Energy substrate utilization during prolonged exercise with and without carbohydrate intake in preadolescent and adolescent girls

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Timmons BW, Bar-Or O, Riddell MC. Energy substrate utilization during prolonged exercise with and without carbohydrate intake in preadolescent and adolescent girls. J Appl Physiol 103: 995–1000, 2007. First published July 5, 2007; doi:10.1152/japplphysiol.00018.2007.—Little information is available on energy metabolism during exercise in girls, particularly the contribution of exogenous carbohydrate (CHOex). The purpose of this study was to determine substrate utilization during exercise with and without CHOex intake in healthy girls. Twelve-year-old preadolescent (YG; n = 12) and 14-year-old adolescent (OG; n = 10) girls consumed flavored water (WT) or 13C-enriched 6% CHO (CT) while cycling for 60 min at ∼70% maximal aerobic power (V02max). Substrate utilization was calculated for the final 15 min of exercise. CHOex decreased fat oxidation by ∼50% in YG but not in OG (P < 0.001) and decreased endogenous CHO oxidation by ∼15% in OG but not in YG (P = 0.006). Endogenous CHO oxidation was lower in YG than in OG regardless of trial (P ≤ 0.01), whereas fat oxidation was higher in YG only during WT (P < 0.001). CHOex oxidation rate was similar between YG and OG (7.1 ± 0.5 and 6.8 ± 0.4 mg·kg−1·min−1, respectively, P = 0.67), contributing ∼19% to total energy expenditure. Serum estradiol levels in all girls correlated with fat (r = −0.50 to −0.59, P = 0.03 to 0.005) and endogenous CHO oxidation (r = 0.50 to 0.63, P = 0.03 to 0.005) but not with CHOex oxidation (r = −0.09, P = 0.71). We conclude that CHOex influences endogenous substrate utilization in an age-dependent manner in healthy girls but that total CHOex oxidation during exercise is not different between YG and OG. Our results also point to potential sex-related differences in energy substrate utilization even during childhood.

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basis of our previous findings of higher fat and CHOexo oxidation relative to body weight in boys compared with men (33) and in younger compared with older boys (34), we hypothesized that the contribution from fat and CHOexo oxidation to total energy yield would also be higher in 12-yr-old preadolescent girls (YG) compared with 14-yr-old adolescent girls (OG).

METHODS

Subjects. Twenty-two girls participated in this study approved by the McMaster University Research Ethics Review Board. All girls were healthy, active, and not taking medication, including oral contraceptives. All girls in the OG group (n = 10) experienced regular menstrual cycles, whereas only 4 of the 12 girls in the YG group had experienced their first menstrual period but none experienced regular cycles. After the purpose, procedures, and risks of the study were explained, the girls agreed verbally to participate, and their parent then signed a written informed consent. Pubertal status of each girl was self-assessed and based on breast development according to Tanner (31). Self-assessment of pubertal status has been shown to be valid and reproducible among girls (18). To provide a more objective indication of each girl’s pubertal status, we also determined their serum estradiol level (see Hormone and metabolism analysis). Table 1 provides the subjects’ characteristics.

Preliminary session. During this visit, height, mass, percent body fat (bioelectrical impedance 101A, RJL Systems, Clinton, MI), and stage of breast development were determined. maximal aerobic power (V˙O2max) of each girl was then assessed on a cycle ergometer (Ergomedic 818E, Monark, Sweden), as previously described (35).

Experimental sessions. Each subject completed two experimental trials a minimum of 4 days and a maximum of 4 wk apart. Trials were conducted in a double-blind and counterbalanced manner. All girls in the OG group were tested in the early follicular phase of their menstrual cycle. Because of the sporadic nature of menstruation in the OG group were tested in the early follicular phase of their menstrual cycle. Experimental sessions were conducted in a double-blind and counterbalanced manner. All girls in the OG group were tested in the early follicular phase of their menstrual cycle. Because of the sporadic nature of menstruation in the OG group were tested in the early follicular phase of their menstrual cycle. All girls in the YG group and twice this for the OG group; this approach was based on our previous findings of higher fat and CHO exocytosis during exercise.

Forty minutes after the resting blood sample (35 min after the snack), subjects began cycling at a power output estimated to be 70% of their predetermined V˙O2max. The exercise duration (60 min) and intensity used in this study were chosen to maintain consistency with our previously published papers (33, 34). The pedaling rate remained constant at 60 rpm throughout exercise, which consisted of two 30-min bouts separated by a 5- to 7-min rest period. Additional expired gas samples were collected throughout the exercise bout to ensure the proper work intensity, with the power output adjusted accordingly. The actual O2 consumption (V˙O2) during exercise was maintained at 67 ± 1% V˙O2max. Expired gas was collected in the second 30-min bout of exercise between minutes 12 and 17 and for the last 5 min; these values were then averaged and used for substrate calculations for each trial. Postexercise blood samples were collected at 60 min of exercise while subjects remained seated on the cycle ergometer.

Substrate utilization. Oxidation rates of fat and total CHO (CHOtotal) were calculated according to the following equations (21):

\[
\text{Fat (g/min) = } -1.70 \cdot \frac{\text{V˙CO}_2 \cdot (l/min) + 1.69 \cdot \text{V˙O}_2 \cdot (l/min)}{\text{CHO}_{\text{total}}} \quad (1)
\]

\[
\text{CHO}_{\text{total}} (g/min) = 4.59 \cdot \text{V˙CO}_2 \cdot (l/min) - 3.23 \cdot \text{V˙O}_2 \cdot (l/min) \quad (2)
\]

where V˙CO2 is CO2 production. The energy provided from fat and CHO oxidation was calculated from their energy potentials (9.75 kcal/g and 3.87 kcal/g, respectively). To measure the ratio of 13C/12C in expired CO2, a 20-ml syringe was used to draw a sample of the expired gas directly from the tube connecting the subject’s mouth piece to the metabolic cart during the last expired breath collection. Duplicate samples (10 ml) were emptied from the syringe into Vacutainer tubes (Becton Dickinson) and subsequently analyzed for the ratio of 13C/12C (BreathMat Plus, Finnigan MAT). CHOexo oxidation was calculated according to the equation modified from Mosora et al. (19):

\[
\text{CHO}_{\text{exo}} (g/min) = \text{V˙CO}_2 \cdot \left[ \frac{R_{\text{ref}} - R_{\text{exo}}}{R_{\text{exo}} - R_{\text{ref}}} \right] \frac{1}{k} \quad (3)
\]

where V˙CO2 (l/min) is in STPD, Rref is the isotopic composition of expired CO2 during CT, Rexo is the isotopic composition of expired CO2 during WT at the corresponding time point, Rexo is the isotopic composition of the CHOexo, and k (0.7426 l/g) is the volume of CO2 produced by the complete oxidation of 1 g of glucose. CHOendo oxidation was calculated by subtraction.

Hormone and metabolism analysis. Whole blood collected at rest was allowed to clot and then centrifuged at 2,000 g for 10 min. Serum was stored at −70°C until analyzed in duplicate for estradiol, which was used as an objective indication of pubertal status, using a commercially available RIA kit (cat. no. TKE21, Diagnostic Products). Growth hormone (GH) was measured in pre- and postexercise serum using a commercially available RIA kit (cat. no. KGHD1, Diagnostic Products). In our hands, the intra- and interassay CVs, respectively, were ≤8% and 12% for estradiol and ≤5 and 12% for GH.

Table 1. Subject characteristics

<table>
<thead>
<tr>
<th></th>
<th>YG (n = 12)</th>
<th>OG (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height, m</td>
<td>1.57±0.02</td>
<td>1.63±0.02*</td>
</tr>
<tr>
<td>Body mass, kg</td>
<td>46.6±2.2</td>
<td>58.2±1.6*</td>
</tr>
<tr>
<td>Body fat, %</td>
<td>18.8±1.9</td>
<td>22.6±1.7</td>
</tr>
<tr>
<td>Pubertal status</td>
<td>3 (2–5)</td>
<td>4 (3–5)*</td>
</tr>
<tr>
<td>Estradiol, pg/ml</td>
<td>88±15</td>
<td>157±29*</td>
</tr>
<tr>
<td>V˙O2max, l/min</td>
<td>1.93±0.11</td>
<td>2.32±0.09*</td>
</tr>
<tr>
<td>V˙CO2max, ml·kg⁻¹·min⁻¹</td>
<td>41±2</td>
<td>40±2</td>
</tr>
</tbody>
</table>

Values are means ± SE (pubertal status is reported as median and range). YG, 12-yr-old preadolescent girls; OG, 14-yr-old adolescent girls; V˙O2max, maximal oxygen uptake. *Significantly different from YG, P ≤ 0.05.
Whole blood collected at rest and at 60 min of exercise was treated with EDTA and reduced glutathione and centrifuged at 2,000 g for 10 min, and the plasma was stored at −70°C until analyzed for epinephrine (Epi) and norepinephrine (NE). Plasma catecholamines were analyzed by high-performance liquid chromatography with electrochemical detection as previously described (16). The intraclass correlation of this procedure is 0.96, representing very high reliability, and the extraction efficiency from plasma ranges between 80 and 85%. Whole blood collected before and immediately after exercise was also treated with EDTA and centrifuged at 2,000 g for 10 min. The plasma was stored at −50°C until analyzed for glucose and lactate concentrations enzymatically (2300L STAT, Yellow Springs Instruments). The intra- and interassay coefficients of variation for this assay were <1.5%.

Statistical analyses. Age differences in physical and fitness characteristics and CHOexo oxidation-related variables were tested by independent t-tests. Substrate utilization data were submitted to group × trial mixed-factorial ANOVAs. Metabolite and hormone data were submitted to group × trial × time mixed-factorial ANOVAs. Where appropriate, a Tukey’s post hoc test was used to determine significance among means. Statistica 5.0 (StatSoft, Tulsa, OK) was used for all statistical comparisons. Pearson correlations between substrate utilization, expressed as a percentage of total EE, and estradiol levels were also performed using GraphPad Prism 4.03 (GraphPad Software, San Diego, CA). The threshold for statistical significance was set at P ≤ 0.05, and data are presented as means ± SE, unless stated otherwise.

RESULTS

Hormones and metabolites (Tables 1 and 2). Serum estradiol levels (Table 1) were lower in YG than in OG (P < 0.05). Regardless of trial, GH, Epi, and NE increased in response to exercise (time effect, P < 0.05), but this response was not different between groups (group × trial × time effect, P ≥ 0.17). The GH response was greater during WT than CT (trial × time effect, P < 0.05). There were no intergroup differences in preexercise glucose in either trial (P ≥ 0.05). There was a trend for a group × trial × time interaction (P = 0.07) for lactate, with values higher in OG than YG during WT but not during CT.

RER (Fig. 1). RER values were lower during WT than CT in YG but remained similar between trials in OG (group × trial effect, P < 0.05). Overall, RER was lower during WT than CT (main effect of trial, P < 0.05) and lower in OG than in YG (main effect of group, P < 0.05).

Substrate utilization (Table 3, Fig. 2). Oxidation rates for fat, CHOtotal, CHOendo, and CHOexo (given in mg·kg⁻¹·min⁻¹) are presented in Table 3. Fat oxidation was higher during WT than CT in YG but remained similar between trials in OG (group × trial effect, P < 0.05). CHOtotal oxidation was lower during WT than CT in OG but remained similar between trials in OG (group × trial effect, P < 0.05). Overall, fat and CHOtotal oxidation was higher and lower, respectively, during WT than CT (P < 0.05). There was a near-significant group × trial effect for CHOendo oxidation rate (P = 0.07). Overall, CHOendo oxidation was higher during WT than CT (P < 0.05). There were no intergroup differences (P = 0.47) in the isotopic composition of expired CO₂, but breath enrichment was greater during CT (−13.0 ± 0.5‰ [δ-13C]PDB-1) than WT (−21.6 ± 0.2‰ [δ-13C]PDB-1) (P < 0.05). CHOexo oxidation rates were similar (P = 0.67) between YG and OG at −7 mg·kg⁻¹·min⁻¹. To highlight the relationship between CHOexo and CHOendo oxidation during exercise, the ratio of CHOexo to CHOendo oxidation was calculated and compared among groups. This ratio provides comparable information to that of ratio between CHOexo and CHOtotal oxidation, as previously reported (28), but provides a clearer representation of the balance between exogenous and endogenous (muscle and liver glycogen) CHO utilization during exercise (34). There was no significant difference between YG (0.31 ± 0.03) and OG (0.26 ± 0.02) for this ratio (P = 0.20). The relative contributions of fat, CHOendo, and CHOexo to total EE during the last 15 min of exercise are presented in Fig. 2. The contribution of fat was higher during WT than CT in YG but remained constant between trials in OG (group × trial effect, P < 0.05). The

![Fig. 1. Respiratory exchange ratio (RER) during last 15 min of exercise in water (WT) and carbohydrate trials (CT) in 12-yr-old preadolescent (YG) and 14-yr-old adolescent girls (OG). Values are means ± SE. Main effects for group (P < 0.05) and trial (P < 0.05), as well as a group by trial interaction (P < 0.05), were found. *Significantly different from YG in same trial, P < 0.05. †Significantly different from WT in same group, P < 0.05.](http://jap.physiology.org/DownloadedFrom)
The purpose of this study was to characterize substrate utilization during exercise performed with and without CHOexo in healthy girls. Whether from the pediatric or adult literature, the majority of exercise metabolism data is derived from male participants. This study is therefore one of only a few to focus on females and the first to incorporate a measure of CHOexo oxidation in exercising girls. Our findings confirm higher fat and lower CHOendo oxidation rates during exercise in young children compared with older adolescents and adults (9, 14, 15, 17, 26, 30, 33, 34). However, in contrast to our previous findings of age-related differences in CHOexo oxidation in boys (34), the reliance on CHOexo oxidation was not different between YG and OG.

A more than twofold higher rate of fat oxidation during exercise performed without CHOexo in YG compared with their OG counterparts (Table 3) is consistent with our previous findings comparing 12- and 14-yr-old boys (34). Thus, compared with older adolescents, younger children have considerably higher rates of fat oxidation during exercise. Higher fat oxidation rates are also observed in women compared with men (32), and acute estrogen supplementation in men increases oxidation rates in women compared with men (32), and acute estrogen supplementation in men increases fat oxidation toward a female profile (10), indicating that an elevated estrogen level may alter the balance of fat and CHO oxidation, as a percentage of total EE, including all girls. The strongest association was found for CHOendo oxidation during exercise. However, our results do not entirely support a role for estrogen because the girls in YG experienced the highest fat oxidation rates despite having ~50% lower serum estradiol concentrations, and, in all girls, the degree of fat oxidation was inversely related to estradiol concentration. It is clear, therefore, that factors other than estrogen promote high rates of fat oxidation in young girls. Increases in serum GH during exercise, for example, are smaller in women than in men (37), and GH is thought to induce lipolysis and mobilization of fatty acids during exercise (4). In the present study, the GH response to exercise was

### Table 3. Substrate utilization during last 15 min of exercise in water and carbohydrate trials in preadolescent and adolescent girls

<table>
<thead>
<tr>
<th>Fat Oxidation</th>
<th>CHOendo Oxidation</th>
<th>CHOexO Oxidation</th>
<th>CHOexo Oxidation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WT</td>
<td>CT</td>
<td>WT</td>
</tr>
<tr>
<td></td>
<td>WT</td>
<td>CT</td>
<td>WT</td>
</tr>
<tr>
<td>YG</td>
<td>3.6±0.7</td>
<td>1.8±0.4†</td>
<td>22.6±2.9</td>
</tr>
<tr>
<td>OG</td>
<td>1.5±0.4*</td>
<td>1.1±0.6</td>
<td>32.4±2.8*</td>
</tr>
</tbody>
</table>

Values are mean ± SE given in mg·kg body mass⁻¹·min⁻¹. Fat, total fat; CHOendo, total carbohydrate; CHOendo, endogenous carbohydrate; CHOexo, exogenous carbohydrate. †Significantly different from YG, P < 0.05. *Significantly different from WT, P < 0.05.

### DISCUSSION

The purpose of this study was to characterize substrate utilization during exercise performed with and without CHOexo in healthy girls. Whether from the pediatric or adult literature, the majority of exercise metabolism data is derived from male participants. This study is therefore one of only a few to focus on females and the first to incorporate a measure of CHOexo oxidation in exercising girls. Our findings confirm higher fat and lower CHOendo oxidation rates during exercise in young children compared with older adolescents and adults (9, 14, 15, 17, 26, 30, 33, 34). However, in contrast to our previous findings of age-related differences in CHOexo oxidation in boys (34), the reliance on CHOexo oxidation was not different between YG and OG.

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### Table 4. Pearson correlations between substrate utilization (% of total EE) and estradiol levels in all girls (OG and YG; n = 22)

<table>
<thead>
<tr>
<th></th>
<th>WT</th>
<th>CT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>P</td>
</tr>
<tr>
<td>Fat oxidation</td>
<td>−0.50</td>
<td>0.03*</td>
</tr>
<tr>
<td>CHOtotal Oxidation</td>
<td>0.50</td>
<td>0.03*</td>
</tr>
<tr>
<td>CHOendo Oxidation</td>
<td>0.50</td>
<td>0.03*</td>
</tr>
<tr>
<td>CHOexo Oxidation</td>
<td>−0.09</td>
<td>0.71</td>
</tr>
</tbody>
</table>

EE, energy expenditure; r, Pearson correlation coefficient; P, probability value. *Statistical significance, P < 0.05.
similar between the YG and OG (Table 2), suggesting that this lipolytic hormone did not play a role in our findings. Catecholamines can also influence glycogenolysis and fatty acid mobilization during exercise, and there is evidence for sex differences in these hormone responses to exercise in adults (5), but there were no differences between groups in either epinephrine or norepinephrine responses in this study (Table 2). Given the lack of differences in catecholamines and GH, it is possible that the greater reliance on fat oxidation during exercise in YG may be due to differences in other lipolytic hormones, such as glucocorticoids, or perhaps differences in enzyme activity within the contracting muscle. These potential differences between YG and OG require further consideration.

In an early study (7), phosphofructokinase, the rate-limiting enzyme in glycolysis, was reported to be lower in children compared with adults. Although these data were derived from only five boys at rest, and age-related variation in this enzyme has not been substantiated by subsequent studies (2, 6, 11), the work of Eriksson (7) led to a commonly held belief that children possess a relatively underdeveloped glycolytic system (1). Other studies have measured lactate dehydrogenase in muscle and found lower activity in children compared with adults (12), higher activity in 13-yr-old children compared with younger children (6 yr old) or older adolescents (17 yr old) (2), or similar activity between adolescents and adults (11). Given the clear discrepancies in muscle enzyme data and because the 12-yr-old girls tested in this study demonstrated a similar capacity to utilize CHOexo compared with the 14-yr-old girls, we do not believe that children possess an underdeveloped glycolytic capacity. In previous studies, we have found the rate of CHOexo oxidation to be, in fact, higher in 9- to 10-yr-old boys compared with adult male (33) and compared with 12- vs. 14-yr-old boys (34), further supporting our notion that the ability to utilize glucose in skeletal muscle is not impaired in young children. Whether enzyme activities of the tricarboxylic acid cycle or β-oxidation are higher in the younger children is not clear, but these enzymes have been found to be comparable (7, 12) or even higher (2, 11) in children than those reported for adults.

The most novel finding in this study is that the contribution of CHOexo to total EE and the balance between exogenous and endogenous CHO utilization during exercise were not different between YG and OG. In contrast, we recently reported that the reliance on CHOexo oxidation was higher in 12-yr-old compared with 14-yr-old boys (34), indicating a greater relative conservation of glycogen in the younger boys. It has been reported in boys that both resting muscle glycogen content and the rate of muscle glycogenolysis during exercise performed without CHOexo increase with testicular volume, a marker of pubertal status, during childhood (8). Indeed, our male data support this finding insofar as the ratio of CHOexo to CHOendo oxidation was also lower in less mature compared with more mature boys who were all at the same chronological age (34). The fact that there was only a small, albeit statistically significant, gap in pubertal status between the girls in the YG and OG groups in the present study (Tanner 3 vs. Tanner 4, respectively) may explain, in part, the lack of difference between groups in the reliance on CHOexo and the ratio of CHOexo to CHOendo oxidation. Consistent with this possibility is the finding that lactate levels were generally similar between the groups of girls during the CHO trial, as the lactate response to exercise tends to be greater in more mature individuals (1). In addition, these observations suggest that the presence of estrogen does not influence CHOexo oxidation, at least in youth. Therefore, it will be important to further elucidate the impact of pubertal status, rather than age per se, on the balance of exogenous and endogenous sources of fuel during exercise in girls.

Given the direct relationship between resting muscle glyco- gen content and its utilization during exercise observed in adults (3), we speculated that age-related differences in the reliance on CHOendo oxidation previously observed in boys (34) is due to lower initial muscle glycogen levels rather than a reduced capacity to utilize glycogen. We therefore suggest that a similar phenomenon occurs in girls, as indicated by the present results. Consequently, children may compensate for reduced muscle glycogenolysis by increasing their reliance on extramuscular sources of fuel (e.g., adipose-derived free fatty acids, liver gluconeogenesis, or CHOexo when available). Given the lack of age differences in CHOexo oxidation among the girls in this study, it remains possible that regulation of extramuscular fuel mobilization during exercise is different between boys and girls. Additional evidence that regulation of fuel mobilization may be different in boys and girls is based on our finding that CHOexo reduced fat oxidation in YG but not in OG, whereas the effect was similar in young compared with older boys (34). Additional studies using minimally invasive stable isotope methodology should help to clarify these points.

In summary, CHOexo intake reduced fat oxidation in YG but did not alter fat oxidation in OG. Despite these effects on fat oxidation, the contribution of CHOexo to total EE was not different between the YG and OG groups. These findings are in contrast to previous studies with boys in which the reliance on CHOexo during exercise was shown to be particularly sensitive to pubertal status, and there were no age-related differences in endogenous fuel sparing with CHOexo intake. These novel findings highlight the notion that sex differences exist in substrate utilization during exercise even in childhood. In addition, our data do not support the idea of underdeveloped glycolytic flux in children but rather an underdeveloped depot of intramuscular fuels.

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GRANTS

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