [63]. Quercetin has been demonstrated to encourage mitochondrial growth and reduce the perceived effort of exercise [23]. The studies summarized in Table 2 were performed with supplementary quercetin rather than food. The effect of quercetin on performance has been the topic of three meta-analyses. Kressler et al. [64] concluded that quercetin had a trivial-to-small benefit, but they did not estimate a percentage effect on performance. In the second meta-analysis, quercetin produced a 0.7 % improvement in power output [65], which represents a small benefit for endurance events. In the most recent meta-analysis, Pelletier and Lacerte [66] quantified the modifying effects of the duration of supplementation, the duration of exercise

Table 2 Details of studies investigating effects of quercetin supplements on exercise performance

References	Quercetin treatment	Timing of final dose	Subjects; design	Performance test[a]	Performance outcome[b]
Daneshvar et al. [69]	1 g day^{-1} for 2 months	Unknown	26 male badminton players; controlled trial	Cycle time in an incremental test (14 min)	↑5.2 %, $p < 0.05$ [↑4.6 %]
Darvishi et al. [70]	1 g day^{-1} for 8 weeks	Unknown	26 female swimmers; controlled trial	Cycle time in an incremental test (14 min)	↑3.6 %, $p = 0.4$ [↑3.2 %]
MacRae and Mefford [71]	0.6 g day^{-1}, green tea extract 0.6 g day^{-1}, vitamin C 300 mg day^{-1}, vitamin E 100 mg day^{-1}, caffeine 90 mg day^{-1}, small amounts of B-group vitamins for 6 weeks	Unknown	11 elite male cyclists; crossover	Time to cycle 30 km (52 min)	↑3.1 %, $p < 0.01$ [↑7.4 %]
Cureton et al. [72]	1 g day^{-1} for 7–16 days	3 h before trial	30 untrained males; controlled trial	Work performed during a 10-min cycle test, after a preload	↑2.5 %, $p > 0.05$ [↑2.5 %[c,e]]
Davis et al. [39]	25 mg kg^{-1} day^{-1} for 7 days	Unknown	8 mice; crossover	Run time to fatigue (100 min)	↑37 %, $p < 0.05$ [↑2.5 %]
	12.5 mg kg^{-1} day^{-1} for 7 days				↑36 %, $p < 0.05$ [↑2.4 %]
Nieman et al. [73]	1 g day^{-1} for 2 weeks	0.5 g 2 h before trial	26 untrained men; crossover	Distance covered in 12 min run after a preload	↑ 2.9 %, $p = 0.04$ [↑1.5 %[d]]
Davis et al. [74]	1 g day^{-1} for 7 days	12 h before trial	7 men, 5 women, untrained; crossover	Cycle time to fatigue @70 % VO_2 max (100 min)	↑13.2 %, $p > 0.05$ [↑0.9 %]
Ganio et al. [75]	1 g day^{-1} for 5 days	24 h before trial	11 untrained males and females; crossover	Run time to fatigue in an incremental test (10 min)	↑0.8 %, $p = 0.75$ [↑0.7 %]
Bigelman et al. [76]	1 g day^{-1} for 6 weeks	Unknown	58 trained males and females; controlled trial	Time to cycle 36.6 m × 2 (6 s)	↑0.5 %, $p > 0.05$ [↑1.2 %]
				Time to run 2 miles (15 min)	↓1.2 %, $p > 0.05$ [↑1.2 %]
				Mean power in a Wingate test	↓2.4 %, $p > 0.05$ [↓2.4 %]
Casuso et al. [24]	25 mg kg^{-1} day^{-1} for 6 weeks	Unknown	17 rats; controlled trial	Run time to fatigue (2.8 h)	↑5.3 %, $p = 0.35$ [↑0.4 %]
Askari et al. [67]	0.5 g day^{-1} for 8 weeks	Unknown	28 trained males; controlled trial	Distance run in an incremental test (5 min)	↓11 %, $p = 0.20$ [↓10 %]

VO_2 *max* maximal oxygen consumption

[a] The approximate duration of the equivalent time trial is shown in parentheses

[b] ↑ denotes performance improvement versus control; ↓ denotes performance impairment versus control; square brackets denote a performance outcome converted to a change in mean power in an equivalent time trial shown in parentheses

[c] Data using animals or an unusual performance test requiring an educated estimate of the adjustment factor

[d] The performance test was completed after a preload exercise session; it was assumed that this would approximately double the performance effect, and the effect was accordingly adjusted by halving it

and the training status of the participants on mean power output. The effect on untrained individuals (0.8 %) would be small on the basis of our thresholds, but the effect on trained individuals (0.1 %) is trivial. The authors also reported little modifying effect of supplementation or exercise duration. Inspection of Table 2 would suggest a small beneficial effect for exercise of longer duration (>100 min), but it is unclear whether this benefit would apply to athletes. Only one of the four studies published since the Pelletier meta-analysis (the first two and last two studies in Table 2) [67–70] showed a statistically significant (clear) beneficial effect on performance.

Our own qualitative analysis of the studies in Table 2 reveals performance outcomes ranging from extremely large impairment to extremely large improvement [39, 67–76]. The majority of studies had small to large clear improvements, while all of the impairments were unclear. Two animal studies favoured performance enhancement [39, 68]. None of the studies were acute, and only two studies stated the timing of the final dose. The contribution of any acute effects of quercetin on performance cannot therefore be determined from the existing studies. Taken together, these results suggest quercetin has a small beneficial effect on endurance performance in athletes when doses of around 1 g are taken daily. More studies of the duration and timing of the final dose are needed before we can recommend quercetin supplementation to athletes.

3.3 Resveratrol

Resveratrol is a naturally occurring polyphenol found in red wine and is thought to be responsible for many of the health benefits of the Mediterranean diet [43]. Resveratrol, as with some other polyphenols, can induce mitochondrial biogenesis, which has subsequently been shown to enhance endurance capacity [24, 77]. With one exception, the studies presented in Table 3 were all performed on rodents, and the effects on performance ranged from extremely beneficial to extremely detrimental [6, 25, 41, 42, 77, 94, 95]. At this stage, it appears resveratrol benefits active rodents and is potentially harmful in inactive rodents. In the only human study, performed in elderly inactive participants, the effect was also potentially harmful [6]. These findings suggest athletes would benefit from chronic supplementation with resveratrol, with more studies needed. Given the dosage in these studies, it seems unlikely athletes will gain sufficient quantities of resveratrol from food. For example, it would take 17 L of red wine daily to provide the equivalent resveratrol as used by Gliemann et al. [6], whereas only 2–7 capsules of a commercially available supplement would be required.

3.4 Beetroot Juice

Beetroot juice contains various phytochemicals, including betalain and polyphenols from the anthocyanin and flavonoid subclass. Compared with that of other vegetables, the polyphenol content of beetroot is high [78]. Beetroot juice also contains nitrate, and all previous authors have attributed performance benefits to the nitrate content. The issue for the present review therefore is whether the antioxidants in beetroot juice confer additional effects on performance.

Table 4 presents the beetroot juice studies ordered into nitrate-free beetroot control (to estimate the effects of nitrate only) and non-beetroot control (to estimate the combined effect of nitrate, antioxidants and all other constituents in beetroot juice) [27, 79, 96–111]. In both groups of studies, the effects ranged from trivial to large performance improvements. Our meta-analysis revealed a clear reduction in the effect on mean power per unit dose of beetroot juice (by −0.9 %, 90 % confidence limits ±1.0 %; small, likely substantial) and clearly less benefit for athletes than non-athletes (−4.4 ± 3.2 %; very large, very likely substantial). Other modifying effects were unclear and either substantial (arms or legs versus the whole body 1.2 ± 2.8 %, effect of non-nitrate components of beetroot juice −1.0 ± 3.5 %) or trivial (acute versus chronic supplementation 0.1 ± 2.5 %). When averaged across the mode of exercise and duration of supplementation, the pure effect of nitrate in beetroot juice on athletes was substantial but unclear (single dose 1.4 ± 2.0 %, double dose 0.5 ± 1.9 %), while the effect of nitrate plus the other components in beetroot juice was trivial but unclear (single dose 0.4 ± 3.2 %, double dose −0.5 ± 3.3 %). However, effects on non-athletes for all levels of modifying factors were clearly beneficial. There was no evidence of publication bias in plots of t-values for the study-estimate random-effect solution versus the study estimate standard errors [44]. Given the clear difference in the effects between athletes and non-athletes, and the fact that athletes are defined mainly by their level of training, it is reasonable to conclude that highly trained athletes will experience either trivial or harmful effects on performance from consuming nitrate or beetroot juice containing nitrate. Nitrate, by causing generalized peripheral vasodilation shunting blood away from active muscle, may be harmful to performance in athletes where oxygen delivery is limited, albeit that this is speculative at this stage.

Hoon and colleagues [46] recently conducted a meta-analysis of effects of nitrate supplementation on performance. They included studies of beetroot juice but did not attempt to estimate and adjust for potential effects of the constituents other than nitrate. Consistent with the outcomes of our meta-analysis, they reported a beneficial

Table 3 Details of studies investigating effects of resveratrol on exercise performance

References	Resveratrol treatment	Timing of final dose	Subjects; design	Performance test[a]	Performance outcome[b]
Dolinsky et al. [42]	146 mg kg^{-1} day^{-1} for 12 weeks	Unknown	25 trained rats; controlled trial	Run time in an incremental test (110 min)	↑21 %, $p < 0.001$ [↑14 %]
Wu et al. [41]	25 mg kg^{-1} day^{-1} for 21 days	1 h	4 trained rats; controlled trial	Swim time to fatigue (20 min)	↑128 %, $p < 0.001$ [↑8.5 %[c]]
	50 mg kg^{-1} day^{-1}				↑72 %, $p < 0.001$ [↑4.8 %[c]]
	125 mg kg^{-1} day^{-1}				↑52 %, $p < 0.001$ [↑3.5 %[c]]
Hart et al. [25]	100 mg kg^{-1} day^{-1} for 12 weeks	3 h	24 trained male rats (bred for high exercise capacity); controlled trial	Run distance in 30 min	↑7 %, $p < 0.01$
Lagouge et al. [94]	400 mg kg^{-1} day^{-1} for 15 weeks	3 h	16 trained rats; controlled trial	Run distance to fatigue (1200 m)	↑85 %, $p < 0.05$ [↑6 %[c]]
Gliemann et al. [6]	250 mg day^{-1} for 8 weeks	Unknown	27 elderly untrained males; controlled trial	Time to walk 5 km (50 min)	↓4.0 %, $p > 0.05$
Hart et al. [25]	100 mg kg^{-1} day^{-1} for 12 weeks	3 h	12 trained rats (bred for low exercise capacity); controlled trial	Run distance in 30 min	↓35 %, $p < 0.01$
Mayers [95]	0.1 % resveratrol-enriched diet for 7 days	3 h	4 untrained obese mice; crossover	Distance run in an incremental test	↓81 %, $p < 0.05$ [↓56 %[c]]

[a] The approximate duration of the equivalent time trial is shown in parentheses

[b] ↑ denotes performance improvement versus control; ↓ denotes performance impairment versus control; square brackets denote a performance outcome converted to a change in mean power in an equivalent time trial shown in parentheses

[c] Data using animals or an unusual performance test requiring an educated estimate of the adjustment factor

effect in non-athletes but concluded that athletes fail to respond to nitrate supplementation. On the basis of these meta-analyses, we cannot recommend beetroot juice or pure nitrate supplements for athletes.

3.5 Other Food-Derived Polyphenols

Polyphenols, independent of their antioxidant properties, can enhance the production of vasodilating factors (nitric oxide, endothelium-derived hyperpolarizing factor and prostacyclin) and inhibit the synthesis of the vasoconstrictor endothelin-1 [22]. Polyphenols have been shown to improve blood pressure and forearm blood flow [26]. The polyphenol studies presented in Table 5 indicate a range of performance outcomes from a large improvement to moderate impairment, although not all outcomes were clear [21, 57, 80–83, 113–115, 118]. Of the 11 studies, three used an acute supplement protocol—one showing a clear, large enhancement of endurance performance [81] and the others showing an unclear moderate to large impairment [82, 83]. More acute polyphenol studies are therefore needed. All of the studies showing trivial or possibly harmful effects reported the timing of the final dose, and in all three studies, there could have been an acute beneficial effect and therefore an increased likelihood that the chronic effects were harmful. The remaining studies of chronic polyphenol intake include one animal study, demonstrating an extremely large, clear improvement with an epicatechin found in cocoa [21]: the epicatechin in combination with exercise demonstrated greater performance improvements in mice than exercise or epicatechin alone [21], and even on its own, the epicatechin improved performance. There were several extremely large unclear performance improvements following supplementation with grape extract and *Ecklonia cava* [81], but we suspect errors in the analysis of these outcomes. For the studies showing beneficial effects, the timing of the final dose was not stated, so the contribution of the possible beneficial effects of acute intake cannot be separated from the chronic effects. In view of the wide range of polyphenols, it is difficult to draw firm conclusions; some polyphenols appear to have promise and are worthy of further investigation, but it will be important to design studies to distinguish between acute and chronic effects.

Table 4 Details of studies investigating effects of beetroot juice on exercise performance

References	Beetroot juice treatment	Timing of final dose	Subjects; design	Performance test[a]	Performance outcome[b]
Studies with nitrate-free beetroot juice control					
Wylie et al. [79]	140 mL (concentrated)	2.5 h before trial	10 non-athletic males; crossover	Cycle time to fatigue in an incremental test after a preload (8 min)	↑14 %, $p < 0.05$ [↑13 %]
	280 mL (concentrated)				↑11 %, $p < 0.05$ [↑10 %]
	70 mL (concentrated)				↑8.1 %, $p > 0.05$ [↑7.5 %]
Lansley et al. [96]	0.5 L	2.5 h before trial	9 elite male cyclists; crossover	Time to cycle 4 km (6 min)	↑2.8 %, $p < 0.05$ [↑6.4 %]
				Time to cycle 16.1 km cycle (27 min)	↑2.7 %, $p < 0.01$ [↑6.2 %]
Wilkerson et al. [97]	0.5 L	2.5 h before trial	8 trained male cyclists; crossover	Time to cycle 50 miles (100 min)	↑0.8 %, $p > 0.05$ [↑1.8 %]
Wylie et al. [98]	280 mL day^{-1} (concentrated) for 2 days	140 mL 2.5 h and 140 mL 1.5 h before trial	14 male recreational team sport athletes; crossover	Distance covered in a Yo-Yo Intermittent Recovery Level 1 test (6.5 min)	↑4.2 %, $p < 0.05$ [↑0.6 %]
Cermak [99]	140 mL day^{-1} (concentrated) for 6 days	3 h before trial	12 trained male cyclists; crossover	Time to cycle 10 km after a preload (15 min)	↑1.2 %, $p < 0.05$ [↑0.6 %[c,d]]
Hoon et al. [100]	70 mL (concentrated)	2 h before trial	10 elite male rowers	Time to row 2000 m (6:17 min)	↑0.1 %, likely trivial [↑0.3 %]
	140 mL (concentrated)				↑0.5 %, possibly beneficial [↑1.5 %]
Hoon et al. [101]	70 mL (concentrated)	75 min before trial	26 elite male cyclists; crossover	Power produced in two 4-min cycle time trials, with a 75-min rest in between	↑0.6 %, unclear
		150 min before trial			↑0.4 %, unclear
	70 mL (concentrated) + 35 mL (concentrated)	150 min and top-up 75 min before trial			↑0.5 %, unclear
Boorsma et al. [102]	210 mL (concentrated)	2 h before trial	8 trained male runners; crossover	Time to run 1,500 m (4:10 min)	0.0 %, $p > 0.05$
	210 mL day^{-1} (concentrated) for 8 days				↑0.4 %, $p > 0.05$
Glaister et al. [103]	70 mL (concentrated)	1 h before trial	14 trained female cyclists; crossover	Power output in a 20 km cycle time trial (26 min)	0.0 %, $p > 0.05$ [0.0 %]
Martin et al. [104]	70 mL (concentrated)	2 h before trial	9 male team sport athletes; crossover	Mean power during a 2-h repeated sprint test	0.0 %, $p = 0.2$ [0.0 %]
Cermak et al. [47]	0.5 L (concentrated)	2.5 h before trial	20 trained male cyclists; controlled trial	Time to cycle 30 km (60 min)	↓0.1 %, $p > 0.05$ [↓0.2 %]
Sheets and Snyder [105]	140 mL (concentrated)	2.5 h before trial	11 trained males and females; crossover	Time to run 5 km (22 min)	↓1.5 %, $p = 0.04$
Studies with non-beetroot juice control					
Bailey et al. [106]	0.5 L day^{-1} for 6 days	Unknown	7 untrained males; crossover	Time to complete a leg ergometer incremental test to fatigue (10 min)	↑25 %, $p < 0.01$ [↑13 %[d]]
Masschelein et al. [107]	0.5 L day^{-1} for 6 days	0.5 L 1–2 h before trial	15 physically active males; crossover	Cycle time to fatigue in an incremental test in hypoxia (15 min)	↑4.5 %, $p < 0.05$ [↑3.6 %[c,d]]
Murphy et al. [108]	200 g (solid beetroot)	75 min before trial	11 fit men and women; crossover	Time to complete 5 km run (25 min)	↑3.3 %, $p = 0.06$

Table 4 continued

References	Beetroot juice treatment	Timing of final dose	Subjects; design	Performance test[a]	Performance outcome[b]
Vanhatalo et al. [109]	0.5 L day^{-1} for 15 days	2.5–5 h before trial	8 untrained males; crossover	Peak power in an incremental cycle test (9 min)	↑2.5 %, $p < 0.05$ [↑2.5 %]
Bond et al. [110]	0.5 L day^{-1} for 6 days	5 h before trial	14 elite male rowers; crossover	Time to complete 6 × 500 m rowing ergometer repetitions (6 min)	↑0.8 %, $p > 0.05$ [↑2.4 %]
Bailey et al. [27]	0.5 L day^{-1} for 6 days	Unknown	8 untrained males; crossover	Cycle time to fatigue at constant load (11 min)	↑16 %, $p < 0.05$ [↑1.0 %]
Muggeridge et al. [111]	70 mL (concentrated)	3 h before trial	8 trained male kayakers, crossover	Time to kayak 1 km following preload (5 min)	0.0 %, $p = 0.5$ [0.0 %[d]]

[a] The approximate duration of the equivalent time trial is shown in parentheses

[b] ↑ denotes performance improvement versus control; ↓ denotes performance impairment versus control; square brackets denote a performance outcome converted to a change in mean power in an equivalent time trial shown in parentheses

[c] Data using animals or an unusual performance test requiring an educated estimate of the adjustment factor

[d] The performance test was completed after a preload exercise session; it was assumed that this would approximately double the performance effect, and the effect was accordingly adjusted by halving it

3.6 Spirulina

Spirulina is an extract of blue-green algae containing tocopherols, β-carotene, polyphenols and phytocyanins, which all exhibit antioxidant activity [84]. Spirulina may reduce excessive levels of exercise-induced reactive oxygen species that may contribute to muscle fatigue [85]. Anecdotal evidence suggests the Chinese and Cuban Olympic teams have consumed spirulina daily for many years and have reported improved performances [87]. As shown in Table 6, three human studies [85, 86, 117] and one rat study [40] have been conducted on chronic spirulina consumption. In two of the human studies, there were moderate performance improvements, although one was non-significant. In the third human study, there were apparently clear increases in quadriceps force, but this outcome measure cannot be converted to power output for comparison with other outcomes in this review. The most convincing study was a post-only controlled trial in rats in which there were clear, moderate to extremely large improvements in a dose-dependent manner. In all of these studies, the timing of the final dosage was not defined and, as such, the acute (hours prior to the exercise test) and chronic effects cannot be distinguished. Further research is required to confirm these initial positive effects and to better understand the mechanism of action. Until such time, it would be premature to recommend spirulina to athletes.

3.7 *N*-acetylcysteine

NAC is an effective antioxidant, which may reduce the harmful effects of excessive reactive oxygen species by direct scavenging and by supplying cysteine for synthesis of an intracellular antioxidant, glutathione [28, 29]. NAC exhibits nonspecific antioxidant properties that delay skeletal muscle fatigue in healthy participants [87], but it may negatively impact performance if taken chronically, inhibiting training adaptations. Of the ingested NAC, only 6–10 % is absorbed, and it is excreted rapidly [88]—hence the use of intravenous administration in six acute studies, all in humans (Table 7). Four studies demonstrated clear small to moderate improvements in endurance performance [28, 89, 90, 118], and another five studies showed non-significant trivial to impaired performance effects [91, 92, 119], although the sample sizes were small.

One study simulating team sport competition demonstrated clear moderate to large improvements in single and repeated sprint performance on NAC [89]. Not shown in the table are the improvements on days 3 and 5 of a simulated tournament, which were even more pronounced. Even with this limited number of studies, it is reasonable to conclude that intravenous NAC enhances high-intensity performance of athletes. Administration of any agent

Table 5 Details of studies investigating effects of various polyphenol supplements on exercise performance (excluding quercetin, resveratrol and beetroot juice)

References	Polyphenol treatment	Timing of final dose	Subjects; design	Performance test[a]	Performance outcome[b]
Lafay et al. [80]	Grape extract 400 mg day^{-1} for 1 month	Unknown	20 elite male athletes; crossover	Mean power in 45 s of vertical rebound jumps	↑24 %, $p < 0.05$ [↑24 %[c]]
				Power in first 10 rebound jumps	↑2.3 %, $p > 0.05$ [↑2.3 %]
Nogueira et al. [21]	2 mg kg^{-1} day^{-1} of epicatechin for 15 days	Unknown	25 male mice; controlled trial	Run time in an incremental test (13 min)	↑26 %, $p < 0.05$ [↑22 %[c,d]]
Oh et al. [81]	180 mL *Ecklonia cava*	30 min prior to trial	23 untrained males; crossover	Run time in an incremental test after a preload (9 min)	↑22 %, $p < 0.05$ [↑5.5 %[c,d]]
Sadowska-Krepa et al. [112]	1170 mg day^{-1} red grape skin extract for 6 weeks	Unknown	14 active males; controlled trial	Time to swim 50 m after a preload (1 min)	↑5.0 %, $p < 0.05$ [↑5.0 %[c,d]]
Eichenberger et al. [113]	159 mg day^{-1} of green tea extract for 3 weeks	Unknown	9 male cyclists; crossover	Distance cycled in 30 min after a preload	↑2.9 %, $p = 0.25$ [↑0.3 %[d]]
Skarpanska-Stejnborn [114]	750 mg day^{-1} of ground blackcurrant fruit for 6 weeks	Unknown	19 elite male rowers; controlled trial	Time to row 2000 m on an ergometer	↑0.2 %, $p > 0.05$ [↑0.6 %]
Kang et al. [56]	200 mg day^{-1} of lychee extract for 30 days	Unknown	46 trained males and females; controlled trial	Run time to fatigue @80 % VO_2 max (28 min)	↑4.3 %, $p = 0.05$ [↑2.9 %[c,d]]
Braakhuis et al. [115]	0.5 L day^{-1} blackcurrant extract drink for 3.3 weeks	8 h before trial	24 trained females; crossover	Time to run 5 km (23 min)	↓0.0 %, $p > 0.05$ [↓0.0 %]
Trinity et al. [82]	500 mL of a polyphenol drink (mostly ellagitannins), twice daily for 7 days	30 min prior	12 trained males	Cycle time to fatigue at a constant load (6 min)	↓3 %, $p < 0.05$ [↓0.2 %]
Dean [116]	270 mg day^{-1} of green tea extract for 6 days	8 h before trial	8 trained male cyclists; crossover	Time to cycle 40 km after a preload (1 h)	↓0.7 %, $p = 0.7$ [↓0.7 %[c,d]]
Labonté et al. [83]	800 mg of cranberry and grapeseed powder	1 h prior to trial	12 elite female and male athletes; crossover	Time to cycle 3 km (4 min)	↓0.7 %, $p = 0.27$ [↓1.8 %]

VO_2 *max* maximal oxygen consumption

[a] The approximate duration of the equivalent time trial is shown in parentheses

[b] ↑ denotes performance improvement versus control; ↓ denotes performance impairment versus control; square brackets denote a performance outcome converted to a change in mean power in an equivalent time trial shown in parentheses

[c] Data using animals or an unusual performance test requiring an educated estimate of the adjustment factor

[d] The performance test was completed after a preload exercise session; it was assumed that this would approximately double the performance effect, and the effect was accordingly adjusted by halving it

Table 6 Details of studies investigating effects of spirulina on exercise performance

References	Spirulina treatment	Timing of final dose	Subjects; design	Performance protocol[a]	Performance outcome[b]
Liping et al. [40]	200 mg kg^{-1} day^{-1} for 6 weeks	Unknown	20 rats per group; controlled trial	Run time in an incremental test (100 min)	↑84 %, $p < 0.05$ [↑5.6 %[c]]
	100 mg kg^{-1} day^{-1} for 6 weeks				↑59 %, $p < 0.05$ [↑3.9 %[c]]
	50 mg kg^{-1} day^{-1} for 6 weeks				↑39 %, $p < 0.05$ [↑2.6 %[c]]
Hsueh-Kuan et al. [86]	7.5 g day^{-1} for 3 weeks	Unknown	16 untrained participants (sex not specified); controlled trial	Run time in an incremental test (7 min)	↑4 %, $p > 0.05$ [↑2.0 %[e]]
Kalafati et al. [85]	6 g day^{-1} for 4 weeks	24 h before trial	9 trained males; crossover	Run time to fatigue after a preload (2 min)	↑32 %, $p = 0.05$ [↑1.1 %[e]]
Sandhu and Shenoy [117]	2 g day^{-1} for 8 weeks	Unknown	20 untrained males and females; controlled trial	Mean quadriceps force over 10 s	↑35 %, $p < 0.01$[d]
			20 trained males and females; controlled trial		↑24 %, $p < 0.01$[d]

[a] The approximate duration of the equivalent time trial is shown in parentheses

[b] ↑ denotes performance improvement versus control; ↓ denotes performance impairment versus control; square brackets denote a performance outcome converted to a change in mean power in an equivalent time trial shown in parentheses

[c] Data using animals or an unusual performance test requiring an educated estimate of the adjustment factor

[d] An unusual performance test for which we are unable to make an educated estimate of the adjustment factor

[e] The performance test was completed after a preload exercise session; it was assumed that this would approximately double the performance effect, and the effect was accordingly adjusted by halving it

intravenously is arguably an unethical strategy for performance enhancement; therefore, oral administration would be more acceptable. Two studies administered NAC orally and found a small clear improvement with a dose of 70 mg kg^{-1} [91] and a moderate performance decrement with 100 mg kg^{-1} [92]. Reports of adverse effects of oral NAC include conjunctival irritation; dysphoria, vomiting, diarrhoea, nausea and loss of coordination are common on high or repeated doses [93]. Lower oral doses or desensitization with short-term repeated doses of NAC would probably reduce adverse effects in sensitive individuals, and no adverse effects have been reported on doses of 50 mg kg^{-1} [18]. While NAC has been studied in an 'endurance' performance context, it may prove equally important in other settings, such as adaptations or recovery from resistance training. Further evidence of performance benefits from safe oral doses of NAC are required before recommendations for its use can be made.

4 Conclusion

Athletes are always on the lookout for the next dietary supplement to support optimal performance in order to gain an edge on the competition. It is the job of the sport dietitian, physiologist and sports physician to clarify the effect dietary antioxidants have on performance, using an evidence-based approach. While many narrative-style reviews have suggested antioxidants play a role in optimal performance, to our knowledge, this is the first to attempt to quantify the magnitude of these effects or discuss the impact of chronic versus acute intakes. We have reported the timing of the final antioxidant dose in an effort to differentiate the chronic studies that may include acute effects. It is difficult to assume that all effects are due to chronic intake if the final dose of the antioxidant was received within a few hours of the exercise test. Each of the dietary antioxidants discussed has demonstrated physiological effects that extend wider than that of reducing reactive species. In summary of this review, chronic vitamin E intake appears to enhance performance at altitude but potentially impairs performance at sea level. Quercetin has a small benefit on endurance performance but only in untrained subjects. Resveratrol appears to benefit performance in fit, healthy rats but is potentially detrimental to inactive rodents and humans. Beetroot juice also improves cycling performance in untrained individuals via its content of nitrate, but it has an unclear, potentially harmful effect in athletes. Effects of other polyphenols range from potentially harmful (green tea extract and cranberry–grapeseed powder) to promisingly beneficial (grape extract and cocoa epicatechins), acknowledging the variation in the polyphenol types. The popularity of spirulina with some athletes appears to be justified on the basis of the handful of studies to date, but a recommendation for its use awaits more research.

Table 7 Details of studies investigating effects of *N*-acetylcysteine (NAC) on exercise performance

References	NAC treatment	Timing of final dose	Subjects; design	Performance protocol[a]	Performance outcome[b]
Cobley et al. [89]	50 mg kg^{-1} (oral)	Before trial	12 trained men; controlled trial	20 m sprint time after a preload (3.5 s)	↑5.2–13 %, $p < 0.05$ [↑2.6–6.4 %[d]]
				Yo-Yo Recovery Test Level 1 after a preload (10 min)	↑23 %, $p < 0.05$ [↑1.5 %[d]]
Matuszczak et al. [87]	150 mg kg^{-1} (IV)	Before trial	18 untrained male and females; controlled trial	Number of repetitive handgrip exercises (5 s every 30 s: approximately 40 exercises)	↑32 %, $p < 0.01$ [↑2.1 %]
Medved et al. [28]	Initial: 125 mg kg^{-1} h^{-1} for 15 min; during: 25 mg kg^{-1} h^{-1} (IV)	Before and during trial	7 trained males; crossover	Cycle time to fatigue (6 min)	↑26 %, $p < 0.05$ [↑1.7 %]
Corn et al. [91]	70 mg kg^{-1} (oral)	1 h before trial	27 males; crossover	Power during a cycle time to fatigue (unknown duration)	↑20 %, $p = 0.03$ [↑1.3 %]
Bailey et al. [119]	Initial: 125 mg kg^{-1} h^{-1} for 15 min; during: 25 mg kg^{-1} h^{-1} (IV)	Before and during trial	8 males; crossover	Cycle time to fatigue (30 min)	↑13 %, $p > 0.05$ [↑0.9 %]
McKenna et al. [90]	Initial: 125 mg kg^{-1} h^{-1} for 15 min; during: 25 mg kg^{-1} h^{-1} (IV)	Before and during trial	8 male endurance athletes; crossover	Cycle time to fatigue after a preload (6 min)	↑21 %, $p < 0.05$ [↑0.7 %[d]]
Reid et al. [120]	150 mg kg^{-1} (IV)	Before trial	10 untrained males; crossover	Decline in force output during 10 Hz stimuli every second for 30 min	15 % less decline, $p < 0.001$[c]
Medved et al. [121]	Initial: 125 mg kg^{-1} h^{-1} for 15 min; during: 25 mg kg^{-1} h^{-1} (IV)	Before and during trial	8 untrained males, crossover	Cycle time to fatigue after a preload (2 min)	↓2.9 %, $p > 0.05$ [↓0.2 %[d]]
Trewin et al. [92]	100 mg kg^{-1} (oral)	30 min before trial	9 elite male cyclists; crossover	Mean power during a 10 km cycle time trial after a preload (10 min)	↓4.9 %, $p > 0.05$ [↓2.5 %[d]]

IV intravenous

[a] The approximate duration of the equivalent time trial is shown in parentheses

[b] ↑ denotes performance improvement versus control; ↓ denotes performance impairment versus control; square brackets denote a performance outcome converted to a change in mean power in an equivalent time trial shown in parentheses

[c] An unusual performance test for which we are unable to make an educated estimate of the adjustment factor

[d] The performance test was completed after a preload exercise session; it was assumed that this would approximately double the performance effect, and the effect was accordingly adjusted by halving it

The vitamin E and NAC studies included chronic and acute supplement protocols; taken acutely, vitamin E may be of benefit if levels can be sufficiently increased. The only antioxidant with good evidence of beneficial acute effects on the performance of trained individuals is NAC, when injected intravenously, but this mode of administration cannot be recommended. Further research with oral NAC administration is needed. Despite promising results from acute intake of some antioxidants¸ acute intake of cranberry and grapeseed polyphenol supplement fails to improve performance. On the basis of the acute effects of vitamin E and NAC, these and presumably other antioxidants are likely to have beneficial effects when administered acutely in sufficient concentration.

NAC and presumably other antioxidants are likely to reduce the impairment of performance that occurs during tournaments or in major competitions requiring repeated efforts, perhaps by limiting the effects of inflammation on muscle function. An area worthy of further investigation is therefore the effect of various dietary antioxidants on performance in such settings.

With regard to the optimal timing of antioxidant consumption, much of the evidence is pointing towards an acute performance benefit but performance impairment when taken chronically. However, it is also reasonably clear that not all antioxidants have the same physiological effects. Results from the animal studies are pointing to a performance benefit when chronic supplementation with epicatechin or resveratrol is combined with training. Further research is warranted to clarify the effects of different antioxidants and optimal timing regimes.

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