5-5-2017

Optimal Nutrition for Endurance Exercise: A Systematic Review

Sarah E. Andrus MS
Gerald J. and Dorothy R. Friedman School of Nutrition Science and Policy, Tufts University, seandrus90@gmail.com

Bruce W. Andrus MD MS
Geisel School of Medicine at Dartmouth, Section of Cardiovascular Medicine, bruce.w.andrus@dartmouth.edu

Follow this and additional works at: https://digitalcommons.dartmouth.edu/facoa

Part of the Cardiology Commons, Exercise Physiology Commons, and the Human and Clinical Nutrition Commons

Recommended Citation
https://digitalcommons.dartmouth.edu/facoa/1013

This Article is brought to you for free and open access by Dartmouth Digital Commons. It has been accepted for inclusion in Open Dartmouth: Faculty Open Access Articles by an authorized administrator of Dartmouth Digital Commons. For more information, please contact dartmouthdigitalcommons@groups.dartmouth.edu.
Optimal Nutrition for Endurance Exercise: A Systematic Review

Sarah E Andrus1,2 and Bruce W Andrus1,4

1Simmons College, Department of Nutrition, Boston, MA
2Gerald J. and Dorothy R. Friedman School of Nutrition Science and Policy, Tufts University, Boston, MA
3Dartmouth Hitchcock Medical Center, Cardiovascular Medicine, Lebanon, NH
4Geisel School of Medicine at Dartmouth, Hanover, NH

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.
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$_{2max}$. 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$_{2max}$ (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 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 VO2 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>
<thead>
<tr>
<th>Trial</th>
<th>N</th>
<th>Sex</th>
<th>Level</th>
<th>Timing of Intervention</th>
<th>Diet Label</th>
<th>Macronutrient Distribution</th>
<th>Primary Endpoint</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helge 1998</td>
<td>15</td>
<td>M</td>
<td>Untrained</td>
<td>4 wks straight</td>
<td>High carb</td>
<td>Carb 65 Fat 20 Protein 15</td>
<td>TTE cycling</td>
<td>No difference</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High Fat</td>
<td>21 62 17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carey 2001</td>
<td>7</td>
<td>M</td>
<td>Well trained competitive</td>
<td>6 days prior to 1 day</td>
<td>High Carb</td>
<td>Carb 70 Fat 15 Protein 15</td>
<td>1 hour cycling TT after 4 hours of at 65% of VO2 max</td>
<td>No difference</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>of Carb loading</td>
<td>High Fat</td>
<td>16 69 15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lambert 2001</td>
<td>5</td>
<td>M</td>
<td>Trained</td>
<td>10 days prior to 3 days</td>
<td>High Carb</td>
<td>Carb &gt;65 Fat &lt;15 Protein 20</td>
<td>20 km cycling TT after 150 mins at 70% of VO2 max</td>
<td>Slight reduction in time required to cover 20 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>of Carb loading</td>
<td>High Fat</td>
<td>&lt;15 &gt;65 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rowlands 2002</td>
<td>7</td>
<td>M</td>
<td>Nationally competitive</td>
<td>14 days straight</td>
<td>High Carb</td>
<td>Carb 70 Fat 16 Protein 14</td>
<td>100 km cycling TT after 45 mins of steady state exercise</td>
<td>No difference</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High Fat</td>
<td>15 66 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High Fat</td>
<td>15 66 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fleming 2003</td>
<td>20</td>
<td>M</td>
<td>Recreationally active</td>
<td>6 wks straight (HF, mod protein) vs control</td>
<td>High Carb</td>
<td>Carb 59 Fat 25 Protein 15</td>
<td>Work output and max power in 45 min cycling test</td>
<td>18% decrease in work output and 10% decrease in peak power in the HF, mod protein group</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High Fat; Mod Protein</td>
<td>8 61 30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 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 sweetened 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 Haakonsen 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 VO₂ max.

---

**Table: Carbohydrate Trials**

<table>
<thead>
<tr>
<th>Study</th>
<th>Gender</th>
<th>Type</th>
<th>Duration</th>
<th>Carbohydrate Form</th>
<th>Time to Exhaustion</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larson-Meyer 2008</td>
<td>M/F</td>
<td>Endurance trained runners</td>
<td>3 days prior to 1 day of &quot;glycogen normalization&quot;</td>
<td>Low Fat 75, Mod Fat 50</td>
<td>10 km running time trial after 90 minute preload run at 62% of VO₂ max</td>
<td>No difference in 10 km running times.</td>
</tr>
<tr>
<td>Couto 2014</td>
<td>M</td>
<td>Physically active adolescents</td>
<td>48 hours</td>
<td>High Carb 69, High Fat 24, Habitual 56</td>
<td>10 km time trial after 10 mins of running at 65% of VO₂ max</td>
<td>10 km times were shorter in high Carb versus high FAT. No difference in high Carb vs habitual.</td>
</tr>
</tbody>
</table>

---

**Table: High Carb vs High Protein**

<table>
<thead>
<tr>
<th>Study</th>
<th>Gender</th>
<th>Type</th>
<th>Duration</th>
<th>Carbohydrate Form</th>
<th>Time to Exhaustion</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macdermid 2006</td>
<td>-</td>
<td>Competitive trained</td>
<td>7 days</td>
<td>High Carb 66, High Protein 44</td>
<td>Long distance cycling time trial</td>
<td>Times were significantly lower in the high carbohydrate group (126 mins vs 153 mins).</td>
</tr>
<tr>
<td>McIay 2007</td>
<td>F</td>
<td>Endurance athletes</td>
<td>3 days</td>
<td>High Carb 47, Normal 77</td>
<td>16 km cycling time trial after 45 min preload ride</td>
<td>No difference in time trial times.</td>
</tr>
</tbody>
</table>

---

**Table: Carbohydrate vs Carbohydrate**

<table>
<thead>
<tr>
<th>Study</th>
<th>Gender</th>
<th>Type</th>
<th>Duration</th>
<th>Carbohydrate Form</th>
<th>Time to Exhaustion</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen 2007</td>
<td>M</td>
<td>Endurance runners</td>
<td>3 days</td>
<td>high index/ high load 73, low index/ low load 73</td>
<td>10 km running time trial after 1 hour preload run at 70% of VO₂ max</td>
<td>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.</td>
</tr>
</tbody>
</table>

---

**Table: Specific Foods**

<table>
<thead>
<tr>
<th>Study</th>
<th>Gender</th>
<th>Type</th>
<th>Duration</th>
<th>Carbohydrate Form</th>
<th>Time to Exhaustion</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yi 2014</td>
<td>Male</td>
<td>Trained cyclists and triathletes</td>
<td>4 weeks</td>
<td>75 g/d almonds N/A, isocaloric cookies N/A</td>
<td>Distance covered in 20 min time trial after 125 mins of steady state cycling</td>
<td>Greater distance covered in the almond group (21.9 vs 20.2 kms)</td>
</tr>
<tr>
<td>Lis 2015</td>
<td>M/F</td>
<td>Endurance</td>
<td>7 days</td>
<td>Gluten free diet N/A, Gluten containing diet N/A</td>
<td>Distance covered in 15 min time trial after 45 minute ride at 70% VO₂ max</td>
<td>No difference</td>
</tr>
</tbody>
</table>

---

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)

<table>
<thead>
<tr>
<th>Trial</th>
<th>N</th>
<th>Sex</th>
<th>Level</th>
<th>Timing of Intervention</th>
<th>Diet Label</th>
<th>Macronutrient Distribution</th>
<th>Primary Endpoint</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murakami</td>
<td>8</td>
<td>M</td>
<td>Collegiate long distance athletes</td>
<td>4 hours prior to test after 3 days of Carb loading</td>
<td>High Carb</td>
<td>71 20 9</td>
<td></td>
<td>TTE on treadmill at 80% of VO2 max following 80 min preload run at 72% of VO2 max.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High Fat</td>
<td>30 55 15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High Fat + maltodextrin (410 kcals)</td>
<td>30 55 15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Carbohydrate vs Carbohydrate

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

### Specific Foods

<table>
<thead>
<tr>
<th>Trial</th>
<th>N</th>
<th>Sex</th>
<th>Level</th>
<th>Timing of Intervention</th>
<th>Diet Label</th>
<th>Macronutrient Distribution</th>
<th>Primary Endpoint</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murphy</td>
<td>11</td>
<td>M/F</td>
<td>Recreationally fit; aged 18-55,</td>
<td>75 mins before endurance test</td>
<td>Nitrate (200 g of beetroot with &gt; 500 mg of nitrates)</td>
<td>N/A N/A N/A</td>
<td>5 km treadmill run</td>
<td>Time was statistically shorter in the beetroot group. This was limited to the final 1.8 kms.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Control (isocaloric cranberry relish)</td>
<td>N/A N/A N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haakonssen</td>
<td>32</td>
<td>F</td>
<td>well trained cyclists</td>
<td>2 hours prior to test</td>
<td>3 servings of dairy (1350 mg Ca+)</td>
<td>N/A N/A N/A</td>
<td>Distance covered in 10 min time trial following 80 mins of exercise at 60% of VO2 max.</td>
<td>No difference in performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>isocaloric control</td>
<td>N/A N/A N/A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 7k/ 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

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


Optimal Nutrition for Endurance Exercise: A Systematic Review


