Dietary Supplements for Aquatic Sports

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Many athletes use dietary supplements, with use more prevalent among those competing at the highest level. Supplements are often self-prescribed, and their use is likely to be based on an inadequate understanding of the issues at stake. Supplementation with essential micronutrients may be useful when a diagnosed deficiency cannot be promptly and effectively corrected with food-based dietary solutions. When used in high doses, some supplements may do more harm than good: Iron supplementation, for example, is potentially harmful. There is good evidence from laboratory studies and some evidence from field studies to support health or performance benefits from appropriate use of a few supplements. The available evidence from studies of aquatic sports is small and is often contradictory. Evidence from elite performers is almost entirely absent, but some athletes may benefit from informed use of creatine, caffeine, and buffering agents. Poor quality assurance in some parts of the dietary supplements industry raises concerns about the safety of some products. Some do not contain the active ingredients listed on the label, and some contain toxic substances, including prescription drugs, that can cause health problems. Some supplements contain compounds that will cause an athlete to fail a doping test. Supplement quality assurance programs can reduce, but not entirely eliminate, this risk.

Keywords: swimming, creatine, caffeine, bicarbonate, doping

The use of dietary supplements is widespread in sport, as it is in the general population. Data from the 1999–2000 National Health and Nutrition Examination Survey of U.S. adults showed that 52% of the sample reported taking a dietary supplement within the past month, with 53% of users taking more than one supplement (Radimer et al., 2004). Data from the corresponding survey covering the period from 2003 to 2006 gave a prevalence of use of 49%, with the majority of people reporting taking only one dietary supplement on a daily basis (Bailey et al., 2011). Surveys of use by athletes have typically shown a higher prevalence of use, with the highest rates of use often seen in elite competitors: A survey of competitors at the International Association of Athletics Federations World Championships revealed that about 85% of these elite track and field athletes reported the use of supplements (Maughan et al., 2007). Dascombe et al. (2010) reported the dietary supplement practices of athletes from a state-based sports institute in Australia; athletes (N = 72) were drawn from seven sports, including water polo and swimming. The large majority (n = 63; 88%) of surveyed athletes reported using nutritional supplements. Athletes believed that nutritional supplements are related to performance enhancements (n = 47; 65%) and that heavy training increases supplement requirements (n = 47; 65%). Among 113 national-level Sri Lankan athletes from six different sports, 106 (94%) reported the use of one or more supplements; all of the 23 swimmers in this survey used supplements, with an average daily intake of 3.4 different supplements (de Silva et al., 2010). Among Canadian swimmers competing at the Olympic Games, 56% reported the use of nutrition supplements (Huang et al., 2006).

Many factors contribute to the widespread use of supplements by athletes. Among these are the limited nutrition knowledge of most athletes and of those who advise them. Coaches and athletic trainers, most of whom have no formal nutrition education and therefore little awareness of the evidence base, are more likely than dietitians to be the sources to which athletes turn for nutrition advice (Burns et al., 2004; Sajber et al., 2013). Surveys of use by athletes. Among these are the limited nutrition knowledge of most athletes and of those who advise them. Coaches and athletic trainers, most of whom have no formal nutrition education and therefore little awareness of the evidence base, are more likely than dietitians to be the sources to which athletes turn for nutrition advice (Burns et al., 2004; Sajber et al., 2013). A recent survey, however, suggested that athletes who were deemed to be at risk for inadequate nutrient intake were more likely to take dietary supplements than those deemed not to be at risk (53% vs. 33%; Kiertscher & DiMarco, 2013). This suggests some awareness among these athletes of their nutrient needs and perhaps also some awareness of the adequacy or otherwise of their dietary habits. Supplements are heavily promoted by the multibillion-dollar industry that has grown up around their use, and athletes are often swayed by the promotional material directed at them. The advertising material of many of these companies is extremely seductive, though there is often little substance and much misrepresentation of the limited information available. Much of this material depends on extrapolation from effects observed in vitro, and little or none is drawn from studies on elite athletes. Even less is based on observations made of athletes from aquatic sports.
A review of the literature using the search terms dietary supplements and swimming produced 72 items (Web of Knowledge, 2013). Of these, only 17 related to humans; the majority involved swimming rats, and whether the swimming rat is a good model for the study of exercise metabolism is somewhat questionable. The hormonal and metabolic responses of an animal struggling to stay afloat—and therefore alive—are very different from those of a swimmer in training or competition. The wider aspects of the metabolic and nutritional issues relating to swimming have also been poorly studied relative to other exercise models such as running and cycling. This reflects the limited availability of laboratory facilities for the study of swimming and the practical difficulties of performing tests in an open pool; opportunities for the sampling of blood and muscle are necessarily limited, and understanding of the physiological and metabolic limitations to swimming performance are therefore also limited. Without such an understanding, the extrapolation from results of studies that have used other exercise models is fraught with difficulties.

**Supplements for Training**

Swimmers perform a high volume of training, much of it at high intensity, in the water and on land. The aim of training is, or at least should be, the enhancement of performance in competition, and there is a temptation to think that more is better. This can lead to issues related to overtraining, which can, in turn, lead to underperformance. Also, some evidence has shown that hard training can lead to a degree of immune suppression and therefore to an increased risk of minor opportunistic infections. Although generally minor in themselves, these infections can lead to missed training days, and the cumulative effects may become significant. It is also essential to ensure that the benefits of training are maximized, which means looking to nutritional support to ensure adequate recovery between training sessions and also to promote the adaptations that take place in muscle and other tissues in response to the training stimulus. In all of these areas, nutrition support plays a key role, and the use of dietary supplements is heavily promoted.

Some populations may be at increased risk of deficiency of one or more of the micronutrients. Poorly planned vegetarian diets may fail to provide adequate amounts of vitamin B₁₂, calcium, omega-3 fatty acids, vitamin D, iron, zinc, riboflavin (vitamin B₂), and iodine. Risks are compounded by a low energy intake or by any diet that excludes specific food groups. Special attention should be given to the assessment of any athlete who practices any form of restrictive eating. Supplements for Training will compromise health and performance, but the use of vitamin and mineral supplements does not improve health or performance in athletes consuming an adequate diet. Athletes are therefore often tempted to subscribe to the just-in-case and more-is-better philosophies without recognizing that, at least in the case of some nutrients, there are significant risks associated with excessive intake. Athletes, and those who advise them, must recognize, however, that it is not necessary for every individual to achieve the recommended daily intake of all nutrients; they should recognize, too, that a few individuals may need more than the recommended intake. This distinction between an individual athlete’s nutrient requirements and the population’s recommended intake should be central to dietary advice for athletes. It is also important to recognize that the high energy intake that accompanies hard training brings with it an increase in micronutrient intake. Except when food intake is restricted to achieve physique goals or for other reasons, micronutrient deficiencies are unlikely. Some athletes may, though, have inadequate intake because of specific conditions such as impaired absorptive capacity.

Given the importance of oxygen availability to athletic performance and the central role of the iron-containing hemoglobin in the transport of oxygen from the lungs to the working muscles, an adequate dietary intake of iron is essential to performance. Iron deficiency is known to impair performance, and even marginal deficiency that does not result in frank anemia may compromise the ability to sustain an intensive training program (Lukaski, 2004). Routine iron supplementation is therefore common in athletes, but it can do more harm than good, and the risk of iron toxicity is very real (Papanikolaou & Pantopoulos, 2005). It has been estimated that, among the population of industrialized countries, twice as many men suffer from iron overload because of the excessive use of iron supplements as suffer from iron deficiency (Eichner, 2000). Tsalis et al. (2004) found little variation in iron status parameters or in performance tests in swimmers over a season of training in response to either iron supplementation or the prescription of an iron-rich diet, confirming the suggestion that simply increasing iron intake may not be beneficial. Lukaski et al. (1996) showed that mineral intakes of a small group of swimmers (five men, five women) who were not taking any supplements were generally adequate. Similar observations were also made in a small group of elite male Brazilian swimmers, though calcium intake was reported to be low (Paschoal & Amancio, 2004). Periodic screening for iron status is recommended for all athletes, with supplementation warranted only when low iron status is demonstrated.

**General Health**

Athletes face many of the same health issues as the general population, but the consequences of illness may be greater. Inadequate intake of any of the essential nutrients

**Supplements for Optimization of Physique**

In sports in which physique and physical appearance can influence either performance or the subjective assessment of judges, athletes face numerous challenges in sustaining
rigorous training programs that optimize muscle mass and function while ensuring a low body fat content. Building muscle and reducing body fat content are consistently two of the most common reasons given for the use of supplements (Kiertscher & DiMarco, 2013). The second of these two aims is also one that is appealing to a large part of the general population, and a large number of supplements are promoted for this purpose. Synchronized swimming and diving are sports that place a strong emphasis on body aesthetics, and water polo and sprint swimming may benefit from increased muscle mass, but muscle building will be limited in swimming over longer distances because of buoyancy issues.

A recent comprehensive overview of the wide range of supplements promoted for weight loss concluded that there was little evidence of benefit from most of them (Manore, 2012). Many of these products contain stimulants—most commonly caffeine, ephedra, synephrine, and related compounds—as active ingredients and are therefore likely to be associated with some adverse effects, especially when consumed in amounts greater than the recommended dose. Methylxanthine, commonly known as 1,3-dimethylamylamine or DMAA, is a stimulant that has been marketed as the primary active ingredient of many popular dietary supplements, with claims that it can promote fat loss and increase energy levels during exercise, though its use is now prohibited in many countries. There is also the risk of an adverse doping outcome with some of these agents because they appear on the prohibited substances list of the World Anti-Doping Agency (2014). A more serious concern is the presence in some of these products of pharmaceuticals that are not declared on the label, that are not permitted in sport, and that are associated with serious adverse health outcomes. We discuss this in detail later in this article.

Promoting Adaptations to Training

A large number of dietary supplements have been promoted over the years as “adaptogens,” that is, as agents that can enhance the adaptations that take place in response to an applied stimulus. These products are mostly based on herbal extracts and include ginseng, *Rhodiola rosea*, *Withania somnifera*, *Schisandra chinensis* (Panossian & Wikman, 2008), *Vitis vinifera*, and others (Koncic & Tomczyk, 2013). The evidence base for these extracts is generally not strong; all can be shown to have some biological actions in vitro and in vivo, but the evidence of any action that affects the outcome of a training program is almost entirely absent.

Ginseng is one of the most popular supplements in this category. It has been extensively studied over many years, and a large literature on its many diverse biological actions exists. Though some reviews have concluded that ginseng can promote both physical and mental performance and increase resistance to imposed stress (Oliynyk & Oh, 2013), it is important to recognize that much of the research in this area has been described as generally poor (Choi et al., 2013). The same conclusion might be reached for most of the supplements in this category.

The ingestion of small amounts (about 20–25 g) of protein in the period around an exercise stimulus is generally accepted to be effective in promoting net muscle protein synthesis (Tipton et al., 2014). The question of whether this protein is best provided in the form of normal foods or as a supplement depends on individual circumstances; foods will provide other nutrients that can contribute to the swimmer’s training goals, but supplements can provide a guaranteed amount of high-quality protein without additional energy, which can be useful for the swimmer with a restricted energy budget. Again, when a large energy intake is necessary to support intensive training, the source of the protein may be less crucial, but when energy intake must be limited, high-quality proteins, especially whey, may have advantages (Phillips & Van Loon, 2011). Some of these effects are attributed to the high leucine content of whey protein, and supplements of branched-chain amino acids are often promoted. There is some evidence that branched-chain amino acid supplementation may reduce the extent of muscle protein breakdown that occurs after swimming exercise (Tang, 2006). Moreover, this supplementation appears to ameliorate muscle soreness after intense exercise (Jackman et al., 2010). However, the applicability of this effect to most aquatic sports is questionable, except perhaps for water polo and dry-land resistance training. It is not clear, though, that such isolated amino acid supplements have any benefit over whole proteins that provide the same essential amino acids (Churchward-Venne et al., 2012).

## Promoting Recovery Between Training Sessions

The nature of the recovery processes that occur after training will depend on numerous factors, and these are discussed in detail elsewhere in this series of articles (Burke et al., 2014). Recovery processes include the restoration of acid–base balance, replenishment of muscle and liver carbohydrate stores, stimulation of protein turnover, replacement of water and solutes lost in sweat, and minimization of any exercise-induced muscle damage. An extensive range of commercial products is produced for use by athletes during recovery, including a variety of drinks, gels, and powders that are usually based on carbohydrate, protein and amino acids, and electrolytes. The efficacy of most of these products has not been evaluated. The general principles on which they are based have been explored in some detail in endurance exercise involving running and cycling and in intense resistance exercise, but limited information is available for swimming (Burke et al., 2014).

This perhaps reflects the limited understanding of the recovery processes taking place in muscle and other tissues. An acute inflammatory response is usually observed after a single bout of prolonged hard exercise and is manifest in subjective sensations of muscle stiffness and
soreness and a reduced range of movement. There are also objective signs of muscle damage, including marked elevations of muscle-specific proteins in the circulation. Muscle damage and the associated delayed-onset soreness may be less of an issue in swimming because of its low-impact forces and small eccentric muscle activity. These effects may persist for some hours or days (Stupka et al., 2000). Suppression of this response was, at one time, thought to be a good thing, and the use of anti-inflammatory agents has been popular with athletes (Mackey et al., 2012). There is, however, evidence that these processes may be an essential part of the adaptive response, and in any case, they are much less marked in well-trained athletes (Stupka et al., 2001).

The possible involvement of elevated levels of reactive oxygen species in the genesis of muscle damage and soreness after exercise (Maughan et al., 1989) has also led to the popularity of agents that may quench these radicals, including a wide range of antioxidant nutrients (most prominently vitamins C and E). Once again, however, some studies have shown suppression of free radical-mediated responses after antioxidant supplementation (Goldfarb et al., 2007), but the balance of the evidence is not convincing, and most studies have failed to show beneficial effects (Tomoeda et al., 2013). Creatine has also been reported to have antioxidant properties, but these are relatively minor, and creatine supplementation, at least in a rat swimming model, does not reduce markers of oxidative stress, inflammation, and muscle damage (Silva et al., 2013). This picture seems to suggest that a number of agents with antioxidant or anti-inflammatory properties may have some effects on free radical-mediated responses, but whether this is beneficial or harmful is not known (Peternelj & Coombes, 2011; Urso & Sawka, 2013). Potentially harmful effects include a blunting of training responses and an attenuation of radical-mediated physiological processes.

**Immune Function**

Athletes want to avoid illness to minimize interruptions to training and to avoid missing competition, but the physical and mental stresses of both training and competition can compromise immune function and increase susceptibility to minor infectious illness. Many nutrition interventions have been proposed to support immune function and increase resistance to invading pathogens, and these are discussed in detail by Pyne et al. (2014). Gleeson et al. (2013) recently followed three groups of endurance athletes who reported that they exercised 3–6 hr/week (low), 7–10 hr/week (medium), or 11 hr/week (high) over a training season. The high and medium groups had more episodes of upper respiratory tract infections than the low group (Ms ± SDs = 2.4 ± 2.8 and 2.6 ± 2.2 vs 1.0 ± 1.6, respectively; p < .05). The high group had approximately threefold higher interleukin-2, interleukin-4, and interleukin-10 production (all ps < .05) by antigen-stimulated whole blood culture than the low group, and the medium group had twofold higher interleukin-10 production than the low group (p < .05). These effects will reduce resistance to infection.

In a similar study, swimmers were followed over a winter training season of gradually increasing intensity; upper respiratory symptoms were more likely during periods of increased training load, and these symptoms were accompanied by changes in immune function parameters (Rama et al., 2013). These observations confirm earlier findings that elite swimmers are more likely to experience episodes of infectious illness over a period of intensive training than are moderately active controls: Salivary immunoglobulin A levels showed an inverse correlation with the number of infections in both elite swimmers and moderately exercising control subjects, which has been interpreted as indicating the need to maintain a robust immune system to reduce the risk of illness (Gleeson et al., 1999). These and other similar findings have led to a strong focus on prevention strategies in athletes, though it should be noted that the presence of respiratory tract infections may not significantly affect swimming performance (Pyne et al., 2001).

A wide range of compounds is promoted for immune support in the general population, with some being specifically targeted toward athletes. Some of these are listed in Table 1, but it is important to note that, notwithstanding the promotional material that often accompanies dietary supplements, few have attracted significant research interest, so their efficacy and safety remain largely unknown. Glutamine is an important fuel for cells of the immune system, and it is well recognized that the plasma concentration of glutamine is decreased after endurance exercise; this has led to the suggestion that reduced glutamine availability may be, at least in part, responsible for the apparent immunosuppression that occurs in these individuals. Initial investigations provided some evidence to support this theory-based proposition (Castell et al., 1996). In a subsequent study, however, the same group of authors were unable to show any effect of glutamine supplementation on components of the immune system in marathon runners (Castell et al., 1997). More recent studies have produced disappointing results and, notwithstanding the sound theoretical basis, the evidence does not support the use of glutamine supplements (Akerström & Pedersen, 2007).

It has been reported that a short period of supplementation with vitamin C can reduce the incidence of upper respiratory tract infection symptoms in the days and weeks after competitive distance running events (Peters, 1997). High doses of vitamin C may, however, blunt the adaptations to training (Ristow et al., 2009). Zinc is known to play an important role in cellular and humoral immunity (Kruse-Jarres, 1989), leading to suggestions that athletes who are susceptible to frequent episodes of infectious illness may be zinc deficient and that zinc supplementation may be useful in promoting immune function, particularly at times of stress. For both
vitamin C and zinc, there is a significant body of research on the effects of supplementation on immune function and the incidence of upper respiratory tract infections; the consensus view in relation to these nutrients is that inadequate dietary intakes are likely to lead to compromised immunity and an increased risk of infections, but that supplementation is not generally beneficial (Gleeson & Williams, 2013). A comprehensive review of the effects of supplements on immune function in athletes concluded that “convincing evidence that so-called ‘immune-boosting’ supplements, including high doses of antioxidant vitamins, glutamine, zinc, probiotics and Echinacea, prevent exercise-induced immune impairment is currently lacking” (Gleeson et al., 2004, p. 115). The experimental evidence that has emerged since then has done little to alter this conclusion.

### Supplements for Competition

An athlete who has trained to the limit of his or her genetic potential will inevitably be tempted to explore all available options for further performance enhancement. This may go some way toward explaining the popularity of supplement use in competition. In assessing the likelihood that any of these might affect performance in the aquatic sports, some understanding of the physiological and metabolic factors that limit performance is required. Although this information is available, albeit to a limited extent, for exercise models such as running and cycling, much less is known of the factors that limit performance in swimming. Even less is known of the performance determinants in technical and team sports, including both diving and water polo.

In assessing the possible benefits of any supplement, it is important to look closely at the literature. The relevance of the subject population used must be considered: Few studies have looked at elite athletes, and they may not respond in the same way as the recreationally active individuals who volunteer for most studies. The choice of exercise model is important; results from laboratory models of strength or of running or cycling may not be relevant to performance in the pool. An often-neglected issue is the fact that most scientific articles are concerned with effects on the whole subject population, and there is inevitably some individual variability in the response. The reasons for this variability in response are not usually apparent, and it has to be acknowledged that many studies have not allowed adequate familiarization trials and most have not used repeated measures to confirm the reproducibility of performance measures.

Rather than looking at whether there is a statistically significant effect, it may be more appropriate to consider whether there is likely to be a beneficial effect for the majority of individuals (Hopkins et al., 2009), though many, perhaps most, studies in this area have lacked sufficient statistical power for any clear conclusion to be reached. There is also a need to look closely at the possibility of adverse effects on either performance or health.

### Creatine

Creatine has become one of the most widely used supplements in sport since its first widespread use by athletes at around the time of the 1992 Barcelona Olympic Games. Its use is supported by a strong evidence base relating to both efficacy and safety, and there are sound mechanisms that can explain its mode of action. There is good evidence that creatine can enhance performance in a number of laboratory exercise models and can influence components of performance that might be important in training and competition. Early studies established that few days of high creatine intake (free creatine plus creatine phosphate) would increase creatine content of skeletal muscle by about 20%–30% (Harris et al., 1992); that it could enhance performance in brief high-intensity exercise, especially when repeated bouts of exercise with short recovery intervals were performed (Greenhaff et al., 1993); and that it could increase muscle strength (Maganaris & Maughan, 1998).

There have been several reports of studies of creatine supplementation on swimming performance. In a comprehensive literature review and meta-analysis published in 2004, Branch concluded that creatine supplementation was effective in increasing lean body mass and total body mass. Analysis of performance in various exercise tasks showed that effect sizes were greater for laboratory

### Table 1: Supplements on Sale With Claims of Providing Enhanced Immune Function

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<th>Antioxidants</th>
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<td>Astragalus</td>
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<td>Multivitamins</td>
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<td>Pycnogenol</td>
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<td>Vitamin C</td>
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*Note. This is not an exhaustive list but gives some indication of the scope of the choices available to athletes.*
tests than for field-based performance measures and that supplementation did not seem to be effective in improving swimming performance. A more recent review (Hopwood et al., 2006) focused on creatine supplementation and swimming performance; this review also concluded that creatine supplementation was not effective in improving performance in a single swim but that it might enhance performance in a repeated-interval swim set. It also found that power development on a swim bench ergometer was likely to be improved by supplementation, leading the authors to suggest that the lack of effect seen in the pool may be related in some way to technique.

New evidence published since those reviews were concluded has not fundamentally changed the view that supplementation with creatine may not be beneficial for swimmers, but it nonetheless remains popular. There is no evidence of harmful effects on performance and the product, at least when consumed in the recommended doses, does not seem to be associated with any adverse effects (Kim et al., 2011). The increase in lean body mass that often accompanies acute creatine supplementation may have a negative effect on buoyancy and drag that would be relevant for most of the aquatic sports (Mujika et al., 1996).

### Caffeine

Caffeine is one of the most extensively investigated of all potential ergogenic aids, reflecting the prevalence of its use in sport and in society in general. An overview of studies on caffeine has recently been published (Burke et al., 2013), and it included an assessment of five separate studies of the effects of caffeine on swimming performance. The overall conclusion was that swimming performance is enhanced by caffeine intake at doses of about 2–6 mg/kg, though the most recent of the studies cited found no effect on performance in a 100-m race.

Caffeine, at least in the doses that appear to be optimal for performance enhancement, does not seem to be associated with adverse health outcomes. In 2004, caffeine was removed from the list of substances whose use was restricted in sport, so there is currently no restriction on its use by athletes. There are some concerns that it may cause difficulties with falling asleep if used in the later part of the day by athletes who must compete on successive days, and this is among the reasons to restrict use to the smallest dose that will produce the desired effect on performance. The diuretic action of caffeine is also often cited, but this effect is small at caffeine doses of less than about 250–300 mg, and habituation develops with regular use (Maughan & Griffin, 2003).

### Bicarbonate and Beta-Alanine

High-intensity exercise that results in fatigue within a few minutes results in a metabolic acidosis that develops in the active muscles and can, if sufficiently severe, limit performance. Buffering the acidity associated with anaerobic glycolysis allows more energy to be produced before the muscle pH falls to a level that inhibits some of the rate-limiting enzymes. Various buffers may be effective, but bicarbonate, which is located primarily in the extracellular space, is one of the most effective. Gao et al. (1988) reported that administration of sodium bicarbonate at a dose of 2.9 mmol/kg 1 hr before exercise was effective in enhancing performance in the fourth and fifth of a series of five 100-yard (91.4-m) swims that were performed with a 2-min recovery after each.

Competition, of course, consists of only a single swim, and there was no effect on the first swim of the series, suggesting perhaps that performance was not limited by the development of acidosis in the active muscles. Subsequent investigations largely, though not always, confirmed these early findings in various repeated swim models (Mero et al.; 2004; Pruscino et al., 2008; Siegler & Gleadall-Siddall, 2010; Zajac et al., 2009), though Zajac et al. (2009) found significant performance improvement only in the first of four 50-m swims. Pierce et al. (1992) looked at the effects of supplementation in simulated swim competitions involving one 91.4-m swim followed by two 182.8-m swims with a 20-min recovery between each and found no effect on performance. An increased speed in the later swims of a set of intervals may be seen as providing a greater stimulus to training adaptation, but blunting of the metabolic acidosis may reduce the adaptation.

Several studies have investigated the effects of chronic bicarbonate administration during periods of intense interval training, though none of these involved swimming training. There is some evidence that bicarbonate supplementation during a period of high-intensity interval cycle ergometer training can enhance the mitochondrial adaptations taking place (Bishop et al., 2010) and can also improve performance (Edge et al., 2006). A more recent study involving well-trained rowers, however, did not find that bicarbonate supplementation during 4 weeks of high-intensity interval training provided any performance advantage over the placebo supplementation condition (Driller et al., 2013).

Few studies seem to have investigated the effects of bicarbonate administration on performance in a single swim test. Joyce et al. (2012) found no improvement in 200-m swim time after bicarbonate treatment. Some of the variation in the reported effects of bicarbonate administration is undoubtedly a result of the nature of the task, but a recent meta-analysis also found that effects are less likely to be observed in well-trained athletes than in recreationally active individuals (Peart et al., 2012).

Tan et al. (2010) investigated the effects of bicarbonate administration in a series of performance tests designed to simulate water polo match play. They concluded that water polo players using bicarbonate supplements “should not expect substantial enhancement in intermittent sprint performance.”

Bicarbonate is primarily an extracellular buffer, acting to increase the efflux of hydrogen ions from the active muscles. Some buffering occurs in the intracellular
space, and the primary intracellular buffer in humans is carnosine, a dipeptide containing histidine and beta-alanine (Derave et al., 2010). Supplementation of the diet with beta-alanine can increase the muscle carnosine concentration (Harris et al., 2006) and has been reported to increase performance in various exercise models in which metabolic acidosis may limit performance (Hill et al., 2007). A recent systematic review and meta-analysis concluded that beta-alanine supplementation was effective in enhancing performance in maximal exercise tasks lasting from 1 to 4 min (Hobson et al., 2012). Two subsequent reanalyses of the same evidence base, however, have questioned this conclusion. Quesnele et al. (2014) highlighted some methodological deficiencies in the Hobson et al. (2012) review but agreed that there appears to be some evidence that beta-alanine supplementation may increase athletic performance; they also urged caution in its use because of insufficient evidence to assess the long-term safety of beta-alanine use.

A further systematic review of the evidence concluded that the available evidence was insufficient to support the use of beta-alanine supplementation for the enhancement of athletic performance (Ko et al., 2014). This agrees with the very limited evidence from studies on the effects of beta-alanine supplementation on swimming performance. Chung et al. (2012) found no clear effect of 10 wk of supplementation on performance in elite and subelite swimmers, though de Salles Painelli et al. (2013) reported significant improvements in 200-m swim performance and a trend toward an improvement in a 100-m swim after 5 wk of supplementation. It is worth noting that, although the improvement in performance was reported not to be statistically significant, all nine swimmers recorded faster times after supplementation, and four of seven in the placebo group swam faster. Many of the studies of beta-alanine supplementation have used models that did not allow a measurement of performance to be made. Although there were some positive results, further evidence is required. The ergogenic mechanism of muscle carnosine loading should be further established and may extend beyond the pH buffering aspect because carnosine was recently shown to improve contractile properties of human muscle fibers (Dutka et al., 2012).

Because bicarbonate and carnosine act on the extracellular and intracellular spaces, respectively, there are grounds for thinking that actions on performance might be independent and therefore additive. De Salles Painelli et al. (2013) looked at the independent and additive effects of bicarbonate and beta-alanine supplementation on 100-m and 200-m swim performance and found that both bicarbonate and beta-alanine supplementation improved 100- and 200-m swimming performance. The coinjection of beta-alanine and bicarbonate induced a further, albeit nonsignificant, improvement in performance.

**Nitrate**

The potential effects of nitrate supplementation on health and performance have attracted much attention in recent years. A relatively small fraction of the energy turnover during exercise is used to do useful work, with the remainder appearing directly as heat. Thus, even a small increase in the efficiency of muscle contraction may be of major significance for exercise performance. Increasing the efficiency of muscle contraction would allow a greater work output for the same oxygen cost.

Athletes may experience a small increase in efficiency—as measured by a reduction in the oxygen cost of a standardized exercise task—in response to prolonged intensive training. Ingestion of large doses of nitrate (NO$_3^-$, about 0.1 mmol of sodium nitrate per kilogram of body mass, or 300–400 mg per day) in the form of either pure sodium nitrate (Larsen et al., 2007, 2010; Vanhatalo et al., 2010) or beetroot juice (Bailey et al., 2009; Bailey, Fulford, et al., 2010) in young healthy individuals rapidly increases plasma nitrite (NO$_2^-$) concentration about two- to threefold, and this elevated nitrite concentration can be maintained for at least 2 weeks (Vanhatalo et al., 2010). Increased plasma nitrite stimulates the production of nitric oxide, an important physiological signaling molecule that is implicated in, among other things, the regulation of muscle blood flow and mitochondrial respiration. Some interesting recent information demonstrated that either acute or short-term ingestion of nitrate allows a given power output to be achieved with a lower rate of oxygen consumption. Thus, Larsen et al. (2007) found a significant reduction in the oxygen cost of submaximal cycling exercise, corresponding to an increase in mechanical efficiency, from a mean of 19.7% (SD = 1.6%) to a mean of 21.1% (SD = 1.3%), owing to oral intake of sodium nitrate. Recent evidence from the same laboratory has identified a mechanism for this effect by showing that nitrate supplementation reduced the expression of adenosine triphosphate–adenosine diphosphate translocase, a protein involved in proton conductance within the mitochondria (Larsen et al., 2011). This resulted in a better oxidative phosphorylation efficiency (mitochondrial phosphate–oxygen ratio) that paralleled the reduction in oxygen cost during exercise.

These effects on the mitochondria have implications for exercise performance, and dietary nitrate supplementation reduces maximal oxygen consumption while maintaining power output in maximal exercise (Larsen et al., 2010). Meanwhile, other investigators reported that the same effects could be achieved with dietary sources of nitrate. Volunteers were fed a placebo or 500 ml of beetroot juice (beetroot, spinach, and a few other vegetables have a high nitrate content) per day for 6 days, the beetroot juice providing 5.5 mmol of nitrate per day (Bailey et al., 2009). This study confirmed the reduction in the oxygen cost of submaximal exercise and also showed that during very intense exercise, the time to exhaustion was extended after ingestion of the beetroot juice (M ± SD = 675 ± 203 s) relative to the placebo trial (M ± SD = 583 ± 145 s).

In a subsequent study, the same authors (Bailey, Fulford, et al., 2010) showed that beetroot juice supplementation for 6 days attenuated the reduction in muscle
potential harmful effects of supplement use

Athletes and coaches often assume—and perhaps reasonably so—that supplements on sale are likely to be beneficial to health and performance and that they are safe for use, but it has increasingly been recognized that the use of dietary supplements is not without some risks to performance and to health (Maughan, 2005). Dietary supplements on sale in most countries, however, are not subject to premarket review for safety or efficacy by government regulatory agencies unless they contain new dietary ingredients. Manufacturers in the United States, for example, are not required to secure Food and Drug Administration approval before producing or selling dietary supplements. Local regulations vary, and some products that are classified as medicines in one country are classified as dietary supplements in another country. Elite athletes are regular international travelers, whether for training camps or for competition, and they are well aware of the opportunities to purchase supplements that are not easily or legally available in their home countries. Internet selling has also eliminated many of the limitations on the supplements that an athlete can obtain and has removed most of the checks on the quality of supplements that are on sale by preventing opportunities for inspection of manufacturing, packaging, and storage premises.

The risks associated with supplement use are not specific to swimmers, and, indeed, many are not specific to athletes generally. The number of case reports of adverse health effects resulting from supplement use in recent years has been increasing, and many of these have affected recreationally active individuals and amateur athletes, with hepatotoxicity being the most common problem (Food and Drug Administration, 2012; Krishnan et al., 2009; Stickel et al., 2009; Timcheh-Hariri et al., 2012).

It was recently reported that dietary supplements now account for nearly 20% of drug-related liver injuries presenting at hospitals, compared with 7% a decade ago (O’Connor, 2013). Methylhexanamine has been linked to a number of adverse events, including the deaths of two soldiers who had fatal heart attacks during a military training exercise in 2010 (“DMAA Products Pulled From Base Shelves,” 2011). A female marathon runner who collapsed and died near the finish of the 2012 London Marathon had been consuming a commercially available product during the race, and the coroner’s investigation concluded that it had likely contributed to her death (BBC News, 2013).

The risk of a failed antidoping test resulting from the use of dietary supplements has been recognized for more than a decade and is a particular concern for athletes who are liable to be tested for the use of prohibited substances. The presence in dietary supplements of agents that can cause an athlete to fail a test has been well established (Maughan, 2005), but limited data are available on the prevalence of contamination because routine analysis for prohibited substances has not been carried out. The available evidence, however, is sufficient to indicate that the risk of the presence of a prohibited substance is very real and also suggests that, notwithstanding the protestations of some parts of the dietary supplements industry, the risk has not been dramatically reduced since it was first recognized (Table 2). Recent reports have also indicated that the presence of even extremely small amounts of some agents will result in a positive test. Analysis of urinary responses to the ingestion of small amounts of a nandrolone precursor (19-norandrostenedione; Watson et al., 2009, 2010) has revealed a high risk of a positive test: Ingestion of a 1.0 μg dose of 19-norandrostenedione in 500 ml of water produced no values that were above the current World Anti-Doping Agency threshold for a positive doping test (2 ng/mL), but five subjects (of 20) tested positive...
when 2.5 µg was ingested, and 15 subjects had urinary 19-norandrostenedione concentrations exceeding the threshold when 5.0 µg of the steroid was ingested. These are extremely low levels of contamination.

Swimming has provided one of the few examples in which an athlete who has failed an antidoping test has successfully pursued a compensation claim against the company that supplied the product responsible for the failed test. Kicker Vencill, a U.S. swimmer who had hoped to compete in the 2004 Olympic Games, tested positive for nandrolone in January 2003; analysis of a multivitamin tablet that he had taken revealed the presence in the supplement of a metabolic precursor of nandrolone. The U.S. Anti-Doping Agency imposed a 4-year suspension, but the Court of Arbitration for Sport reduced the suspension to 2 years. A U.S. court awarded damages of $578,635 against the manufacturer. The suspension from competition, however, was not affected by this decision, and Vencill’s career was effectively ended.

Several programs are now in place that allow athletes who use supplements to make choices that will reduce the risk of a positive doping outcome as a result of using contaminated supplements. These programs cannot eliminate the risk entirely, but the sensible athlete will choose only supplements that have been screened for the presence of doping agents. The focus of these programs is on the testing of samples provided by manufacturers or distributors for the presence of World Anti-Doping Agency–prohibited substances. These sports-related programs are not complete quality assurance programs in that the presence of active ingredients is not usually verified. Athletes and those who are responsible for their care often see these programs as a guarantee of the integrity of products that have been tested, but it is important to recognize that a limited panel of substances is tested for and that the tests have limited sensitivity. In the Informed-Sport program in the United Kingdom, for example, the level of detection is set at 10 ng/g for steroids and 100 ng/g for stimulants (Informed Sport, 2013a), but some other schemes operate at different levels. For supplements that are consumed in large amounts, such as protein powders or drinks, a much more sensitive test is required than for supplements taken as small pills or capsules. Few screening programs test for contaminants other than stimulants and steroids, so the potential for problems remains.

**Conclusion**

A few supplements may benefit some athletes in training or competition, but all athletes should be aware that there are real risks as well as potential benefits associated with supplement use. Any athlete contemplating supplement use should seek the advice of a qualified professional who understands the issues at stake.

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**References**


**Table 2 Surveys on the Undeclared Presence of Steroids and Stimulants in Dietary Supplements**

<table>
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<th>Year</th>
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<td>54</td>
<td>12</td>
<td>22</td>
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<td>16</td>
<td>15</td>
<td>Parr et al. (2003)</td>
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<tr>
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<td>16</td>
<td>11</td>
<td>Informed Sport (2008)</td>
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<tr>
<td>2013</td>
<td>114</td>
<td>11</td>
<td>10</td>
<td>Informed Sport (2013a)</td>
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