Eur J Appl Physiol (1988) 57:70—74

European Journal of
Applied
Physiology
and Occupational Physiology

Simple and complex carbohydrate-rich diets and muscle glycogen content of marathon runners

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Summary. The effects of simple-carbohydrate (CHO)- and complex-CHO-rich diets on skeletal muscle glycogen content were compared. Twenty male marathon runners were divided into four equal groups with reference to dietary consumption: depletion/simple, depletion/complex, nondepletion/simple, and nondepletion/complex. Subjects consumed either a low-CHO (15% energy [E] intake), or a mixed diet (50% CHO) for 3 days, immediately followed by a high-CHO diet (70% E intake) predominant in either simple-CHO or in complex-CHO (85% of total CHO intake) for another 3 days. Skeletal muscle biopsies and venous blood samples were obtained one day prior to the start of the low-CHO diet or mixed diet (PRE), and then again one day after the completion of the high-CHO diet (POST). The samples were analysed for skeletal muscle glycogen, serum free fatty acids (FFA), insulin, and lactate and blood glucose. Skeletal muscle glycogen content increased significantly ($p < 0.05$) only in the nondepletion/simple group. When groups were combined, according to the type of CHO ingested and/or utilization of a depletion diet, significant increases were observed in glycogen content. Serum FFA decreased significantly ($p < 0.05$) for the nondepletion/complex group only, while serum insulin, blood glucose, and serum lactate were not altered. It is concluded that significant increases in skeletal muscle glycogen content can be achieved with a diet high in simple-CHO or complex-CHO, with or without initial consumption of a low-CHO diet.

Key words: Energy metabolism — Carbohydrate-rich diet — Glycogen — Low-carbohydrate diet

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Introduction

Since the introduction of the classical CHO-loading diet (Astrand 1967; Bergstrom et al. 1967; Hermansen et al. 1967), several variations have been reported (Sherman et al. 1981; Sherman 1983; Sherman and Costill 1984). These include the elimination of the depletion phase in favour of a mixed diet (Sherman et al. 1981; Sherman and Costill 1984) and consumption of simple or complex carbohydrates during the loading phase (Costill et al. 1981). While enhanced muscle glycogen levels are of benefit to the endurance athlete, there is still some controversy as to the importance of the depletion phase (Sherman et al. 1981) or the type of carbohydrate consumed (Costill et al. 1981; Ledoux et al. 1983) in achieving elevated muscle glycogen content.

The present study was undertaken to investigate the effects of simple and/or complex CHO diets and the inclusion of a depletion phase upon skeletal muscle glycogen stores in a group of endurance trained athletes.

Materials and methods

Subjects. Twenty long distance runners volunteered to participate after being informed of the experimental procedures and inherent risks. Mean (±SD) age, weight, and height were 34.8 (±8.5) years, 68.8 (±8.1) kg, and 178 (±6) cm respectively. All were endurance trained men who had been running a mean (±SD) of 7.4 (±5.1) years averaging 85 (±22) km · week^{-1}, and had run 5 (±4) marathon (42.2 km) races, with a best time of 168 (±12) min.

Diet. The subjects were randomly divided into four equally sized groups. Each adhered to a different dietary protocol that consisted of either a low-CHO diet (<15%E — depletion diet) or a mixed diet (50% CHO — nondepletion diet) for days 1 to 3, followed by a high-CHO diet (>70%E) predominant in

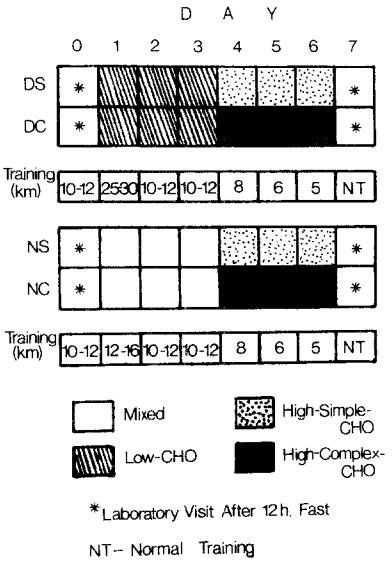

Fig. 1. Dietary intake, training and laboratory visit schedule for depletion/simple *(DS)*, depletion/complex *(DC)*, nondepletion/simple *(NS)*, and nondepletion/complex *(NC)* groups

either simple-CHO or in complex-CHO (>85% of total CHO intake) for days 4 to 6 (see Fig. 1). These groups were classified as: depletion/simple, depletion/complex, nondepletion/simple, and nondepletion/complex. Subjects were given detailed food lists from which to choose the appropriate dietary composition. These lists were prepared using the data from the "Nutrient Value of Some Common Foods" (Health and Welfare, Canada 1979) booklet, with reference to lists of specific CHO content of food (Hardinge et al. 1965). For an estimate of actual dietary intake, subjects recorded deletions and/or additions from the menus. Dietary composition was recorded (Roberts et al. 1987).

Training. Subjects consuming the low-CHO diet were required to run for approximately 2 h (25—30 km) on the first day of the diet in order to deplete muscle glycogen stores, while subjects on the mixed diet were restricted to 12—16 km. On days 2 and 3, all subjects ran 10—12 km d^{-1}. During the high-CHO diet, training for all subjects was limited to 8 km on day 4, to as little as 5 km on day 6 in order to allow the repletion of glycogen stores (see Fig. 1).

Tissue collection. The subjects reported to the laboratory after a 12 h overnight fast, one day before starting the low-CHO or mixed diet (PRE), and then one day after the completion of the high-CHO phase (POST). During these visits, a skeletal muscle biopsy (5—10 mg) was taken from the lateral head of the gastrocnemius (Bergstrom 1962), and venipuncture from a superficial forearm vein was performed to draw 5 cc of whole blood. The muscle tissue was frozen immediately in liquid nitrogen and stored at −70° until assayed for glycogen content (Lo et al. 1970). The blood sample was divided into 2 aliquots. A portion was utilized immediately for glucose analysis (Rapid Stat Kit, Pierce Chemical Co., Rockford Il., USA). Following centrifugation, the serum was removed from the aliquot and stored at −20° C for later analyses of FFA and insulin. The second aliquot of blood was deproteinized in cold 8% perchloric acid, mixed and centrifuged for 10 min at 3000 × g. The clear supernatant was stored at −20° C until assayed for lactic acid concentration. Serum FFA concentration was determined as described elsewhere (Costill et al. 1979) with modifications (Duncombe 1964; Laurell and Tibbling 1967; Noma et al. 1973). Serum insulin was determined using a RIA kit which utilized ^{125}I as a tracer (Immuno Nuclear Corp., 1983). Blood lactate was determined using the Sigma kit (Sigma Chemical Co., St. Louis, MO, USA).

Mean values for glycogen content of all four dietary groups were tested for significance using the student's *t* test for paired observations (Ferguson 1976). Comparisons of specific dietary manipulations were tested using a two-way ANOVA, with post-hoc analysis performed using Scheffe's Multiple Comparison Test (Keppel 1982). Differences at the 0.05 level were considered significant.

Results

All dietary groups exhibited a tendency to increase skeletal muscle glycogen content after their high-CHO diets, but this increase was significant only for the nondepletion/simple group ($p < 0.05$) (see Table 1). When the subjects were grouped according to predominant CHO source, POST glycogen values increased significantly for both simple-CHO ($p < 0.01$) and complex-CHO diets ($p < 0.05$) (see Table 1 and Fig. 2). In addition, a high carbohydrate diet resulted in significant increases in muscle glycogen content whether a depletion phase was included ($p < 0.05$) or not ($p < 0.01$) (see Fig. 3).

Significant decreases ($p < 0.05$) in POST-diet serum FFA for the nondepletion/complex group were noted, although all other groups exhibited a similar trend. Significant changes were not observed for serum insulin and lactate, or blood glucose (see Table 2).

Discussion

The effects of a high-CHO diet on skeletal muscle glycogen content have been well documented (Bergstrom et al. 1967; Karlsson and Saltin 1971; Sherman et al. 1981). The various alterations of the original CHO-loading regimen (Bergstrom et al. 1967) have all resulted in elevated muscle glycogen stores. However, one best method for increasing muscle glycogen content does not appear to exist. In effect, it was the aim of this study to determine which procedure would most likely produce the optimal result with regards to glycogen storage. Of the four dietary regimens followed in this study, only the nondepletion/simple group demonstrated a significant ($p < 0.05$) in-

Table 1. Mean (SD) skeletal muscle glycogen content following dietary manipulation

Group	Glycogen ($g \cdot 100g^{-1}$)		Combined Groups	Glycogen ($g \cdot 100g^{-1}$)	
	PRE	POST		PRE	POST
Depletion/simple	2.33	3.60	Depletion/simple plus	2.43	4.10**
	(1.09)	(1.21)	Non-depletion/simple	(0.81)	(0.46)
Non-depletion/simple	2.52	4.60*	Depletion/complex plus	2.19	3.19*
	(0.70)	(0.28)	Non-depletion/complex	(0.24)	(1.38)
Depletion/complex	2.61	3.52	Depletion/simple plus	2.47	3.56*
	(0.91)	(1.73)	Depletion/complex	(0.83)	(1.46)
Non-depletion/complex	1.76	2.86	Non-depletion/simple plus	2.14	3.73**
	(0.70)	(0.80)	Non-depletion/complex	(0.71)	(1.22)

* Increased from PRE values ($p < 0.05$)
** Increased from PRE values ($p < 0.01$)

crease in skeletal muscle glycogen content. When the groups were compared on the basis of dietary CHO both the simple-CHO group ($p < 0.01$) and complex-CHO group ($p < 0.05$) were noted to have significant increases in muscle glycogen content. Previously, Costill et al. (1981) noted that a two day CHO-loading regimen predominant in complex-CHO resulted in greater muscle glycogen content than that achieved following a simple-CHO-rich diet. The results of the present study suggest that a simple-CHO-rich diet is also effective in increasing muscle glycogen content.

From the current results and previous literature, a possible dietary scheme for the CHO-loading phase may be devised. Consumption of a diet predominant in simple-CHO for the first half, followed by a diet predominant in complex-CHO for the second half of the loading phase may prove to be an optimal regimen. This method would stimulate glycogen synthesis early by providing the necessary monosaccharides for glycogen incorporation. Once the glycogen synthesizing process is stimulated, a complex-CHO diet would ensure continued glycogen storage. Newsholme and Leech (1983) suggest that a complex CHO source be ingested throughout the loading phase, as these molecules are absorbed more slowly. Simple-CHO is absorbed rapidly and may be stored as fat instead of glycogen. Therefore, a shift to complex CHO during the latter stages of glycogen snythesis may prevent the storage of fat and increase skeletal muscle glycogen content.

When the subjects were grouped according to depletion or nondepletion phase, regardless of the

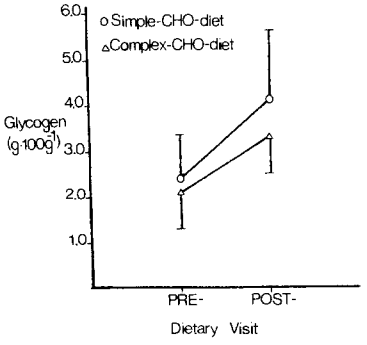

Fig. 2. Mean glycogen (±SD) changes after simple- and complex-CHO-rich diets. Significant increases in glycogen content were observed for both simple ($p < 0.01$) and complex ($p < 0.05$) diets

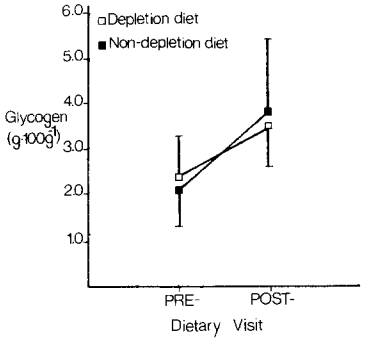

Fig. 3. Mean glycogen (±SD) changes after depletion and nondepletion phases. Significant increases in glycogen content were observed for both the depletion ($p < 0.05$) and the nondepletion ($p < 0.01$) phases

Table 2. Mean (SD) serum FFA, and insulin, blood lactate and glucose levels following dietary manipulation

Group	FFA mmol l^{-1}		Insulin pmol l^{-1}		Glucose mmol l^{-1}		Lactate mmol l^{-1}	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST
Depletion/Simple	0.79 (0.12)	0.60 (0.02)	50.0 (22.0)	56.4 (22.8)	4.91 (0.21)	4.90 (0.34)	0.92 (0.51)	0.69 (0.33)
Depletion/ Complex	0.81 (0.10)	0.78 (0.08)	57.8 (13.4)	63.6 (26.0)	5.22 (0.41)	5.14 (0.27)	0.84 (0.25)	0.59 (0.16)
Nondepletion/ Simple	0.86 (0.14)	0.72 (0.11)	55.4 (13.6)	64.2 (25.6)	4.86 (0.24)	4.93 (0.48)	0.83 (0.32)	0.72 (0.20)
Nondepletion/ Complex	0.98 (0.31)	0.76* (0.18)	39.0 (18.3)	47.0 (20.0)	4.87 (0.47)	4.76 (0.63)	0.75 (0.19)	0.73 (0.33)

* Decreased from PRE values ($p < 0.05$)

CHO consumed, similar increases in muscle glycogen were achieved. The concentration of skeletal muscle glycogen can be increased without the initial consumption of a low-CHO diet. These observations are similar to those of Sherman et al. (1981) who noted equally elevated muscle glycogen levels following a mixed or low-CHO diet, during the 3-day preliminary phase. By eliminating the depletion phase, the athlete may avoid the stress of an unfamiliar diet. It has been reported however, that depletion of glycogen stores with exhaustive exercise, and consumption of a low-CHO diet followed by a high-CHO diet results in the greatest increase in muscle glycogen stores (Bergstrom et al. 1967). The subjects in the present study, and in the study of Sherman et al. (1981) were experienced long-distance runners, familiar with the CHO-loading regimen whereas the subjects in the Bergstrom et al. study were not trained athletes. Supporting this differential response, practical observation has suggested that glycogen loading should be used infrequently if optimal glycogen levels are to be achieved (Costill and Miller 1980). Consequently, the depletion phase of the CHO-loading diet may be most beneficial to the novice distance runner or to those who have never attempted the glycogen loading diet.

In summary, in preparation for prolonged physical activity, a CHO-loading diet predominant in simple-CHO will enhance glyogen stores. Further, for endurance trained athletes, enhanced glycogen deposition may be achieved without the inclusion of a glycogen depletion phase in the training regimen.

Acknowledgement. This research was supported by NSERC grants A2787 and A8170.

References

Astrand P-O (1967) Interrelationship between physical activity and metabolism of carbohydrate, fat, and protein. In: Blix G (ed) Nutrition and physical activity. Almqvist, Wikseles, Uppsala, pp 1—6

Bergstrom J (1962) Muscle electrolytes in man. Scand J Clin Lab Invest [Supp 68]

Bergstrom J, Hultman E (1967) A study of the glycogen metabolism during exercise in man. Scand J Clin Lab Invest 19:218—228

Bergstrom J, Hermansen L, Hultman E, Saltin B (1967) Diet, muscle glycogen, and physical performance. Acta Physiol Scand 71:140—150

Costill DL, Miller JM (1980) Nutrition for endurance sport: carbohydrate and fluid balance. Int J Sports Med 1:2—14

Costill DL, Craig W, Fink WJ, Katz A (1983) Muscle and liver glycogen resynthesis following oral glucose and fructore feedings in rats. In: Knuttgen HG, Vogel JA, Poortmans J (eds) Biochemistry of exercise. Human Kinetics Publishers, Champaign, IL, pp 281—285

Costill DL, Sherman WN, Fink WJ, Maresh C, Witten M, Miller JM (1981) The role of dietary carbohydrates in muscle glycogen resynthesis after strenuous running. Am J Clin Nutr 34:1831—1836

Costill DL, Fink WJ, Van Handel PJ, Miller JM, Sherman WM, Watson PA, Witzmann FA (1979) Analytical methods for the measurement of human performance. Ball State University, Muncie, pp 28—29

Duncombe WG (1964) The colormetric micro-determination of non-esterified fatty acids in plasma. Clin Chim Acta 9:122—125

Ferguson GA (1976) Statistical analysis in psychology and education (ed 4). McGraw-Hill Book Company, New York, pp 166—170

Harding MG, Swarner JB, Crooks H (1965) Carbohydrates in foods. J Am Diet Assoc 46:197—204

Health and Welfare Canada (1979) Nutrient value of some common foods. Minister of National Health and Welfare, Ottawa

Hermansen L, Hultman E, Saltin B (1967) Muscle glycogen during prolonged severe exercise. Acta Physiol Scand 71:129—139

Keppel G (1982) Design and analysis: a researcher's hand-

book (ed 2). Prentice-Hall Inc, Englewood Cliffs, pp 151—153

Laurell S, Tibbling G (1967) Colormetric micro-determination of free fatty acids in plasma. Clin Chim Acta 16:57—62

Ledoux L, Voghel L, Brassard L, Brisson G, Peronnet F (1983) Glycogen overloading in rats: effects of various sugar intakes. In: Knuttgen HG, Vogel JA, Poortmans J (eds) Biochemistry of exercise. Human Kinetics Publishers, Champaign, IL, pp 520—523

Lo S, Russell JC, Taylor AW (1970) Determination of glycogen in small tissue samples. J Appl Physiol 28:234—236

Newsholme EA, Leech T (1983) The runner. Walter L. Maegher, Roosevelt, NJ, p 64

Noma A, Okabe H, Kita M (1973) A new colormetric microdetermination of free fatty acids in serum. Clin Chim Acta 43:317—320

Roberts KM, Noble EG, Hayden DB, Taylor AW (1987) Lipoprotein lipase activity in skeletal muscle and adipose tissue of marathon runners after simple and complex carbohydrate-rich diets. Eur J Appl Physiol 57:75—80

Sherman WN (1983) Carbohydrates, muscle glycogen, and muscle glycogen supercompensation, In: Williams MH (ed) Ergogenic aids in sports. Human Kinetics Publishers, Champaign, IL, p 1—25

Sherman WM, Costill DL (1984) The marathon: dietary manipulation to optimize performance. Am J Sports Med 12:44—51

Sherman WN, Costill DL, Fink WJ, Miller JM (1981) Effect of exercise-diet manipulation on muscle glycogen and its subsequent utilization during performance. Int J Sports Med 2:114—118

Accepted July 16, 1987