Optimal Nutrition for Endurance Exercise:  
A Systematic Review

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Received: March 03, 2017; Accepted: April 17, 2017; Published: May 05, 2017

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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 fatty acids during exercise. Other experiments have compared diets with an increased protein content and others have tested enzymes to allow more lipolysis and more efficient use of free fatty acids during exercise.
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 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 \( \text{VO}_2 \). 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 \( \text{VO}_2 \) 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 high 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 isonenergetic 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 kcsals 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 21, Protein 15</td>
<td>TTE cycling</td>
<td>No difference</td>
</tr>
<tr>
<td>Carey 2001</td>
<td>7</td>
<td>M</td>
<td>Well trained</td>
<td>6 days prior to 1 day of Carb loading</td>
<td>High Carb</td>
<td>Carb 70, Fat 16, 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>Lambert 2001</td>
<td>5</td>
<td>M</td>
<td>Trained</td>
<td>10 days prior to 3 days of Carb loading</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>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 15, 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>11.5 days prior to 2.5 days of Carb loading</td>
<td>High Fat</td>
<td>Carb 15, Fat 66, Protein 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 8, Protein 30</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>
</tbody>
</table>

**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**

*References for the text:*

1. Carey 2001
2. Rowlands 2002
3. Fleming 2003
4. Larson-Meyer et al.
5. Guimaraes et al.
6. Chen et al.
7. Macdermid et al.
8. Yi et al.
9. Lis et al.
10. Yi et al.
11. Larson-Meyer et al.
12. Guimaraes et al.
13. Macdermid et al.
14. Lis et al.
15. Chen et al.
**Optimal Nutrition for Endurance Exercise: A Systematic Review**

<table>
<thead>
<tr>
<th>Study</th>
<th>Gender</th>
<th>Age</th>
<th>Type of Training</th>
<th>Duration</th>
<th>Carbohydrate Type</th>
<th>Distance Covered</th>
<th>VO2 max</th>
<th>Time Trial</th>
<th>VO2 max</th>
<th>Distance Covered</th>
<th>VO2 max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larson-Meyer 2008</td>
<td>M/F</td>
<td>21</td>
<td>Endurance runners</td>
<td>3 days</td>
<td>Low Fat</td>
<td>10 km running</td>
<td>75</td>
<td>10</td>
<td>15</td>
<td>10 km running</td>
<td>62%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mod Fat</td>
<td>trial after 90 minute preload run at 62% of VO2 max</td>
<td>50</td>
<td>35</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Couto 2014</td>
<td>M</td>
<td>19</td>
<td>Physically active adolescents</td>
<td>48 hours</td>
<td>High Carb</td>
<td>10 km time trial after 10 mins of running</td>
<td>69</td>
<td>15</td>
<td>15</td>
<td>10 km times were shorter in high Carb versus high FAT. No difference in high Carb vs habitual.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High Fat</td>
<td></td>
<td>24</td>
<td>60</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Habitual</td>
<td></td>
<td>56</td>
<td>27</td>
<td>16</td>
<td></td>
<td></td>
</tr>
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**High Carb vs High Protein**

<table>
<thead>
<tr>
<th>Study</th>
<th>Gender</th>
<th>Age</th>
<th>Type of Training</th>
<th>Duration</th>
<th>Carbohydrate Type</th>
<th>Distance Covered</th>
<th>VO2 max</th>
<th>Time Trial</th>
<th>VO2 max</th>
<th>Distance Covered</th>
<th>VO2 max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macdermid 2006</td>
<td>-</td>
<td>7</td>
<td>competitive trained</td>
<td>7 days</td>
<td>High Carb</td>
<td>Long distance cycling time trial</td>
<td>66</td>
<td>23</td>
<td>11</td>
<td>Times were significantly lower in the high carbohydrate group (126 mins vs 153 mins).</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High Protein</td>
<td></td>
<td>44</td>
<td>26</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McLay 2007</td>
<td>F</td>
<td>9</td>
<td>endurance athletes</td>
<td>3 days</td>
<td>High Carb</td>
<td>16 km cycling time trial after 45 min preload ride</td>
<td>47</td>
<td>35</td>
<td>17</td>
<td>No difference in time trial times</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Normal</td>
<td></td>
<td>77</td>
<td>7</td>
<td>14</td>
<td></td>
<td></td>
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</table>

**Carbohydrate vs Carbohydrate**

<table>
<thead>
<tr>
<th>Study</th>
<th>Gender</th>
<th>Age</th>
<th>Type of Training</th>
<th>Duration</th>
<th>Carbohydrate Type</th>
<th>Distance Covered</th>
<th>VO2 max</th>
<th>Time Trial</th>
<th>VO2 max</th>
<th>Distance Covered</th>
<th>VO2 max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen 2007</td>
<td>M</td>
<td>9</td>
<td>endurance runners</td>
<td>3 days</td>
<td>high index/low load</td>
<td>10 km running time trial after 1 hour preload run at 70% of VO2 max</td>
<td>73</td>
<td>14</td>
<td>13</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>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>low index/low load</td>
<td></td>
<td>73</td>
<td>14</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>high index/low load</td>
<td></td>
<td>30</td>
<td>49</td>
<td>21</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Specific Foods**

<table>
<thead>
<tr>
<th>Study</th>
<th>Gender</th>
<th>Age</th>
<th>Type of Training</th>
<th>Duration</th>
<th>Food Type</th>
<th>Distance Covered</th>
<th>VO2 max</th>
<th>Time Trial</th>
<th>VO2 max</th>
<th>Distance Covered</th>
<th>VO2 max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yi 2014</td>
<td>Male</td>
<td>10</td>
<td>trained cyclists and triathletes</td>
<td>4 weeks</td>
<td>75 g/d almonds</td>
<td>Distance covered in 20 min time trial after 125 mins of steady state cycling</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Greater distance covered in the almond group (21.9 vs 20.2 kms)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>isocaloric cookies</td>
<td></td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lis 2015</td>
<td>M/F</td>
<td>13</td>
<td>endurance</td>
<td>7 days</td>
<td>Gluten free diet</td>
<td>Distance covered in 15 min time trial after 45 minute ride at 70% VO2 max</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>No difference</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Gluten containing diet</td>
<td></td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</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 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 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 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>Total Carb: 71, Fat: 20, Protein: 9</td>
<td>TTE on treadmill at 80% of VO2 max after 80 min preload run at 72% of VO2 max.</td>
<td>TTE was significantly greater in the High FAT + maltodextrin group compared to the other two groups</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>Total Carb: 75, Dietary Fiber: 6.8, Soluble Fiber: 2.3</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, Dietary Fiber: 3.1, Soluble Fiber: 1.6</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>
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</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 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>
<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 7kJ/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>vs Placebo</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 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</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>individuals</td>
<td></td>
<td></td>
<td>CHO-PRO</td>
<td>53.1g/hr; 13.6g/hr (whey)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<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, 10g 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 point 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 recommend providing the timing of each nutrient 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 index [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 diet. 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 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


