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Fat oxidation rate and the exercise intensity that elicits maximal fat oxidation decreases with pubertal status in young male subjects

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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/jappphysiol.00018.2007.— Little information is available on energy metabolism during exercise in girls, particularly the contribution of exogenous carbohydrate (CHO_{exo}). The purpose of this study was to determine substrate utilization during exercise with and without CHO_{exo} intake in healthy girls. Twelve-yr-old preadolescent (YG; *n* = 12) and 14-yr-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 (V_{O₂max}). Substrate utilization was calculated for the final 15 min of exercise. CHO_{exo} 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). CHO_{exo} 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 CHO_{exo} oxidation (*r* = -0.09, *P* = 0.71). We conclude that CHO_{exo} influences endogenous substrate utilization in an age-dependent manner in healthy girls but that total CHO_{exo} 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.

children; cycling; energy metabolism; stable isotope tracers

SUBSTRATE UTILIZATION during exercise differs markedly between children and adults. Children rely more on endogenous fat and less on endogenous carbohydrate (CHO_{endo}) oxidation compared with adults (9, 15, 17, 26, 30, 33), and this pattern of fuel selection is similar to that observed in women compared with men (32). Adult studies have targeted sex hormones as potential mediators of these differences in substrate utilization (5), with strong evidence that elevated estrogen levels increase fat oxidation and decrease CHO_{endo} oxidation at the whole body level (10). The mechanisms underlying child-adult differences, however, remain less clear, and few studies have investigated substrate utilization during exercise in girls, in whom estrogen levels increase with normal growth and development. Although some studies report a lower respiratory exchange ratio (RER) in prepubertal girls compared with adult women (17) and an increased RER with increasing age during

submaximal exercise (14), another study did not show age-related differences in RER in girls (27). Given these discrepancies in the available literature, further study of fat and CHO_{endo} oxidation during exercise in girls of different ages is warranted.

To further explore the impact of growth and development on energy metabolism during exercise, we have employed ¹³C stable isotope methodology in healthy boys and in boys with insulin-dependent diabetes mellitus (22–24, 33, 34). This technique, which provides quantification of exogenous carbohydrate (CHO_{exo}) and CHO_{endo} oxidation, is safe and noninvasive and therefore appealing for use in children. Using this approach, it has been found that, compared with adult men, pre- and early-pubertal boys exhibit a higher rate of CHO_{exo} oxidation (33) and that advanced pubertal status, independently of chronological age, reduces the contribution of CHO_{exo} oxidation to total energy expenditure (34). These findings were somewhat surprising because a common view in pediatric exercise physiology is that children possess an underdeveloped glycolytic capacity and are, therefore, “immature” in their ability to oxidize glucose in skeletal muscle (1). Despite the new information gained from our studies with ¹³C-labeled CHO, a significant limitation of these studies was that they were exclusively conducted with male participants. Only a few studies have been conducted that examine CHO_{exo} oxidation rates during exercise in adult females, but none with young girls. The available adult studies report a similar (13, 36) or slightly higher (25) contribution of CHO_{exo} oxidation to total energy expenditure (EE) in women compared with men. Whether the presence of sex steroids influences the reliance on CHO_{exo} oxidation during exercise remains unclear. On the basis of the above adult studies, it has been suggested that, compared with men, women may derive at least as much benefit from consuming CHO_{exo} during athletic competition (36). Whether this possibility also holds true in young girls is not known, but we have shown that CHO_{exo} supplementation improves endurance performance in boys (24). If similar age-related differences in CHO_{exo} oxidation exist in girls as they do in boys (34), this information would be important for age- and sex-specific dietary recommendations for sport and athletic performance.

The purpose of this study was therefore to characterize substrate utilization during exercise performed with and without CHO_{exo} in healthy preadolescent and adolescent girls. To achieve this objective, we employed an established protocol of endurance exercise and ¹³C stable isotope methods. On the

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basis of our previous findings of higher fat and CHO_{exo} 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 CHO_{exo} 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 metabolite analysis*). Table 1 provides the subjects' characteristics.

Preliminary session. During this visit, height, mass, percent body fat (bioelectric impedance 101A, RJL Systems, Clinton, MI), and stage of breast development were determined. Maximal aerobic power ($\dot{V}O_{2max}$) of each girl was then assessed on a cycle ergometer (Ergo-med 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 four of the girls in the YG group, we did not attempt to test these girls at a particular time. Nutrient intake and physical activity over the 2 days before both experimental trials were standardized by having the girls repeat the same nutrient intake and physical activity. Strenuous exercise was also avoided for these 2 days. Corn products or food derived from plants with the C₄ photosynthetic cycle was avoided to reduce background enrichment of expired CO₂ from naturally derived ¹³C (29). Subjects arrived to the laboratory at the same time on the day of testing in a ~10-h fasted state. An indwelling venous catheter (Becton Dickinson) was placed in either an arm or a hand, followed by 10 min of supine rest before the preexercise blood sample was drawn (~40 min before the start of exercise). Subjects then consumed a small breakfast with their first drink (12 ml/kg body mass) to standardize preexercise nutrition. This snack, consumed within 3–5 min, consisted of one slice of toast with sugar-free jam (~90 kcal) for girls in the YG group and twice this for the OG group; this approach is consistent with our previously published work (33, 34). Volumes of

4 ml/kg body mass were subsequently consumed at 15-min intervals throughout exercise. This drinking schedule is similar to that used in our previous studies (33, 34). In the CHO trial (CT), subjects consumed 28 ml/kg body mass of a 6% CHO-electrolyte solution (4% sucrose, 2% glucose, ~18 mM Na⁺, ~3 mM K⁺), and in the water trial (WT), an identical volume of flavored water (identical in flavor, sweetness, and electrolyte concentration, but without CHO) was consumed. Both beverages were prepared in powder form by the Gatorade Sports Science Institute (Barrington, IL). The CHO drink was artificially enriched with uniformly labeled [¹³C]glucose to an isotopic composition of +10.0 change per 1,000 difference vs. the ¹³C/¹²C ratio from the international standard ¹³C Pee Dee Belemnite-1 (+10.0‰[δ-¹³C]PDB-1). This value was determined using gas chromatography-mass spectrometry. Previous work by us (23, 24) and others (20) shows that the use of [¹³C]glucose rather than ¹³C-labeled glucose/sucrose as a tracer is quite reasonable, given the similar oxidation rates of these carbohydrates 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 $\dot{V}O_{2max}$. 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 ($\dot{V}O_2$) during exercise was maintained at $67 \pm 1\%$ $\dot{V}O_{2max}$. 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 (CHO_{total}) were calculated according to the following equations (21):

$$\text{Fat (g/min)} = -1.70 \cdot \dot{V}CO_2 \text{ (l/min)} + 1.69 \cdot \dot{V}O_2 \text{ (l/min)} \quad (1)$$

$$\text{CHO}_{\text{total}} \text{ (g/min)} = 4.59 \cdot \dot{V}CO_2 \text{ (l/min)} - 3.23 \cdot \dot{V}O_2 \text{ (l/min)} \quad (2)$$

where $\dot{V}CO_2$ 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). CHO_{exo} oxidation was calculated according to the equation modified from Mosora et al. (19):

$$\text{CHO}_{\text{exo}} \text{ (g/min)} = \dot{V}CO_2 [(R_{\text{exp}} - R_{\text{ref}})/R_{\text{exo}} - R_{\text{ref}}] (1/k) \quad (3)$$

where $\dot{V}CO_2$ (l/min) is in STPD, R_{exp} is the isotopic composition of expired CO₂ during CT, R_{ref} is the isotopic composition of expired CO₂ during WT at the corresponding time point, R_{exo} is the isotopic composition of the CHO_{exo}, and k (0.7426 l/g) is the volume of CO₂ produced by the complete oxidation of 1 g of glucose. CHO_{endo} oxidation was calculated by subtraction.

Hormone and metabolite 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, are ≤8 and 8% for estradiol and ≤5 and 12% for GH.

Table 1. Subject characteristics

	YG ($n = 12$)	OG ($n = 10$)
Height, m	1.57±0.02	1.63±0.02*
Body mass, kg	46.6±2.2	58.2±1.6*
Body fat, %	18.8±1.9	22.6±1.7
Pubertal status	3 (2–5)	4 (3–5)*
Estradiol, pg/ml	88±15	157±29*
$\dot{V}O_{2max}$, l/min	1.93±0.11	2.32±0.09*
$\dot{V}O_{2max}$, ml·kg ⁻¹ ·min ⁻¹	41±2	40±2

Values are means ± SE (pubertal status is reported as median and range). YG, 12-yr-old preadolescent girls; OG, 14-yr-old adolescent girls; $\dot{V}O_{2max}$, maximal oxygen uptake. *Significantly different from YG, $P \leq 0.05$.

Whole blood collected at rest and at 60 min of exercise was treated with EGTA 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 CHO_{exo} oxidation-related variables were tested by independent *t*-tests. Substrate utilization data were submitted to group \times trial mixed-factorial ANOVAs. Metabolite and hormone data were submitted to group \times trial \times 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 $P \leq 0.05$, and data are presented as means \pm 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 \times trial \times time effect, $P \geq 0.17$). The GH response was greater during WT than CT

Table 2. Hormone and metabolite responses to exercise in water and carbohydrate trials in preadolescent and adolescent girls

	WT		CT	
	Preexercise	Postexercise	Preexercise	Postexercise
<i>Growth hormone, ng/ml*†</i>				
YG	0.7 \pm 0.1	17.7 \pm 2.9	0.7 \pm 0.1	9.8 \pm 2.0
OG	1.3 \pm 0.5	14.5 \pm 1.9	1.6 \pm 0.5	9.6 \pm 2.4
<i>Epinephrine, pg/ml*</i>				
YG	40 \pm 5	73 \pm 18	44 \pm 9	88 \pm 15
OG	28 \pm 7	74 \pm 10	28 \pm 7	124 \pm 26
<i>Norepinephrine, pg/ml*</i>				
YG	284 \pm 31	561 \pm 94	241 \pm 27	678 \pm 70
OG	236 \pm 28	918 \pm 260	267 \pm 39	995 \pm 177
<i>Glucose, mmol/l†</i>				
YG	5.0 \pm 0.1	5.0 \pm 0.1	4.9 \pm 0.1	5.4 \pm 0.2
OG	4.7 \pm 0.2	5.1 \pm 0.2	4.7 \pm 0.2	5.8 \pm 0.3
<i>Lactate, mmol/l*†</i>				
YG	1.2 \pm 0.1	1.6 \pm 0.2	1.2 \pm 0.1	2.3 \pm 0.2
OG	1.0 \pm 0.1	2.6 \pm 0.4	1.0 \pm 0.1	2.6 \pm 0.4

Values are mean \pm SE. WT, water trial; CT, carbohydrate trial; Preexercise, 40 min before exercise; Postexercise, immediately after exercise. *Main effect of time, $P < 0.05$. †Trial \times time interaction, $P < 0.05$.

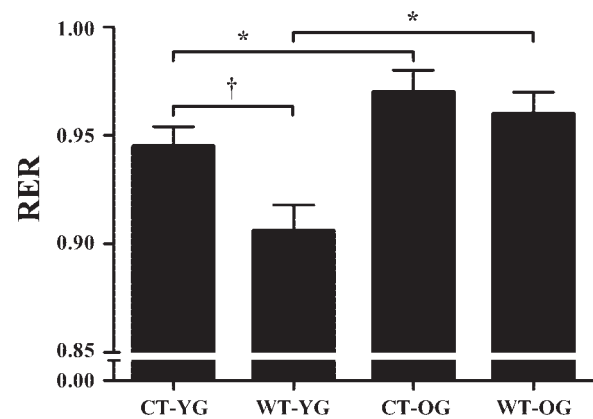


Fig. 1. Respiratory exchange ratio (RER) during last 15 min of exercise in water (WT) and carbohydrate trials (CT) in 12-yr-old preadolescent (YG) and 14-yr-old adolescent girls (OG). Values are means \pm SE. Main effects for group ($P < 0.05$) and trial ($P < 0.05$), as well as a group by trial interaction ($P < 0.05$), were found. *Significantly different from YG in same trial, $P < 0.05$. †Significantly different from WT in same group, $P < 0.05$.

(trial \times time effect, $P < 0.05$). There were no intergroup differences in preexercise glucose in either trial ($P \geq 0.60$). There was a trend for a group \times trial \times 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 \times trial effect, $P < 0.05$). Overall, RER was lower during WT than CT (main effect of trial, $P < 0.05$) and lower in YG than in OG (main effect of group, $P < 0.05$).

Substrate utilization (Table 3, Fig. 2). Oxidation rates for fat, $\text{CHO}_{\text{total}}$, CHO_{endo} , and CHO_{exo} (given in $\text{mg}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) are presented in Table 3. Fat oxidation was higher during WT than CT in YG but remained similar between trials in OG (group \times trial effect, $P < 0.05$). $\text{CHO}_{\text{total}}$ oxidation was lower during WT than CT in YG but remained similar between trials in OG (group \times trial effect, $P = 0.05$). Overall, fat and $\text{CHO}_{\text{total}}$ oxidation was higher and lower, respectively, during WT than CT ($P < 0.05$). There was a near-significant group \times trial effect for CHO_{endo} oxidation rate ($P = 0.07$). Overall, CHO_{endo} oxidation was higher during WT than CT ($P < 0.05$). There were no intergroup differences ($P = 0.47$) in the isotopic composition of expired CO_2 , but breath enrichment was greater during CT ($-13.0 \pm 0.5\%$ [$\delta\text{-}^{13}\text{C}$]PDB-1) than WT ($-21.6 \pm 0.2\%$ [$\delta\text{-}^{13}\text{C}$]PDB-1) ($P < 0.05$). CHO_{exo} oxidation rates were similar ($P = 0.67$) between YG and OG at $\sim 7 \text{ mg}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. To highlight the relationship between CHO_{exo} and CHO_{endo} oxidation during exercise, the ratio of CHO_{exo} to CHO_{endo} oxidation was calculated and compared among groups. This ratio provides comparable information to that of the ratio between CHO_{exo} and $\text{CHO}_{\text{total}}$ 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, CHO_{endo} , and CHO_{exo} 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 \times trial effect, $P < 0.05$). The

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

	Fat Oxidation		CHO _{total} Oxidation		CHO _{endo} Oxidation		CHO _{exo} Oxidation	
	WT	CT	WT	CT	WT	CT	WT	CT
YG	3.6±0.7	1.8±0.4†	22.6±2.9	31.3±2.0†	22.6±2.9	24.1±1.8	7.1±0.5	
OG	1.5±0.4*	1.1±0.6	32.4±2.8*	34.4±2.8	32.4±2.8*	27.6±2.6*†	6.8±0.4	

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

contribution from CHO_{endo} remained constant between trials in YG but was higher during WT than CT in OG (group × trial effect, $P < 0.05$). Overall, the contribution of fat and CHO_{endo} was higher during WT than CT ($P < 0.05$). The contribution from CHO_{exo} was similar ($P = 0.44$) between YG and OG at ~19%.

Correlations (Table 4). To further investigate the influence of pubertal status on substrate utilization, we performed Pearson correlations between estradiol levels, as an objective marker of pubertal status, and the contribution of fat and CHO oxidation, as a percentage of total EE, including all girls. The strongest association was found for CHO_{endo} oxidation during CT as a percentage of total EE ($r = 0.63$, $P < 0.05$).

DISCUSSION

The purpose of this study was to characterize substrate utilization during exercise performed with and without CHO_{exo} 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 CHO_{exo} oxidation in exercising girls. Our findings confirm higher fat and lower CHO_{endo} 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 CHO_{exo} oxidation in boys (34), the reliance on CHO_{exo} oxidation was not different between YG and OG.

A more than twofold higher rate of fat oxidation during exercise performed without CHO_{exo} 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 fat oxidation toward a female profile (10), indicating that an elevated estrogen level may alter the balance of fat and CHO_{endo} 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

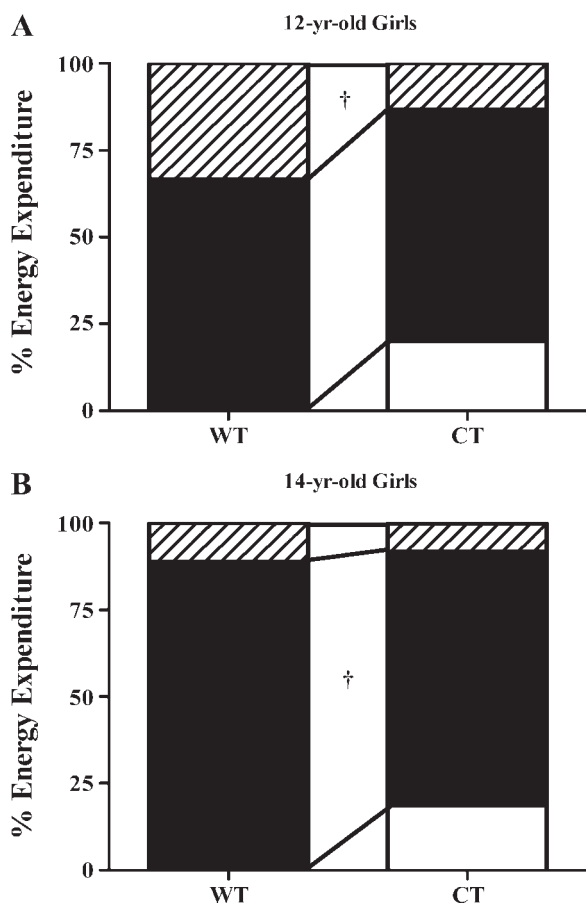


Fig. 2. Percent of energy expenditure derived from substrate during last 15 min of exercise in 12-yr-old preadolescent (A) and 14-yr-old adolescent girls (B). Hatched bars, fat oxidation; solid bars, endogenous carbohydrate (CHO_{endo}) oxidation; open bars, exogenous carbohydrate (CHO_{exo}) oxidation. †Significantly different from WT in same group, $P < 0.05$.

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

	WT		CT	
	R	P	r	P
Fat oxidation	-0.50	0.03*	-0.59	0.005*
CHO _{total} oxidation	0.50	0.03*	0.59	0.005*
CHO _{endo} oxidation	0.50	0.03*	0.63	0.002*
CHO _{exo} oxidation			-0.09	0.71

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 CHO_{exo} 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 CHO_{exo} 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 CHO_{exo} 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 CHO_{exo} 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 CHO_{exo} increase with testicular volume, a marker of pubertal status, during childhood (8). Indeed, our male data support this finding insofar as the ratio of CHO_{exo} to CHO_{endo} 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 CHO_{exo} and the ratio of CHO_{exo} to CHO_{endo} 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 CHO_{exo} 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 glycogen content and its utilization during exercise observed in adults (3), we speculated that age-related differences in the reliance on CHO_{endo} 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 CHO_{exo} when available). Given the lack of age differences in CHO_{exo} 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 CHO_{exo} 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, CHO_{exo} intake reduced fat oxidation in YG but did not alter fat oxidation in OG. Despite these effects on fat oxidation, the contribution of CHO_{exo} 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 CHO_{exo} during exercise was shown to be particularly sensitive to pubertal status, and there were no age-related differences in endogenous fuel sparing with CHO_{exo} 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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