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Nutritional strategies to optimize training and racing in middle-distance athletes

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Abstract

Middle-distance athletes implement a dynamic continuum in training volume, duration, and intensity that utilizes all energy-producing pathways and muscle fibre types. At the centre of this periodized training regimen should be a periodized nutritional approach that takes into account acute and seasonal nutritional needs induced by specific training and competition loads. The majority of a middle-distance athlete's training and racing is dependant upon carbohydrate-derived energy provision. Thus, to support this training and racing intensity, a high carbohydrate intake should be targeted. The required energy expenditure throughout each training phase varies significantly, and thus the total energy intake should also vary accordingly to better maintain an ideal body composition. Optimizing acute recovery is highly dependant upon the immediate consumption of carbohydrate to maximize glycogen resynthesis rates. To optimize longer-term recovery, protein in conjunction with carbohydrate should be consumed. Supplementation of β-alanine or sodium bicarbonate has been shown to augment intra- and extracellular buffering capacities, which may lead to a small performance increase. Future studies should aim to alter specific exercise (resistance vs. endurance) and/or nutrition stimuli and measure downstream effects at multiple levels that include gene and molecular signalling pathways, leading to muscle protein synthesis, that result in optimized phenotypic adaptation and performance.

Keywords: *Periodized nutrition, middle distance, recovery, adaptation, supplements, performance*

Introduction

The middle-distance runner is the most diverse athlete in the athletics arena when it comes to the utilization of a myriad of energy systems to supply adenosine triphosphate (ATP) to meet energy demands. Highly trained athletes can achieve 20 times resting oxygen uptake ($\dot{V}O_2$) values (Daniels & Daniels, 1992), and in a 1500-m race athletes work at $\sim$115% of maximal oxygen uptake ($\dot{V}O_{2max}$) for approximately 4 min, with post-race blood lactate concentrations exceeding 20 mmol · l^{-1} (Osnes & Hermansen, 1972). However, $\sim$60 and $\sim$75% of energy production is still derived from aerobic sources in 800-m and 1500-m events, respectively (Spencer & Gastin, 2001).

Thus, middle-distance athletes must develop all energy pathways and muscle fibre types through a dynamic continuum in training volume, duration, and intensity. The remarkable diversity of training stimuli is evident when examining athletes' schedules (Martin & Coe, 1991). During the aerobic development phase a middle-distance athlete's volume will rival that of a marathon runner, but during the competition phase, it will nearly mimic a sprinter's intensity. Moreover, most athletes undergo resistance and plyometric exercises to develop neuromuscular and nervous system adaptations. This understanding of the different energy systems, and required fuels to produce ATP, must be taken into consideration when recommending both acute and seasonal nutritional intakes to optimize training adaptations and race performance.

Therefore, the aim of the current review is to outline nutrition recommendations during training and racing specific to middle-distance athletes, with an emphasis on the 800-m and 1500-m events. This paper will focus on modern science in conjunction with practical training and racing constraints to develop usable guidelines. Finally, some of the limitations that athletes face, such as global championship racing schedules, as well as some emerging data on supplements and training adaptations, are also explored.

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Periodized nutrition for yearly periodized training

Periodization involves the progressive cycling of various aspects of a training programme during a specific period of time into discrete phases, to optimize the yearly training structure towards a peak championship performance (Martin & Coe, 1991). In short, the training stimuli during these different phases can differ drastically in terms of intensity, volume, and duration, and thus so do the types of fuels that are used to generate ATP (Tables I and II). A brief overview of energy systems, fuel utilization, and associated muscle fibre types used during exercise will set the structure for the subsequent nutritional recommendations.

Energy metabolism

During the transition from rest to maximal exercise intensity, the demand for ATP can increase more than 100-fold in elite athletes, and carbohydrate provides the majority of the fuel for exercise intensities exceeding 75% $\dot{V}O_{2max}$. Carbohydrate can act as a fuel for ATP provision for both substrate phosphorylation and oxidative phosphorylation (also collectively referred to as ''anaerobic'' glycolysis and ''aerobic'' metabolism, respectively), while fat is exclusively metabolized via oxidative phosphorylation (Table II). Oxidative phosphorylation provides the bulk of ATP provision during training of low to moderate intensity, primarily utilizing fat as a fuel. Fat can be provided in both endogenous muscle stores (intramuscular triacylglyceride) and as fat stored in peripheral adipocytes and released as plasma free fatty acids. During low-intensity exercise, primarily Type I slow twitch oxidative fibres are recruited, which have a high oxidative capacity to utilize primarily fat. However, during exercise that involves increasing intensity, when ATP production from oxidative phosphorylation cannot match the rate of ATP hydrolysis, the shortfall in oxidative energy supply is met by substrate phosphorylation. Substrate phosphorylation provides energy via phosphocreatine utilization, and the metabolism of muscle glycogen, via the glycolytic pathway with lactate formation (Saltin, 1990). During high anaerobic energy production, there is an increased firing of Type IIa fibres. These fibres have both a high oxidative capacity as well as a large capacity for glycolysis, leading to an increased reliance on carbohydrate as a fuel. Since these fibres can provide energy via both aerobic and anaerobic means, it is not surprising that elite middle-distance runners have highly developed Type IIa muscle fibre morphology (Saltin, Henriksson, Nygaard, Andersen, & Jansson, 1977). Finally, at very high workloads, Type IIb glycolytic muscle fibres become activated to maintain the high demand of ATP provision via anaerobic glycogenolysis (Table II). This leads to the extreme levels of lactate production associated with all middle-distance races and many training situations. Therefore, middle-distance athletes have several highly developed energy-producing pathways that utilize different blends of phosphocreatine, carbohydrate, and/or fat, coupled with greater muscle buffering capacity, to handle a range of different metabolic demands during varying training intensities and racing.

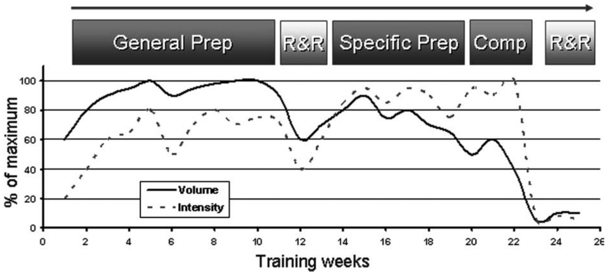
General macronutrient recommendations

Carbohydrate. When exercising above 75% $\dot{V}O_{2max}$, the amount of carbohydrate used during exercise rises abruptly (Romijn *et al.*, 1993). During resistance exercise, the body also relies heavily on anaerobic ATP production, with declines reported in muscle glycogen of 25 – 40% after a multiple-set resistance exercise bout (Koopman *et al.*, 2005). Since much middle-distance training is performed at or above 75% $\dot{V}O_{2max}$, and this dependency on carbohydrate-based ATP provision increases throughout the training year towards a championship peak, carbohydrate-rich foods must provide the majority of the energy provision. Bergstrom and colleagues (Bergstrom, Hermansen, Hultman, & Saltin, 1967) were the first to show that a high carbohydrate diet results in augmented glycogen stores, translating into an increased time to exhaustion, compared with a low carbohydrate diet. Conversely, low carbohydrate diets (3 – 15% carbohydrate) have uniformly been shown to impair performance in high-intensity and endurance-based exercise (Coggan & Coyle, 1991). Consequently, recommendations have been made to endurance athletes to eat a diet chronically high in carbohydrate, which will enable longer and harder training sessions to optimize the training adaptation. However, mixed results have been published about whether a high carbohydrate diet (60 – 70% of total energy) provides increased performance benefits over a moderate carbohydrate diet (50 – 55% of total energy) (Burke, Kiens, & Ivy, 2004), and new evidence suggests the possibility of conducting *some* training in a glycogen-depleted state for improved adaptation and performance (see ''Future Directions'').

In dietary recall records, male endurance athletes report consuming between 8.4 and 9.1 grams of carbohydrate per kilogram of body weight per day ($\text{g CHO} \cdot \text{kg BW}^{-1} \cdot \text{day}^{-1}$), which is within the recommended range (Burke, Cox, Cummings, & Desbrow, 2001). The diet of world-class African runners is also predominantly carbohydrate (Onywera, Kiplamai, Boit, & Pitsiladis, 2004). In contrast, female endurance athletes report much

Table I. Daily macronutrient intake recommendations during different yearly training phases.

Training phase



	General prep.		Specific prep.		Competition		Transition/R&R	
	Light	Heavy	Light	Heavy	Light	Heavy	Light	Heavy
Estimate weekly training volume								
km · week^{-1}	< 100 km	> 150 km	< 80 km	> 130 km	< 70 km	> 90 km	< 15 km	> 50 km
h · week^{-1}	5–8 h	10 h+	4–7 h	6–9 h	3–5 h	4–7 h	< 2 h	2–4 h
Training intensity	Low		Moderate to high		Tapered training volume and intense racing		Very low to complete rest	
Recommended daily macronutrient intake (g · kg^{-1} · day^{-1})								
CHO	7	10	7	10	7	10	4	6
FAT	1.5	2	1	1.5	0.8	1.2	1	1.5
PRO	1.5	1.7	1.5	1.7	1.2	1.5	0.8	1.2
Percent of total daily energy intake								
%CHO	~ 60%		~ 66%		~ 70%		~ 57%	
%FAT	~ 28%		~ 22%		~ 18%		~ 32%	
%PRO	~ 12%		~ 12%		~ 12%		~ 11%	
Total daily energy intake								
kJ	~ 13900	~ 18900	~ 12600	~ 17600	~ 11700	~ 16600	~ 8200	~ 12400
kcal	~ 3300	~ 4500	~ 3000	~ 4200	~ 2800	~ 4000	~ 2000	~ 2900

Note: Nutrition recommendations for a 70-kg athlete (adapted from Burke *et al.*, 2001, 2004; Tarnopolsky, 1999; Tipton & Wolfe, 2004). Prep, preparation; CHO, carbohydrate; FAT, fat; PRO, protein; kJ, kilojoules; kcal, nutritional calorie. R&R, rest & recovery/transition phase.

lower relative daily carbohydrate intakes (5.5 g CHO · kg BW^{-1} · day^{-1}), and also lower values for mean energy intake per kilogram of body weight, than male athletes [170 kJ · kg BW^{-1} · day^{-1} for females; 230 kJ · kg BW^{-1} · day^{-1} for males (Burke *et al.*, 2001)]. Hence, a greater emphasis needs to be placed on helping females meet their recommended carbohydrate and energy intake needs. It is also vital during situations of high carbohydrate intakes that athletes do not neglect the other important macro- and micronutrients. Therefore, to maintain immune function (Gleeson, 2002), recover glycogen storage (Costill, Bowers, Branam, & Sparks, 1971), and reduce over-reaching (Achten *et al.*, 2004), a habitually high carbohydrate diet (7–10 g CHO · kg BW^{-1} · day^{-1}) is recommended.

Fat. Fat provides fuel at a low to moderate exercise intensities. Fat also provides about 4-fold more ATP per molecule (~ 145 vs. 38 ATP) than carbohydrate, but the ATP provision per litre of oxygen is about 10% less when fat is the fuel than when carbohydrate is oxidized. When oxygen supply is limiting, this difference is critical. However, due to its energy density, over-consumption of dietary fat can lead to unwanted increases in body weight. The majority of fat is stored in adipose tissue, but skeletal muscle also stores a significant amount of fat in the form of intramuscular triacylglyceride (IMTG). There continues to be considerable interest in the function of IMTG as a fuel source during exercise (Watt, Heigenhauser, & Spriet, 2002), and whether a lack of post-exercise lipid intake can influence IMTG content enough to limit endurance performance or decrease the training load (Decombaz, 2003). Interestingly, Koopman *et al.* (2005) recently reported a 27% decline in IMTG after a 45-min resistance exercise protocol, which suggests that IMTG can also contribute significant energy during intense exercise. It was recently reported that a "fat-adaptation/carbohydrate-restriction" protocol, in which individuals consumed elevated amounts of

Table II. Acute post-exercise dietary recommendations with respect to the adaptations incurred by periodized training.

Training objective, development, and adaptation	Examples of training sessions	Vol./Time	Inten.	Energy system	Fibre type	Fuels utilized	Acute dietary recommendations
Aerobic capacity – oxidative Enzymes/fat metabolism/ endurance	easy/recov. run of 30 – 75 min long runs 1 – 3 h	High	Low	Oxid. phos.	ST Oxid.	Mainly FATS	*During aerobic training:* CHO: ~ 1 – 1.4 $g \cdot kg^{-1} \cdot h^{-1}$
Aerobic power – oxidative & glycolytic enzymes/anaerobic threshold/lactate tolerance	8 × 3 min reps on 3-min recov. 1 – 2 min reps on 2 – 4 min recov. hill runs of 45 – 60 s	↑	↑	↑	↑	↑ FATS/CHO ↕	*Short-term* (<4 *h*) *recov:* CHO: 1.2 – 1.5 $g \cdot kg^{-1} \cdot h^{-1}$
Anaerobic capacity – glycolytic enzymes/CHO metabolism/lactate tolerance/ muscular strength	8 – 10 × 1 min on 1 min recov. 45 – 90 s reps on 3 – 6 min recov.					CHO ↕	*Longer term* (>20 *h*) *recov:* CHO: ~ 1 $g \cdot kg^{-1} \cdot h^{-1}$ EAA: ~ 0.1 $g \cdot kg^{-1} \cdot h^{-1}$ over first 2 h post-exercise
CP capacity & power – near maximal repeatable muscular contraction strength	15 – 30 s reps with ~ 3 – 4 min rests	Mod.	Mod.	Subs. phos.	FTa Oxid./ Glycolytic	CHO & ATP/PCr	
Muscular endurance – sub-maximal repeated muscular strength	Circuit-based training e.g. 3 – 4 sets of 15 – 20 reps lower weight	↓	↓	↓	↓	↓	
Muscular strength – maximal contraction ability & muscular hypertrophy	Weight training 2 or 3 sets of 1 – 5 reps near maximal weight						*During resistance exercise and 2 s post-exercise:* CHO: ~ 0.5 $g \cdot kg^{-1} \cdot h^{-1}$
Neural firing – Technique, economy & effectiveness of effort	Plyometric training, sprints, speed & hurdle drills	Low	High	CP energy	FTb Glycolytic	ATP/PCr	EAA: ~ 0.1 $g \cdot kg^{-1} \cdot h^{-1}$

Note: Nutrition recommendations adapted from Burke *et al.* (2004), Tarnopolsky (1999), and Tipton and Wolfe (2004). ATP, adenosine triphosphate; CHO, carbohydrate; CP, creatine phosphate; EAA, essential amino acids; FTa, fast-twitch oxidative Type II muscle fibre; FTb, fast-twitch glycolytic Type II muscle fibre; Int., intensity; Mod., moderate; Oxid. phos., oxidative phosphorylation; recov., recovery; reps, repetitions; ST, slow-twitch oxidative Type I muscle fibre; Subst. Phos., substrate phosphorylation; Vol., volume.

fat (>4 g fat · kg BW^{-1} · day^{-1}) while training for 5 days, followed by a carbohydrate loading day, resulted in a decreased use of carbohydrate by measured decreases in glycogenolysis and pyruvate dehydrogenase activation (Stellingwerff *et al.*, 2006). This "glycogen use impairment" would most likely decrease performance for a middle-distance athlete by inhibiting glycogen breakdown and aerobic carbohydrate oxidation via pyruvate dehydrogenase. Therefore, it is currently not recommended for middle-distance athletes to undertake any type of dietary fat adaptation in search of increased performance enhancement. However, fat is an important component of a healthy balanced diet.

Protein. Protein serves several key functions, which include roles as enzymes, the processes of cell signalling, and as fibrous structural proteins that comprise cell cytoskeletons and muscle fibres. During endurance exercise, protein oxidation accounts for only 2–5% of total energy expenditure. However, this proportion of amino acid oxidation can increase when training at higher intensities, during longer exercise durations, or when carbohydrate stores are depleted (for reviews, see Tarnopolsky, 1999; Tipton & Wolfe, 2004). Since protein (PRO) intake in excess of 1.7 g PRO · kg BW^{-1} · day^{-1} has been shown to be oxidized, Tarnopolsky (1999) has estimated that highly trained endurance athletes who undertake a large and intense training load should ideally aim for between 1.5 and 1.7 g PRO · kg BW^{-1} · day^{-1}. Some athletes (primarily females) are over-mindful of the benefit that low body weight brings to performance, and many believe that post-exercise protein consumption may bring unwanted gains in muscle mass, ultimately leading to weight gain. However, recent evidence has suggested that the specific exercise stimulus (resistance vs. endurance), rather than the nutrition intervention, plays a more dominant role in the divergent signalling pathways and the types of proteins that are synthesized after exercise, which explains the adaptive response and divergent phenotypes (Atherton *et al.*, 2005). Aerobic exercise also reduces the stimulus for hypertrophy (Hickson, 1980) and increases mitochondrial, instead of myofibrillar, proteins (Holloszy & Coyle, 1984). Therefore, it could be hypothesized that protein intake after endurance exercise is necessary not only for the recovery and repair of damaged myofibrillar proteins, but also for the optimized synthesis of mitochondrial and possibly sarcoplasmic proteins.

Despite some reservations regarding protein intake by endurance athletes, the scientific discussion regarding the optimum daily protein intake for athletes appears irrelevant. Dietary studies in endurance athletes from Western countries have consistently shown that athletes generally consume more protein than any elevated dietary recommendation (Tarnopolsky, 1999). In summary, it appears that elite endurance athletes in a hard training phase should ideally consume between 1.5 and 1.7 g PRO · kg BW^{-1} · day^{-1} (Table I). For a 70-kg athlete consuming 3500 kcal · day^{-1}, this would require only about 12% energy intake from protein, which can easily be met in a balanced diet without the need for protein supplementation.

Ultimately, all of the above general macronutrient recommendations need to be appropriately implemented within the individual athlete's training plans and competition goals. Therefore, periodized nutrition recommendations will be made across the four primary mesocycles of (1) general preparation, (2) specific preparation, (3) competition, and (4) transition (Table I). The recommended macronutrient intakes in each training phase are broad enough to cover a wide range of training programmes and caloric needs, but individual fine-tuning may be needed to meet the specific nutrition goals of each phase.

General preparation phase: Aerobic and strength development

Training. Aerobic training during this phase comprises large training volumes at lower intensities ($\sim$50–75% $\dot{V}O_{2max}$), in which fat can be the dominant fuel, but large amounts of carbohydrate are oxidized at exercise intensities approaching the onset of blood lactate accumulation. Aerobic conditioning improves oxidative capacities in heart and in Type I skeletal muscle fibres, through the proliferation of mitochondrial and capillary density (Holloszy & Coyle, 1984). Contemporary training regimens during this phase also place great emphasis on strength-based training, such as resistance exercises, circuit training, and short-hill repeats. Furthermore, due to the large energy expenditures during this training phase, athletes can gradually improve body composition goals (percent body fat, weight) towards the competition phase.

Nutrition. The general preparation phase is dominated by elevated energy expenditure to support the large training load. Thus, carbohydrate intake should be high, ranging from 7 to 10 g CHO · kg BW^{-1} · day^{-1}. Due to the large contribution of fat stores to aerobic ATP production, recommended fat intake is highest during this phase (1.5–2.0 g fat · kg BW^{-1} · day^{-1}), translating into $\sim$30% of total energy. With high training volumes, coupled with resistance exercise, recommendations for protein during this phase are 1.5–1.7 g PRO · kg BW^{-1} · day^{-1} (Table I).

Specific preparation phase: Anaerobic, power, and speed development

Training. In the specific preparation phase there is an increased emphasis on anaerobic capacity and aerobic power, while still maintaining the developed aerobic capacity from the previous mesocycle. Furthermore, there is continued development of anaerobic tolerance ($\sim$75–90% $\dot{V}O_{2max}$), with some sessions targeted at $\dot{V}O_{2max}$. The primary adaptations include maximizing the heart and cardiovascular system ($\dot{V}O_{2max}$ sessions), activating more Type II fibres, increasing glycolytic enzyme density, and progressively adapting skeletal muscles to higher levels of muscle acidosis. Any final body composition goals should be met during this period, prior to the start of the competition phase. Over-restriction of energy and/or carbohydrate intake can hinder performance and impair immune function (Gleeson, 2002). Thus, the athlete should not attempt either rapid or considerable weight loss regimes before, or during, the competition phase.

Nutrition. The primary fuel for the type of intense training dominated by the specific preparation phase is carbohydrate, and thus intake remains at 7–10 g $CHO \cdot kg\ BW^{-1} \cdot day^{-1}$. Due to the decreased total energy expenditure, the relative intake of dietary fat can be reduced to about 20–25% of total energy, or 1–1.5 g $fat \cdot kg\ BW^{-1} \cdot day^{-1}$. Protein recommendations should be maintained at 1.5–1.7 g $PRO \cdot kg\ BW^{-1} \cdot day^{-1}$ (Table I).

Competition phase: Taper and peaking

Training. The competition phase is characterized by short, intensive exercise and tapering of training volume towards a championship peak. This results in a decrease in total energy expenditure, but most workouts and races are conducted at very high intensities, ($<$130% $\dot{V}O_{2max}$) and at nearly maximum speed to fully develop lactate tolerance. The enhancement of neural firing capacity needs to be developed through the full activation of all fibre types. The primary goal is to have the athlete reach a physiological and psychological peak, in which the year's best performances are achieved.

Nutrition. The ever increasing intensity of training and racing demands a consciously high carbohydrate intake of 7–10 g $CHO \cdot kg\ BW^{-1} \cdot day^{-1}$. Fat intake is reduced further during the competition phase to $\sim$1 g $fat \cdot kg\ BW^{-1} \cdot day^{-1}$, while protein intake should be at a level to maintain lean muscle mass (1.2–1.5 g $PRO \cdot kg\ BW^{-1} \cdot day^{-1}$) (Table I). Finally, it has been shown that *ad libitum* energy intake is not immediately matched by reduced energy expenditure, as found during the competition phase (Stubbs *et al.*, 2004). Therefore, athletes need to make conscious decisions about limiting their total energy intake during this phase to maintain an ideal peak body composition.

Transition phase/rest days: Physical recovery

Training. The primary goal of the transition phase or rest day is to recover from the previous meso- or microcycle, allowing for training adaptations to occur while preventing over-reaching symptoms. Thus, training volume and intensity are generally very low. Although small shifts in body weight and percent body fat will occur during the transition phase, the athlete should attempt to maintain a relative weight balance throughout the year. Weight gains should be limited to less than 5% of total body weight. Accordingly, the training load and required energy expenditure throughout each training phase vary significantly, and thus the total energy intake should also vary accordingly (Table I).

Nutrition. Due to the diminished training volume and intensity, nutritional energy intake during this phase/day must be reduced, and thus the macronutrient recommendations are much the same as for the general public (Table I).

Acute and specialized nutrition recommendations

Nutrition strategies during training

A large body of evidence has shown the beneficial performance effects of carbohydrate and fluid intake during prolonged endurance exercise (for a review, see Coyle, 2004). Since middle-distance events are only a few minutes in duration, it is vital that athletes commence their races euhydrated and with full muscle glycogen stores. However, given that some endurance training sessions approach 2 h in total length, there is ample opportunity to benefit from carbohydrate and fluid intake during training, and current recommendations are set to about 30–60 g $CHO \cdot h^{-1}$ for athletes during exercise (American College of Sports Medicine, 2000; Table II). More information on carbohydrate and fluid intake recommendations during exercise are covered by Burke and colleagues (Burke, Millet, & Tarnopolsky, 2007) and Shirreffs and colleagues (Shirreffs, Casa, & Carter, 2007), respectively. Tipton and co-workers (Tipton, Jeukendrup, & Hespel, 2007) highlight the potential benefits of consuming protein and amino acids before and during resistance training to enhance net protein balance.

Nutrition for optimized recovery

After a hard training session or competition, the overriding priority for every athlete should be recovery. The primary roles of post-exercise nutrition are to (1) immediately maximize glycogen resynthesis rates in the short term (<4 h), and (2) replenish endogenous fuel stores, repair muscle damage, and increase protein synthesis over the longer term (24 h+).

Short-term recovery (<4 h). Enhancing immediate recovery is especially important when an athlete is faced with a short recovery period, such as between rounds of races at a major championship event, or between hard training sessions on the same day. The highest rates of muscle glycogen synthesis occur during the hour immediately after exercise (Ivy, Katz, Cutler, Sherman, & Coyle, 1988), due to glycogen phosphorylase activation from the preceding glycogen-depleting exercise (Wojtaszewski, Nielsen, Kiens, & Richter, 2001) and greater post-exercise insulin sensitivity (Richter, Mikines, Galbo, & Kiens, 1989). Ivy *et al.* (1988) also showed that delaying the ingestion of a carbohydrate supplement post-exercise (>2 h) will result in a reduced rate of muscle glycogen storage. The type of carbohydrate consumed during recovery may also influence glycogen synthesis rates. Burke and colleagues (Burke, Collier, & Hargreaves, 1993) showed that 24-h glycogen recovery was enhanced when participants consumed high glycaemic index (GI) carbohydrates, compared with low GI carbohydrates. To maximize post-exercise glycogen resynthesis rates, contemporary studies suggest using frequent smaller doses (20 – 30 g carbohydrate every 20 – 30 min) for an overall intake rate of 1.2 – 1.5 g $\text{CHO} \cdot \text{kg BW}^{-1} \cdot \text{h}^{-1}$ for the first several hours of recovery (van Hall, Shirreffs, & Calbet, 2000; van Loon, Saris, Kruijshoop, & Wagenmakers, 2000b) (Table II).

It is well known that certain amino acids are insulinotropic [e.g. leucine, phenylalanine (van Loon, Kruijshoop, Verhagen, Saris, & Wagenmakers, 2000b)], so this theoretically could result in enhanced glycogen recovery through the addition of protein to a carbohydrate-based recovery drink to increase the response of insulin-mediated glycogen synthesis. Several studies have shown augmented glycogen storage when protein is added to carbohydrate ingested after exercise (Berardi, Price, Noreen, & Lemon, 2006; Ivy *et al.*, 2002; Zawadzki, Yaspelkis, & Ivy, 1992), but the majority of studies have found no further effect of the co-ingestion of carbohydrate and protein mixtures on post-exercise glycogen recovery (Carrithers *et al.*, 2000; Tarnopolsky *et al.*, 1997; van Hall *et al.*, 2000; van Loon *et al.*, 2000b). These conflicting results can be explained by differences in experimental designs, the amounts of carbohydrate and protein used, and the dosing patterns, but most likely the fact that several of the earlier studies featured nutritional interventions of varying energy content between treatment groups. Taken together, it would appear that when carbohydrate intake is sufficient for maximal glycogen resynthesis rates (1.2 – 1.5 g $\text{CHO} \cdot \text{kg BW}^{-1} \cdot \text{h}^{-1}$; Table II), the addition of protein will not further increase glycogen storage.

Long-term recovery (>24 h). During longer-term recovery, protein intake in conjunction with carbohydrate is vital to maximize muscle glycogen resynthesis, protein synthesis rates, and the repair of damaged muscle tissues, which is primarily accomplished through the intake of regular meals (for reviews, see Tarnopolsky, 1999; Tipton & Wolfe, 2004). Delaying the timing of post-exercise protein intake (>3 h) can also result in a negative net protein balance (Levenhagen *et al.*, 2001). Several recent studies have suggested a positive effect of attenuating muscle damage and perceived muscle soreness after running when protein was added to a carbohydrate-based recovery drink (Luden, Saunders, & Todd, 2007; Millard-Stafford *et al.*, 2005). The explanation for the decreased muscle soreness found in the latter study is confounded by the addition of antioxidants in conjunction with carbohydrate and protein in the recovery drink. Despite the protein + carbohydrate drink decreasing muscle soreness after two runs to fatigue separated by 2 h, performance during a 5-km time-trial conducted 24 h later was unaffected (Millard-Stafford *et al.*, 2005).

In summary, current literature suggests that, during longer-term recovery, to initiate acute post-exercise protein synthesis, athletes should consume ~ 0.1 $\text{g} \cdot \text{kg BW}^{-1}$ of essential amino acids (Tipton & Wolfe, 2004), together with 1 – 4 g $\text{CHO} \cdot \text{kg BW}^{-1}$ within 4 h after exercise (Table II). Decombaz (2003) has suggested that carbohydrate intake should be the immediate priority during the initial 6 – 8 h after hard training, with increasing amounts of dietary fat taken through subsequent regular meals. However, it remains to be clarified what is the best macronutrient blend, feeding pattern, type of carbohydrate and/or protein, and the intake timing to optimize recovery and adaptation after different types of exercise stimuli.

For athletes at major championships that feature multiple races, recovery after each race can be the key to success in the final. Thus, it is imperative that the athlete have a sound and well-practised nutrition regimen, as outlined below:

- Before a championship, evaluate several individualized pre-competition meal options during

training that are convenient, readily available, and feel "right" for the athlete (no gastrointestinal discomfort). These meals should be high in carbohydrate ($1-4$ g · kg BW^{-1}) and consumed $1-6$ h before competition.
- Athletes should aim for between 400 and 600 ml of either a sport drink and/or water with electrolytes in the $60-120$ min before competition, unless the weather is cold and/or they are sure that they are well hydrated.
- A common mistake during the high stress of major championships is when athletes become *too* aware and compulsive about eating and drinking, or are influenced by what other athletes might be consuming. Athletes then tend to consume too much, too little, or drastically change their normal habits to mimic others. The key is to focus on what works for the individual, and consume the same amount and types of fluids/foods as during previous competitions. Implement a specific nutrition plan for athletes susceptible to compulsive eating.
- Many athletes also consume a small snack (e.g. sports bar, fruit) and sports drinks $1-3$ h before warming up for an event.
- It is vital that the athlete and coach plan ahead and always have the proper amount of post-race foods and fluids available *immediately* to optimize post-race glycogen and muscle recovery. Carbohydrate-rich foods and fluids with a medium to high glycaemic index at an intake rate of about $1-1.5$ g CHO · kg BW^{-1} · h^{-1} for the first 4 h should be the target.
- Due to usual competition constraints, it is normally very difficult to get a meal immediately after the race. Sports nutrition products can meet many of these initial carbohydrate and protein needs, and are convenient and familiar, until a normal meal can be consumed.

Supplements and the middle-distance runner

Fatigue during any maximal-intensity exercise lasting from ~2 to 10 min is a consequence of the limitations imposed by anaerobic glycolysis. Although anaerobic glycolysis can regenerate ATP at a very high rate, the resultant metabolic acidosis from the production of lactate (La$^-$) and hydrogen ions (H$^+$) can alter acid–base homeostasis. This augmented H$^+$ production causes a drop in intramuscular pH, which has been shown to inhibit glycolytic enzymes, interfere with calcium handling, and inhibit actin–myosin interactions (Maughan & Greenhaff, 1991). Thus, any process that can directly buffer intramuscular H$^+$, or increase the rate of H$^+$ efflux from the muscle, will theoretically lead to a performance increase. It has long been known that metabolic alkalosis can be induced through the consumption of sodium bicarbonate ($NaHCO_3$) or sodium citrate (Dill, Edwards, & Talbot, 1932), and a plethora of studies with mixed findings have followed (for a review, see McNaughton, 2000). Researchers have examined both the acute and chronic dosing effects of $NaHCO_3$ on high-intensity exercise performance. More recently, the effects of β-alanine on intramuscular H$^+$ buffering have been examined. All of these substances are not on the World Anti Doping Agency's (WADA) prohibited substances list. [For further information on other ergogenic substances, see Maughan, Depiesse, and Geyer, 2007).]

Acute bicarbonate loading

A meta-analysis of 29 studies on the performance effects of sodium bicarbonate, featuring predominately untrained individuals, found that bicarbonate supplementation resulted in a performance effect that was 0.44 standard deviations better than in the control trial (Matson & Tran, 1993). An improvement of 0.44 of the standard deviation would bring the 2006 average men's 800-m Golden League time of 1:46.36 down to 1:45.52, which is a worthwhile improvement.

In summary, most data suggest that the ingestion of 0.3 g · kg BW^{-1} of either sodium bicarbonate or citrate administered in solution approximately $1-2$ h before exercise offers a small, but significant, effect on middle-distance race performance (McNaughton, 2000). Given that some individuals exhibit urgent gastrointestinal distress with $NaHCO_3$, such as vomiting and diarrhoea, a pragmatic and individualized approach needs to be taken. It is important for athletes to experiment with bicarbonate in training that features daily consecutive races, since much of the gastrointestinal distress seems to occur after a race (semi-finals), which could limit performance in any subsequent race (finals).

Multi-day bicarbonate ingestion

Several recent studies have shown more favourable gastrointestinal tolerance effects after chronic multi-day $NaHCO_3$ supplementation (Douroudos *et al.*, 2006; McNaughton & Thompson, 2001), as compared to acute pre-exercise single-dose administration. These chronic $NaHCO_3$ supplementation studies found the effective daily dose to be 0.5 g · kg BW^{-1} taken over 5 days (sometimes split up into four daily doses). A recent study showed a 12% improvement in the average power output during Wingate testing (Douroudos *et al.*, 2006). Further evidence suggests that performance in high-intensity exercise may be enhanced for a full 2 days after cessation of chronic $NaHCO_3$ supplementation (McNaughton & Thompson, 2001), which might alleviate many of the severe gastrointestinal side-effects found with acute bicarbonate loading. Notwithstanding these results, more research is needed to show performance efficacy for chronic $NaHCO_3$ ingestion protocols in elite athletes, and to better elucidate the dosing and time-course effects between the cessation of dosing and exercise performance testing.

β-alanine/carnosine supplementation

It has been known for over 50 years that muscle carnosine (β-alanyl-L-histidine) can act as an intracellular buffering agent (for a review, see Begum, Cunliffe, & Leveritt, 2005). Recent evidence suggests that β-alanine supplementation may lead to an increase in muscle carnosine content, leading to an increase in performance during exercise where muscle acidosis may be a limiting factor. It appears that muscle carnosine synthesis may be limited by the intracellular availability of β-alanine (Harris *et al.*, 2006b). In support of this, chronic β-alanine supplementation can lead to significant increases in muscle carnosine content (Harris *et al.*, 2006b; Hill *et al.*, 2007). Dosing protocols include taking a single daily dose of 3.2 g, or up to eight daily doses of 0.4 – 1.6 g β-alanine per single dose, to reach a total daily ingestion of 3.2 – 6.4 $g \cdot day^{-1}$ (Harris *et al.*, 2006b; Hill *et al.*, 2007). These daily dosing protocols appear to lead to a 50 – 60% increase in muscle carnosine contents in about 4 weeks (Harris *et al.*, 2006b).

Large acute doses of β-alanine appear to induce mild pseudo-allergic skin reactions of paraesthesia (mild flushing and tingling sensations) (Harris *et al.*, 2006b; Hill *et al.*, 2007). However, these vasodilation type responses appear to be short-term side-effects that dissipate within about 2 h, as many individuals have reached a total intake of 400 g β-alanine over several weeks without any reported adverse health consequences (Harris *et al.*, 2006b; Hill *et al.*, 2007). In short, chronic supplementation of β-alanine appears to be safe, despite some acute side-effects of mild flushing with large single doses, but there are no data to show whether long-term supplementation would lead to adverse health issues.

Despite the relatively consistent finding that β-alanine supplementation leads to an increase in muscle carnosine, the subsequent performance effects have not been so obvious. During a cycling time to exhaustion test of ~15 min, there was no effect on performance (Zoeller, Stout, O'Kroy, Torok, & Mielke, 2006). However, at steady-state cycling at 110% maximum power output, there was a 15% increase in total work done over a test of approximately 2 min 45 s duration (Hill *et al.*, 2007). In support of this, Harris *et al.* (2006a) found an 11% improvement in endurance time (8 s increase in time over a ~75-s test) during isometric knee extensor exercise at 45% of maximal voluntary contraction. The ventilatory threshold was improved in one study with β-alanine supplementation (Stout *et al.*, 2006), but not in another (Zoeller *et al.*, 2006). Alternatively, muscular strength as assessed by one-repetition maximum testing was found to improve with 10 weeks of supplementation (Hoffman *et al.*, 2006).

Much work remains to determine if chronic β-alanine ingestion can lead to a clear-cut improvement in exercise performance and to establish the effective dosing protocol. Despite some positive findings on performance with β-alanine supplementation, the current evidence is inconclusive and a definitive recommendation pertaining to middle-distance athletes cannot be made. Finally, the use of any ergogenic aid should be closely monitored between the athlete, coach, and possibly health professional to be conscious of any possible supplement contamination issues, adverse effects or athlete habituation and dependency.

Future directions for new advances in nutrition and training adaptations in middle-distance runners

Concurrent training, which many middle-distance athletes undertake, has been described as "the concomitant integration of endurance and resistance training in a periodized training plan" (Coffey & Hawley, 2007). It has been established that with a specific and regular exercise stimulus (resistance vs. endurance), skeletal muscle is highly adaptable, from a molecular perspective, leading to functional phenotypic alterations. Recent reviews have attempted to elucidate these complex and divergent molecular mechanisms (Baar, 2006; Coffey & Hawley, 2007). Several emerging and future scientific directions for nutrition and exercise adaptations for athletes undertaking concurrent training will be highlighted below. [For further discussion, see Hawley, Gibala, and Bermon, 2007).]

A given acute stimulus of either exercise and/or nutrition leads to altered synthesis of specific proteins (e.g. mitochondrial vs. myofibrillar), which, over time, results in an exercise-specific and optimized remodelling of skeletal muscle. However, opposing results have been found when examining the net protein balance, or skeletal muscle protein turnover rate, between resistance and endurance exercise stimuli (for reviews, see Tarnopolsky, 1999; Tipton & Wolfe, 2004). Recent molecular data suggest that athletes undertaking daily endurance and resistance training should phase these differing exercise stimuli with at least several hours of nutritional recovery between bouts (Coffey & Hawley, 2007). However, much research is needed to better characterize the adaptations induced by concurrent training on divergent responses in molecular signalling that lead to functional protein synthesis.

Previous recommendations contend that athletes should consume carbohydrate immediately after exercise to ensure subsequent training bouts are conducted in a glycogen-compensated state. However, anecdotal reports exist of elite athletes purposely undertaking training in a glycogen-depleted state, attempting to "force the muscle to adapt to the next level". Accordingly, a recent training study reported increased adaptation and performance when 50% of endurance training was undertaken in a glycogen-depleted state (Hansen *et al.*, 2005). This has resulted in a degree of uncertainty behind the idea that athletes should *always* strive to endurance train with ample exogenous and endogenous carbohydrate available. Conversely, it appears that the molecular responses to resistance training are optimized when training with full muscle glycogen stores (Churchley *et al.*, 2007; Creer *et al.*, 2005). Perhaps athletes may need to cycle glycogen stores during concurrent training regimens of endurance and strength/power for optimal adaptation to these varied stimuli. Ultimately, future studies need to utilize a completely integrative approach by altering specific exercise and/or nutrition factors and measuring downstream effects at multiple levels that include gene and molecular signalling pathways, leading to muscle protein synthesis, that result in optimized phenotypic adaptations and performance.

Conclusions

Training involves meticulous planning, in which there is an ideal time, place, duration, and intensity of training that is periodized for optimal performance. This same rigorous approach should also be applied to nutritional interventions. Nutrition, training, and racing interactions need to be monitored closely and continually altered and individualized. We outline below the key messages to optimize an athlete's acute and long-term training and racing. Future developments will need to look to integrate practical nutritional and training applications of all these varied stimuli into a periodized/individualized approach for each athlete. Peaking at the exact time of a major championship is one of the most difficult things to achieve. However, realizing the important and integrated role of nutrition in this quest will bring the athlete one step closer to their goals.

Summary of nutritional guidelines for middle-distance athletes

Consensus for:

- A periodized nutritional approach that takes into account acute and seasonal differences in training volume and intensity should be implemented.
- Carbohydrate-rich foods must provide the majority of the daily energy provision ($7-10$ g CHO $\cdot$ kg BW$^{-1}\cdot$ day^{-1}).
- Daily protein intake should be targeted at $1.5-1.7$ g PRO $\cdot$ kg BW$^{-1}\cdot$ day^{-1} during periods of hard training.
- To maximize glycogen resynthesis rates during short-term recovery (<4 h), aim for approximately $1.2-1.5$ g CHO $\cdot$ kg BW$^{-1}\cdot$ h^{-1}.
- The ingestion of $NaHCO_3$ may offer a small increase in performance.

Consensus against:

- Low carbohydrate diets ($3-15\%$ of total energy) have uniformly been shown to impair high-intensity and endurance-based performance.

Issues that are equivocal:

- Future studies need to elucidate if athletes need to "cycle" their glycogen stores during concurrent training regimens of endurance and strength/power for optimum adaptation to varied stimuli.
- For optimum recovery, it remains to be clarified as to what are the best macronutrient blends, feeding patterns, type of carbohydrate and/or protein, and the intake timing after different types of exercise stimuli.
- Recent evidence suggests that prolonged β-alanine supplementation may improve high-intensity exercise performance.

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