Carbohydrate intake considerations for young athletes

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Abstract

Good nutritional practices are important for exercise performance and health during all ages. Athletes and especially growing children engaged in heavy training have higher energy and nutrient requirements compared to their non-active counterparts. Scientific understanding of sports nutrition for the young athlete is lacking behind the growing number of young athletes engaged in sports. Most of the sports nutrition recommendations given to athletic children and adolescents are based on adult findings due to the deficiency in age specific information in young athletes. Therefore, this review reflects on child specific sports nutrition, particularly on carbohydrate intake and metabolism that distinguishes the child athlete from the adult athlete. Children are characterised to be in an insulin resistance stage during certain periods of maturation, have different glycolytic/metabolic responses during exercise, have a tendency for higher fat oxidation during exercise and show different heat dissipation mechanisms compared to adults. These features point out that young athletes may need different nutritional advice on carbohydrate for exercise to those from adult athletes. Sport drinks for example may need to be adapted to children specific needs. However, more research in this area is warranted to clarify sports nutrition needs of the young athlete to provide better and healthy nutritional guidance to young athletes.

Key words: Exercise, diet, nutrients, children, sport drinks.

Introduction

Captain Barclay who in 1809 walked 1000 miles in 1000 hours described how a training diet should be: "*Animal diet is alone prescribed, and beef and mutton are preferred. Biscuit and stale bread are the only preparations of vegetable matter, which are permitted. Vegetables are never given as they are watery and of difficult digestion. Fish must be avoided. Salt, spices, and all kind of seasonings, with exception of vinegar, are prohibited. Liquors must always be taken cold, and home brewed beer, old but not bottled, is best. Water is never given alone. It is an established rule to avoid liquids as much as possible*" excerpt from Thorn (1813) cited by Maughan and Burke (2000). Nearly 200 years later carbohydrates (CHO) have *conquered* proteins and specific carbohydrate guidelines for endurance sports have been published for adult athletes (Burke 2000) and updated by the Working Group on Sports Nutrition of the IOC (Burke et al., 2004). Despite the wide number of studies evaluating performance enhancement of carbohydrates in adults, there is a lack of sufficient evidence to apply these guidelines to the paediatric athletic population.

Although it is possible to speculate on similar glycogen depletion mechanisms in adults compared to young athletes, there is little evidence to support it. Moreover, the paediatric sports science literature reveals increasingly more differences between adult and children's exercise physiology. Thus, in children and adolescents it is not known whether the additional energy expenditure from exercise needs to be compensated by an overall equal increase in all macronutrients. Neither is it known that an increase in specific nutrients such as carbohydrate, fat or protein, or an increase in carbohydrate intake is positively related to performance enhancement. Since no child specific evidence is available, some authors have adventured to recommend for young athletes the same 50 - 55 % carbohydrate intake of total energy as for normal active children (Bass and Inge, 2000; Petrie et al., 2004). The American Dietetic Association (A.D.A., 1996b) in their statement for the child athlete refrains from giving any specific guidelines on amounts of carbohydrate or protein intakes. It states "*the key message of variety, balance, and moderation in food choices should be promoted … … Helping children to establish healthful eating patterns will give them a solid foundation to build on during adolescence*". Whereas for the adolescent athlete, it puts forward the following statement: "*To meet nutrition needs for physical activity and health, the training diet should provide about 55 % to 60 % of total energy from carbohydrate,....*" (A.D.A. 1996a). Unfortunately, 10 years after ADA's statement on the carbohydrate intake for the paediatric population, research has not advanced.

There are an increasing number of junior athletes involved in high training loads. Good nutritional practice is important for health and exercise performance during all ages, especially during growth. The transition from childhood to adolescent and to adulthood involves important physiologic and metabolic changes. Growth and the energy expenditure arising from exercise unquestionably influence the dietary needs of children and adolescent athletes with protein as the most important nutrient for growth. However, the intake of this nutrient does not appear to be limited in young athletes (Fogelholm et al., 2000).

Paediatric exercise scientists and nutritionists are still undecided by questions such as: how much is the habitual CHO intake of the young athlete? Does the CHO intake for example adjust to the sport practiced? How does the endogenous and exogenous CHO oxidation in children compare to that of adults during exercise? Should we recommend adults' CHO intake guidelines or sport drinks? If so, should the same concentration of commercial sport drinks be used as adults? If carbohydrate supplementation in adults during prolonged exercise does enhance endurance capacity (Martinez and Haymes,

1992; Timmons et al., 2003), why should it be different in young athletes? Or perhaps fat intake may have a major role in the young athletic population since fat appears to be the preferred fuel for oxidation during exercise during the transition from childhood to adulthood (Boisseau and Delamarch, 2000).

Potential reasons to consider age or perhaps maturation related CHO recommendations, arise from the metabolic and physiologic differences compared to adults such as: higher risk of heat-related illness, reduced enzymatic activity, e.g. lower PFK activity in children, glycogen differences, insulin resistance, greater fat oxidation during prolonged exercise, lower endogenous but greater exogenous carbohydrate oxidation rates.

Thus, this review will focus on the emerging field in paediatric sports nutrition, specifically, related to carbohydrate intake for exercise in the paediatric population.

Carbohydrate intake in young athletes

According to Burke et al. 2001) nutritional surveys indicate a slight increase in the carbohydrate consumption in the last decade with male athlete's ingestion accounting for approximately 7.6 g·kg^{-1} and female's intake 5.8 g·kg^{-1}. Longitudinal surveys on energy and CHO intake in young athletes are few. The few nutritional surveys in the paediatric population are cross-sectional, ranging in ages from 12 to 18 years, and without consideration on the maturity stage. Data on children athletes show that male's CHO intake may vary between 6 and 9 g·kg^{-1} (Chen et al., 1989; Leblanc et al., 2002; Montfort-Steiger, 2005) whereas females average intakes appear to be lower, around 3 to 5.5 g·kg^{-1} (Cupisti et al., 2002; Papadopoulou et al., 2002; Wiita et al., 1996). From cross sectional observations in our laboratory of a group of 15-17 y adolescent male cyclists (unpublished data), CHO intakes were higher compared to other nutrition surveys of young athletes, namely 7.5 ± 2 g·kg^{-1}·d^{-1} (492 ± 12 g·d^{-1}). Longitudinal nutrient intake assessments are needed to estimate the macronutrients shift in relation to body changes. Leblanc et al. (2002) reported the energy intake of 19 young French soccer players who were followed up for three years starting at age 13. Average energy intake increased by 2 MJ (480 kcal) from 13 to 14 years and then by 0.4 MJ (95 kcal) more by the age of 15 years. The absolute average daily CHO intake significantly increased from 320 ± 54 g to 360 ± 36 g and to 396 ± 81 g between ages 13, 14 and 15, respectively. However, as body mass increased, carbohydrate intake per body mass did not increase throughout the years: 6.5 g·kg^{-1}·d^{-1}, 6.8 g·kg^{-1}·d^{-1} and 6.4 g·kg^{-1}·d^{-1}, respectively. Thus, the observed increases in absolute amounts of CHO did not appear to be related to a natural response of body weight increases.

Glycolytic capacity

Data from mixed studies in children and adolescents under resting and exercising conditions point to different nutrient oxidation routes compared to adults. Accordingly, the carbohydrate and fat oxidation during exercise may be different to adults and consequently, the carbohydrate guidelines for adult athletes may not apply to younger athletes, or perhaps the commercial sport drinks should be adjusted in their nutrient content to child specific requirements. Certainly, there is a lack of sufficient information to support age specific guidelines, however efforts should be taken to investigate this issue for this population group.

Data that support the suggestion to rethink that nutrition recommendations should be age (or maturity) related come from the different metabolic pathways observed in children and compared to adults. Lower blood lactate concentrations [BLa$^-$] have been found in prepubertal children compared to adults at the same relative submaximal and maximal exercise intensities (Armstrong and Welsman, 1994). Higher lactate thresholds (LT) have been reported in children 9 to 11 years compared to adults (Martinez and Haymes, 1992). Or, post peak VO$_2$ blood lactate levels appear to increase with age, yet other longitudinal studies have not supported this view (Armstrong and Welsman, 1994). Based on the studies by Eriksson and colleagues (1980), the lower blood lactate levels may be related to a lower capacity for lactate production. The rate-limiting enzyme for glycolysis namely phosphofructokinase (PFK) was observed to be lower in children than in adults, increased with training (Eriksson, 1980), and was found to be age dependent (Berg and Keul, 1988). However, the group led by Haralambie and colleagues have failed to identify differences in glycolytic enzymes in children and adolescents (Armstrong and Welsman, 1994).

Measurement of glycogen depletion has been restricted by its unethical and invasive approach. Nonetheless, glycogen depletion in children was firstly studied in the late sixties by (Eriksson et al., 1971). The work by Eriksson although innovative, was limited by a small sample size and a diverse range of maturity stages between boys (8 boys, 13 to 15 y who had muscle biopsies taken when admitted to hospital for minor surgical interventions). Despite these limitations, these authors have been the main referenced source for muscle metabolism in children. After a maximal ergometer test to exhaustion they found similar creatine phosphate (CP) and ATP levels in boys (11 to 13 years) compared to adults, but lower muscle lactate concentrations. Children had on average a muscle glycogen concentration of 69 mmol glucose units·kg^{-1} wm at rest and decreased to 34 mmol·kg^{-1} after the maximal aerobic test (Eriksson et al., 1971). The younger boys (~ 11.5 y) appeared to have lower glycogen concentrations (~ 55 mmol glucose units·kg^{-1} ww) compared to older ones (12.5 to 13.5 y) with ~ 70 mmol glucose units· g^{-1} ww, and compared to adolescents (15.5 y) with ~ 85 mmol glucose units·kg^{-1} ww (Eriksson et al., 1971) at rest. These findings together with lower maximal lactate levels indicate that glycogenolysis is reduced in children and adolescents. A further observation by Eriksson (1971) was that the enzyme succinate-dehydrogenase (SDH) seems to increase somewhat with age. Similar to PFK, training appears to increase the levels of SDH activity considerably in the studied group (~ 5.5 to 6.8 μmoles·min^{-1}) after 6 weeks of training and has been reported to be higher than in untrained children (~3.8 μmoles·min^{-1}) (Eriksson 1980).

These findings suggest an enhanced ability to provide energy via the oxidative pathways and reflected by an increased oxidation of pyruvate (Armstrong and Welsman, 1994).

In children and adolescents glycogen storage capacity or response to different diets after intervention studies have not been studied. From the observations in animals it has been suggested that puberty may be related with a lower glycogen storage capability (Banerjee et al., 1997). As insulin sensitivity has been associated with greater fat deposition during puberty, therefore an inhibition of glycolysis may prevent or reduce glycogen storage. A study performed in post pubertal rats demonstrated a relationship in fat deposition and a reduced ability to storage fat (Banerjee et al., 1997). By preventing body fat accumulation during and after puberty in rats with a restricted caloric diet, glycogen synthesis was restored to pre-pubertal levels, these characterised by a 'normal' insulin control.

With the use of modern technology, the ^{13}C-MRS, muscle glycogen was measured before and after a simulated football match in a group of late adolescent (17.5 years) professional football players (Zehnder et al., 2001). Initial muscle glycogen concentrations were 134 ± 16 mmol·kg^{-1} ww which declined to 80 ± 29 mmol·kg^{-1} ww after the match. The aim of the study was to evaluate whether a habitual diet would restore muscle glycogen concentrations after 24 hours. From the participants reported food intake (their intake was not controlled), carbohydrate intake averaged 327 ± 116 g·d^{-1} (50 % of total energy) or 4.8 ± 1.8 g·kg^{-1}. The carbohydrate intake for the 2 hours post-exercise was 104 ± 16 g. Twenty four hours post muscle glycogen concentration was below baseline levels, namely 122 ± 33 mmol·kg^{-1} ww (not significantly different). The authors found a positive relation between glycogen utilisation and initial glycogen stores and subsequent glycogen synthesis, indicating the central role of glycogen stores before exercise in young athletes. This study offers an insight into young athletes' glycogen metabolism, many questions remain however unanswered. With a low carbohydrate intake, basal levels were nearly restored. If however, athletes engage on a daily basis in intense training, sub-optimal glycogen stores are likely to occur. Furthermore, the question remains would a post exercise high CHO intake diet result in a greater glycogen compensation?

Insulin sensitivity during puberty

Insulin is a key hormone that regulates glycogen metabolism during rest and exercise. This hormone plays an important role during puberty and may assist in the understanding of the glucose responses in adolescent athletes during exercise. Specifically, puberty is associated by a transient decreased glucose tolerance, characterised by compensatory increases in basal and in glucose-stimulated insulin, commonly known as insulin sensitivity (Amiel et al., 1986; Moran et al., 1999). Insulin sensitivity appears to be reduced by ~ 30 % (Bloch et al., 1987).

The studies by Amiel et al., (1986) have shown that Tanner stages are associated with an attenuated insulin-stimulated glucose metabolism. Less glucose is required to maintain euglycemia during an euglycemic insulin-clamp in normal (diabetes free) pubertal children in Tanner stage II to IV, as compared to normal prepubertal children in Tanner stage I and adults, despite similar insulin levels in all age groups. No sex differences were observed. Insulin-like growth hormone (IGF-I) and mean 24-hours GH were negatively correlated to the insulin response. In later investigations by Amiel et al., (1991) and Heptulla et al., (2003) insulin resistance was found to affect peripheral glucose rather than central tissue (liver).

Smith et al., (1988) suggests that insulin resistance reverts to pre-pubertal levels in adult life, and that enhanced growth hormone and sex steroid secretion during puberty may be implicated in the different insulin responses. They found that whereas basal insulin and insulin responses at 10 to 60 minutes rose with advancing puberty, basal glucose and glucose disposal were not related to pubertal stage or age. Children in Tanner stage I and young adults had similar levels. Thus, it appears that an increase in insulin resistance from Tanner stage 2 to 4, which then declines at Tanner stage 5 to almost stage 1, is a puberty related phenomenon. Due to natural changes in body composition during puberty, body composition changes have been proposed as potential but not exclusive mediators in insulin resistance.

Children's physiological responses to high versus low carbohydrate diets on substrate oxidation, hormone concentrations, glucose production, gluconeogenesis and insulin sensitivity have been conducted only under resting conditions (Sunehag et al., 2002), but not during exercise. Isoenergetic and isonitrogenous diets were provided to prepubertal (Tanner stage I) and adolescents (Tanner stage IV and V), which consisted of a high CHO-diet (60 % carbohydrate and 25 % fat), and low CHO-diet (30 % carbohydrate and 55 % fat). Unfortunately, carbohydrate intake was not adjusted to body mass, resulting in a greater carbohydrate intake per body mass by the prepubertal children compared to the adolescents. Results showed higher baseline plasma insulin concentrations in adolescents compared to prepubertal children, and higher in adolescent girls compared to adolescent boys, independent from diet. Plasma insulin levels were slightly higher during the high CHO-diet in both groups compared to the low CHO-diet. Insulin sensitivity was higher in the prepubertal children compared to the adolescents independent of diet. Interestingly, insulin sensitivity improved when adolescents received the high carbohydrate diet. From this study, it was demonstrated that children and adolescents adapt rapidly to changes in the carbohydrate content of the diet, by adjusting carbohydrate and fat oxidation to macronutrient intake. Furthermore, acute consumption of a high carbohydrate diet did not adversely affect insulin sensitivity in either group, remaining unchanged in the younger group and increasing in adolescents. A protective mechanism to maintain normal glucose (during an insulin sensitive phase) was proposed. Lipolysis, as measured by glycerol appearance rate, was not affected by diet composition, age, or gender.

Substrate utilisation during exercise

Substrate metabolism in children has not been researched extensively. Similar to adults children demonstrate an exercise intensity dependent substrate oxidation pattern (Achten et al., 2002; Duncan and Howley, 1999; Foricher et al., 2003b). This is, an increase of fat utilisation with increasing exercise intensity up to 60 – 65 % peak VO_2, thereafter fat oxidation decreases while carbohydrate oxidation continues to increase with increasing intensity.

Although conflicting reports in substrate metabolism between children and adults exist, the majority of research indicates adult-child differences in substrate metabolism, with children showing a higher fat oxidation compared to adults (Boisseau and Delamarch, 2000; Delamarch et al., 1992a; Duncan and Howley, 1998; Martinez and Haymes, 1992). Methodological differences between studies are partly responsible for contradictory results, for example exercise intensity (relative versus absolute intensities), mode of exercise (treadmill or cycle ergometer), postabsorptive or fasted status, gender, the lack of standardisation in adult females relative to their menstrual cycle, different training status. All these aspects are known to alter substare metabolism in adults.

Girls (10-12 y) for example, performing prolonged exercise (treadmill running for 30 min at 70 % peak VO_2) showed higher fat oxidation levels compared to adult females at the same relative intensities but only after 25 minutes of exercise, however not at absolute intensities. Yet, glycerol and FFA blood levels increased similarly in both groups over time (Martinez and Haymes, 1992). Rowland and Rimany (1995) on the other hand, did not find differences in RER values (both decreased similar) between girls (9-13 y) and adult females during 40 min of cycling at 63 % peak VO_2. Adult females had different training backgrounds however. In boys compared to men, greater fat mobilisation (e.g. FFA, glycerol) during treadmill running and cycling exercise, at intensities between 55 and 70 % peak VO_2 were observed (Delamarch et al., 1992b).

Data in trained children are less available than in normal active children. After 12 sessions of aerobic training (30 min at 50 % peak VO_2) children 7 to 12 y old increased fat oxidation (Duncan and Howley, 1998). The results may be confounded by mixing boys and girls in boys and girls, whereas in adults gender differences in substrate metabolism have been confirmed (Tarnopolski, 2000). Furthermore, training adaptations may have occurred and not been accounted for, since post training peak VO_2 was not assessed. Substrate oxidation differences have also been documented when comparing athletic boys and adults (Foricher et al., 2003b). At 40 % W_{max} (60 min cycling at 40 and 60 % W_{max}), prepubertal swimmers oxidised less carbohydrate and more fat compared to adult swimmers. At 60 % W_{max}, children oxidised less carbohydrate than men. The main drawback from this study, was that the researchers did not use a within subject design but four different groups which does not allow for individual comparison at the different intensities.

In children, RER has been reported to drop during exercise when water and exogenous carbohydrates are provided (Riddell et al., 2000b; 2001; Timmons et al., 2003). Alternatively, no decreases in RER have also been reported when water or carbohydrates are ingested during exercise (Riddell et al., 2000a; 2000b; Timmons et al., 2003). The observations by Wojtaszewski and Richter (1998) may partially help to explain the non-significant decreases in the RER. They observed that when adult's diet is manipulated towards higher carbohydrate content (65 %), then the usual RER decrease is not observed. In all the above studies, children were provided with a standardised CHO intake before the commencement of the studies, which may have influenced substrate oxidation.

Compared to the previously referred studies in children, trained adolescents appear to have overall higher RER values during exercise at similar intensities (Montfort-Steiger, 2005). In Table 1 we have summarised RER findings from different studies on children and adolescents. The RER in non-trained boys appears lower within the first 20 min of exercise ($\sim 0.87 – 0.92$ for water and carbohydrate intake, respectively), compared to adolescents (0.96 and 0.97). Interestingly, adolescent cyclists show similar RER values to normal active adults (Timmons et al., 2003) and endurance trained adults (Riddell et al., 2003). These differences may suggest that endurance training in adolescents shifts the substrate metabolism towards higher carbohydrate oxidation. The hypothesis has however not been demonstrated yet in adolescent athletes in longitudinal studies.

Riddle et al., (2001) support the age related substrate oxidation pattern from the series of conducted cross-sectional studies, which are presented in Table 1. Percent energy contribution from fat to total energy reached ~ 50 % in 10 to 14 year old boys and was reduced to ~ 30 % in boys 14 to 17 y when water was provided (Riddell et al., 2000a; 2000b). In slightly older boys (15 to 17 y), fat contribution averaged 15 to 20 % in the last hour of exercise, similar to normal active adults and endurance trained adults (Bergman and Brooks 1999; Riddell et al., 2003). However, others have found higher fat contributions (~ 40 %) to total energy expenditure in endurance trained adults (Burelle et al., 1999). It appears that endurance trained adolescents have higher carbohydrate oxidation rates than younger non-endurance trained adolescents, but similar to moderately trained adults, but not to highly trained athletes who usually show a greater shift towards fat utilisation.

Carbohydrate supplementation during exercise in children

The first study that directly investigated these effects was performed in the late nineties by Hendelman et al., (1997) but lacked a well-designed protocol. The authors gave normal active boys (15 y) a pre-exercise standard liquid breakfast 3 h before arriving at the laboratory. Three hours after the standard breakfast and 10 minutes before the cycling test commenced, snacks varying in the amount of CHO were ingested: 1) a chocolate bar (CHO 36 g, P 4 g, F 14 g ; 280 kcal); 2) fig bars (CHO 44 g, P 2 g, F 0 g; 200 kcal) and 3) artificial sweetened drink (0 kcal). Enhancement in performance was tested based on a 2500 m time trial after 75 minutes cycling at 60 % peak VO_2. No

Table 1. Substrate oxidation during exercise in children, adolescents and adults with CHO or water intake.

	Age (years)	CHO intake Ex. protocol	Treatment	Time (min)	RER [1]	Substrate Fat (%)	Oxidation CHO(%)
Riddell, 2000a	15	1.5 g·kg^{-1}·h^{-1} 91 g·h^{-1} 60 min at 60% peak VO$_2$	water CHO	60 60	0.92 0.94	20-25 18-23	80-75 82-77
Riddell, 2000b	15	1.4 g·kg^{-1}·h^{-1} ~170 g·2h^{-1} 120 min at 60% peak VO$_2$	control CHO	60 90 60 90	0.92 - 0.91 - 0.91 0.95 - 0.94 - 0.93	24-30 24-54 15-23 15-20	76-70 76-46 85-77 85-80
Riddell, 2001	12.5	~1.5 g·kg^{-1}·h^{-1} 67 ±15 g·h^{-1} approx av. for G & GF drinks 90 min at 55% peak VO$_2$	control CHO	30-60 90 30-60 90	0.87 - 0.83 - 0.83 0.90 - 0.86 - 0.85	40-55 40-55 32-45 32-45	60-45 60-45 67-55 67-55
Timmons, 2001	10	~1.4 g·kg^{-1}·h^{-1} boys ~50 g·h^{-1} men ~119 g·h^{-1} 60 min at 70% peak VO$_2$	control boys control men CHO boys CHO men	30-60 30-60 30-60 30-60	0.91 - 0.88 0.96 - 0.93 0.91 - 0.91 0.96 - 0.94	32-35 15-20 30-30 15-18	68-65 85-80 70-70 85-82
Montfort, 2005	15-17	1.4 g·kg^{-1}·h^{-1} 65 ±7.2 g · h^{-1} ~ 102 g ·90 min	control CHO	30-60 90 30-60 90	0.96 – 0.95 0.93 0.96 – 0.96 0.94	11-15 19 10-10 17	89-85 - 81 90-90 - 83
Riddell, 2003	adults	1 g·kg^{-1}·h^{-1} ~ 78 g · h^{-1} ~ 117 g ·90 min 90 min at 60% peak VO$_2$	control [2] adults CHO adults	60 90 60 90	0.95 - 0.92 - 0.91 0.97 - 0.94 - 0.94	22 16	72 80

[1] RER does not include resting values; [2] Substrate oxidation data (% fat and carbohydrate) represent the last 60 min of exercise.

improvements were shown with any of the snacks. Blood glucose and RER also did not show any differences between conditions. The major weaknesses of this study were that the conditions (snacks) were not standardised for macronutrient and energy content. Participants were provided with absolute amounts of carbohydrates without adjusting for body mass, which resulted in twice as much carbohydrate intake in relation to body mass for the lightest boy (47 kg) compared to the heaviest (97 kg) participant. Finally, the time trial used had not been previously tested for reliability in young people and the performance trial (2500 m time trial, performed in 5 to 6 minutes) was too short to expect any differences due to substrate availability. Also worthwhile mentioning is that this study was the first attempt to gain a better understanding into carbohydrate supplementation in children during exercise.

In prepubertal boys, slight decreases in blood glucose have been reported at the onset of exercise. Delamarch et al., (1992b) observed a peak in noradrenaline at 15 minutes of exercise compared to adult's peak at the end of the exercise. A plausible explanation is a preventive mechanism against hypoglycaemia. Based on the findings by Delamarch et al., (1992b) investigated the effects of a single glucose dose (0.5 g·kg^{-1} dissolved in 150 mL of water) given to two groups of pre-pubertal girls (n = 7 and 8) at the start of a 30 minutes cycling exercise at 70 % peak VO$_2$. After 15 minutes of cycling, blood glucose dropped significantly in the control group by ~2 mmol·L^{-1} compared to the glucose-intake group. Despite a significant increase in blood glucose in the glucose-group, the insulin response was not different between groups. However, a lower average insulin con-

centration was found in the control group with a large inter-individual response. Foricher et al., (2003a) explained these observations as a result of the insulin-resistance phase commonly observed during the pre-pubertal stage. Although this holds true, the girls (approximately 10 y old) were at Tanner stage I; at this pre-pubertal stage insulin resistance has presumably not yet been documented (Amiel et al., 1986). Unfortunately, the use of two groups of participants prevents a within-subject comparison under both treatment conditions.

Other investigators have also observed a transitional decrease in blood glucose concentration in 10 to 14 year old boys (Tanner stage 2 – 4) at 10 minutes into the exercise with water or a glucose-fructose carbohydrate drink intake (Riddell et al., 2001). However, when a one shot -glucose drink was provided, blood glucose increased by ~ 1 mmol·L^{-1} above baseline compared to water or to a glucose-fructose drink. Children's rebound in blood glucose was assumed to be related to insulin resistance. Whereas the insulin response to the fructose-glucose drink was accompanied with a blunted response of insulin (slight decrease below baseline with time), in the glucose drink condition insulin was greatly elevated in the first 20 minutes then decreased until reaching levels below baseline, suggesting an impairment in their glucoregulatory response.

Refined studies have been performed by the Canadian group with isotopic labelling of glucose (Riddell et al., 2000a; 2000b; 2001; Timmons et al., 2003). The first study was designed to explore differences in substrate metabolism between insulin-dependent diabetes mellitus and healthy boys when drinking a carbohydrate supple-

mented drink (Riddell et al., 2000a). The percent energy contribution from the carbohydrate drink during 60 minutes of cycling was 12.4 % and endogenous glucose was spared by 12.6 %. Healthy boys were able to keep an adequate glycaemic level during the water trial, which did not decline below basal levels. Delamarche et al., (1992a) have suggested that during prolonged exercise, children's greater fat oxidation is a regulatory mechanism to prevent the drop of blood glucose (by reducing the rate of the glycolytic pathway). In agreement with this assumption is the study by Riddle et al., (2000a), where FFA and glycerol increased significantly with time during the control trial, whereas during the CHO-drink trial both remained relatively stable.

As part of their systematic investigation in substrate metabolism with carbohydrate supplementation during exercise, the next study by Riddle et al., (2000b) consisted of increasing the cycling time to 120 minutes at a similar intensity as in the previous study. The boys ingested water (200 mL) at regular intervals and consumed an 8 % CHO-beverage with the total amount of glucose consumed equal to the endogenous CHO amount oxidised during the water trial. The response for the same variables (blood glucose, FFA and glycerol) followed a similar pattern as in the previous study and did not change after 60 minutes of cycling. That is, blood glucose remained stable during both trials, but was on average 2 $mmol \cdot L^{-1}$ higher during the CHO-drink trial. FFA and glycerol appearance in blood increased with time in the control trial, but stayed unchanged during the CHO-drink. Concerning substrate utilisation, it was shown that the intake of a CHO-drink spares endogenous fat and glucose oxidation. In the water trial, during the first 70 minutes, fat oxidation accounted for 20 - 25 % of the total energy, thereafter increased to a maximum of 46 % at the end of the 120 minutes. In the CHO-drink trial, fat oxidation was stable throughout the entire exercise and accounted for 15 -20 % of the total energy. Approximately 34 % of the ingested CHO was oxidised and by the end of the 2nd hour it accounted for nearly 50 % of the total CHO oxidation and contributed to ~ 40 % of the total energy expenditure of the exercise. Exogenous CHO oxidation increased steadily until it stabilised after 100 minutes of exercise. Consequently, endogenous CHO was spared (with the CHO-drink) by approximately ~16 % and fat by ~20 %. Oxidation rates of the exogenous CHO-drink peaked at 0.81 $g \cdot min^{-1}$ at the end of the exercise (range from 0.63 to 0.95 $g \cdot min^{-1}$) [In adults peak oxidation rates have been reported to be between 1-1.2 $g \cdot min^{-1}$ (McConell et al., 1994)]. In adults, exogenous carbohydrate has been consistently reported to be oxidised at around 1 $g \cdot min^{-1}$ and will be dependent upon exercise intensity and the type of carbohydrate ingestion (Coyle, 2004; Jeukendrup, 2004). In children, maximal exogenous CHO oxidation increases with exercise time and may be dependent on exercise intensity and type of carbohydrate ingested, yet this has not been systematically investigated. At 55 % peak VO_2, exogenous glucose reached maximal oxidation rates of 0.36 $g \cdot min^{-1}$ and 0.31 $g \cdot min^{-1}$ for glucose and glucose-fructose drinks, respectively at 90 minutes of cycling. At slightly higher exercise intensities (~ 60 % peak VO_2) maximal rates of 0.48 $g \cdot min^{-1}$ have been reported at 60

min, and increased to a maximum of 0.81 $g \cdot min^{-1}$ at 120 min (Riddell et al., 2000a; 2000b; 2001; Jeukendrup, 2004).

The third study in the series of carbohydrate supplementation in children, investigated the effect of fructose on substrate metabolism (Riddell et al., 2001). During 90 minutes of cycling at 53 ± 1 % of peak VO_2, an additional all out test to volitional exhaustion at 90 % peak power was performed to investigate performance enhancement. Active adolescents but not competitive boys, drank at 15 minutes intervals a placebo, a 6 % glucose or 3 % glucose + 3 % fructose (GF) beverage. The total intake was set to approximately 1.5 $g \cdot kg^{-1}$. The results indicate that there were no significant differences in substrate oxidation (total fat, total CHO, endogenous and exogenous CHO oxidation) between both carbohydrate drinks, but different from the water trial (Riddell et al. 2001). As expected, total fat oxidation, as a percent of total energy, was greater in the water trial compared to fat oxidation in the CHO-drink trials. An average of ~ 17 % of fat oxidation was spared. Exogenous CHO oxidation contributed 10 – 15 % from total CHO oxidation, which ranged between 50 - 55 % of the total energy. In relation to blood glucose, a drop in glucose was observed after the first 15 minutes of exercise, thereafter glucose stabilised at baseline levels in water and GF conditions, but stayed elevated in the glucose condition by 1 $mmol \cdot L^{-1}$. A performance enhancement was reported in the GF trial compared to the water trial, but not with the glucose trial (142 ± 37 s vs 202 ± 40 s, respectively). The authors proposed a possible difference in initial muscle and liver glycogen levels between trials. However, a habituation session was not included in the design of the protocol. The reliability of tests to volitional exhaustion have not yet been investigated in children. In adults, prolonged tests to exhaustion have a high CV (Jeukendrup et al., 1996). And in adolescents it has been reported that a habituation test is required to reduce the CV (Montfort-Steiger et al., 2005). Therefore, it is most likely that the enhancement from carbohydrate drinks could be related to individual variability.

The final study in the series aimed to compare exogenous carbohydrate oxidation between boys and men (Timmons et al., 2003). The authors hypothesised that the contribution of exogenous CHO to total energy metabolism might be higher in children and adolescents based on their previous observations. Participants cycled at 70 % of their peak VO_2 for 60 minutes. Beverages consisted of a 6 % CHO concentration. Compared with men, boys utilised ~ 70 % more fat and ~ 23 % less carbohydrate during the water exercise condition. The oxidation rate of exogenous CHO (relative to body mass), was higher by ~ 37 % in the boys compared with men during exercise at 70 % peak VO_2. Consequently, the authors demonstrated that the relative contribution of CHO to total energy metabolism was higher in boys (~ 22 %) compared to men (~ 15 %). Moreover, the boys had higher relative fat oxidation rates with the CHO-drink compared to the men. These data show that children and adolescents as well as men, may benefit from exogenous carbohydrate intake during prolonged exercise however in a different concentration.

Based on the previous observations, Montfort-Steiger (2005) hypothesised that exogenous CHO intake would increase cycling performance in adolescent cyclists. For the first time an athletic group of adolescents was studied. The adolescent cyclists cycled for 90 min followed by a ~ 30 min time trial. The total CHO intake consisted of 130 ± 14.4 g (1 g·kg^{-1}·h^{-1}). Results revealed no performance enhancement with a continuous exogenous carbohydrate intake during prolonged cycling. At least for 90 minutes, endurance trained adolescents did not appear to have difficulties in regulating their blood glucose during moderate intensity exercise. After 2 hours of exercise, blood glucose may drop if carbohydrates are not supplied.

The authors concluded that until no further research is performed, CHO and water intake during 2 hours of moderate to hard exercise have similar physiological responses and neither drink had performance enhancing effects. A criticism to this study is the small sample size used. Nevertheless, individual considerations should be taken when working with adolescent athletes as some participants did demonstrate physiological benefits from the carbohydrate intake. Furthermore, children and adolescents' thermoregulatory response to exercise differs to that of adults (Falk, 1998; Malina et al., 2004). The heat transfer during childhood and adolescence is associated with changes in growth, maturation and body surface area. It has also been shown that children's fluid intake during exercise is enhanced with the intake of flavoured and CHO beverages (Wilk et al., 1998). In practical terms, if the flavoured drink diminishes voluntary dehydration, then offering a flavoured and/or CHO drink would be of benefit for a better hydration.

In summary, sparing effects of endogenous carbohydrates have been observed in normal active boys when given a carbohydrate drink during prolonged cycling. The studies which analysed exogenous carbohydrate ingestion in children have reported that exo-CHO contributes between 12 -16 % (Riddell et al., 2000a; 2001; Timmons et al., 2003) and up to a maximum of 25 % (Riddell et al., 2000b) to the total energy expenditure, of which about 30 % of the carbohydrate ingested is oxidised. In adults, similar ~ 18 % (Burelle et al., 1999) or lower ~11 % (Riddell et al., 2003) exogenous carbohydrate contributions to total energy have been reported. The sparing effect may be greater in children. Whether it improves performance is uncertain. Whereas exogenous CHO intake has shown to improve a short all-out performance test, neither a carbohydrate rich snack taken before prolonged exercise nor intermittently CHO drinking during prolonged exercise has succeeded to improve cycling performance. Since growth and maturation influence the metabolic, hormonal and motor-development, and in addition the insufficient well designed studies, all may contribute to the lack of clear benefits of CHO supplementation to prolonged exercise in children and adolescents compared to adults. More and better designed studies should be completed to clarify the CHO needs or perhaps fat needs to support their training and competition related diets, especially as more and more children and adolescents are engaged in athletic training.

Gastric emptying of carbohydrate drinks

Exogenous carbohydrate ingestion has been documented to be limited by the rate of digestion and absorption. In adolescent athletes demonstrated volumes of fluid intake of ~ 1 L·h^{-1} during moderate to intense exercise have prevented body mass changes (Iuliano et al., 1998). Thus, fluid intake has been suggested to be in the order of 200 – 250 mL every 15 to 20 min. However, it is still not known whether all the ingested fluid is absorbed and whether some may have been accumulated in the gastrointestinal tract, thus preventing adequate fluid delivery.

The amount of fluid per time that can empty from the stomach under exercising conditions has been reported to range from 8 to 20 mL·min^{-1} in adults (Houmard et al., 1991; Lambert et al., 1996) and is dependent upon the volume present in the stomach. Whereas at rest the general belief is that water empties at a slightly faster rate than a CHO drink (Houmard et al., 1991; Sherman and Lamb, 1988)), during exercise both water and low CHO solutions seem to be delivered at similar rates (Mitchell et al., 1988). The greater the energy density of the drink the slower the gastric emptying rate (GER), especially in concentration above 10 %. Following ingestion of fluids < 8 % CHO concentration, a fast emptying phase has been identified compared to higher CHO concentrated drinks (Mitchell and Voss, 1991). Larger volumes will accelerate the delivery into the duodenum, whereas the higher the exercise intensity the slower the fluid emptying rate from the stomach. Furthermore, the GER between drinks of similar concentration appears not to be altered when the exercise intensities are less than 70 % (Murray, 1987; Noakes et al., 1991). Leiper et al., (2001) reported that GER were similar between resting conditions and constant cycling at 66 % VO$_{2max}$, but GER slowed down in the trials of intermittent intensity at 66 and 75 % VO$_{2max}$ interspersed with bouts of 100 % VO$_{2max}$ sprints. More recently, the same authors have shown that beverages of ~ 6 % empty at a similar rate as water during moderate exercise intensity, and high intensity sprinting interspersed combined with lower intensity exercise does delay the GER similar to water (Leiper et al., 2005).

Most methods used to evaluate GER are highly invasive and therefore unethical for the use in children. Magnetic resonance imaging (MRI) is a powerful tool, which can be used to examine the gastrointestinal tract without being invasive. In children GER has only been studied in clinical settings and under pathological circumstances (Gomes, 2004; Gomes et al., 2003). Therefore, in our laboratory (Montfort, 2005) we addressed the questions of whether water and carbohydrate drinks given to trained adolescent cyclists would empty completely from the stomach. Adolescents cycled for 60 minutes (4 bouts of 15 min each) at approximately 53 % W$_{max}$, followed by a ~ 15 min time trial. Water or CHO drinks (1 g·kg^{-1}·h^{-1}) were distributed in amounts of 200-250 mL. After an initial baseline MRI scan, cyclists ingested the first drink, cycled 15 min, followed by an MRI scan to assess the remaining gastric volume. This feeding-exercise-scanning protocol was followed thereafter. The present study was the first to explore the gastric emptying pattern of

different fluids during exercise in adolescent athletes. The main findings from this study were that water and a CHO drink empty at similar rates during exercise of moderate and high intensity. During exercise in adults, most of the research has reported similar GER between water and CHO concentrations lower than 8 %. From the total amount given to the adolescent cyclists, 95 % of water and 91 % of the CHO drinks were emptied. However, after each bout of exercise different responses were observed between drinks with a tendency for greater residual volumes with the CHO drink, suggesting a possible delayed GER. Furthermore, during the higher intensity, the GER of the CHO drink showed an inhibitory trend compared to water. From this study, volumes of 200 to 250 mL of either water or a CHO drink given every 15 min can be recommended to adolescent cyclists as more than 90 % is emptied into the duodenum during moderate intensity exercise ~ 60 % peak VO_2. At higher intensities, a CHO drink may reduce the GER more than water yet further research is warranted to verify these initial findings with adolescent athletes.

Conclusions

Further research is needed to explore this topic due to the increasing number of athletes who engage at earlier and earlier ages in serious training and competition. Parents often ask experts on the best nutritional practices for their children, whilst coaches play an important role, it is the scientific community that are faced therefore with the main challenge to investigate the best nutritional practices for the young athletes performance, well-being and health. Most studies have been performed in adult men, with a bias against studies with women and children. Although adults participate in longer races than adolescent athletes, CHO intake is more likely to be beneficial as the evidence is stronger when exercise is longer than 90 minutes. Children and adolescents are not so frequently exposed to extreme prolonged tasks as adults are, yet adolescents are getting ever more involved in stage races and have experienced dehydration in hot weather conditions, some youth athletes have also been reported with heat illnesses in hot day's matches such as American Football. On the other hand, we should be careful though not to fall into the excessive fluid or carbohydrate recommendations. The former will prevent severe hyponatremia, but with the latter it is not yet clear whether carbohydrate is the optimal nutrient for children and adolescent athletes. Perhaps in children fat may be the preferred nutrient for prolonged exercise as a result of higher fat oxidation rates in children, and perhaps adolescents may benefit from both substrates similarly due to their maturity related transition into adulthood. These are the questions worthy of study and which hold an exciting future for this research topic.

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Key points

• Athletic girls show lower carbohydrate intakes compared to boys.
• Substrate oxidation during exercise appears to be maturity related, fat being the preferred fuel for oxidation in younger athletic children.
• Children appear to have lower endogenous but greater exogenous carbohydrate oxidation rates during exercise.
• Carbohydrate intake during exercise appears to show no additional performance improvement in young athletes. Perhaps fat intake or a combination of both nutrients may be a better approach for nutrient supplementation during exercise.
• Gastric emptying physiology of young athletes is not well known. Adult sport drinks showed a tendency to delay gastric emptying in young athletes during exercise at higher intensities.
• More research is needed in paediatric sports nutrition.

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