

Substrate metabolism when subjects are fed carbohydrate during exercise

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Horowitz, Jeffrey F., Ricardo Mora-Rodriguez, Lauri O. Byerley, and Edward F. Coyle. Substrate metabolism when subjects are fed carbohydrate during exercise. *Am. J. Physiol.* 276 (*Endocrinol. Metab.* 39): E828–E835, 1999.— This study determined the effect of carbohydrate ingestion during exercise on the lipolytic rate, glucose disappearance from plasma (R_{dGlc}), and fat oxidation. Six moderately trained men cycled for 2 h on four separate occasions. During two trials, they were fed a high-glycemic carbohydrate meal during exercise at 30 min (0.8 g/kg), 60 min (0.4 g/kg), and 90 min (0.4 g/kg); once during low-intensity exercise [25% peak oxygen consumption ($\dot{V}O_{2peak}$)] and once during moderate-intensity exercise (68% $\dot{V}O_{2peak}$). During two additional trials, the subjects remained fasted (12–14 h) throughout exercise at each intensity. After 55 min of low-intensity exercise in fed subjects, hyperglycemia (30% increase) and a threefold elevation in plasma insulin concentration ($P < 0.05$) were associated with a 22% suppression of lipolysis compared with when subjects were fasted (5.2 ± 0.5 vs. $6.7 \pm 1.2 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, $P < 0.05$), but fat oxidation was not different from fasted levels at this time. Fat oxidation when subjects were fed carbohydrate was not reduced below fasting levels until 80–90 min of exercise, and lipolysis was in excess of fat oxidation at this time. The reduction in fat oxidation corresponded in time with the increase in R_{dGlc} . During moderate-intensity exercise, the very small elevation in plasma insulin concentration ($\sim 3 \mu\text{U/ml}$; $P < 0.05$) during the second hour of exercise when subjects were fed vs. when they were fasted slightly attenuated lipolysis ($P < 0.05$) but did not increase R_{dGlc} or suppress fat oxidation. These findings indicate that despite a suppression of lipolysis after carbohydrate ingestion during exercise, the lipolytic rate remained in excess and thus did not limit fat oxidation. Under these conditions, a reduction in fat oxidation was associated in time with an increase in glucose uptake.

insulin; lipolysis; glucose uptake; exercise intensity; glyco-
gen; stable isotopes

FAT AND CARBOHYDRATE are the two primary substrates oxidized by skeletal muscle during exercise (17). Carbohydrate ingestion during exercise can modify the relative contribution of these substrates to total energy production (1). However, the influence of carbohydrate ingestion on substrate oxidation depends on the intensity of exercise (24). Carbohydrate ingestion during low-intensity exercise [25–45% peak oxygen consumption ($\dot{V}O_{2peak}$)] reduces fat oxidation $\sim 40\%$ below fasted levels (1, 15). In contrast, carbohydrate ingestion

during moderate-intensity exercise (65–75% $\dot{V}O_{2peak}$) does not reduce fat oxidation during the first 120 min of exercise (5, 6).

The differential effects of carbohydrate ingestion during low and moderate-intensity exercise may be related to differences in insulin response. During low-intensity exercise, carbohydrate ingestion increases plasma insulin concentration two- to threefold above fasting levels (1, 15) and increases glucose uptake by skeletal muscle (1). Furthermore, the increase in plasma insulin concentration is associated with a reduction in plasma free fatty acid (FFA) concentration (1, 15, 24) and probably a suppression of triglyceride hydrolysis (i.e., lipolysis; Ref. 3). These events favor an increase in carbohydrate oxidation and a decrease in fat oxidation (1). Unlike low-intensity exercise, the insulin response to carbohydrate ingestion during moderate-intensity exercise is almost completely suppressed (5, 12). This may explain why carbohydrate ingestion during moderate-intensity exercise does not affect fat oxidation, carbohydrate oxidation, muscle glycogen utilization (5, 12), or presumably blood glucose oxidation during the first 2 h of exercise at moderate intensity (2). Interestingly, carbohydrate ingestion during moderate-intensity exercise does not reduce fat oxidation despite a significant suppression in plasma FFA and glycerol concentrations (5, 6).

Because there is only a very small pool of unesterified fatty acids within the human body (10–40 $\mu\text{mol/kg}$), the rate of fat oxidation cannot exceed the rate of lipolysis for more than a few minutes during exercise. Therefore, a low lipolytic rate can limit fat oxidation by reducing the amount of FFA available for oxidation. In a recent study, we reported that carbohydrate ingestion 1 h before exercise (45% $\dot{V}O_{2peak}$) and a subsequent modest elevation in plasma insulin concentration (10–30 $\mu\text{U/ml}$) suppressed lipolysis sufficiently to reduce fat oxidation during exercise (13). However, when exercise is initiated while subjects are fasted, lipolysis increases rapidly to relatively high levels and exceeds fat oxidation by as much as 50% (25); thus lipolysis does not limit fat oxidation in this condition. The principal aim of this study was to determine whether an elevation in plasma insulin concentration during exercise, after lipolysis has been increased to relatively high rates while subjects are fasted, will allow the lipolytic rate to remain in excess and therefore not limit fat oxidation.

It seems that in addition to suppressing lipolysis, preexercise carbohydrate ingestion and the resultant increase in plasma insulin concentration also can suppress fat oxidation during exercise by a phenomenon specific to the exercising muscle (8, 13), whereby in-

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creased glycolytic flux may directly reduce fat oxidation within muscle (8, 10, 26). An additional aim of this study was to determine whether an increase in glucose uptake and glycolytic flux after carbohydrate ingestion during exercise is associated with a reduction in fat oxidation. We measured the rate of glycerol appearance in plasma ($R_{\text{aglycerol}}$; an index of whole body lipolysis) and the rate of glucose disappearance from plasma (R_{dGlc}) after carbohydrate ingestion during exercise. Carbohydrate was ingested during low-intensity exercise (25% $\dot{V}O_{2\text{peak}}$) to elicit a modest elevation in plasma insulin concentration (10–20 $\mu\text{U/ml}$) and during moderate-intensity exercise (68% $\dot{V}O_{2\text{peak}}$) to elicit a very small insulin response (<5 $\mu\text{U/ml}$).

METHODS

Subjects. Six moderately trained males participated in this experiment. Their $\dot{V}O_{2\text{peak}}$, blood lactate threshold (% $\dot{V}O_{2\text{peak}}$ at lactate threshold), body weight, and age were 4.5 ± 0.7 l/min (60.3 ± 4.9 ml·kg⁻¹·min⁻¹), 74.3 ± 3.1 % $\dot{V}O_{2\text{peak}}$, 75.1 ± 7.3 kg, and 25 ± 2 yr, respectively. Subjects were informed of the possible risks, and each signed a consent form approved by the Internal Review Board of the University of Texas at Austin.

Experimental design. On four separate occasions, subjects arrived at the laboratory in the morning after an overnight fast (12 h) and cycled continuously for 2 h. On two occasions, subjects ingested a high-glycemic sports bar (glycemic index = 99 ± 4 ; Gator Bar; Quaker Oats, Barrington, IL) at 30 min (0.8 g/kg body wt), 60 min (0.4 g/kg), and 90 min (0.4 g/kg) during either low-intensity exercise [*trial 1*; 25% $\dot{V}O_{2\text{peak}}$ (Low-Fed)] to elicit a modest elevation in plasma insulin concentration (10–20 $\mu\text{U/ml}$) or moderate-intensity exercise [*trial 2*; 5% below lactate threshold; 68% $\dot{V}O_{2\text{peak}}$ (Mod-Fed)] to elicit a very small insulin response (<5 $\mu\text{U/ml}$). During the other two trials, Low-Fast (*trial 3*) and Mod-Fast (*trial 4*), the subjects remained fasted throughout the exercise bout at each intensity. During all trials, water (2.8 ml/kg body wt; ~200 ml) was provided at 30, 60, and 90 min of exercise. Trials were separated by ≤ 3 days, and the order of the trials was counterbalanced.

Isotope infusion. On the arrival of the subjects at the laboratory, Teflon catheters were inserted into veins of both forearms (one for isotope infusion and the other for blood sampling). A heating pad was affixed to the hand and forearm of the sampling arm. A blood sample was then withdrawn for determination of background isotopic enrichment. This was followed by a primed, constant rate infusion of [6,6-²H₂]-glucose (0.41 $\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; prime of 35 $\mu\text{mol/kg}$) and [²H₅]-glycerol (0.22 $\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; prime of 3.2 $\mu\text{mol/kg}$) with calibrated syringe pumps (Harvard Apparatus, South Natick, MA). Subjects received isotope infusions for ≤ 1 h before exercise.

Blood sampling and analysis. For determination of resting glucose and glycerol kinetics, blood samples (8 ml) were withdrawn 10 min before and immediately before exercise. During exercise, blood samples were drawn every 10 min for the first 90 min and then at 105 and 120 min of exercise. Each blood sample was divided into three different tubes for subsequent analysis and immediately placed in an ice bath until the end of the trial. Three milliliters of each blood sample were placed in evacuated tubes containing 143 USP units of sodium heparin (Vacutainer; Becton-Dickinson, Rutherford, NJ). These samples were later analyzed for isotopic enrichment of the aldonitrile acetate derivative of [6,6-

²H₂]-glucose (30) and the Tris-trimethylsilyl derivative of [²H₅]-glycerol (31), via gas chromatography-mass spectrophotometry (GC-MS). An additional 2-ml amount of each blood sample was placed in test tubes containing 0.2 ml of an aprotinin (0.5 TiU/ml) and EDTA (82 mM) solution and later were analyzed for plasma insulin concentration (radioimmunoassay; ICN Biomedicals, Costa Mesa, CA). The final 3 ml of each blood sample were placed into a test tube containing 0.15 ml of EDTA (82 mM) for later determination of plasma glycerol (fluorometric assay; Ref. 9), glucose (glucose oxidase autoanalyzer; Yellow Springs Instruments, Yellow Springs, OH), and FFAs (colorimetric assay; Ref. 22). In each tube, plasma was separated by centrifugation (3,000 rpm for 20 min at 4°C), immediately frozen, and stored at -70°C until analysis.

Isotope enrichment sample preparation. Plasma samples (1 ml) were deproteinized by adding 1 ml 0.3 N Ba(OH)₂ and 1 ml 0.3 N Zn(SO)₄. Each tube was then vortexed and incubated in an ice bath for 20 min. After centrifugation (3,000 rpm for 15 min at 4°C), the supernatant was placed into separate tubes for glucose (0.5 ml) and glycerol (1.5 ml) analysis and the water was removed from the tubes via vacuum centrifugation (Savant Instruments, Farmingdale, NY). The aldonitrile acetate derivative of glucose was prepared by adding 100 μl of hydroxylamine-hydrochloride solution (20 mg/ml in pyridine) to the dried sample. After a 30-min incubation at 100°C, 75 μl of acetic anhydride (Supelco, Bellefonte, PA) were then added and the samples remained incubating for an additional hour. Finally, the samples were evaporated under N₂. Before injection into the GC-MS, the samples were reconstituted with ethyl acetate. The Tris-trimethylsilyl derivative of glycerol was prepared by reconstituting the dried sample with 30 μl of a trimethylsilyl solution (Tri-Sil; Pierce, Rockford, IL).

Preliminary testing and diet. $\dot{V}O_{2\text{peak}}$ was determined while subjects were cycling an ergometer (Monark, model 819; Varberg, Sweden) with a continuous protocol that lasted 7–10 min. Blood lactate threshold was determined on a separate occasion as previously described (6). Subjects consumed the same meals during the day before each experimental trial (~500 g carbohydrate). In the evening before each day of testing (12 h before planned arrival at the laboratory), a standardized meal was consumed, containing ~200 g of carbohydrate. Subjects performed a standardized exercise-training bout 2 days before each experiment, and they did not exercise again until the experimental trial.

Measurement of gas exchange. Inspired air volume was measured with a Parkinson-Cowan CD4 dry gas meter (Rayfield Equipment, Waitsfield, VT), as subjects inhaled through a two-way Daniel's valve. The expired gases were continuously sampled from a mixing chamber and analyzed for oxygen (model SA3, Applied Electrochemistry; Ametek, Pittsburgh, PA) and carbon dioxide (Beckman, model LB-2; Schiller Park, IL). These instruments were interfaced to a computer for calculations of the rate of oxygen consumption ($\dot{V}O_2$) and respiratory exchange ratio.

Calculations. The $R_{\text{aglycerol}}$ was measured to quantify whole body lipolysis. The accuracy of this calculation requires that one mole of glycerol appears in blood after the hydrolysis of every triglyceride. It has recently been suggested that $R_{\text{aglycerol}}$ may underestimate whole body lipolysis because of phosphorylation of glycerol within the muscle by glycerol kinase and by incomplete triglyceride hydrolysis, forming di- and monoglycerides (18). Both of these possibilities would prevent glycerol from appearing in the systemic circulation after lipolysis. To the contrary, others have indicated that neither of these phenomena occur in skeletal muscle or in adipose tissue

(21, 31) and that glycerol enters the circulation (19), providing an accurate index of lipolysis.

$R_{\text{aglycerol}}$, as well as the rate of appearance of glucose (R_{aGlc}) and the R_{dGlc} , was calculated with the non-steady-state equation of Steele (29) modified for use with stable isotopes

$$R_a = \frac{F - V_d[(C/(1 + E)(dE/dt)]}{E}$$

$$R_d = R_a - \frac{V_d[dC/dt(1 + E) - C(dE/dt)]}{(1 + E)^2}$$

where F is isotope infusion rate, V_d is volume of distribution (estimated to be 230 ml/kg for glycerol and 100 ml/kg for glucose), C is plasma concentration of the tracee, E is tracer isotopic enrichment, and dE/dt and dC/dt are maximum rates of change of enrichment and concentration, respectively, with respect to time. Fat (i.e., triglyceride) and carbohydrate oxidations were calculated from $\dot{V}O_2$ respiratory exchange ratio (nonprotein respiratory quotient), measured from expired air during the 20- to 30-, 50- to 60-, 80- to 90-, and 105- to 120-min periods of exercise (20). Muscle glycogen oxidation was calculated as the difference between total carbohydrate oxidation and R_{dGlc} , as calculated in previous studies (25). The validity of this calculation requires that R_{dGlc} represents blood glucose oxidation. It has been reported recently that ~90% of R_{dGlc} is directly oxidized (4). Thus R_{dGlc} does provide a reasonable representation of blood glucose oxidation.

Statistical analysis. A two-way ANOVA (treatment by time) for repeated measures with Tukey's post hoc analysis was used to determine significant differences among trials. Planned comparisons for mean values of insulin and glucose were evaluated with paired Student's t -test with a Bonferroni correction factor ($P < 0.05$).

RESULTS

Low-intensity exercise. During Low-Fast, plasma glucose and insulin concentrations remained near basal levels throughout exercise (4.6–5.1 mM and 6–8 $\mu\text{U}/\text{ml}$, respectively; Fig. 1). Thirty minutes after the first carbohydrate ingestion during Low-Fed (60 min of exercise), plasma glucose concentration increased >30% and plasma insulin concentration increased nearly threefold (9.1 ± 1.3 vs. 26 ± 4.9 $\mu\text{U}/\text{ml}$ for 30 and 60 min, respectively; $P < 0.05$). Both plasma glucose and insulin concentrations remained significantly elevated ($P < 0.05$) during the second hour of Low-Fed vs. Low-Fast (Fig. 1).

$R_{\text{aglycerol}}$ (i.e., index of whole body lipolysis) increased ~80% above preexercise levels during the first 30 min of exercise (Fig. 2A). During Low-Fast, $R_{\text{aglycerol}}$ increased an additional 50% during the 30- to 120-min period. Conversely, carbohydrate ingestion attenuated any further rise in $R_{\text{aglycerol}}$ during the 30- to 120-min period of exercise. However, the absolute rate of lipolysis did not decline below the 30-min value when subjects were fed carbohydrate, and it remained >5 $\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ throughout exercise (Fig. 2A). Similar to $R_{\text{aglycerol}}$, plasma FFA concentration increased twofold above basal levels by the end of exercise when subjects were fasted and carbohydrate ingestion attenuated this increase (Fig. 2B). As a result, during the second hour of exercise, $R_{\text{aglycerol}}$ and plasma FFA

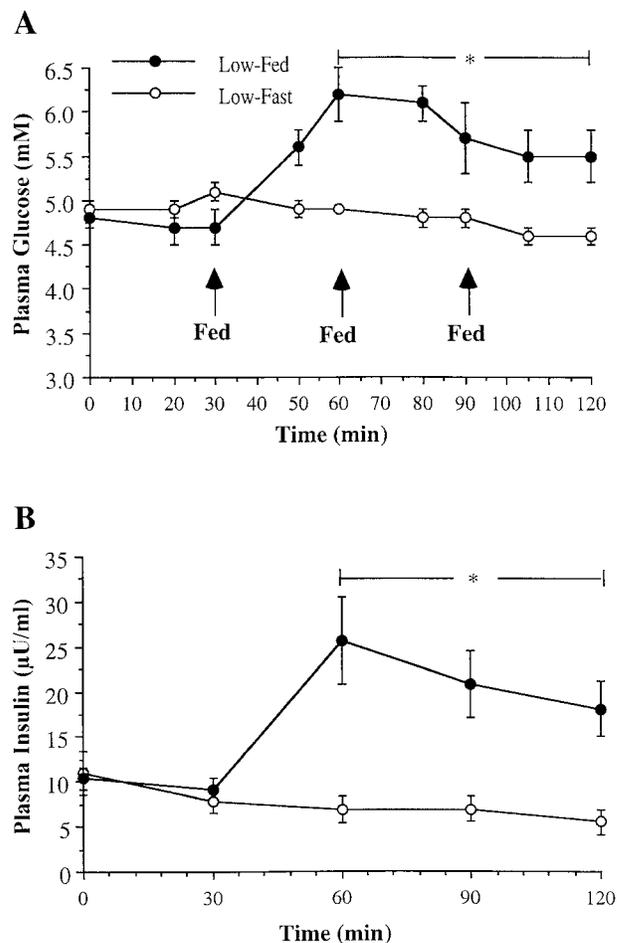


Fig. 1. Plasma glucose concentration (A) and plasma insulin concentration (B) during exercise at 25% peak oxygen consumption ($\dot{V}O_{2\text{peak}}$; Low) when subjects were fasted (Fast) or fed carbohydrate at 30, 60, and 90 min (Fed). *Mean values during 60- to 120-min period of exercise significantly greater during Low-Fed than Low-Fast, $P < 0.05$.

concentrations were lower ($P < 0.05$) during Low-Fed vs. Low-Fast. Despite a >20% suppression in $R_{\text{aglycerol}}$ and plasma FFA concentration during the 50- to 60-min period of Low-Fed vs. Low-Fast, fat oxidation was identical when subjects were fed and fasted at this time (5.3 ± 0.7 vs. 5.3 ± 0.8 $\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, respectively). Fat oxidation was not different among trials until the 80- to 90-min period of exercise (Fig. 3), and lipolysis was >25% in excess of fat oxidation at this time (5.1 ± 0.7 vs. 4.0 ± 0.4 $\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, respectively; $P < 0.05$).

Similar to plasma glucose and insulin concentrations, R_{aGlc} and R_{dGlc} remained relatively unchanged from resting levels throughout exercise when subjects were fasted (Fig. 4). During Low-Fed, R_{aGlc} doubled during the 30 min after the first carbohydrate ingestion (from 12.8 ± 0.7 to 24.9 ± 2.8 $\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ at 25 and 55 min, respectively; $P < 0.05$) and remained about twofold greater ($P < 0.05$) than Low-Fast throughout the second hour of exercise (Fig. 4A). Furthermore, plasma glucose concentration increased during the 30- to 60-min period of Low-Fed (Fig. 1). However, R_{dGlc} did

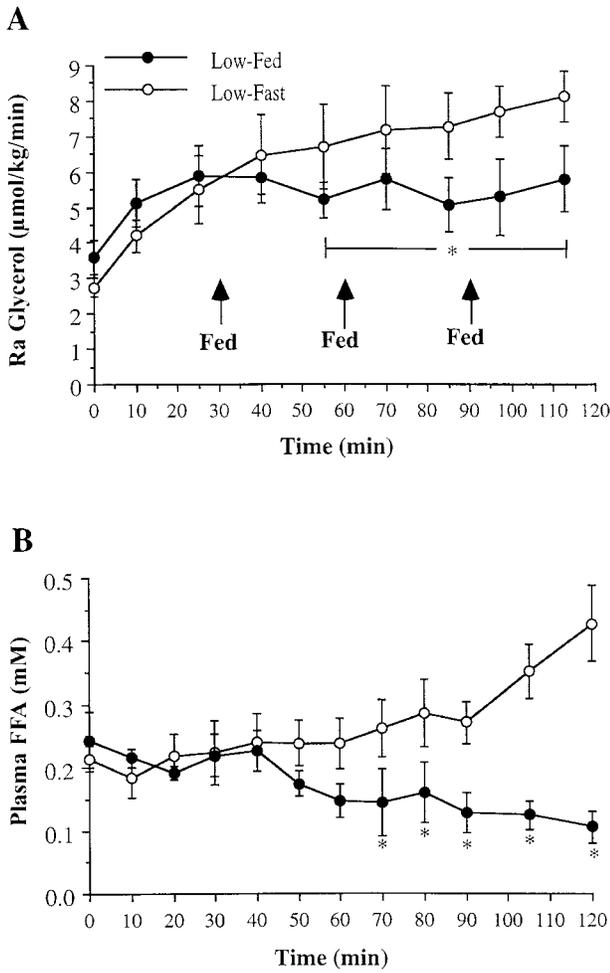


Fig. 2. Rate of glycerol appearance in plasma ($R_{\text{aglycerol}}$; A) and plasma free fatty acid (FFA) concentration (B) during exercise at Low-Fast or Low-Fed. *Significantly different from Low-Fast, $P < 0.05$.

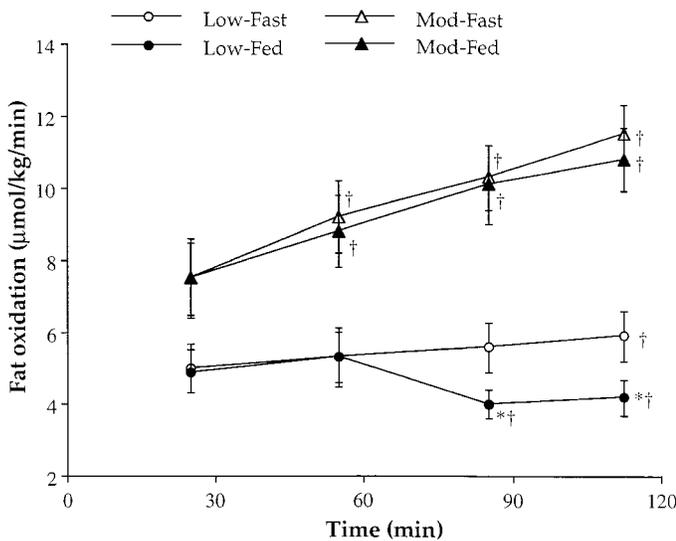


Fig. 3. Rate of fat oxidation ($\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) during exercise at Low-Fast or Low-Fed and 68% $\dot{V}O_{2\text{peak}}$ (Mod)-Fast or Mod-Fed. *Significantly lower than Low-Fast, $P < 0.05$. †Significantly different from 20- to 30-min value, $P < 0.05$.

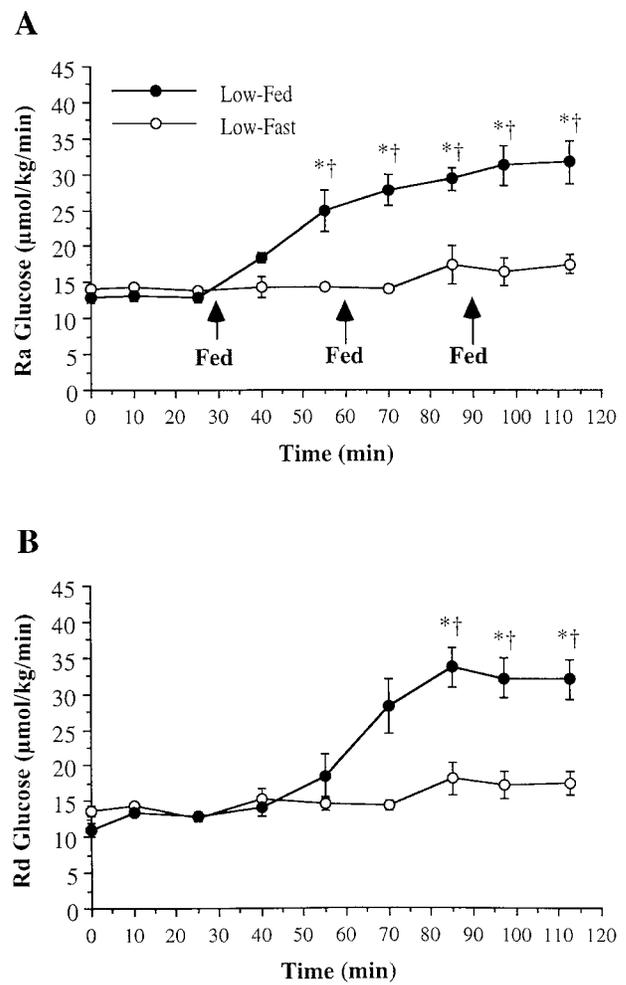


Fig. 4. Rate of glucose appearance in plasma (R_{aGlc} ; A) and rate of glucose disappearance from plasma (R_{dGlc} ; B) during exercise at Low-Fast or Low-Fed. *Significantly different from Low-Fast, $P < 0.05$. †Significantly greater than 25-min value, $P < 0.05$.

not increase until 70 min (nonsignificant) and was not significantly ($P < 0.05$) elevated above Low-Fast until the 80- to 90-min period of exercise (Fig. 4B), the same time that fat oxidation was first significantly reduced (Fig. 3). Figure 5 compares the time course of the

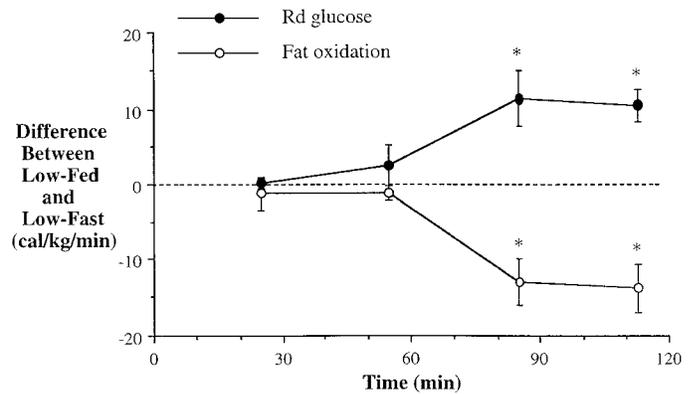


Fig. 5. Comparison of the time course for the increase in R_{dGlc} during Low-Fed vs. Low-Fast to reduction in fat oxidation during exercise ($\text{cal}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). *Low-Fed significantly different from Low-Fast, $P < 0.05$.

Table 1. Carbohydrate oxidation, R_{dGlc} , and muscle glycogen oxidation rate in subjects during exercise at low and moderate oxygen consumption when fasted or fed carbohydrate

	20–30 min		50–60 min		80–90 min		105–120 min	
	Low-Fast	Low-Fed	Low-Fast	Low-Fed	Low-Fast	Low-Fed	Low-Fast	Low-Fed
CHO oxidation	44 ± 3	44 ± 6	42 ± 4	45 ± 4	39 ± 5	58 ± 2*†	39 ± 4†	58 ± 2*†
R_{dGlc}	13 ± 1	13 ± 1	15 ± 1	18 ± 3	18 ± 2	34 ± 3*†	18 ± 2	32 ± 3*†
Glycogen oxidation	31 ± 3	31 ± 6	27 ± 4	27 ± 6	21 ± 4	24 ± 3	21 ± 3	26 ± 4
	20–30 min		50–60 min		80–90 min		105–120 min	
	Mod-Fast	Mod-Fed	Mod-Fast	Mod-Fed	Mod-Fast	Mod-Fed	Mod-Fast	Mod-Fed
CHO oxidation	188 ± 13	187 ± 8	168 ± 18†	176 ± 12†	159 ± 15†	162 ± 11†	144 ± 14†	149 ± 11†
R_{dGlc}	20 ± 2	19 ± 1	27 ± 2	31 ± 2	35 ± 5†	42 ± 3†	46 ± 5†	50 ± 4†
Glycogen oxidation	168 ± 13	168 ± 8	141 ± 19	145 ± 12	124 ± 13†	120 ± 10†	98 ± 11†	99 ± 12†

Values are means ± SE in units of $\mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. *Significantly greater than when fasted, $P < 0.05$. †Significantly different from 20- to 30-min value, $P < 0.05$. R_{dGlc} , rate of glucose disappearance; $\dot{V}O_{2\text{peak}}$, peak oxygen consumption; Low, 25% $\dot{V}O_{2\text{peak}}$; Mod, 68% $\dot{V}O_{2\text{peak}}$; Fast, fasted; Fed, fed carbohydrate at 30, 60, and 90 min; CHO, carbohydrate.

increase in R_{dGlc} during Low-Fed vs. Low-Fast with the reduction in fat oxidation during exercise (both converted to $\text{cal} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$). It is evident that both the time course and the magnitude of the increase in R_{dGlc} were closely matched to the reduction in fat oxidation.

After carbohydrate ingestion, carbohydrate oxidation increased, and thus fat oxidation decreased, in parallel with the increase in R_{dGlc} (Table 1). As a result, the calculated rate of muscle glycogen oxidation was not different between Low-Fed and Low-Fast at any time (Table 1).

Moderate-intensity exercise. During Mod-Fast, plasma glucose concentration decreased ~25% during the second hour of exercise (Fig. 6). Similarly, plasma insulin concentration decreased progressively and was very low by the end of exercise when subjects fasted ($1.1 \pm 0.2 \mu\text{U/ml}$ at 120 min). Carbohydrate ingestion during Mod-Fed prevented these reductions in plasma glucose and insulin concentrations (Fig. 6). The small but significantly greater ($P < 0.05$) mean plasma insulin concentration during the second hour of Mod-Fed vs. Mod-Fast (5.4 ± 1.3 vs. $2.0 \pm 0.4 \mu\text{U/ml}$) was associated with a slight yet significant suppression ($P < 0.05$) in $R_{a\text{glycerol}}$ during the final 20 min of exercise and in plasma FFA concentration during the final 30 min of exercise (Fig. 7). However, this elevation in plasma insulin concentration was apparently not sufficient to significantly affect R_{aGlc} or R_{dGlc} during Mod-Fed vs. Mod-Fast (Fig. 8) nor did it affect glycogen oxidation (Table 1). Consequently, fat oxidation was not different whether subjects were fasted or fed during moderate-intensity exercise (Fig. 3).

DISCUSSION

The principal finding of the present study was that despite a >50% lower lipolytic rate and plasma FFA concentration throughout the final 1 h of exercise when subjects were fed carbohydrate during low-intensity exercise compared with when they were fasted, fat oxidation was not reduced below Low-Fast levels until 80–90 min of exercise. At this time, lipolysis was 25% greater ($P < 0.05$) than fat oxidation and thus was not a limiting factor. Similarly, when subjects were fed carbo-

hydrate during moderate-intensity exercise, lipolysis and plasma FFA concentration were reduced 20–25% during the final 1 h of exercise. However, lipolysis remained in excess of fat oxidation, and fat oxidation was not reduced below Mod-Fast levels at any time.

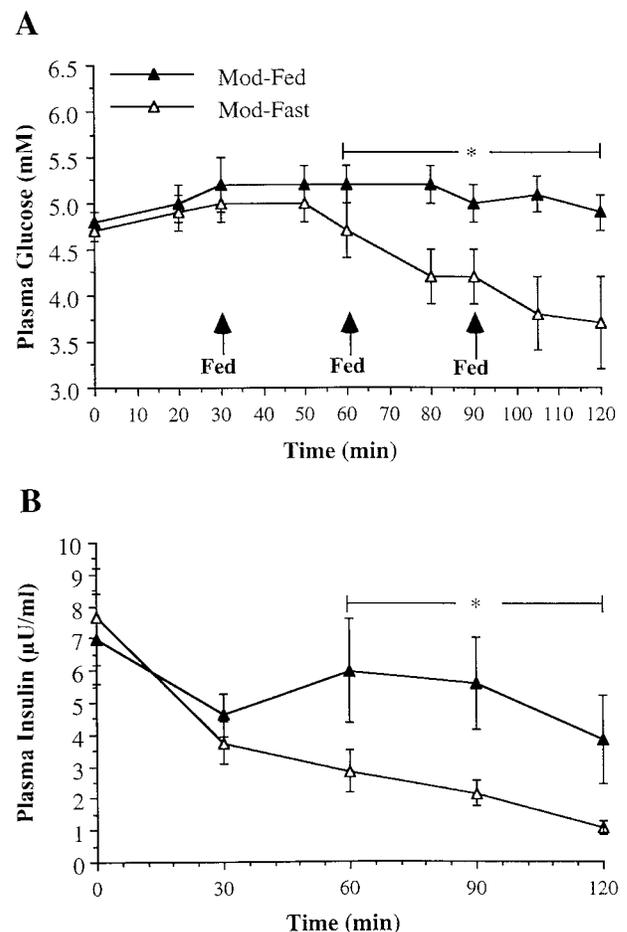


Fig. 6. Plasma glucose concentration (A) and plasma insulin concentration (B) during exercise at Mod-Fast or Mod-Fed. *Mean values during the 60- to 120-min period of exercise significantly greater during Mod-Fed than Mod-Fast, $P < 0.05$.

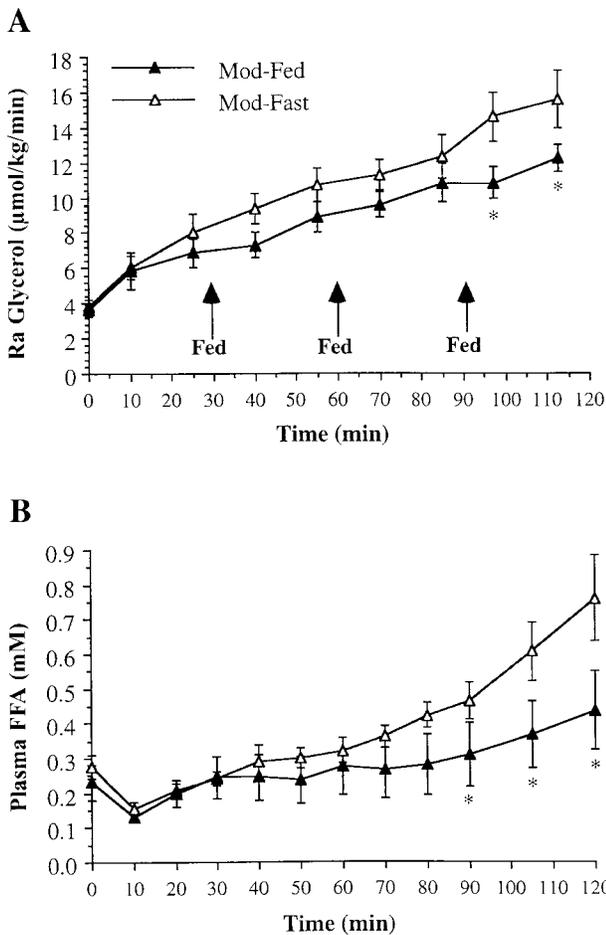


Fig. 7. $R_{a\text{glycerol}}$ (A) and plasma FFA concentration (B) during exercise at Mod-Fast or Mod-Fed. * Significantly different from Mod-Fast, $P < 0.05$.

Clearly, when whole body lipolysis is suppressed below the ability of the muscle to oxidize fatty acids, fat oxidation is limited by a low lipolytic rate. For example, we have recently reported that elevating plasma insulin concentration to 10–30 $\mu\text{U/ml}$ before exercise prevented lipolysis from increasing above $4 \mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ during exercise at 45% $\dot{V}O_{2\text{peak}}$ and that this low rate of lipolysis limited fat oxidation during exercise (13). In the present study, however, despite a suppression of both lipolysis and fat oxidation when subjects were fed carbohydrate during low-intensity exercise, lipolysis was maintained above $5 \mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. Therefore, after carbohydrate ingestion during low-intensity exercise, lipolysis was not suppressed to the low levels we observed during exercise after a preexercise meal (13) and lipolysis remained in excess of fat oxidation. It is unlikely that a high rate of intracellular reesterification limited FFA availability sufficiently to reduce fat oxidation in the present study, because the rate of intracellular reesterification is very low during exercise (32) and has been shown to be unaffected by an elevation in plasma insulin concentration in vivo (3). Our findings imply that more fatty acids were liberated via lipolysis than were oxidized, and thus the suppression of lipolysis after carbohydrate ingestion during

exercise apparently did not limit fat oxidation. Maintenance of a relatively high lipolytic rate in the present study was likely due to the fact that exercise was initiated while subjects were fasted and was maintained for 30 min before ingestion of carbohydrate. Lipolysis increased dramatically with the onset of exercise when subjects were fasted (25). In the present study, lipolysis increased $\sim 80\%$ during the first 30 min of low-intensity exercise, before carbohydrate ingestion. Thereafter, when the subjects were fed, lipolysis remained stable, whereas it increased when they were fasted.

Interestingly, as shown presently, as well as by others (5, 6), fat oxidation does not decline after carbohydrate ingestion during moderate-intensity exercise, when plasma insulin concentration was only slightly elevated ($\sim 3 \mu\text{U/ml}$), despite a 40–50% lower plasma FFA concentration. A decline in plasma FFA concentration is indicative of a reduction in adipose tissue lipolysis. The present observation that an $\sim 25\%$ lower lipolytic rate when subjects were fed carbohydrate resulted in a 30–40% lower plasma FFA concentration without reducing total fat oxidation suggests that the suppression of lipolysis occurred predominantly in the adipocyte. Although the use of intramuscular triglycer-

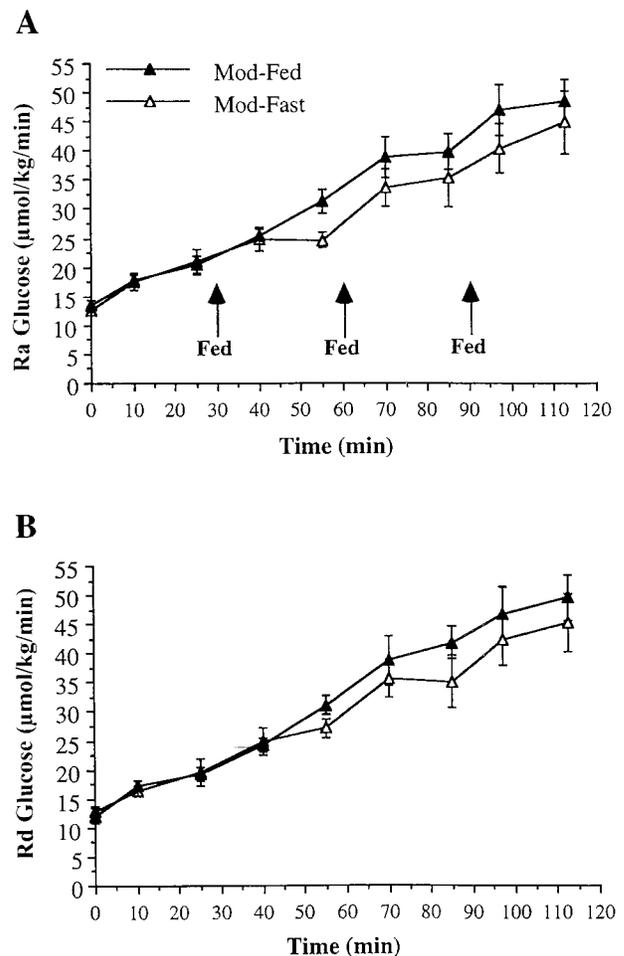


Fig. 8. $R_{a\text{Glc}}$ (A) and $R_{d\text{Glc}}$ (B) during exercise at Mod-Fast or Mod-Fed.

ides (IMTG) during exercise is controversial (16, 28), several studies have reported that IMTG provide the majority of total fat oxidized in endurance-trained individuals during moderate-intensity cycling (8, 14, 25). It has recently been demonstrated that elevating plasma insulin concentration to 42 $\mu\text{U/ml}$ before exercise lowered IMTG oxidation during exercise in trained subjects (8). However, the relative reduction in plasma FFA oxidation after carbohydrate ingestion was >60% greater than the reduction in IMTG oxidation (8). These observations imply that IMTG may be less sensitive to the antilipolytic effect of insulin compared with triglycerides in adipose tissue. It seems that this relative insensitivity of IMTG to the very small increase in plasma insulin concentration observed after carbohydrate ingestion during moderate-intensity exercise ($\sim 3 \mu\text{U/ml}$) may have prevented the reduction in lipolysis from limiting fat oxidation during exercise by allowing whole body lipolysis to exceed fat oxidation.

It has been demonstrated that when lipolysis was suppressed sufficiently to reduce fat oxidation, muscle glycogen oxidation was increased to maintain energy production during exercise (11, 13). However, it is well-known that carbohydrate ingestion during continuous exercise at moderate to high intensities ($>65\% \dot{V}O_{2\text{peak}}$) does not affect the change in muscle glycogen concentration during exercise (5, 12). Our findings confirm that the calculated rate of muscle glycogen oxidation is not altered by carbohydrate ingestion during exercise. Because the reduction in lipolysis from carbohydrate ingestion does not impair fat oxidation or increase muscle glycogenolysis during moderate- to high-intensity exercise, the ingested carbohydrate provides extra energy in the form of blood glucose, leading to maintained carbohydrate oxidation and enhanced performance.

The inability of carbohydrate ingestion to reduce muscle glycogen oxidation during moderate-intensity exercise may be explained by the relative insensitivity of IMTG lipolysis to insulin (allowing lipolysis to exceed fat oxidation) and by the fact that carbohydrate ingestion at this intensity failed to significantly increase blood glucose uptake during the 30- to 120-min period. During low-intensity exercise, however, the hyperglycemia and hyperinsulinemia and elevation in R_{dGlc} glucose after carbohydrate ingestion were compensated by a reduction in fat oxidation. In a previous study from our laboratory, hyperglycemia and hyperinsulinemia ($>10 \text{ mM}$ and $\sim 20 \mu\text{U/ml}$, respectively) evoked by intravenous glucose infusion during moderate-intensity exercise ($73\% \dot{V}O_{2\text{peak}}$) increased carbohydrate oxidation (and reduced fat oxidation) without affecting muscle glycogen utilization, despite very high rates of glucose disposal ($120\text{--}200 \mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; Ref. 7). These observations indicate that when plasma glucose and insulin concentrations are increased sufficiently to increase R_{dGlc} , regardless of intensity (i.e., low or moderate), blood glucose oxidation increases with a compensatory reduction in fat oxidation, rather than a decline in muscle glycogen oxidation.

Presently, we found that the reduction in fat oxidation during low-intensity exercise elicited by hyperglycemia and hyperinsulinemia coincided in time with the increase in R_{dGlc} (Fig. 4). R_{dGlc} provides a reasonable representation of blood glucose uptake and oxidation in exercising muscle (4). Although this association between an increase in R_{dGlc} and a decline in fat oxidation does not directly imply a causal relationship, an increase in blood glucose uptake and oxidation during exercise may have a direct effect on muscle, reducing its ability to oxidize fat. This supports the notion that carbohydrate metabolism in general, and increased glycolytic flux from blood glucose in this case, may regulate the relative contribution of fat and carbohydrate to total energy production during exercise.

It has recently been reported that acute hyperglycemia and hyperinsulinemia and a subsequent increase in glycolytic flux directly reduced muscle fatty acid oxidation by impairing long-chain fatty acid entry into the mitochondria (8, 27). The proposed mechanism for this impairment is that an increase in glycolytic flux increases the concentration of malonyl-CoA concentration in muscle (10), which, in turn, inhibits the enzyme that regulates the entry of long-chain fatty acids into the mitochondria (i.e., carnitine palmitoyltransferase I). Thus malonyl-CoA "senses" the availability of carbohydrate (26) and modifies the ability of the muscle to oxidize fat (i.e., via carnitine palmitoyltransferase I inhibition). This indicates that carbohydrate metabolism in muscle, as reflected by glycolytic flux, is the primary factor regulating fat oxidation under conditions where both FFA and carbohydrate are available to muscle for oxidation. This mechanism has been documented in rat heart and skeletal muscle, whereas evidence of this mechanism in human muscle remains less clear (23).

In summary, carbohydrate ingestion and the resultant insulin response during exercise suppressed lipolysis. However, the lipolytic rate remained in excess of fat oxidation after carbohydrate ingestion during both low- and moderate-intensity exercise, indicating that this suppression in lipolysis was not responsible for reducing fat oxidation. A reduction in fat oxidation occurred at the time of an increase in R_{dGlc} and glycolytic flux. Therefore, carbohydrate ingestion during both low- and moderate-intensity exercise did not suppress lipolysis sufficiently to reduce fat oxidation. However, under conditions where lipolysis is in excess of fat oxidation, carbohydrate ingestion and the resultant insulin response may regulate carbohydrate oxidation by increasing blood glucose uptake and, by doing so, fat oxidation may be reduced by a phenomenon specific to the exercising muscle.

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REFERENCES

- Ahlborg, G., and P. Felig. Influence of glucose ingestion on fuel-hormone response during prolonged exercise. *J. Appl. Physiol.* 41: 683–688, 1976.
- Bosch, A. N., S. M. Weltan, S. C. Dennis, and T. D. Noakes. Fuel substrate turnover and oxidation and glycogen sparing with carbohydrate ingestion in non-carbohydrate-loaded cyclists. *Pflügers Arch.* 432: 1003–1010, 1996.
- Campbell, P. J., M. G. Carlson, J. O. Hill, and N. Nurjhan. Regulation of free fatty acid metabolism by insulin in humans: role of lipolysis and reesterification. *Am. J. Physiol.* 263 (Endocrinol. Metab. 26): E1063–E1069, 1992.
- Coggan, A. R., W. M. Kohrt, R. J. Spina, D. M. Bier, and J. O. Holloszy. Endurance training decreases plasma glucose turnover and oxidation during moderate intensity exercise in man. *J. Appl. Physiol.* 68: 990–996, 1990.
- Coyle, E. F., A. R. Coggan, M. K. Hemmert, and J. L. Ivy. Muscle glycogen utilization during prolonged strenuous exercise when fed carbohydrate. *J. Appl. Physiol.* 61: 165–172, 1986.
- Coyle, E. F., J. M. Hagberg, B. F. Hurley, W. H. Martin, A. A. Ehsani, and J. O. Holloszy. Carbohydrates during prolonged strenuous exercise can delay fatigue. *J. Appl. Physiol.* 59: 429–433, 1983.
- Coyle, E. F., M. T. Hamilton, J. Gonzalez Alonso, S. J. Montain, and J. L. Ivy. Carbohydrate metabolism during intense exercise when hyperglycemic. *J. Appl. Physiol.* 70: 834–840, 1991.
- Coyle, E. F., A. E. Jeukendrup, A. J. M. Wagenmakers, and W. H. M. Saris. Fatty acid oxidation is directly regulated by carbohydrate metabolism during exercise. *Am. J. Physiol.* 273 (Endocrinol. Metab. 36): E268–E275, 1997.
- Eggstein, M., and E. Kuhlmann. Triglycerides and glycerol. Determination after alkaline hydrolysis. In: *Methods of Enzymatic Analysis* (2nd ed.), edited by H. U. Bergmeyer. New York: Academic, 1974, p. 1825–1831.
- Elayan, I. M., and W. W. Winder. Effect of glucose infusion on muscle malonyl-CoA during exercise. *J. Appl. Physiol.* 70: 1495–1499, 1991.
- Gollnick, P. D., B. Pernow, B. Essen, E. Jansson, and B. Saltin. Availability of glycogen and plasma FFA for substrate utilization in leg muscle of man. *Clin. Physiol.* 1: 27–42, 1981.
- Hargreaves, M., and C. A. Briggs. Effect of carbohydrate ingestion on exercise metabolism. *J. Appl. Physiol.* 65: 1553–1555, 1988.
- Horowitz, J. F., R. Mora-Rodriguez, L. O. Byerley, and E. F. Coyle. Lipolytic suppression following carbohydrate ingestion limits fat oxidation during exercise. *Am. J. Physiol.* 273 (Endocrinol. Metab. 36): E768–E775, 1997.
- Hurley, B. F., P. M. Nemeth, W. H. Martin, J. M. Hagberg, G. P. Dalsky, and J. O. Holloszy. Muscle triglyceride utilization during exercise: effect of training. *J. Appl. Physiol.* 60: 562–567, 1986.
- Ivy, J. L., W. Miller, V. Dover, L. G. Goodyear, W. M. Sherman, S. Farrell, and H. Williams. Endurance improved by ingestion of a glucose polymer supplement. *Med. Sci. Sports Exerc.* 15: 466–471, 1983.
- Kiens, B., and E. A. Richter. Utilization of skeletal muscle triacylglycerol during postexercise recovery in humans. *Am. J. Physiol.* 275 (Endocrinol. Metab. 38): E332–E337, 1998.
- Krogh, A., and J. Lindhard. The relative value of fat and carbohydrate as sources of muscular energy. *Biochem. J.* 14: 290–363, 1920.
- Kurpad, A., K. Khan, A. G. Calder, S. Coppack, K. Frayn, and I. MacDonald. Effect of noradrenaline on glycerol turnover and lipolysis in the whole body and subcutaneous adipose tissue in humans in vivo. *Clin. Sci. (Colch.)* 86: 177–184, 1994.
- Lin, E. C. C. Glycerol utilization and its regulation in mammals. *Annu. Rev. Biochem.* 46: 765–795, 1977.
- Lusk, G. *The Elements of the Science of Nutrition*. Philadelphia, PA: Saunders, 1928.
- Newsholme, E. A., and K. Taylor. Glycerol kinase activity in muscles from vertebrates and invertebrates. *Biochem. J.* 112: 465–474, 1969.
- Novak, M. Colorimetric ultramicro method for determination of free fatty acids. *J. Lipid Res.* 6: 431–433, 1965.
- Odland, L. M., G. J. F. Heigenhauser, G. D. Lopascuk, and L. L. Spriet. Human skeletal muscle malonyl-CoA at rest and during prolonged submaximal exercise. *Am. J. Physiol.* 270 (Endocrinol. Metab. 33): E541–E544, 1996.
- Pirnay, F., J. M. Crielaard, N. Pallikarakis, M. Lacroix, F. Mosora, G. Krzentowski, A. S. Luyckx, and P. J. Lefebvre. Fate of exogenous glucose during exercise of different intensities in humans. *J. Appl. Physiol.* 53: 1620–1624, 1982.
- Romijn, J. A., E. F. Coyle, L. S. Sidossis, A. Gastaldelli, J. F. Horowitz, E. Endert, and R. R. Wolfe. Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity. *Am. J. Physiol.* 265 (Endocrinol. Metab. 28): E380–E391, 1993.
- Saha, A. K., T. G. Kurowski, and N. B. Ruderman. A malonyl-CoA fuel-sensing mechanism in muscle: effects of insulin, glucose, and denervation. *Am. J. Physiol.* 269 (Endocrinol. Metab. 32): E283–E289, 1995.
- Sidossis, L. S., C. A. Stuart, G. I. Shulman, G. D. Lopaschuk, and R. R. Wolfe. Glucose plus insulin regulate fat oxidation by controlling the rate of fatty acid entry into the mitochondria. *J. Clin. Invest.* 98: 2244–2250, 1996.
- Starling, R. D., T. A. Trappe, A. C. Parcell, C. G. Kerr, W. J. Fink, and D. L. Costill. Effects of diet on muscle triglyceride and endurance performance. *J. Appl. Physiol.* 82: 1185–1189, 1997.
- Steele, R. Influences of glucose loading and of injected insulin on hepatic glucose output. *Ann. NY Acad. Sci.* 82: 420–430, 1959.
- Tserng, K.-Y., and S. C. Kalhan. Estimation of glucose carbon recycling and glucose turnover with [^{13}C]glucose. *Am. J. Physiol.* 245 (Endocrinol. Metab. 8): E476–E482, 1983.
- Wolfe, R. R. *Radioactive and Stable Isotope Tracers in Biomedicine: Principles and Practice of Kinetic Analysis* (1st ed.). New York: Wiley-Liss, 1992, p. 471.
- Wolfe, R. R., S. Klein, F. Carraro, and J. M. Weber. Role of triglyceride-fatty acid cycle in controlling fat metabolism in humans during and after exercise. *Am. J. Physiol.* 258 (Endocrinol. Metab. 21): E382–E389, 1990.