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Optimal Nutrition for Endurance Exercise: A Systematic Review

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Abstract

Introduction: As fatigue in endurance events correlates with depletion of muscle glycogen, the traditional approach to nutritional support has been carbohydrate loading. However, there has been recent interest in improving athletic endurance performance by novel diets in the days to weeks prior to endurance events, the pre-event meal, and during exercise.

Methods: We searched PubMed and SCOPUS for randomized trials published from 1992-2017 with a primary endpoint of endurance performance. We identified 407 citations which were examined against our inclusion criteria of randomization or crossover allocation to diet and for which a primary outcome was endurance performance.

Results: Twenty full text articles met our inclusion criteria and were included in the present review. In the days to weeks prior to testing, one trial of a high-fat diet versus carbohydrate improved performance, the others were neutral. There was no benefit of substituting protein for carbohydrate during this time period, but almond intake did result in ergogenic benefits. In the pre-event meal, fat only showed ergogenic benefits when combined with carbohydrate intake. A single study suggested that vegetable-derived nitrates did provide benefit. During endurance events, partial substitution of carbohydrates with protein had varying results on performance and should be further examined.

Conclusion: Carbohydrates remain the best fuel source both before and during events for overall endurance performance compared to other macronutrients, including water. Partial substitution of carbohydrate with fat and protein immediately before and during events warrants further investigation. Additional trials on nitrates and almond consumption are also needed.

Introduction

Physical activity is recommended as an important element of a healthy lifestyle [1]. Though the traditional advice is to achieve 30 minutes of moderate activity most days of the week, there is recent evidence that two days per week can provide similar improvements in fitness [2]. Those who find physical and emotional reward in exercise often challenge themselves to participate in longer distance endurance events such as half marathons, century (100 mile) cycling events, nordic ski marathons, and triathlons. For some, endurance athletic achievement is simply an enjoyable means of maintaining health and socializing while for others it becomes a vocation as a professional athlete. However, whether one is consolidating a week's work of exercise into one session, training to finish a half marathon, or vying for a position on a national team, the issue of optimal nutrition for endurance exercise is of great interest. This fact has not been missed by the food industry. It is estimated that the international sports nutrition market will reach $44 billion US by 2021 [3]. These products include bars, gels, beverages and nearly countless micronutrient supplements.

Of the metabolic pathways that generate ATP to power muscular contraction, it is the oxidative pathways that are most relevant in endurance events. The energy substrates available for cellular respiration include muscle and liver glycogen, intramuscular lipid, triglycerides stored in adipose, and protein. Compared to free fatty acids, carbohydrate generates more ATP per unit of oxygen and thus provides greater gross exercise efficiency [4]. In addition, during endurance events, the onset of fatigue is closely correlated with depletion of muscle glycogen [5]. For these reasons, much of the research on sports nutrition in the hours and days prior to exercise has focused on carbohydrate loading to maximize liver and muscle glycogen stores. However, over the past decade, investigators have explored alternatives to this traditional approach. These alternatives include attempts to induce adaptive changes in intracellular transporters and enzymes to allow more lipolysis and more efficient use of free fatty acids during exercise. Other experiments have compared diets with an increased protein content and others have tested specific foods. Our conceptual view of the literature is shown in Table 1.

Table 1: Grouping of Selected Trials

	Time Relative to Endurance Event			
	Days to Weeks Prior	**Pre Event Meal**	**During Event**	**Immediately Post**
Carb vs Fat	**A**	**E**	**I**	M
Carb vs Protein	**B**	**F**	**J**	N
Carb vs Carb	**C**	**G**	**K**	O
Specific Foods	**D**	**H**	**L**	P

Our primary aim is to perform a systematic review of randomized trials of nutrition consumed before or during endurance exercise during the past 25 years and present a clear summary of the findings (sections A-J in our concept table). A second aim is to review the major societal recommendations regarding endurance nutrition.

Methods

Search Strategy

Two separate literature searches were conducted in PubMed and SCOPUS on February 12th, 2017. The following keywords were used in PubMed: (endurance OR aerobic) AND (exercise OR workout OR training) AND (performance OR recovery) AND (diet OR dietary intake) AND (carbohydrate intake OR fat intake OR protein intake) AND (trial OR randomized controlled trial OR longitudinal OR double-blind OR single-blind OR intervention OR comparative OR comparison) AND (human OR humans) AND English [Language].

In SCOPUS, the following keywords were used (endurance exercise OR aerobic OR endurance performance) AND (performance OR recovery) AND (diet) AND (carbohydrate intake OR fat intake or protein intake) AND English [Language]. Additional publications were also retrieved from the authors' files and the references of selected papers. A total of 348 articles from PubMed and 59 articles from SCOPUS resulted from the initial search.

Screening

All titles were reviewed by 1 author (SEA) to determine eligibility for abstract review. Full text PDFs were obtained for the remaining 51 articles. Abstracts were divided in half and reviewed by both authors (SA, BWA). Thirty-one full texts were reviewed for primary findings by both authors (SA, BWA). Of those, twenty unique articles were included in the final systematic review.

Inclusion Criteria

We defined our inclusion criteria as follows:

- randomized control trial and/or crossover design
- dietary intervention before and/or during endurance event
- endurance event was moderate-to-high intensity
- endurance performance (timed trials or duration) as primary endpoint
- primary endpoint results included in publication
- published between 1992 and 2017

Results

NUTRITION DAYS TO WEEKS PRIOR TO EVENT (Table 2)

High Fat vs High Carbohydrate Diets

Helge et al randomized 15 untrained young men to either high fat or high carbohydrate diet and measured time to exhaustion after baseline and after two and four weeks of training. The investigators found no difference in this measure. Secondary findings included a lower Respiratory Exchange Ratio (RER) and higher muscle triglyceride levels in the high fat group and higher muscle glycogen levels in the high CHO group [6]. Carey et al compared 6 days of fat adaptation diet vs a high carbohydrate diet in a randomized crossover study of 7 well trained competitive cyclists [7]. All subjects rested for one day and consumed a high CHO diet on the 7th day and then consumed a high CHO pre exercise meal. Although power output was 11% greater in the fat adaptation group, there was no difference in the primary endpoint of distance covered in a 1 hour time trial performed after 4 hours of exercise at 65% of max VO_2. Fat oxidation was higher and CHO oxidation lower in the fat adaptation group. Lambert et al also studied fat adaptation in 5 endurance trained male athletes in a randomized cross-over trial [8]. Ten days of a high fat diet was compared to a high carbohydrate diet. In both groups, this was followed by 3 days of carbohydrate loading. There was a slight reduction in the time required to complete a 20 km time trial after 150 mins of steady state cycling at 70% of VO_2 max (29.3 mins vs 30.7 mins) in the high fat group. The high fat diet was also associated with greater fat oxidation and lower oxidation of total carbohydrate, muscle glycogen, and lactate. Rowland et al also examined fat adaptation in a cross over study of 7 nationally competitive cyclists [9]. In this study, 3 dietary approaches were compared; high carb for 14 days, high fat for 14 days, and high fat for 11.5 days followed by carb loading for 2.5 days, in 7 nationally competitive cyclists. Sports bars and a 5% energy drink were supplied during the time trial. Contrary to Lambert et al, there was no difference in the primary endpoint of a 100 km time trial or in a shorter 15 minute time trial. There were metabolic differences including a lower plasma insulin concentration before exercise, and a higher plasma-glucose, plasma glycerol, and peak fat-oxidation rate. Fleming et al compared the impact of 6 weeks of a high fat/moderate protein diet versus a standard diet in 20 recreationally active men [10]. The investigators found a decrease in work output and peak and mean power in the high fat groups. As noted in the earlier trials, fat oxidation increased and the RER decreased in the high fat/moderate protein group. Larson-Meyer et al compared the impact of 3 days of a very low fat versus a moderate fat diet prior to one day of glycogen normalization on a 10km run following a 90 minute preload run in 21 men and women [11]. The very low fat diet produced 30% lower intramyocellular lipid levels and 22% greater muscle glycogen levels but no change in time required to run 10 kms. In a population of 19 adolescent boys, Guimaraes et al, compared the impact of a high fat, high carbohydrate, and a habitual diet on the time required to run 10 km after a 10 min preload run at 65% of VO2 max [12]. These investigators observed faster 10 km times in the high carbohydrate group compared to the high fat group. There was no difference in the high carbohydrate and habitual diet groups.

Carbohydrate vs Protein

Macdermid et al investigated the effect of 7 days of a high carb versus a high protein diet on long distance time trial performance in 7 competitive cyclists [13]. They found superior time trial performance in the high carbohydrate group. Conversely, in a population of 9 female endurance athletes, McLay found no difference in 16 km time trial times after 45 mins of preload riding after 3 days of a moderate protein diet versus a high carbohydrate diet [14].

High vs Low Glycemic Index

The influence of glycemic index and load on a 1 hour run followed by a 10 km time trial time was examined by Chen et al in a study of 9 male runners [15]. In this 3 group randomized crossover design, there was no difference in the time trial in the two high carbohydrate groups, but the high carbohydrate low glycemic index, low glycemic load group had faster times than the low carbohydrate, high glycemic index, low glycemic load group.

Food Based Interventions

In contrast to the studies of macronutrients above, Yi et al. employed a randomized cross-over design to compare a 4 week intervention of 75 grams of almonds per day compared to isoenergetic cookies on distance covered in a 20 minute cycling time trial [16]. They found the almond group was able to ride further than the cookie group (21.9 vs 20.2 km). In a study of gluten, Lis et al randomized 13 men and women competitive cyclists without celiac disease to 7 days of gluten containing or gluten free food [17]. No significant difference was found in distance covered in 15 mins after a 45 minute preload ride at 70% of VO_2 max.

NUTRITION PRE-EVENT (Table 3)

Carbohydrate vs Fat

Murakami et al compared the effect of a single pre exercise meal after 3 days of carbohydrate loading in 8 collegiate long distance athletes on time to exhaustion running at 80% of VO2 max immediately following a 80 minute preload run at 72% [18]. A high fat meal supplemented with 410 kcals of maltodextrin jelly immediately prior to exercise was associated with longer run times (100 mins vs 90 mins) than both the high carbohydrate meal plus placebo jelly and the high fat meal plus placebo jelly.

Table 2: Study characteristics of the randomized trials in the systematic review related to nutrition days to weeks before exercise

High Carbohydrate vs High Fat										
Trial	**N**	**Sex**	**Level**	**Timing of Intervention**	**Diet Label**	**Macronutrient Distribution**			**Primary Endpoint**	**Result**
						Carb	**Fat**	**Protein**		
Helge 1998	15	M	Untrained	4 wks straight	High carb	65	20	15	TTE cycling	No difference
					High Fat	21	62	17		
Carey 2001	7	M	Well trained competitive	6 days prior to 1 day of Carb loading	High Carb	70	15	15	1 hour cycling TT after 4 hours of at 65% of VO2 max	No difference
					High Fat	16	69	15		
Lambert 2001	5	M	Trained	10 days prior to 3 days of Carb loading	High Carb	>65	<15	20	20 km cycling TT after 150 mins at 70% of VO2 max	Slight reduction in time required to cover 20 km
					High Fat	<15	>65	20		
Rowlands 2002	7	M	Nationally competitive	14 days straight	High Carb	70	16	14	100 km cycling TT after 45 mins of steady state exercise	No difference
					High Fat	15	66	20		
				11.5 days prior to 2.5 days of Carb loading	High Fat	15	66	20		
Fleming 2003	20	M	Recreationally active	6 wks straight (HF, mod protein) vs control	High Carb	59	25	15	Work output and max power in 45 min cycling test	18% decrease in work output and 10% decrease in peak power in the HF, mod protein group
					High Fat; Mod Protein	8	61	30		

Larson-Meyer 2008	21	M/F	Endurance trained runners	3 days prior to 1 day of "glycogen normalization"	Low Fat	75	10	15	10 km running time trial after 90 minute preload run at 62% of VO2 max.	No difference in 10 km running times.
					Mod Fat	50	35	15		
Couto 2014	19	M	Physically active adolescents	48 hours	High Carb	69	15	15	10 km time trial after 10 mins of running at 65% of VO2 max	10 km times were shorter in high Carb versus high FAT. No difference in high Carb vs habitual.
					High Fat	24	60	15		
					Habitual	56	27	16		
High Carb vs High Protein										
Macdermid 2006	7	-	competitive trained	7 days	High Carb	66	23	11	Long distance cycling time trial	Times were significantly lower in the high carbodydrate group (126 mins vs 153 mins).
					High Protein	44	26	30		
McLay 2007	9	F	endurance athletes	3 days	High Carb	47	35	17	16 km cycling time trial after 45 min preload ride	No difference in time trial times
					Normal	77	7	14		
Carbohydrate vs Carbohydrate										
Chen 2007	9	M	endurance runners	3 days	high index/ high load	73	14	13	10 km running time trial after 1 hour preload run at 70% of VO2 max.	No difference in the two high carb groups but the low index/low load group had faster 10 km run times than the high index/low load group.
					low index/ low load	73	14	13		
					high index/ low load	30	49	21		
Specific Foods										
Yi 2014	10	Male	trained cyclists and triatheletes	4 weeks	75 g/d almonds	N/A	N/A	N/A	Distance covered in 20 min time trial after 125 mins of steady state cycling	Greater distance covered in the almond group (21.9 vs 20.2 kms)
					isocaloric cookies	N/A	N/A	N/A		
Lis 2015	13	M/F	endurance	7 days	Gluten free diet	N/A	N/A	N/A	Distance covered in 15 min time trial after 45 minute ride at 70% VO2 max	No difference
					Gluten containing diet	N/A	N/A	N/A		

Carbohydrate Trials

Kirwan et al compared the time to exhaustion on recumbent cycle ergometers in 6 recreationally active college women randomly assigned to a pre endurance test of sweetened rolled oats or sweated whole oat flour (both 75 grams of carbohydrate but varying in dietary fiber and soluble fiber or water 45 mins prior to exercise) [19]. The rolled oat group cycled 16% longer than the control group. There was no difference between the oat flour and the control groups. Among trained male cyclists, a recent systematic review and meta-analysis focused on carbohydrate supplementation immediately before and during endurance exercise found a reduction in time to cycle a fixed distance after steady state cycling and in mean power output with carbohydrate containing beverages compared to placebo [20]. This effect was most evident in beverages with a 6 and 8% carbohydrate concentration and exercise lasting greater than 90 mins.

Food Based Interventions

The impact of vegetable-derived nitrates on 5 km treadmill was studied in 11 recreationally fit men and women who were randomized to 200 grams of beetroot (providing > 500 mg of nitrates) or an isocaloric relish 75 mins prior to exercise [21]. The beetroot group ran significantly faster; the difference was seen in the final 1.8 km. Dairy rich foods were studied by Haakonssen et al in 32 well trained female cyclists who were randomized to 3 servings of dairy (1350 mg of Ca+) 2 hours before exercise [22]. There was no difference in distance covered in a 10 min cycle time trial performed after 80 mins of steady state cycling at 60% of VO_2 max.

Table 3: Study characteristics of the randomized trials in the systematic review related to nutrition immediately before exercise

High Fat vs High Carbohydrate vs (High Fat + Simple Carbohydrate)

Trial	N	Sex	Level	Timing of Intervention	Diet Label	Macronutrient Distribution			Primary Endpoint	Result
						Total Carb	Fat	Protein		
Murakami 2012	8	M	Collegiate long distance athletes	4 hours prior to test after 3 days of Carb loading	High Carb	71	20	9	TTE on treadmill at 80% of VO2 max following 80 min preload run at 72% of VO2 max.	TTE was significantly greater in the High FAT + maltodextrin group compared to the other two group
					High Fat	30	55	15		
					High Fat+ maltodextrin (410 kcals)	30	55	15		

Carbohydrate vs Carbohydarte

Trial	N	Sex	Level	Timing of Intervention	Diet Label	Total Carb	Dietary Fiber	Soluble Fiber	Primary Endpoint	Result
Kirwan 1998	6	F	Recreationally active college women	45 mins before endurance test	Sweetened rolled oats (high fiber/ moderate GI)	75 g	6.8 g	2.3 g	Time to exhaustion on cycle ergometry	TTE was 16% greater in the SRO group than the control group. No difference between SOF and control.
					Mod Fiber (sweetened oat oat flour)	75 g	3.1 g	1.6 g		
					Control (water)	0	0	0		

Specific Foods

Trial	N	Sex	Level	Timing of Intervention	Diet Label	Total Carb	Dietary Fiber	Soluble Fiber	Primary Endpoint	Result
Murphy 2012	11	M/F	Recreationally fit; aged 18-55.	75 mins before endurance test	Nitrate (200 g of beetroot with > 500 mg of nitrates)	N/A	N/A	N/A	5 km treadmill run	Time was statistically shorter in the beetroot group. This was limited to the final 1.8 kms.
					Control (isocaloric cranberry relish)	N/A	N/A	N/A		
Haakonssen 2014	32	F	well trained cyclists	2 hours prior to test	3 servings of dairy (1350 mg Ca+)	N/A	N/A	N/A	Distance covered in 10 min time trial following 80 mins of exercise at 60% of VO2 max.	No difference in performance
					isocaloric control	N/A	N/A	N/A		

NUTRITION DURING EXERCISE (Table 4)

Carbohydrate vs Placebo

High-intensity exercise lasting longer than 1.5-2 hours typically results in depleted muscle and liver glycogen stores. Previous research has led to recommendations of CHO as the primary fuel source for optimal performance during endurance exercise longer than 1 hour [23]. A recent meta-analysis revealed pool effect sizes that favored CHO ingestion compared to water-only across all performance-based tests [20].

Carbohydrate vs Protein

Osterberg et al randomized thirteen trained, male cyclists in a double-blind crossover design to three beverages: CHO-only vs CHO-PRO vs placebo (noncaloric, artificially sweetened, identical electrolyte profile) [24]. Each participant consumed identical 24-hr diets and fasted overnight before each trial. Data collection occurred over 4 weeks for each participant. No significant differences were observed in time-trial performance (completed 7kJ/kg of work), power output, or rate of perceived exertion between CHO-only and CHO-PRO. While CHO-only performed significantly faster (6%) than placebo, CHO-PRO did not. Interestingly, greater inter-individual variability was observed in CHO-PRO compared to other beverages. Hansen et al randomized eighteen male cyclists to a CHO-only beverage or a lower CHO-PRO beverage and to long-distance or short-distance rides during a one-week trial [25]. Diet was kept consistent throughout the week. An 18g PRO recovery beverage was also consumed daily by each group, but was not factored into protein content of CHO-PRO group's diet. No significant differences were found in peak power output compared to baseline. The average power output during the performance test decreased in both CHO and CHO-PRO groups compared to baseline. Markers of muscle damage increased in CHO-PRO group compared to baseline, whereas no significant changes were seen in CHO group.

Siegler et al further examined partial protein substitutions by comparing CHO-only and CHO-PRO beverages to an isocaloric CHO-PRO-peptide beverage in 12 healthy men in a randomized crossover design [26]. No significant effect on timed trial or mean power output in a 5km time trial were observed between conditions. However, several metabolic conditions differed between conditions. RER was consistently higher in the CHO-PRO condition than the other conditions and mean heart rate was consistently lower in CHO condition compared to the others. Conversely, Cathcart et al did observe differences in endurance performance after randomizing 28 competitive mountain bikers to either CHO-only (control) supplements or CHO-PRO supplements [27]. Overall, those consuming the CHO-PRO supplement performed significantly faster than the placebo. However, it is difficult to attribute the enhancement specifically to protein as those in the CHO-PRO also consumed more calories on average during the race. Of note, this is the only experiment performed at very high ambient temperatures.

Table 4: Study characteristics of the randomized controlled trials in the systematic review related to nutrition during exercise

Carbohydrate vs Protein									
Trial	**N**	**Sex**	**Level**	**Timing of Intervention**	**Type of Fuel**	**Diet Label**	**Nutrient Composition**	**Primary Endpoint**	**Result**
Osterberg 2008	13	M	trained	4 weeks	Beverage	CHO	6% (glucose, fructose, sucrose)	TT and power output to complete 7kj/kg of work	No significant differences
						CHO-PRO	7.5% (glucose, fructose, sucrose) vs 1.6% (whey)		
						Placebo	noncaloric beverage		
Hansen 2016	18	M	trained; competitive	6 days	Beverage	CHO	1.2g/kg/h	5-min power output TT	No significant differences
						CHO-PRO	1g/kg/h; 0.2g/kg/h		
Siegler 2013	12	M	untrained, healthy individuals	2 months	Beverage	CHO	67 g/hr (maltodextrin)	5 km TT and power output	No significant differences
						CHO-PRO	53.1g/hr; 13.6g/hr (whey)		
						CHO-PRO-PEP	53.1g/hr; 11.0g/hr; 2.4g/hr (marine-based)		
Cathcart 2011	28	M/F	trained	8 days	Food (Liquid and Solid)	CHO-PRO	Liquid: 72g CHO, 18g whey PRO Solid: 24g CHO, 13g whey PRO, 4g fat	TT of 8-day mountain bike race	TT faster in CHO-PRO compared to CHO-only
						Placebo	Liquid: 76g CHO Solid: 37g CHO, 3g whey PRO, 5g fat		

Societal Recommendations

Academy of Nutrition and Dietetics, Dietitians of Canada, and American College of Sports Medicine

While fat adaptation may have beneficial metabolic effects, these societies points out several benefits specific to carbohydrates, including its higher availability of ATP per unit of oxygen for mitochondria [5]. In terms of dietary intake guidelines, they recommend specifying CHO, PRO, and energy needs based on kilogram of body weight given the wide range of body size amongst competitive athletes. In addition, they recommends providing the timing of each nutrient should be specific to the sport rather than general daily goals.

In terms of daily CHO consumption during the training season, current recommendations include 6-10g/kg/day of CHO for those lasting 1-3 hours and 8-12g/kg/day for those lasting longer than 4 hours. During the events, the American College of Sports Medicine (ACSM) recommends 30-60g/hour of CHO for events lasting 1.5-2h and up to 90g/hour of CHO for those lasting 2.5-3 hours.

American Fitness Professionals and Associates

The organization's website presents recommendations from the director of research and development of E caps and Hammer nutrition to consume 75-100 grams of complex CHO no less than 3 hours prior to the event [28]. Fructose is discouraged as a source of CHO due to the need for hepatic metabolism. CHO containing solutions are recommended during exercise to target 60-70 grams per hour but limiting osmolality to 280-300 mOsm/L.

Discussion

Diet Days to Weeks Prior (Adaptive Phase)

Fat adaptation has become popular among competitive endurance athletes [29]. By improving fat oxidation, it is hypothesized that one may rely less on muscle glycogen and thus improve performance [30]. Fat adaptation consistently occurred in individuals who followed a moderate to high-fat diet as evidenced by decreased muscle glycogen, increased fat oxidation, and/or lower RER [6-11]. Despite these metabolic changes, high fat diets typically had a negligible [6-11] or negative effect [12] on performance compared to a high carbohydrate diet. The one trial that did observe an ergogenic benefit in high fat diet groups CHO loaded before the endurance event [8].

The quality of carbohydrate may also influence performance. Specifically, a high carbohydrate diet with a low glycemic load [15]. Unlike the glycemic index, a low glycemic load takes into account the quantity of the carbohydrate, which may prove more helpful in assessing carbohydrate quality.

Following a high-protein diet compared to high-carbohydrate diet had either a neutral [14] or negative [13] effect on timed trials compared to a high carbohydrate diets. Interestingly, athletes who supplemented with almonds exercised longer than those supplemented with isocaloric cookies, despite the lower carbohydrate content of the almonds [16]. Given the rising popularity of the Paleo diet, which favors high protein intake and lower carbohydrate intake, this food-based study is particularly timely. Further research should examine the potential benefits that may be specific to almonds or other nuts, such as the fatty acid profile. In general, given the wide range of study duration among these studies, additional RCTs are warranted to better elucidate the effect of high protein diets on endurance performance.

Diet Immediate Prior to Event

Fat had a ergogenic benefit only if consumed with a simple CHO before an endurance event [18]. It is difficult to determine whether the additional calories or a complementary effect of fat on carbohydrate loading benefitted the overall performance. Additional studies using isoenergic fuel sources before an event are warranted to elucidate the mechanism behind this beneficial effect. A moderate GI diet that is high in fiber has been shown to improve performance, independent from calories [19]. No trials on protein immediately before a race were reviewed in this paper, but an investigation in the partial substitution of carbohydrate with protein is warranted, particularly given the rise of low-carbohydrate, high-protein diets.

While nitrates from beetroots show promise for performance enhancement [21], additional studies with larger sample sizes are needed to address nitrates' possible benefit, especially considering the rise in the consumer market of beetroot juice. Conversely, despite dairy's growing popularity as a recovery food, calcium from dairy sources showed no benefit in performance when consumed immediately before an event [22].

Diet During Event

During endurance events lasting longer than 1.5-2 hours, carbohydrates have consistently provided ergogenic benefit compared to fat and protein [20, 23]. While CHO has historically been the primary fuel source during long, moderate-intensity endurance events, various studies have also suggested a threshold exists to exogenous carbohydrate oxidation during exercise. Partially substituting CHO intake with protein during exercise has been hypothesized as an additional means to improve performance [25]. To date, protein ingestion during high-intensity exercise has shown limited effect on endurance performance. Given the short duration of these trials, longer studies are warranted to further investigate whether partial substitution of protein may help spare glycogen stores. The type of protein also does not seem to have an ergogenic effect, though few studies have investigated this to date. Solution osmolality may have an effect on gut motility and absorption [26]. Most studies to have found an effect on endurance performance with protein supplementation have been confounded by the higher caloric intake of the CHO-PRO condition compared to control [31]. Interestingly, a few previous studies not included in this review have observed better performance in the protein-supplemented group despite the higher caloric intake of the CHO-only group [31]. Further examination of these discrepancies are warranted. To date, carbohydrate is still the recommended fuel source during exercise, which is consistent with the ACSM and AND guidelines.

Limitations

Aside from macronutrient quantity, the composition of meals was not typically standardized throughout the trials in this review. Specifically, meals were often individualized and the particular foods consumed within each macronutrient category were rarely recorded or monitored. Therefore, exogenous dietary factors related to specific foods consumed by participants may have confounded studies that did not utilize a cross-over design.

The rise of a wide-range of diet trends amongst athletes, from the Paleo diet to the vegan diet, further emphasizes the call for future trials to investigate the relationship between macronutrient quality and endurance performance. In a preliminary report from a recent international study examining the prevalence of plant-based runners, it is estimated that 21% and 35% of runners currently ascribe to a vegetarian and vegan diet, respectively [32]. However, only one study in this review examined the effects of a specific protein source (almonds). Most studies only accounted for the quantity of the protein. Considering the contrasting nutritional composition between animal and plant-based protein, particularly in terms of iron, studies should at least differentiate between these two protein sources when analyzing the nutrient composition of meals. Studies may also benefit from accounting for the specific foods consumed within each of these categories.

The generalizability of these results is limited given the nature of the articles included in this review. The trials discussed in this review only examined endurance events related to cycling or running. In addition, most studies investigated men under the age of 50, indicating a strong gender and age bias. In addition, small sample size of these studies, which ranged from 5 - 32 participants. Finally, it is likely that not all relevant papers were included in this review as the literature search was not strictly systematic in its methodology.

Conclusion

CHO remains the most important fuel source both before and during events for overall endurance performance. Further research is warranted to better elucidate how the quality of carbohydrates may influence performance, as several studies indicate a high carbohydrate, low glycemic load diet has potential ergogenic benefits. While fat adaptation results in improved metabolic responses, no ergogenic benefits have been observed to date. Isoenergic partial substitution of CHO with PRO or fat should be further investigated, however, as early trials have suggested some potential benefits. Finally, the focus of future trials should shift towards food-based interventions rather than simply macronutrient-based particularly given the recommendation by the Dietary Guidelines for Americans to focus on foods rather than individual nutrients.

References

1. Eckel RH, John M Jakicic, Jamy D Ard, Van S Hubbard, Janet M de Jesus, I-Min Lee, et al. 2013 AHA/ACC guideline on lifestyle management to reduce cardiovascular risk: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines. Circulation, 2014;129(25 Suppl 2):S76-99.
2. O'Donovan G, Lee IM, Hamer M, Stamatakis E. Association of "Weekend Warrior" and Other Leisure Time Physical Activity Patterns With Risks for All-Cause, Cardiovascular Disease, and Cancer Mortality. JAMA internal medicine. 2017;77(3):335-342. doi: 10.1001/jamainternmed.2016.8014
3. Upadhyay S. Sports Nutrition Market by Type (Protein Powder, Iso Drink Powder, Creatine, BCAA, Supplement Powder, RTD Protein Drinks, Iso & Other Sports Drinks, Carbohydrate Drinks, Protein Bars, Carbohydrate/Energy Bars), Distribution Channel (Large Retail & Mass Merchandisers, Small Retail, Drug & Specialty Stores, Fitness Institutions, Online) - Global Opportunity Analysis and Industry Forecasts, 2014 - 2021. 2016 [cited 2017 28 Feb 2017].
4. Spriet LL and MJ Watt. Regulatory mechanisms in the interaction between carbohydrate and lipid oxidation during exercise. Acta physiologica Scandinavica. 2003;178(4):443-452.
5. Thomas DT, KA Erdman and LM Burke. Position of the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine: Nutrition and Athletic Performance. Journal of the Academy of Nutrition and Dietetics. 2016;116(3):501-528. doi: 10.1016/j.jand.2015.12.006
6. Helge JW, B Wulff, B Kiens. Impact of a fat-rich diet on endurance in man: role of the dietary period. Medicine and science in sports and exercise. 1998;30(3):456-461.
7. Carey AL, Staudacher HM, Cummings NK, Stepto NK, Nikolopoulos V, Burke LM, et al., Effects of fat adaptation and carbohydrate restoration on prolonged endurance exercise. Journal of applied physiology. 2001;91(1):115-122.
8. Lambert EV, Goedecke JH, Zyle C, Murphy K, Hawley JA, Dennis SC, et al. High-fat diet versus habitual diet prior to carbohydrate loading: effects of exercise metabolism and cycling performance. International journal of sport nutrition and exercise metabolism. 2001;11(2):209-225.
9. Rowlands DS and WG Hopkins. Effects of high-fat and high-carbohydrate diets on metabolism and performance in cycling. Metabolism: clinical and experimental. 2002;51(6):678-690.
10. Fleming J, Sharman MJ, Avery NG, Love DM, Gómez AL, Scheett TP, et al., Endurance capacity and high-intensity exercise performance responses to a high fat diet. International journal of sport nutrition and exercise metabolism. 2003;13(4):466-478.
11. Larson-Meyer DE, Borkhsenious ON, Gullett JC, Russell RR, Devries MC, Smith SR, et al. Effect of dietary fat on serum and intramyocellular lipids and running performance. Medicine and science in sports and exercise. 2008;40(5):892-902. doi: 10.1249/MSS.0b013e318164cb33
12. Guimaraes Couto P, Marani Lima H, Pinheiro Soares R, Bertuzzi R, De-Oliveira FR, Lima-Silva AE. et al., Effect of fat- and carbohydrate-rich diets on metabolism and running performance in trained adolescent boys. Journal of pediatric gastroenterology and nutrition. 2014;59(3):380-385.
13. Macdermid PW and SR Stannard. A whey-supplemented, high-protein diet versus a high-carbohydrate diet: effects on endurance cycling performance. International journal of sport nutrition and exercise metabolism. 2006;16(1):65-77.

14. McLay RT, Thomson CD, Williams SM, Rehrer NJ. Carbohydrate loading and female endurance athletes: effect of menstrual-cycle phase. International journal of sport nutrition and exercise metabolism. 2007;17(2):189-205.
15. Chen Y, Wong SH, Xu X, Hao X, Wong CK, Lam CW. Effect of CHO loading patterns on running performance. International journal of sports medicine. 2008;29(7):598-606.
16. Yi M, Fu J, Zhou L, Gao H, Fan C, Shao J, et al. The effect of almond consumption on elements of endurance exercise performance in trained athletes. Journal of the International Society of Sports Nutrition. 2014;11:18. doi: 10.1186/1550-2783-11-18
17. Lis D, Stellingwerff T, Kitic CM, Ahuja KD, Fell J. No Effects of a Short-Term Gluten-free Diet on Performance in Nonceliac Athletes. Medicine and science in sports and exercise. 2015;47(12):2563-2570. doi: 10.1249/MSS.0000000000000699
18. Murakami I, Takayuki Sakuragi, Hiroshi Uemura, Hajime Maeda, Munehiro Shindo, and Hiroaki Tanaka. Significant effect of a pre-exercise high-fat meal after a 3-day high-carbohydrate diet on endurance performance. Nutrients. 2012;4(7):625-637. doi:10.3390/nu4070625
19. Kirwan JP, DO'Gorman, WJ Evans. A moderate glycemic meal before endurance exercise can enhance performance. Journal of applied physiology. 1998;84(1):53-59.
20. Pochmuller M, Schwingshackl L, Colombani PC, Hoffmann G. A systematic review and meta-analysis of carbohydrate benefits associated with randomized controlled competition-based performance trials. Journal of the International Society of Sports Nutrition. 2016;13:27. doi: 10.1186/s12970-016-0139-6
21. Murphy M, Eliot K, Heuertz RM, Weiss E. Whole beetroot consumption acutely improves running performance. Journal of the Academy of Nutrition and Dietetics. 2012;112(4):548-552. doi: 10.1016/j.jand.2011.12.002
22. Haakonssen EC, Ross ML, Cato LE, Nana A, Knight EJ, Jenkins DG, et al.Dairy-based preexercise meal does not affect gut comfort or time-trial performance in female cyclists. International journal of sport nutrition and exercise metabolism. 2014;24(5):553-558. doi: 10.1123/ijsnem.2014-0069
23. Temesi J, Johnson NA, Raymond J, Burdon CA, O'Connor HT. Carbohydrate ingestion during endurance exercise improves performance in adults. The Journal of nutrition. 2011;141(5):890-897. doi: 10.3945/jn.110.137075
24. Osterberg KL, JJ Zachwieja, JW Smith. Carbohydrate and carbohydrate + protein for cycling time-trial performance. Journal of sports sciences. 2008;26(3):227-233.
25. Hansen M, Bangsbo J, Jensen J, Krause-Jensen M, Bibby BM, Sollie O, et al. Protein intake during training sessions has no effect on performance and recovery during a strenuous training camp for elite cyclists. Journal of the International Society of Sports Nutrition. 2016;13:9. doi: 10.1186/s12970-016-0120-4
26. Siegler JC, Richard Page, Mark Turner, Nigel Mitchell and Adrian W Midgely. The effect of carbohydrate and marine peptide hydrolysate co-ingestion on endurance exercise metabolism and performance. Journal of the International Society of Sports Nutrition. 2013;10:29. DOI: 10.1186/1550-2783-10-29
27. Cathcart AJ, Murgatroyd SR, McNab A, Whyte LJ, Easton C. Combined carbohydrate-protein supplementation improves competitive endurance exercise performance in the heat. European journal of applied physiology. 2011;111(9):2051-2061. doi: 10.1007/s00421-011-1831-5
28. Misner B. Endurance Nutrition: What to Eat Before, During and After Exercise. Athletes and Sports Conditioning. 2013 [cited 2017 1 March 2017].
29. Zajac A, Poprzecki S, Maszczyk A, Czuba M, Michalczyk M, Zydek G. The effects of a ketogenic diet on exercise metabolism and physical performance in off-road cyclists. Nutrients. 2014;6(7):2493-2508. doi: 10.3390/nu6072493.
30. Burke LM. Re-Examining High-Fat Diets for Sports Performance: Did We Call the 'Nail in the Coffin' Too Soon? Sports medicine. 2015;45 Suppl 1:S33-49. doi: 10.1007/s40279-015-0393-9
31. McLellan TM, SM Pasiakos, HR Lieberman. Effects of protein in combination with carbohydrate supplements on acute or repeat endurance exercise performance: a systematic review. Sports medicine. 2014;44(4):535-550. doi: 10.1007/s40279-013-0133-y
32. Wirnitzer KE. The NURMI Study: Methodology and First Results of the Prevalence of Vegetarians and Vegans in Running Events. Research in Complementary Medicine. 2016;23(36).