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SCHOLARLY REVIEW

Contemporary Nutrition Interventions to Optimize Performance in Middle-Distance Runners

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Middle-distance runners utilize the full continuum of energy systems throughout training, and given the infinite competition tactical scenarios, this event group is highly complex from a performance intervention point of view. However, this complexity results in numerous potential periodized nutrition interventions to optimize middle-distance training adaptation and competition performance. Middle-distance race intensity is extreme, with 800- to 5,000-m races being at ~95% to 130% of VO_2max. Accordingly, elite middle-distance runners have primarily Type IIa/IIx fiber morphology and rely almost exclusively on carbohydrate (primarily muscle glycogen) metabolic pathways for producing adenosine triphosphate. Consequently, the principle nutritional interventions that should be emphasized are those that optimize muscle glycogen contents to support high glycolytic flux (resulting in very high lactate values, of >20 mmol/L in some athletes) with appropriate buffering capabilities, while optimizing power to weight ratios, all in a macro- and microperiodized manner. From youth to elite level, middle-distance athletes have arduous racing schedules (10–25 races/year), coupled with excessive global travel, which can take a physical and emotional toll. Accordingly, proactive and integrated nutrition planning can have a profound recovery effect over a long race season, as well as optimizing recovery during rounds of championship racing. Finally, with evidence-based implementation and an appropriate risk/reward assessment, several ergogenic aids may have an adaptive and/or performance-enhancing effect in the middle-distance athlete. Given that elite middle-distance athletes undertake ~400 to 800 training sessions with 10–25 races/year, there are countless opportunities to implement various periodized acute and chronic nutrition-based interventions to optimize performance.

Keywords: elite, ergogenic aids, nutrition periodization

Middle-distance running events are highly complex from a performance optimization point of view. For example, elite middle-distance specialists need to have the aerobic system development approaching marathoners, coupled with some of the mechanical properties of elite sprinters, while concurrently having world-class anaerobic capacities with polished tactical race instincts (Hanley & Hettinga, 2018; Sandford et al., 2018). These performance requirements result in highly complex training approaches, with significant differences within and between athletes throughout macro- (yearly/monthly) and micro- (weekly/within-day) cycle periods (Martin & Coe, 1991). Accordingly, given that elite middle-distance athletes undertake ~400 to 800 unique yearly training sessions, and race 10–20 times per year (*personal observations*), there are countless opportunities to implement various periodized acute and chronic nutrition-based interventions. Therefore, the purpose of this review is to provide an evidence-based update since the last International Association of Athletics Federations (IAAF) consensus meeting (Stellingwerff et al., 2007) on contemporary nutrition recommendations to optimize adaptation to training and enhance competition performance in elite middle-distance athletes. The focus of this review will be on IAAF events ranging from 800 to 5,000 m, termed middle-distance events hereafter. Where possible we will integrate practical recommendations coupled with peer-reviewed data to support our nutritional recommendations. However, given the event group complexity and the numerous potential interventions, many of the other IAAF papers will be referenced, and this review will focus exclusively on key novel interventions for middle-distance athletes.

Physiological and Bioenergetic Determinants of Middle-Distance Success

The complexity of middle-distance running performance determinants includes physiological aspects such as bioenergetics/energy

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systems (Duffield et al., 2005; Spencer & Gastin, 2001), but most certainly also includes elements such as biomechanics/structural (force, stride frequency, body mass [BM]) aspects (Weyand & Davis, 2005) as well as numerous sociological and psychological constructs. However, the majority of nutritional-based interventions that impact middle-distance performances are bioenergetically based and, thus, will be the determinants of performance focus in this article (Figures 1 and 2). For individuals interested in nutrition interventions in events of a biomechanical and structural performance origin, please see Sygo et al. (2018). In order to understand how these interventions may relate to the energetic demands of a given exercise bout, it is imperative to understand how the various metabolic pathways interact in order to produce the required amounts of adenosine triphosphate (ATP). This understanding best informs potential nutritional interventions that may impact training adaptation and/or performance in a periodized manner. This is especially important in middle-distance events since they rely heavily on both substrate-level phosphorylation (anaerobic) and oxidative phosphorylation (aerobic) ATP production. The energy system aspects of middle-distance running has been well described previously (Duffield et al., 2005; Spencer & Gastin, 2001), and only key elements will be described here (Figure 1).

Middle-distance race intensity is extreme, with 800- to 5,000-m races being at ~95% to 130% of VO_2max (Duffield et al., 2005), or 75–85% of maximum sprint speed (Figure 1). Given these race intensities and required training intensities, middle-distance athletes have a high number and highly developed Type IIa/IIx (intermediate) fiber morphology (Costill et al., 1976) and rely almost exclusively on carbohydrate (CHO; primarily muscle glycogen) and phosphocreatine metabolic pathways for producing ATP. Accordingly, most middle-distance athletes can generate peak lactate values over 20 mmol/L resulting in muscle pH values as low as 6.6 (Hermansen & Osnes, 1972). Therefore, middle-distance athletes have highly refined anaerobic capacities, or tolerance, which is certainly a product of highly developed intermediate Type IIa (fast oxidative) fiber types, which are especially high in muscle carnosine concentrations. Carnosine is an undisputed pH buffer contributing as much as 15% to total muscle buffering capacity, as it has long been known that sprinters and rowers have nearly double the amount of muscle carnosine than marathon runners, strongly correlating to their Type II muscle fiber

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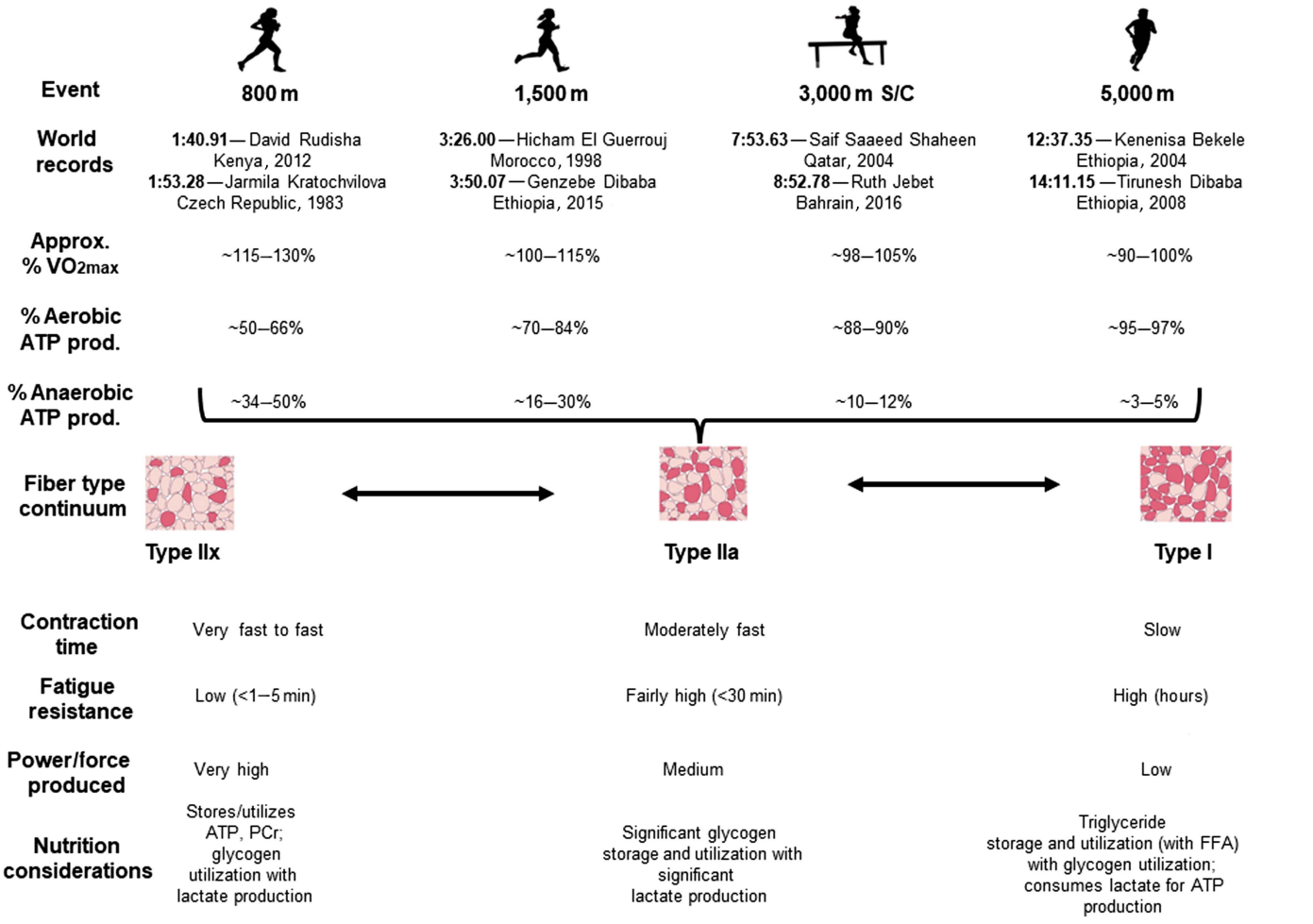

Figure 1 — Differences in ATP energy source provision in middle-distance events within the context of fiber types and endogenous nutrition considerations. It should be noted that fiber typing is a continuum, and only 100- to 400-m athletes have >60% Type IIx fiber types, while most middle-distance athletes Type I fibers range from 40% to 70% (Costill et al., 1976). ATP = adenosine triphosphate; FFA = free fatty acids; PCr = phosphocreatine; prod. = production. Data adapted from Astrand et al. (1986), Costill et al. (1976), Gaston (1998), and Spencer and Gastin (2001).

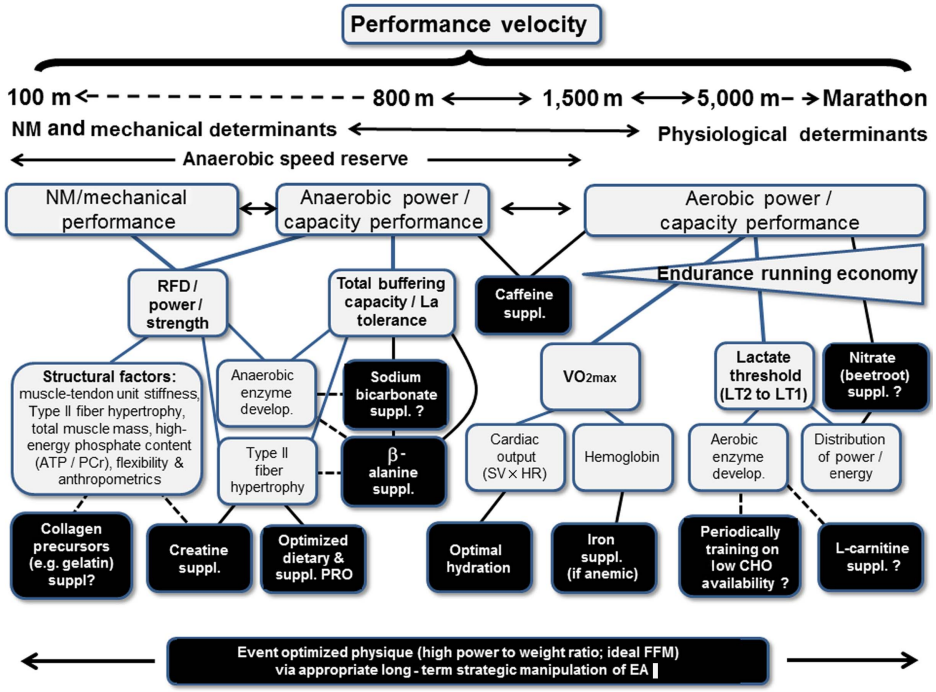

Figure 2 — Framework of the interactions between the structural and physiological determinants of performance (in white boxes) and potential nutritional interventions (black boxes) in middle-distance athletes. It should be highlighted that performance determinates are a continuum, with middle-distance athletes featuring both structural and physiological elements. Some nutrition interventions are acute (e.g., caffeine), while others are chronic in combination with training (e.g., creatine supplementation). A dotted line indicates a potential training-induced nutritional adaptation. A question mark (?) highlights the requirement for more scientific validation. ATP = adenosine triphosphate; CHO = carbohydrate; EA = energy availability; FFM = fat-free mass; HR = heart rate; La = lactate; LT = lactate threshold; NM = neuromuscular; PCr = phosphocreatine; PRO = protein; RFD = rate of force development; suppl. = supplementation; SV = stroke volume; VO_2max = maximal oxygen consumption.

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morphology (Parkhouse et al., 1985). However, when considering the entire spectrum of middle-distance race durations (~1.5 to 15 min), the majority of middle-distance events are highly aerobic and require significant aerobic capacity development, as the measured aerobic contributions from 800 to 5,000 m range from ~50% to 95% (Figure 1). Indeed, the majority of aerobic ATP production during intense exercise comes from glycolysis (primarily glycogen breakdown) and the aerobic disposal of pyruvate via the enzyme pyruvate dehydrogenase into the mitochondria (Parolin et al., 1999). There is also very large variability between athletes in aerobic versus anaerobic ATP contribution, especially over the 800-m event (1.5–2 min), with anaerobic contributions to the 800-m event ranging from 19% to 48%, depending on the fitness of the subject and methods used (Duffield et al., 2005; Spencer & Gastin, 2001). A lot of this variability is probably due to the fact that middle-distance racing also involves nearly peak speed running (Sandford et al., 2018), which is more impacted by biomechanics and structural constraints (Weyand et al., 2005) outlined in Figure 2, including the key emerging concept of anaerobic speed reserve (Buchheit & Laursen, 2013). Anaerobic speed reserve is the difference between an athlete's maximal sprint speed and velocity at VO_2max, featuring structural/biomechanical considerations for maximal sprint speed as well as energy system interventions for velocity at VO_2max (Figure 2).

Bioenergetics during racing is exponentially more complicated when considering the infinite tactical situations. For example, middle-distance events are not run in lanes and feature drafting (drafting in still wind at middle-distance speeds has been shown to reduce VO_2 cost by ~2% to 4% (~0.3 to 1.0 s/lap; Pugh, 1971) and constant tactical decision making, which affect aerobic versus anaerobic components and the anaerobic speed reserve continuum. Furthermore, since middle-distance events are run at such high intensities, there is very little room for tactical errors because they come at such a high metabolic cost. Therefore, aerobic and anaerobic pathways need to produce remarkable rates of ATP for middle-distance success. Accordingly, from a bioenergetic perspective, optimizing muscle glycogen contents to support high glycolytic flux (resulting in very high lactate values) with appropriate buffering capabilities, while optimizing power to weight ratios, are the principle nutritional interventions to emphasize in middle-distance runners (Figure 2).

Periodized Nutritional Strategies to Support Periodized Training

The concept of nutrition periodization has been emerging as a key construct to optimize sports-specific nutrition recommendations (Jeukendrup, 2017; Stellingwerff et al., 2007, 2011), with most of these papers focusing on macronutrition periodization. More recently the concept of dietary microperiodization (weeks to within-day) has been termed, which examines the temporal associations between specific training stimuli, daily life demands and associated nutrition choices (Heikura et al., 2017a). This section will focus on novel macro- to micronutrition periodization interventions in middle-distance athletes, with further nutrition

periodization recommendations made by Morton et al. (Stellingwerff et al., 2018).

Macroperiodization (Months to Weeks) Nutrition Recommendations

Theoretical guidelines for seasonal macroperiodization of nutrition for middle-distance runners across their periodized plans have previously been presented (Stellingwerff et al., 2007, 2011), and data on typical dietary intakes of middle-distance athletes are featured here (Heikura et al., 2017a, 2017b; 2018). Most elite middle-distance runners train like marathoners during the general preparation phase, with high, but highly variable, volumes during the fall/winter (~40 to 180 km/week). Subsequently, training gradually shifts throughout the season to higher intensities/lower volumes and major anaerobic-based sessions toward the peak season. Therefore, the optimal nutrition for an athlete will vary considerably in amount (calories) and type (macronutrient profile) in conjunction with the phase-specific training demands. Since the majority of middle-distance training is performed at or above 75% VO_2max, and this dependency on CHO-based ATP provision increases throughout the training year toward a championship peak, CHO -rich foods must provide the majority of the energy provision. Accordingly, a habitually high CHO diet with 7–10 g CHO·kg BM^{-1}·day^{-1} is recommended to restore glycogen stores, with protein (PRO) intake during hard training phases at ~1.5 to 1.7 g PRO^{-1}·kg BM^{-1}·day^{-1}, but substantially less CHO is required on easy days, and during rest and recovery phases. There have been no major alternations to these original recommendations (Stellingwerff et al., 2007, 2011); instead, this review will focus on novel approaches.

Regarding the appropriate macroperiodization of calories, a research field that has received much recent attention has been the relative energy deficiency in sport (RED-S) and the impact that chronic energy availability (EA) can have on health, body composition, and performance (reviewed here: Melin et al., 2018). Macroperiodization of EA (defined as energy intake minus exercise energy expenditure) underpins the optimization of body composition periodization. In terms of middle-distance athlete health, a very recent multicenter/multicountry paper ($n = 59$ athletes) examined relative energy deficiency in sport indicators, prevalence, and symptoms. This paper demonstrated that amenorrheic females (37% of females) and males in the lowest quartile of testosterone (15.1 ± 3.0 nmol/L; 42% of males) had 10-fold higher missed training days and 4.5 times the number of bone injuries than the rest of the athletes (Heikura et al., 2018). Given that the likelihood of achieving a performance goal decreases sevenfold in track and field athletes over a 5-year period when completing less than 80% of planned training weeks (Raysmith & Drew, 2016), the impact that optimal dietary EA can have on health and performance of middle-distance runners is profound.

However, a key performance indicator for elite middle-distance runners is having a very high power to weight ratio, which features elite athletes who have very low levels of body fat during peak championship season, which may result in undesirable relative energy deficiency in sport outcomes. Therefore, it is not sustainable from a health perspective to be at peak body composition year-round, so body composition needs to be strategically periodized. The limited published body composition ranges suggest elite female middle-distance runners are ~8% to 12% body fat (~40 to 60 mm for International Society for the Advancement of Kinanthropometry sum of 8) and males are ~4% to 6% body fat (~30 to 40 mm International Society for the Advancement of Kinanthropometry sum of 8) in peak competition season (Fleck, 1983). However, very little scientific information exists on how to optimally implement interventions around body composition periodization throughout a given year or over a career. A recent case study featured the body composition of an Olympic-level female middle-distance runner throughout a 9-year international career (Stellingwerff, 2018). During the general preparation phase, the athlete was at ~2% to 4% over ideal competition phase BM with optimal EA being prioritized. In the lead-up to the competition phase, body composition was optimized by creating an individualized time frame and mild caloric deficit (~300 kcal). As a result, significant and purposeful seasonal fluctuations were observed in anthropometric outcomes between training phases. Importantly, the athlete only suffered two injuries over the 9-year follow-up. Despite a strong conceptual underpinning, more research is needed on the optimal implementation of periodized body composition strategies in short- and long-term planning.

Microperiodization (Week to Within-Day) Nutrition Recommendations

Many elite middle-distance athletes can undertake two to three training sessions per day (e.g., track-specific interval session, easy off track run, and weights), all of which are higher intensity; thus, optimizing recovery (muscle glycogen and PRO resynthesis) between sessions is a primary objective if training quality is to be maintained. Furthermore, high-intensity training can result in appetite suppression (Hazell et al., 2016), which might impact ad libitum caloric intake. To optimize nutrition around training and competition, athletes need to plan their days well, as some athletes will be away from home the entire day due to school and/or work. Thus, having portable and quickly accessible high-quality nutrition and hydration is sometimes the largest challenge facing athletes. From a practical perspective, it is important for nutrition practitioners to not just give nutritional education/advice but also actively assess if the athlete is able to actually implement the recommendations into their daily routines, as there can be a mismatch between nutrition advice and athlete practice. In support of this, several recent studies conducted primarily in a large cohort of elite middle-distance athletes ($n = 38$) were surveyed on their nutritional knowledge. Interestingly, most athletes reported to have sound recovery nutrition knowledge, as they said they focused on adequate fueling (96%) and CHO and PRO recovery (87%) around key training sessions (Heikura et al., 2017b). However, when this same cohort of athletes undertook 7 days of dietary recording and assessment, on average, no males or females actually reached the recommended postworkout PRO intake levels, and only males on hard training days reached the CHO recovery recommendations (Heikura et al., 2017a). Therefore, despite these athletes having decent nutrition recovery knowledge, most athletes did not systematically follow the most recent sports nutrition guidelines to optimize recovery.

It is beyond the scope of this review to cover the daily CHO and PRO recommendations in depth. In terms of within-day macronutrient microperiodization, PRO is especially important to not only optimize acute recovery, but daily overall muscle/body PRO synthesis and adaptation (for review see: Phillips et al., 2018). Furthermore, there is growing evidence that strategically manipulating acute within-day CHO availability can serve as a potent mediator in the adaptive response to endurance training, of which the interested reader should be referred (Impey et al., 2018; Stellingwerff et al., 2018).

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Optimizing Competition Nutrition

Most elite middle-distance athletes will race between 10 and 25 times per year with substantial traveling to meets throughout the global IAAF circuit. Most of these meets are "one-off" races, with athletes flying the day or two before the meet and leaving the day after competition. Considerations around travel fatigue, jet lag, and racing fatigue (emotional/physical) must all be considered (Table 1).

In the weeks prior to major championships, athletes start tapering, resulting in significantly reduced training (~30% to 60%) and exercise energy expenditure, coupled with staying in prechampionship training camps or in an athlete's village. All of this requires significant travel, which brings a whole host of associated nutritional challenges beyond the scope of this review (see Halson et al., 2018). Conversely, for some athletes entering competition phase, race anxiety may affect their appetite cues and result in significantly reduced energy intake. It should be noted that our scientific understanding of the impact of changes in acute exercise energy expenditure (e.g., tapering) and competition anxiety on energy intake and appetite cues in athletes is poorly understood and rife for further scientific exploration.

To optimize either race day nutrition or major championship nutrition choices, the athlete needs to be motivated to make an individualized plan, of which all factors for consideration are highlighted in Table 1. Although a single race is unlikely to exhaust fuel stores for middle-distance runners, athletes competing many times over a championship or over the season, coupled with excessive travel fatigue, can take a physical and emotional toll, of which proactive and integrated nutrition planning can have a profound recovery effect over a long race season.

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Ergogenic Aids for Middle-Distance Runners

The physiological and bioenergetic determinants of performance for middle-distance running tend to be the focus of most training plans as well as targets for nutritional interventions and dietary ergogenic aid/supplementation (Figure 2, black intervention boxes). Unfortunately, while there are countless commercially available supplements that promise to improve performance, very few have been validated by scientific studies (Peeling et al., 2018). The focus of this section will therefore be on those supplements that both have an evidence-based support and second, ones that are applicable to middle-distance runners and published since the last consensus (Table 2).

Caffeine

Caffeine is a natural central nervous system stimulant that has many proposed effects relevant for performance, including improved neuromuscular function, increased alertness, and reduced fatigue and ratings of perceived exertion (RPE) during exercise (Burke, 2008). The summary of evidence suggests that best practice is supplementation with 3–6 mg/kg·BM consumed ~60 min prior to exercise. However, there is also growing interest in the use of low (≤3 mg/kg BM) doses of caffeine as this may maximize any performance-enhancing effects while simultaneously minimizing the risk of negative side effects including anxiety, insomnia, and restlessness associated with larger doses (Spriet, 2014). In addition to traditional methods of delivery such as coffee and caffeine capsules/tablets, there is an increasing amount of research focused on alternative delivery methods such as caffeinated gum (Wickham & Spriet, 2018), which may also be relevant for in-competition use. A recent systematic review (Ganio et al., 2009) addressed the effect of caffeine on endurance performance, including 33 sport-specific trials of varying modalities and duration. In the context of middle-distance running, four of these studies were of a relevant duration (~2 to 15 min) and displayed a ~1.1 ± 0.3% improvement over placebo. This is consistent with findings in well-trained club-level runners (Table 2), as studies have shown a 1–2% improvement in time-trial (TT) performance over both 1 mile (Clarke et al., 2018) and 5,000 m (O'Rourke et al., 2008). A recent meta-analysis (Christensen et al., 2017) also found a small but meaningful (ES = 0.41, $P = .002$) effect of caffeine supplementation on exercise speed in performance tests lasting 0.75 to ~8 min. Taken altogether, the evidence suggests that caffeine may be useful for improving performance across the entire spectrum of middle-distance events.

Inorganic Nitrate

Nitric oxide (NO) is a potent signaling molecule that targets and affects multiple tissues, including skeletal muscle. While NO can be produced endogenously via NO synthases, supplementation with inorganic nitrate in a variety of forms (the most common of which are nitrate salts, beetroot juice) can also increase whole-body NO bioavailability. In recent years, nitrate supplementation has gained popularity due to early studies demonstrating improvements in exercise efficiency (decreased O_2 cost at the same absolute workload) and a reduction the VO_2 slow component (which reflects a loss in muscle efficiency during high-intensity exercise), following both acute and chronic supplementation (reviewed in Jones, 2014). Recent work has also demonstrated that nitrate can also improve high-intensity exercise performance, possibly due to enhanced function of Type II muscle fibers (Bailey et al., 2015), and there is a growing field examining the effects of nitrate in unique environmental conditions such as altitude, of which many elite middle-distance athletes implement into their programs (Shannon et al., 2017b). Given its purported exercise-related effects, nitrate presents as an attractive candidate for enhancing performance across all middle-distance events. A recent study examined the effects of both acute and chronic beetroot juice supplementation compared with a nitrate-depleted beetroot juice placebo in elite 1,500-m runners (personal best 3 min 56 s; VO_2peak: 80 ± 5 ml·min^{-1}·kg BM^{-1}; Boorsma et al., 2014). Despite large increases in plasma nitrate in both the acute and chronic trials compared with the placebo condition, submaximal running VO_2 and subsequent 1,500-m TT performance was unaffected (Table 2). In contrast, Shannon et al. (2017a) demonstrated a 1.9% improvement in 1,500-m treadmill TT performance, albeit in a less trained population (VO_2: 62 ± 8 ml·min^{-1}·kg BM^{-1}). Overall, these findings are consistent with a number of other studies that have failed to demonstrate an improvement in exercise economy in elite and/or well-trained athletes (Jones, 2014). Indeed, a recent meta-analysis that included a subgroup analysis of well-trained/elite athletes showed no significant effect (ES = –0.04, $P = .8$; Van De Walle & Vukovich, 2018), while a meta-analysis focusing on TTs found a slight, but trivial difference (ES = 0.19, $P = .09$) following nitrate supplementation compared with placebo (Christensen et al., 2017). At present, it is unclear why elite athletes respond differently to supplementation; however, it is possible that a higher basal concentration of nitrate and nitrite and/or adaptation

Table 1 Nutritional Challenges and Solutions Facing Elite Middle-Distance Runners Travelling and at Major Competitions

Nutrition challenges (from least to most important)	Challenges	Nutrition solutions/considerations
Travel	The time for ground transportation and long-haul flights can sometimes mean 24+ hr of travel.	Individualized and optimal nutrition/hydration availability is key. Understand the travel logistics and food options available while traveling and plan ahead to bring any food/fluids the athlete may need.
	The timing of meals is an important consideration for travel fatigue and jet-lag symptoms.	An athlete's eating and drinking pattern is also a zeitgeber for circadian readjustment; so try to eat and drink to the new time zones meal pattern as soon as possible upon arrival (Reilly et al., 2007).
	Long-haul flights are very dry and increase the risk for athlete illness.	Remember to drink enough fluids on longer flights, both to stay hydrated and to keep mucous moist for optimal function and avoidance of air-borne viruses (Halson et al., 2018).
Food choices at event/ championship	Athletes do not have direct influence on what food is served at events.	Plan ahead by knowing what will be served and augmenting choices with one's own food.
	All you can eat buffets (e.g., Olympic Village) are often the norm and boredom and/or stress eating can easily occur.	Having an individualized nutrition plan to help circumvent this.
	At rest days between races or at pre-championship camps, the energy output is less than when in normal training.	It has been shown that ad libitum energy intake is not immediately matched by reduced energy expenditure (Stubbs et al., 2004). Therefore, athletes should microperiodize with less energy intake when not training hard or during the taper to maintain an ideal peak body composition.
Recovery during multiple races/rounds	Consider potential transportation delays back to the hotel/village or an athlete being selected for a doping test at the stadium or prolonged media requests that will interfere with the optimal recovery plan.	Bring recovery products to the stadium to allow for optimal recovery timing. Have a clear plan for media requests and timing during the rounds of a championship.
	Middle-distance runners who initiate racing with low muscle glycogen will not perform optimally (Maughan & Poole, 1981).	Optimization of recovery, and specifically CHO, is fundamental to race performance in later rounds of a championship. Athletes should aim for large amounts of exogenous carbohydrate (1–1.5 $g \cdot kg^{-1} \cdot hr^{-1}$; Jentjens & Jeukendrup, 2003) and 0.3 g/kg of intact protein in the hours after the race (Moore et al., 2009).
Race-day nutrition	Do not let race stress/anxiety dictate over- or undereating.	Athletes should make a plan for their entire race day, that includes a meal plan.
	Racing late in the evening.	Make a plan to implement meal timing for later evening races; ideally practice it during training or smaller races. Hydrate appropriate to the weather.
	Racing early in the morning.	Get up ~3 to 4 hr prior to race to allow the body to wake up and get a carbohydrate-rich breakfast to fill up the liver-glycogen stores. Hydrate appropriate to the weather.
	Athletes can experience stomach issues or diarrhea prior races due to nervousness.	Eat well-tolerated foods, and ones the athlete prefers. Stick to easily digested carbohydrate and some protein-rich food.
	The circuit and championships are located all over the world, with related differences in food options.	Consider food options that are easily available worldwide. The prerace meal should be high in carbohydrates and consumed 1–6 hr before competition.
	Hydration in usual hot climates during competition season.	Drink enough during the day. Last 60–120 min before the warm-up athletes should aim to drink 400–600 ml water or sports drink.
	Timing of prerace snacks and ergogenic aids are important.	Eat last meal 1–4 hr prior the warm-up. And follow the guidelines for caffeine, bicarbonate, or nitrate as discussed in this paper.
	Race tactics is crucial for optimal performance.	Carbohydrate intake during warm-up can give the runners neuromuscular support via the attenuation of cognitive fatigue that can reduce technical and tactical errors as shown in soccer players (Currell et al., 2009).
	Middle-distance athletes start their warm-up more than 60 min before the start of the race and need to stay hydrated and fueled before they get to the start line.	Bring sports drink for the warm-up, as even carbohydrate mouth rinsing has been shown to have performance-enhancing effect (Stellingwerff & Cox, 2014).

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Table 2 Summary of Recent (2007–2018) Studies Utilizing Ergogenic Aids to Improve Middle-Distance Running Performance in Trained/Elite Cohorts

Reference	Sample size	Cohort details/study design	Supplement and dose	Performance test	Trial result	%Change (negative = faster for supplement)
CAFF supplementation						
O'Rourke et al. (2008)	$n = 15$	Well-trained club-level runners/double-blind placebo-controlled cross-over	5-mg/kg CAFF vs. PLA pills taken 60 min prior to TT	5,000-m TT (400-m outdoor track)	CAFF: 1,047 ± 69 s PLA: 1,058 ± 68 s	−1.1*
Clarke et al. (2018)	$n = 13$	Well-trained club-level runners/double-blind placebo-controlled cross-over	~3-mg/kg CAFF in form of coffee vs. DEC (0.19-mg/kg CAFF) and PLA (hot coffee-flavored water) taken 60 min prior to TT	1-mile TT (200-m indoor track)	CAFF: 275 ± 11 s DEC: 279 ± 11 s PLA: 281 ± 10 s	 +1.4 vs. CAFF* +2.0 vs. CAFF*
NO_3^- supplementation						
Peacock et al. (2012)	$n = 10$	Junior-elite cross-country skiers/double-blind placebo-controlled crossover	1-g KNO_3^- (9.9 mmol·NO_3^-) taken 2.5 hr prior to exercise	5,000-m TT (250-m indoor track)	NO_3^-: 1,005 ± 53 s PLA: 996 ± 49 s	−0.9
Boorsma et al. (2014)	$n = 8$	Elite 1,500-m runners/double-blind placebo-controlled crossover	210-ml BRJ (19.5 mmol·NO_3^-) 1.5 hr prior to exercise	1,500-m TT (200-m indoor track)	NO_3^-: 250.7 ± 4.3 s PLA: 250.4 ± 7 s	+0.12
Boorsma et al. (2014)	$n = 8$	Elite 1,500-m runners/double-blind placebo-controlled crossover	Day 1, 8: 210-ml BRJ (19.5 mmol·NO_3^-), Day 2–7: 140-ml BRJ (13.0 mmol·NO_3^-) with last dose 1.5 hr prior to exercise	1,500-m TT (200-m indoor track)	NO_3^-: 250.5 ± 6.2 s PLA: 251.4 ± 7.6 s	−0.36
Porcelli et al. (2015)	$n = 6$	High aerobic fitness/double-blind placebo-controlled crossover	500-ml water containing NO_3^- (~5.5 mmol·NO_3^-) for 6 days, last taken 3.5 hr prior to exercise	3,000-m TT (400-m outdoor track)	NO_3^-: 627 ± 30 s PLA: 629 ± 28 s	−0.32
Sandbakk et al. (2015)	$n = 9$	Junior-elite cross-country skiers/double-blind placebo-controlled crossover	1 g·KNO_3^- (9.9 mmol·NO_3^-) taken 2.5 hr prior to exercise	5,000-m TT (250-m indoor track)	NO_3^-: 1,016 ± 52 s PLA: 1,005 ± 47 s	+1.09
Shannon et al. (2017a)	$n = 8$	Trained runners or triathletes/double-blind placebo-controlled crossover	140-ml BRJ (12.5 mmol·NO_3^-) taken 3 hr prior to exercise	1,500-m TT (treadmill)	NO_3^-: 319.6 ± 36.2 PLA: 325.7 ± 38.8 s	−1.87*
BA supplementation						
Ducker et al. (2013)	$n = 18$	Recreational club runners/randomized, placebo-control	28 days 80-mg/kg BA vs. PLA	800-m TT (400-m outdoor grass track)	BA (pre): 145.73 ± 5.71 s BA (post): 142.09 ± 4.64 s PLA (pre): 156.80 ± 12.27 s PLA (post): 156.21 ± 12.34 s	−2.56 vs. BA pre* −0.38 vs. PLA pre

Note. CAFF = caffeine; PLA = placebo; TT = time trial; DEC = decaf; NO_3^- = nitrate; KNO_3^- = potassium nitrate; BRJ = beetroot juice; BA = β-alanine.
*Significantly faster than opposing treatment. No new (2007–2018) studies investigating sodium bicarbonate supplementation on middle-distance running performance in trained cohorts were found. Percent differences were calculated by the authors of this publication based on provided mean data.

to several years/decades of training negates any further effect given via nitrate supplementation.

β-Alanine—Intracellular Buffering

Carnosine is an intracellular dipeptide found in a variety of tissues, including skeletal muscle, and has a variety of proposed physiological roles including acting as an intracellular buffer (Harris & Stellingwerff, 2013) and, more recently, as an intracellular shuttle of hydrogen cation (H^+) and calcium (Ca^{2+}) from the sarcoplasmic reticulum to the actin–myosin cross-bridge locations within the muscle (Blancquaert et al., 2015; Swietach et al., 2014). Carnosine is produced in muscle via the combination of the amino acids L-histidine and β-alanine (BA), with dietary intake of the latter amino acid limiting synthesis (Harris et al., 2006). High-intensity exercise causes an accumulation of H^+, which is involved in the drop of intracellular pH from ~7.0 to ~6.6 (Hermansen & Osnes, 1972) which could potentially be one of the contributing factors to fatigue (although H^+ is certainly not the only reason for changes in muscle pH and fatigue; Gladden, 2004). As such, supplementation with BA resulting in increased muscle carnosine presents an opportunity to increase skeletal muscle pH buffering capacity and/or shuttling of H^+ and Ca^{2+}, thereby potentially delaying the onset of fatigue and improving performance (Saunders et al., 2017a). Research has demonstrated that supplementation can increase carnosine concentration equally in both Type I and Type II fibers in the range of 40–80% depending on dose and timing (Stellingwerff et al., 2012). Furthermore, recent data (Saunders et al., 2017b) demonstrate that chronic supplementation (24 weeks with 6.4 g/day BA) can result in further increases beyond those seen with a more typical 2- to 4-week loading period (skeletal muscle carnosine had increased by ~51% by Week 4 in contrast to the 90–95% increase seen by Weeks 20–24). Importantly, the additional increase in carnosine content at Week 20 and 24 coincided with an increase in the likelihood of positive improvement in time to exhaustion (ES = 0.62, 1.21, and 0.83 at Weeks 4, 20, and 24, respectively). Therefore, while current recommendations are daily consumption of ~3 to 6 g BA for a minimum of 2–4 weeks (Saunders et al., 2017a), longer periods may result in additional increases in skeletal muscle carnosine content. In the context of middle-distance running performance, athletes running 800–1,500 m are the most likely to benefit from BA supplementation, as compared with 5,000-m athletes, as a recent meta-analysis demonstrates that the strongest effect is on exercise lasting 60–240 s (Hobson et al., 2012; Saunders et al., 2017a). This has previously been demonstrated in recreational club runners, as 28 days of supplementation with BA improving 800-m running performance by 2.6% (Table 2; Ducker et al., 2013). However, despite the well-established evidence demonstrating the ability to increase skeletal muscle carnosine stores through BA supplementation, the results of several meta-analyses suggest that the effects of BA are stronger on exercise capacity tests (e.g., time to exhaustion), as opposed to specific performance tests (Christensen et al., 2017; Hobson et al., 2012; Saunders et al., 2017a). Furthermore, effects appear to be stronger in nontrained recreationally active individuals (Saunders et al., 2017a), with smaller, but potentially meaningful, effect sizes in well-trained and elite athletes (possibly due to the smaller overall number of studies performed in this population). Consequently, it is difficult to definitively say whether BA supplementation will improve performance in elite middle-distance athletes, given the lack of data in this cohort, the prevalence of nonperformance related tests and the smaller effect sizes. However, given the absence of side effects and the potentially meaningful improvements in performance outlined previously, individual athletes and their support teams may consider trialing BA supplementation to determine if it is effective for them.

Sodium Bicarbonate—Extracellular Buffering

Sodium bicarbonate ($NaHCO_3^-$) is a key extracellular buffer, which can improve performance by increasing extracellular bicarbonate (concentrations and blood pH. In doing so, the efflux of lactate and H^+ cations out of skeletal muscle is increased thereby minimize intracellular metabolic perturbations linked to fatigue (Jubrias et al., 2003). As with BA, research has typically focused on high-intensity exercise lasting 60–360 s (800–1,500 m) where H^+ accumulation and decreases in both intra- and extracellular pH are most likely to occur. While the timing and ingestion patterns vary greatly between studies, it has been suggested that a 5–6 mmol/L increase in blood bicarbonate concentration is required to improve performance (Carr et al., 2011a). As a result, current guidelines suggest supplementing with 0.2–0.4 g/kg BM 60–150 min prior to exercise (Carr et al., 2011a). A recent meta-analysis by Christensen et al. (2017) found a small but meaningful (ES = 0.40, $P < .001$) effect of $NaHCO_3^-$ supplementation on exercise speed in TT-based performance tests indicating it can improve intense endurance performance. These findings are supported by other published work assessing a broader scope of performance measures and protocols demonstrating a moderate effect of $NaHCO_3^-$ on performance outcomes (ES = 0.41, $P = .007$), although it is worth noting the effects were greater in untrained versus trained participants (Peart et al., 2012). Classical work also supports use of $NaHCO_3^-$ for improving running performance, as both 800- (Wilkes et al., 1983) and 1,500-m (Bird et al., 1995) performance was improved in trained runners compared with placebo and control. It is however important to note that some individuals suffer from gastrointestinal (GI) upset following supplementation with $NaHCO_3^-$, particularly when consuming doses greater than 0.3 g/kg BM (Carr et al., 2011b) and that individuals experiencing GI upset do not improve performance postsupplementation (Price & Simons, 2010; Saunders et al., 2014). Runners may be particularly sensitive to these issues given the nature of the sport (upright posture and prone to jostling of fluids in the stomach), and thus, strategies such as consuming the supplement with food (Carr et al., 2011b) may prove beneficial to minimize adverse effects. An additional concern that is of particular relevance for weight-dependent runners is the potential for increased fluid retention, and therefore an increase in BM, as a result of the increased sodium intake (Sims et al., 2007a, 2007b). Taken together, these findings suggest that supplementation with $NaHCO_3^-$ has the potential to improve middle-distance running performance. Furthermore, it is possible that the overall "strength" of the effect of $NaHCO_3^-$ on subsequent performance in the previously mentioned meta-analyses may be underestimated by the inclusion of individuals who suffer from GI issues. Supplementation should therefore be tailored to each individual athlete to determine susceptibility to GI upset and/or body weight gain (fluid retention) and efficacy of supplementation to improve performance.

Further Considerations Regarding Supplements and Elite Middle-Distance Runners

Beyond the lack of female and/or elite subjects the relative lack of running-based performance studies is also striking (Table 2), as most studies seem to implement cycling-based interventions. However, we would hypothesize that potentially the response of

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some ergogenic aids in elite middle-distance runners may be unique from cyclists. Accordingly, given the very high neuromuscular demands (ground contact times approaching 100 ms) coupled with a high anaerobic component (greatest acidosis [H^+] of any event), anything that might improve contractile forces/twitch dynamics, or efficiency of mechanisms associated with muscle contraction, should theoretically improve middle-distance race performance. Therefore, alternative and emerging mechanisms of carnosine (Swietach et al., 2014) and nitrate (Coggan et al., 2018; Whitfield et al., 2017) involving calcium handling, recycling, and/or shuttling, and increasing contractile force and twitch kinetics, requires more research in elite running models, which would notionally accentuate these performance mechanism(s) more than cycling models. Obviously, more performance and mechanistically related ergogenic aid data are required in elite runners. The reader interested in responders versus nonresponders, combinations of ergogenic aids and ergogenic aid periodization should see Peeling et al. (2018) and Stellingwerff et al. (2018).

Conclusion and Future Research Considerations

Given that middle-distance races are at the crossroads of metabolism, featuring both high aerobic and anaerobic ATP production, there are numerous opportunities for various nutrition interventions to make a significant training and/or race performance impact. Indeed, as an event group, middle-distance athletes might feature the greatest polarization and diversity of training periodization between athletes and between various training seasons, and future nutrition studies should attempt to address this diversity. Indeed, the fiber type and bioenergetics diversity in elite middle-distance athletes requires further nutritional investigation and consideration. Finally, more research on the impact that nutrition has in running/structural modes of exercise, as compared with the dominate mode of cycling, needs to be addressed. Currently, given the extreme intensities of training and racing in middle-distance athletes, optimizing muscle glycogen contents to support high glycolytic flux (resulting in very high lactate values) with appropriate buffering capabilities, while optimizing power to weight ratios, all in a macro- and microperiodized manner, are the principle nutritional interventions to emphasize.

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