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Effect of resistance exercise, with or without carbohydrate supplementation, on plasma ghrelin concentrations and postexercise hunger and food intake

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Abstract

The effects of resistance exercise with and without carbohydrate (CHO) supplementation on hunger, postexercise food intake, and plasma ghrelin, an orexigenic gastric peptide, are poorly characterized. We examined the individual and combined effects of a resistance exercise bout and CHO consumption on plasma ghrelin and postexercise food intake. Twenty-one apparently healthy young male participants ([mean ± SD] age = 20 ± 1.8 years, body mass index = 24.8 ± 3.3 kg/m^2) completed in random order 3 treatment conditions: (1) ExCHO—80-minute resistance exercise bout while consuming CHO (~77 g CHO, 306 kcal); (2) ExPLA—identical exercise with a noncaloric placebo; and (3) NoExCHO—no-exercise trial of quiet sitting and CHO consumption. Blood samples were obtained before, during, and immediately postexercise, and 110 minutes after exercise. At 2 hours postexercise, they were provided a buffet of food from which they ate ad libitum. There was a significant time × treatment interaction for plasma ghrelin caused by a decline from pre- to postexercise in the 2 exercise conditions compared with an increase over time in the NoExCHO condition. At 110 minutes postexercise, ghrelin was 21% and 13% lower in ExCHO and ExPLA compared with NoExCHO (both *P*s < .05). However, despite the lower ghrelin concentrations for the 2 exercise conditions, the subjective ratings of hunger were not lower for these conditions compared with the NoExCHO. There were no differences in absolute ad libitum energy intake from the buffet among the 3 conditions, but relative energy intake from the buffet accounting for the estimated cost of exercise was lowest among the 2 exercise conditions. We conclude that (1) weight lifting lowers plasma ghrelin concentrations during exercise and attenuates its rise during the postexercise period in young men and (2) the lower plasma ghrelin concentration is not associated with lower subjective feelings of hunger measured 100 minutes postexercise, but is associated with a lower relative food intake.

1. Introduction

Heavy exercise is, by its very nature, characterized by an acute state of negative energy balance. It is intuitive then that acute exercise would stimulate a compensatory postexercise hunger leading to subsequent food intake and restoration of energy homeostasis. However, heavy exercise may actually result in a prolonged negative energy balance. We [1] and others [2-4] have shown that, despite heavy endurance exercise, energy intake during the exercise day and possibly even for days after exercise is often not sufficiently increased to compensate for the energy cost of the activity. Less is known about the effects of resistance exercise on postexercise energy homeostasis, but there is evidence that a single vigorous bout of weight lifting can produce a prolonged metabolic perturbation in both men [5] and women [6]. Reasons for the failure to immediately compensate for the increased energy expenditure from exercise are not clear, but might be at least partially explained by exercise-induced changes in neural and/or hormonal stimuli that influence sensations of hunger and satiety.

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Appetite and energy balance are regulated in part by various gut peptides including peptide YY (PYY), glucagon-like peptide–1 (GLP-1), and ghrelin [7,8]. Peptide YY and GLP-1 are involved in the suppression of appetite [9], whereas ghrelin, conversely, has been shown to stimulate food intake [10,11]. Circulating ghrelin increases with fasting and in turn is linked to increased hunger and food intake by activating hypothalamic neurons that release neuropeptide Y and agouti-related protein [12]. Circulating ghrelin peaks in the preprandial state that stimulates food intake, and decreases after meal ingestion [13]. This decline is tied to increased satiety. One might surmise that, in defense of energy homeostasis, an acute energy deficit associated with exercise could result in changes in gut peptide concentrations that would lead to compensatory feeding and rapid restoration of acute energy balance. In line with this argument, Leidy et al [14] found a combination of energy restriction and exercise over a 3-month period to increase 24-hour plasma ghrelin. However, the study did not address the effect of acute exercise independent of long-term dietary restriction; nor did it address the acute effects of vigorous exercise independent of weight loss. In a recent study, acute aerobic exercise for 60 minutes resulted in lower postexercise hunger levels and lower relative food intake, which were linked to increased GLP-1 and PYY [15]. These data support the notion that acute aerobic exercise induces a postexercise anorexia and that the failure to rapidly defend the acute energy deficit is associated with increases in anorexigenic gut peptides.

In addition to changes in GLP-1 and PYY, the failure to rapidly restore energy homeostasis in response to vigorous exercise could be related to low circulating ghrelin, leading to a lower physiologic stimulus to eat. However, acute endurance exercise does not appear to affect plasma ghrelin concentrations [15,16], although several recent reports suggest the possibility that such exercise may reduce circulating ghrelin in the postexercise period [17,18], especially its most active acetylated form. A recent study in animals showed that endurance exercise had no effect on plasma ghrelin concentrations, but reduced hypothalamic ghrelin. The latter was related to a decrease in appetite and to exercise-induced weight loss [19]. Although only a few studies have examined the effect of resistance exercise on plasma ghrelin, the results suggest that acute weight lifting exercise suppresses plasma ghrelin concentrations [20,21]. The lower ghrelin concentration could then contribute to a reduced sense of hunger and a lower drive to eat, thus contributing to the postexercise anorexia. However, in these resistance exercise studies, there was no attempt by the authors to measure the possible effects of the lower postexercise plasma ghrelin concentrations on hunger and food intake.

It is also possible that attenuating the acute energy deficit resulting from exercise by caloric consumption, as in the case of drinking a carbohydrate (CHO) beverage during exercise, could alter postexercise hunger and food intake. For example, we have previously found that, in response to ingesting a CHO beverage during exercise compared with noncaloric placebo, young women compensated by consuming less energy during the remainder of the day [1]. Given that administration of both oral and intravenous glucose lower plasma ghrelin in humans [22], such compensation seen in our previous study could be related to lower postexercise plasma ghrelin concentrations. The possible effect of energy consumption vs noncaloric placebo during resistance exercise on ghrelin and postexercise energy intake has not been studied. Accordingly, the purpose of this study was to examine the effect of resistance exercise, with and without at least partial energy replacement using a CHO beverage, on plasma ghrelin, glucose, insulin, hunger, and postexercise energy intake. We hypothesized that, if blood glucose were better maintained during and after exercise because of CHO ingestion, this might result in lower subjective ratings of hunger and less buffet food intake compared with the placebo condition. We further hypothesized that, if the exercise produced a decline in ghrelin, this would result in lower subjective feelings of hunger and lower energy intake from the buffet.

2. Methods

2.1. Study design

A randomized, double-blind, placebo-controlled study was used to test the effects of a CHO beverage consumption during acute resistance exercise on postexercise hunger, satiety, energy intake, and plasma ghrelin concentrations. Study participants completed each of 3 different conditions in random order: (1) exercise-CHO condition (ExCHO)—participants completed a strenuous resistance exercise session (weight lifting) while drinking the CHO beverage at specified periods throughout the study protocol; (2) exercise-placebo condition (ExPLA)—participants completed the resistance exercise session while consuming a noncaloric placebo supplement at the same specified periods as the ExCHO condition; and (3) no-exercise–carbohydrate condition (NoExCHO)—participants received the same CHO beverage at the same periods as the ExCHO condition, but sat quietly rather than exercising. The CHO beverage (Gatorade, Barrington, IL) contained 6% CHO in the form of glucose and sucrose.

2.2. Subjects

Twenty-one apparently healthy men between the ages of 19 and 24 years participated in the study. Potential subjects were screened with a medical history questionnaire to exclude those with diabetes or any impairment or injury that would affect participation in the resistance exercise protocol. Subjects were nonsmokers, had no self-reported history of disordered eating, and were recreational weight lifters (2-4 sessions per week) and therefore familiar with the lifting machines. One subject did not participate in the blood sampling protocol, so blood biomarkers are reported for 20 subjects.

2.3. Specific procedures

2.3.1. Resting energy expenditure

Resting energy expenditure (REE) was measured for the purpose of estimating daily energy requirements. Subjects reported to the laboratory between 7:00 and 9:00 AM after a 12-hour fast. Resting metabolic rate (RMR) was measured via indirect calorimetry (CPX Express; Med Graphics, St Paul, MN). Respiratory gas exchange was measured during 30 minutes of quiet rest in a supine position. During this time, VO_2 and VCO_2 were measured, with the values during the final 15 minutes averaged to determine REE. The deWeir [23] equation was used to convert respiratory gas exchange values to energy expenditure (in kilocalories).

2.3.2. Dietary protocol

Subjects' habitual eating patterns were analyzed using 3-day diet records. A food preference questionnaire was also completed by each subject to rate his preferences for various food items to ensure acceptability of the food provided during each of the treatment conditions. The Food Intake Analysis Software (FIAS version 3; University of Texas Health Sciences Center, School of Public Health, 1998) was used to analyze total energy and macronutrient intake and to create each subject's diet. This software consists of the Primary Data Set and the Survey Nutrient Data Base of the National Nutrient Data Bank, which the United States Department of Agriculture developed and maintains.

Because energy balance and macronutrient intake can influence hunger, satiety, and feeding behavior, it was important to provide the same diet during the 24 hours before each testing day, as well as the same breakfast the morning of each of the 3 treatments. Each subject's sedentary 24-hour energy intake requirement was determined by multiplying his 24-hour REE by an activity factor of 1.4. Food was provided the day before each treatment, with diets composed of approximately 65% CHO, 20% fat, and 15% protein. Diets were consistent within each subject for all 3 trials. Each participant was instructed to only eat the food provided for the pretrial day, to stop eating and drinking anything but water 12 hours before he came to the laboratory the next day, and to refrain from exercise during the pretrial day as well. For the breakfast the morning of each trial, 25% of the previous day's kilocalories for each subject were provided in a standardized meal. An example of a typical breakfast was a slice of whole wheat toast with peanut butter, an individual 8-oz container of fruit-flavored yogurt, a banana, an apple, and a glass of milk.

2.4. Exercise protocol

2.4.1. Pretesting

At least 1 week before the first workout session, subjects reported to the weight lifting gymnasium to determine the maximum weight the individual could lift at 1 time (1 RM) for each of the 8 different lifts. Because the subjects were experienced with weight lifting exercise, they first estimated their own theoretical 1 RM for each lift. They then engaged in a warm-up protocol that involved several sets at a lighter weight (eg, 10 reps at ~40% of the estimated 1 RM, 8 reps at ~60%, 2 reps at 80%, 1 rep at 90%). After an attempt at their estimated 1 RM, the resistance was adjusted after investigator-subject discussion as to the ease or difficulty of the lift, using approximately 2.5- to 5-kg increments until the subject could only execute a single repetition of the particular lift using correct form. All attempts were separated by at least 3 minutes of rest.

In addition, at least 4 days before the first experimental exercise condition, subjects participated in the identical weight lifting protocol used for the ExPLA and ExCHO conditions to familiarize them with the protocol.

2.4.2. Resistance exercise protocol

The morning of the trial, participants reported to the laboratory after a 12-hour fast, at which time they were weighed, were fed a standardized breakfast, and completed a postprandial visual analog scale (VAS) hunger questionnaire. Two hours after the onset of breakfast, the participants' first blood samples were obtained to measure preexercise glucose, insulin, and ghrelin. All subjects then completed a second hunger questionnaire. Immediately before beginning the exercise protocol, subjects were weighed using a standard balance beam scale.

Participants completed an 8-exercise protocol (ie, 8 different lifts) addressing the major skeletal muscle groups. These included chest press, seated rows, shoulder press, triceps extension, biceps curls, leg press, leg extensions, and leg curls. A total of 4 sets were completed for each of the 8 different lifts. The first 3 sets of each exercise consisted of 10 repetitions at a weight equivalent to 70% of the subject's 1 RM. Each set was separated by a 2-minute timed interval from the start of one set to the start of another set. The resistance for the fourth and the final set was 55% of the subject's 1 RM, with the subject completing as many reps as possible until the onset of exhaustion (ie, failure to complete the lift unaided through the full range of motion). A 3-minute rest period separated the final set of one particular exercise and the commencement of the first set of the next exercise. In addition, there was an 8-minute rest period between the fourth and fifth of the 8 total exercises performed, during which time blood samples were obtained and the hunger/satiety questionnaire was administered. In a previous work in our laboratory [5] in which subjects performed a similar protocol and respiratory gas exchange measures were obtained, we estimated the gross energy cost of the exercise bout to be 7 to 9 kcal/min. Given the longer rest interval in the current study halfway through the exercise session, which was not present in our previous study, we used a gross energy cost estimate of the exercise session to be at the lower end of the range at 7 kcal/min and calculated the estimated net energy cost of the exercise bout for each subject according to the following formula: net energy cost = (7 kcal/min * 80 minutes) – REE for 80 minutes. The REE for 80 minutes was determined by multiplying each subject's measured RMR (in kilocalories per minute) by 80 minutes. The estimated mean net energy cost of the exercise sessions was 452 ± 18 kcal.

2.4.3. Carbohydrate supplement

Study volunteers consumed 150 mL of CHO or placebo 5 minutes before beginning the exercise or sitting session and consumed this same amount 5 minutes after the exercise or sitting session. During the actual exercise and controlled sitting sessions, the total volume of fluid ingested was 12 mL/kg of body weight divided into 32 servings, for a mean fluid intake of approximately 990 mL during the 80 minutes of exercise or sitting. The mean total supplemental CHO or placebo that was consumed each session (before, during, and after exercise or rest) was 76.6 ± 1.96 g (1278.33 ± 32.67 mL). This was equivalent to 306.4 ± 7.9 kcal.

2.5. Timeline

The specific order of events by time is provided below:

- 7:00 AM: Study participant reports to laboratory. Breakfast is consumed, and hunger/satiety questionnaire is administered immediately post–breakfast consumption.
- 9:10 AM: Hunger/satiety questionnaire is administered, body weight is measured, and blood samples are obtained.
- 9:25 AM: 150 mL of CHO or placebo beverage is consumed.
- 9:30 AM: Exercise or quiet sitting protocol begins.
- 10:10 AM: Blood sample is obtained after the fourth resistance exercise for ExCHO and ExPLA, and at the midpoint of the quiet sitting protocol. Hunger/satiety questionnaire is administered.
- 10:50 AM: Blood sample is obtained immediately after the final lift of the exercise session, hunger/satiety questionnaire is administered, body weight is measured, and 150 mL of CHO beverage is consumed.
- 12:20 PM: Blood sample is obtained.
- 12:30 PM: Hunger/satiety questionnaire is administered.
- 12:45 PM: Buffet.
- 13:15 PM: Hunger/satiety questionnaire is administered, and final blood sample is obtained.

2.6. Subject measurement of hunger and satiety

A VAS questionnaire for hunger and satiety was used a total of 6 times throughout the protocol: postbreakfast (7:15 AM), preexercise (9:10 AM), middle of exercise (10:10 AM), postexercise (10:50 AM), prebuffet (12:30 PM), and postbuffet (13:15 PM). Self-reported perceptions of hunger and fullness were obtained from the questionnaire. Subjects provided ratings by placing a mark on a 100-mm line with the 2 opposite extremes identified at the respective ends of the line.

2.7. Blood sampling

Blood samples were obtained by venipuncture at 5 different time points during each of the 3 treatment protocols: at baseline just before beginning the exercise session or controlled rest (9:10 AM), halfway through the exercise or controlled rest session (10:10 AM), immediately postexercise or rest (10:50 AM), at 110 minutes postexercise or rest (12:20 PM), and at 150 minutes postexercise or rest, after consumption of food from the "buffet" (13:15 PM). Blood was drawn into Vacutainer tubes containing EDTA, which were then immediately put on ice. After all 5 samples were collected, they were centrifuged; and plasma was removed and stored in a −70°C freezer for later analysis. Upon completion of all 3 protocols by all of the subjects, the plasma was taken to the University of Colorado Health Sciences Center and analyzed for glucose by the glucose oxidase method, and for insulin and ghrelin by enzyme-linked immunosorbent sandwich assays.

2.8. Measured food intake

Two hours after the cessation of the exercise bout, subjects were presented with a food buffet. They were instructed to sit at the buffet for a total of 30 minutes and eat whatever foods in whatever amounts they wanted. Participants were not told that their food consumption was being measured, in an attempt to decrease any confounding variables that could influence the amount and types of food consumed. The same food items were present in every buffet, set up in the same place, and weighed (Ohaus CS2000 Compact Scale, Pine Brook, NJ), before setting up the buffet to determine the same gram weight for each food item. After the 30-minute period, every food item, container, and wrapper were reweighed to calculate the amounts (in grams) of each food item consumed. The macronutrient composition of the meal was then analyzed with FIAS399 for total kilocalories.

Given the additional CHO consumed in 2 of the 3 conditions (ExCHO and NoExCHO) and the additional energy expenditure in 2 of the 3 conditions (ExCHO and ExPLA), the energy intake from the buffet was calculated as a relative value, adjusting for the CHO supplement and for the net energy cost of exercise using the following formula: relative energy intake from the buffet = buffet energy intake plus supplemental CHO intake during exercise or sitting, minus the estimated net exercise energy expenditure.

2.9. Data analysis

Data were analyzed by SPSS (Chicago, IL) software using a 2-way (condition × time) repeated-measures analysis of variance, with post hoc comparisons made where

Table 1
Physical characteristics of the subjects (n = 21; mean ± SD)

Age (y)	20 ± 1.8
Weight (kg)	82.3 ± 13.6
Height (cm)	181.7 ± 7.3
BMI (kg/m²)	24.8 ± 3.3
Fasting blood glucose (mg/dL)	83.1 ± 13.0
RMR (kcal)	1940 ± 315

appropriate using least significant difference tests. Statistical significance was set at *P* less than .05.

3. Results

The physical characteristics of study participants (n = 21) are reported in Table 1. All subjects were normal-weight young men who engaged in resistance exercise 2 to 4 times per week, but none were competitive body builders or participants in intercollegiate sports that required a specific training regimen.

3.1. Exercise bouts

Table 2 shows the mean amount of weight lifted for each specific lift as well as the mean total amount of weight lifted for each of the 2 exercise treatments. These values were determined based on the amount of weight lifted for each exercise multiplied by the number of repetitions during all 4 sets. The total amount of weight lifted for all 8 lifts was similar for the 2 exercise conditions; that is, there were no differences in weight lifted whether the CHO beverage was consumed or not.

3.2. Plasma glucose, insulin, and ghrelin changes over time

Baseline plasma glucose concentrations did not differ among the 3 conditions the morning of each trial (Fig. 1). A significant time × treatment interaction was found ($P < .001$), with post hoc comparisons revealing that, at the completion of exercise session, plasma glucose concentrations were higher for ExCHO than for both other conditions. However,

Table 2
Amount of weight lifted (in kilograms) (weight x repetitions x sets) for each of the 2 exercise bouts (n = 21)

Exercise	ExCHO mean ± SD	ExPLA mean ± SD
Chest	2708 ± 577	2748 ± 552
Row	2543 ± 456	2520 ± 472
Leg press	6096 ± 2031	6351 ± 2089
Leg extension	2943 ± 787	2959 ± 832
Leg curl	1936 ± 380	1883 ± 386
Shoulder	1658 ± 389	1652 ± 328
Biceps	1050 ± 286	1058 ± 277
Triceps	1031 ± 250	1042 ± 287
Total weight lifted	19779 ± 3402	20142 ± 3875

There were no significant treatment differences in the amount of weight lifted for any single exercise or for the total bout.

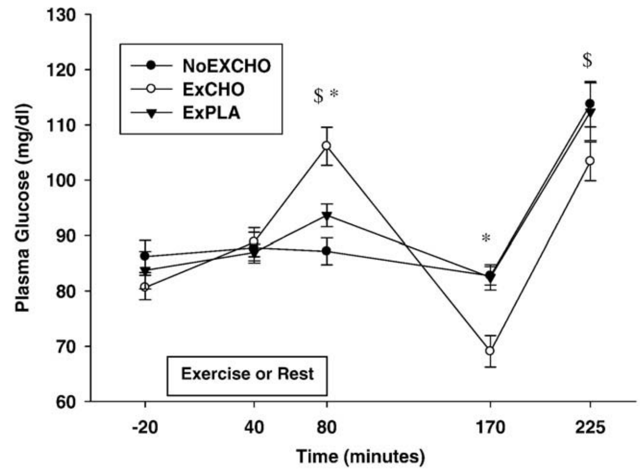

Fig. 1. Plasma glucose concentrations (mean ± SEM) determined before, during, and postexercise, and before and after food consumption from the buffet in 20 subjects, each completing the 3 conditions. There was a significant time × condition interaction with plasma glucose. *ExCHO different than ExPLA ($P < .05$); $ExCHO different from NoExCHO ($P < .05$).

glucose concentrations 90 minutes postexercise (minute 170) were lower for the ExCHO compared with the ExPLA and NoExCHO conditions ($P < .001$). Immediately after buffet consumption, plasma glucose remained lower for ExCHO compared with NoExCHO ($P < .05$).

There were no significant differences in baseline insulin concentrations the morning before each trial (Fig. 2). A significant time × treatment interaction was found ($P < .001$); and post hoc comparisons revealed that, at the midpoint of exercise, the insulin concentrations differed significantly among all 3 conditions. Immediately after exercise, ExPLA had significantly lower plasma insulin than ExCHO ($P < .001$) and NoExCHO ($P < .001$). Insulin concentrations were not different among conditions at the measured time interval between the end of exercise and buffet consumption. As

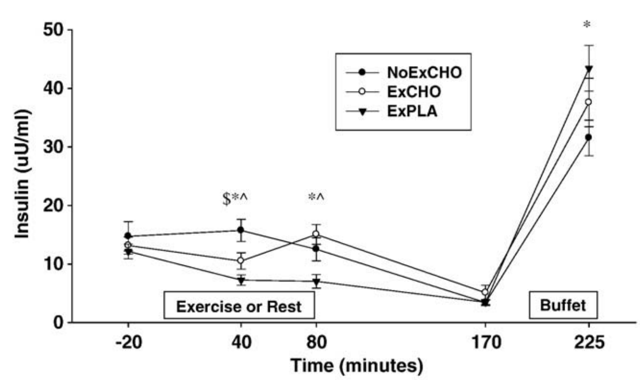

Fig. 2. Plasma insulin concentrations (mean ± SEM) determined before, during, and postexercise, and before and after food consumption from the buffet in 20 subjects, each completing the 3 conditions. There was a significant time × condition interaction with plasma insulin. *ExCHO different from ExPLA ($P < .05$); $ExCHO different from NoExCHO ($P < .05$); ^ExPLA different from NoExCHO ($P < .05$).

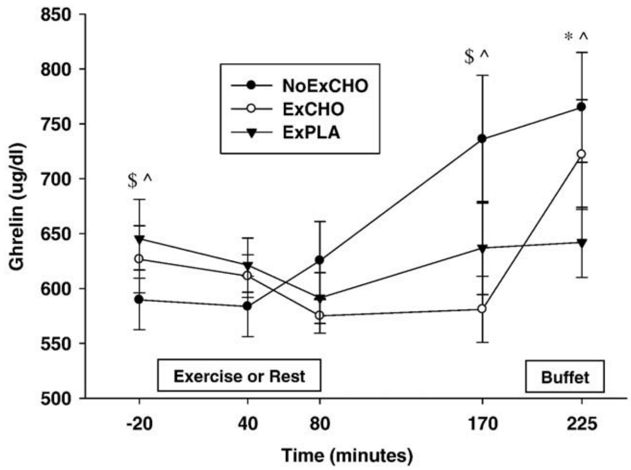

Fig. 3. Plasma ghrelin concentrations (mean ± SEM) determined before, during, and postexercise, and before and after food consumption from the buffet in 20 subjects, each completing the 3 conditions. There was a significant time × condition interaction with plasma ghrelin. *ExCHO different from ExPLA ($P < .05$); $ExCHO different from NoExCHO ($P < .05$); ^ExPLA different from NoExCHO ($P < .05$).

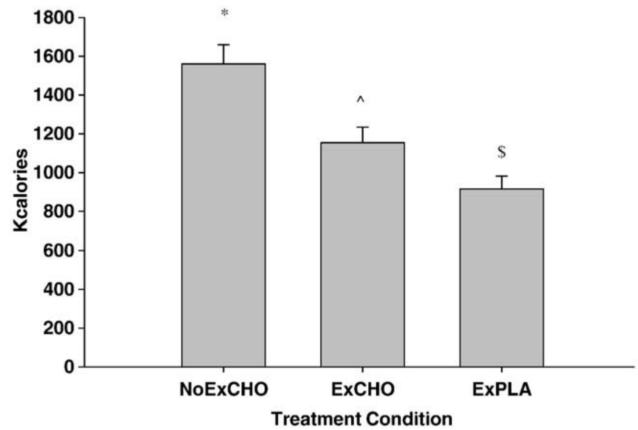

Fig. 5. Relative buffet energy intake (mean ± SEM). There were significant differences among all 3 conditions. Different symbols indicate group differences at P less than .05.

expected, insulin levels rose sharply in response to feeding from the buffet in all conditions.

There was a significant baseline difference in plasma ghrelin concentrations at the morning of each trial between the no-exercise and exercise conditions ($P < .05$). Ghrelin decreased in response to exercise compared with an increase in the no-exercise condition (treatment × time interaction, $P < .05$) (Fig. 3). Carbohydrate consumption during exercise did not lower plasma ghrelin concentrations at the midpoint and end of exercise any more than exercise alone. Ninety minutes after exercise, ghrelin concentrations remained significantly lower for the ExCHO and ExPLA conditions than for NoExCHO ($P < .05$). At this same time point, plasma ghrelin was lower for ExCHO than ExPLA; but the difference did not reach statistical significance ($P = .1$). Immediately after buffet consumption, plasma ghrelin concentrations were at their highest, with values being significantly lower for ExPLA than for ExCHO and NoExCHO. There was no significant difference in post-buffet ghrelin concentrations between the ExCHO and NoExCHO conditions.

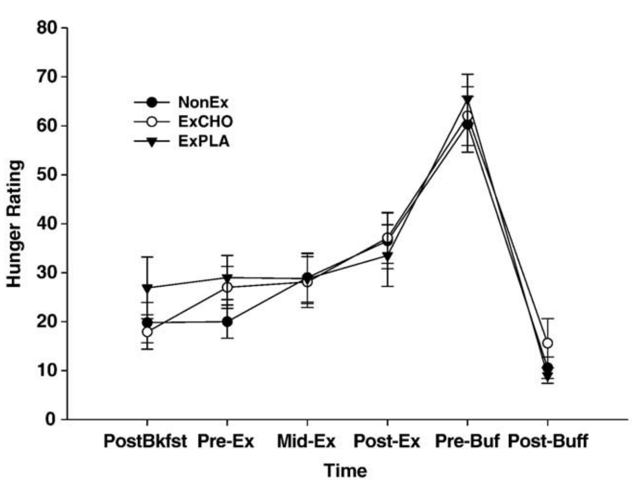

Fig. 4. Subject hunger ratings (mean ± SEM) in response to the question "How hungry do you feel right now?" on a VAS from 0 to 100 (0 = not hungry at all; 100 = extremely hungry). Hunger ratings displayed a time effect based on a progressive increase until the buffet feeding and then a subsequent decrease postbuffet. There was no significant treatment effect and no treatment × time interaction.

3.3. Hunger and energy intake

For hunger ratings, there was a significant time effect, with hunger increasing sharply 30 minutes before the buffet and diminishing upon completion of the buffet. However, there was no condition × time interaction for subjective feelings of hunger (Fig. 4) or satiety (not shown in figure format as these data are similar to those in Fig. 4, but in the opposite direction). These data indicate that the CHO compared with placebo consumed during exercise did not affect subsequent subjective hunger or satiety ratings, nor did exercise compared with rest affect hunger ratings.

3.3.1. Buffet

There were no differences in ad libitum absolute energy intake from the buffet after any of the trials ([mean ± SD] NoExCHO, 1251 ± 440 kcal; ExCHO, 1297 ± 347 kcal; ExPLA, 1367 ± 303 kcal). These data indicate that the study volunteers did not lower their postexercise energy intake to compensate for the additional energy intake from the CHO beverage in the NoExCHO and ExCHO conditions. It is also apparent from these data that, for the 2 exercise conditions, the subjects did not compensate for the additional energy expended during the exercise bout by increasing their energy intake from the buffet relative to their buffet intake in the resting condition.

Fig. 5 shows that the relative buffet energy intake was significantly different among all 3 conditions, being lowest in the ExPLA condition and highest in the NoExCHO condition. The relative buffet energy intake differences among the 3 conditions indicate that, when feeding ad libitum from the buffet, these young men failed to compensate for the supplemental CHO ingested in the ExCHO and NoExCHO conditions relative to the ExPLA condition, and also failed to compensate for the energy cost of exercise in the ExCHO and ExPLA relative to the NoExCHO condition.

4. Discussion

4.1. Major findings

There were several noteworthy findings of this study: (1) In young physically active men, resistance exercise significantly attenuated the rise in plasma ghrelin concentrations as the time interval increased after the preexercise breakfast meal; but the lower concentrations of this hormone had no effect on subjective measures of postexercise hunger. (2) Minimizing the acute energy deficit from exercise by consumption of approximately 300 kcal of CHO during the resistance exercise protocol did not lower plasma ghrelin concentrations more than exercise without partial energy replacement. (3) Attenuating the acute energy deficit by use of a CHO beverage during resistance exercise did not lower postexercise energy intake relative to the exercise condition without CHO. (4) Despite the energy cost of the resistance exercise (estimated to be ~450 kcal), the subjects did not immediately compensate by increasing energy intake from the buffet relative to the no-exercise condition. There remains the possibility that the lower postexercise plasma ghrelin contributes to the lower relative energy intake in a meal 2 hours after resistance exercise.

4.2. Ghrelin response

The significantly higher baseline plasma ghrelin levels for the 2 exercise conditions are difficult to interpret, given the fact that the same meals were provided the day before each trial and subjects reported to the laboratory in the fasted state for each trial. Perhaps the anticipation of the impending exercise led to a rise in ghrelin concentrations. It has been shown in mice that ghrelin secretion is increased with stress; and because the participants knew that they were going to exercise later, there could have been an increase in stress that may have affected baseline ghrelin levels [24].

In the current study, the nadir of plasma ghrelin was reached immediately after the exercise bouts. This attenuation of the rise in plasma ghrelin resulting from resistance exercise is supported by previous literature. Although the mechanism behind this phenomenon is currently unknown [25], the rise in plasma growth hormone (GH) concentrations with strenuous exercise has been implicated. Because ghrelin is a secretagogue for GH [26], there could potentially be a negative feedback loop such that suppression of ghrelin occurs when GH levels are high [27]. It has been shown that resistance exercise increases GH concentrations to a greater degree than aerobic exercise [28], which may explain why resistance compared with endurance exercise appears to have a greater suppressive effect on ghrelin concentrations.

Hunger and satiety result from the integration of numerous signals, not just a single peptide like ghrelin. For example, an acute bout of aerobic exercise was shown to increase the anorexigenic gut peptides PYY and GLP-1 in concordance with reduced hunger and relative energy intake from a buffet [15]. We did not measure these gut peptides; but it has recently been demonstrated that PYY, an appetite-suppressing peptide, appears more responsive to aerobic than resistance exercise, whereas the reverse may be true for ghrelin [29]. It seems possible then that different types of exercise may affect distinctive gut peptides, the levels of which act in concert to affect postexercise hunger, satiety, and food intake.

We hypothesized that young men completing a strenuous resistance exercise bout would report less hunger during a short postexercise recovery period as has been previously shown [7], which would be related to lower ghrelin concentrations. However, subjective measures of hunger were not different after either exercise bout compared with a resting control condition despite the lower ghrelin concentrations. Possibly, the time interval between the breakfast meal and the postexercise buffet was so long that any tendency toward exercise-induced suppression of hunger was completely overwhelmed by the subject's not having eaten for almost 6 hours [7]. Perhaps, had subjects been provided access to food immediately after the exercise bout when ghrelin was at its nadir, food intake would have been lower. Food consumption immediately after vigorous exercise is often recommended for athletes to maximize glycogen restoration, minimize skeletal muscle protein degradation, and enhance protein synthesis. However, our study subjects were not trained athletes or body builders; and we chose to feed the study participants 2 hours postexercise, as this seemed like a more realistic reflection of people's normal eating habits, given the usual decrease in appetite after strenuous exercise [15,30]. Examining food intake, gut peptides, and hunger scores immediately after cessation of resistance exercise is recommended for a future study.

Plasma ghrelin progressively increased after exercise, reaching a peak concentration immediately after the buffet. Cummings [11] found that subjective feelings of satiety and termination of a meal occur before ghrelin concentrations decline and that the decline in plasma ghrelin did not reach significance until 60 minutes after the start of the meal. Blom et al [31] did not find changes in postprandial ghrelin concentrations among 3 different CHO breakfasts (low-calorie, high-calorie simple CHO, and high-calorie complex CHO) until 120 minutes postmeal [31]. Because of the evidence that feeding is terminated before a significant decline in ghrelin, there must be other physiologic factors that have a stronger impact in meal initiation and termination. These factors could be from sensory cues [32,33], gastric distension, increased blood glucose concentrations [34], and several short-acting, meal-stimulated intestinal satiation factors (ie, cholecystokinin) [11]. We hypothesized that, if plasma glucose were better maintained during and after exercise because of CHO ingestion, this might result in lower ghrelin concentrations, lower subjective ratings of hunger, and less buffet food intake compared with the placebo condition. However, we found plasma glucose fluctuations over time to be greatest in the ExCHO, such that 90 minutes postexercise the glucose concentrations were significantly lower in ExCHO compared with the other 2 conditions. Although plasma ghrelin levels often decrease with higher glucose and insulin, our data and those of others [35] suggest that this is not always a tight relationship. In the ExCHO condition, the plasma glucose was lowest at the same time point that ghrelin was also the lowest. Given that transient declines in blood glucose levels are known to induce feeding [34], there is the possibility that the hunger-suppressing effect of low plasma ghrelin was offset by the hunger-stimulating effect of low plasma glucose. Moreover, data from Erdmann et al [36] suggest that the effect of ghrelin on hunger may not appear until 4 hours postmeal and therefore is not necessarily involved in immediate food intake. If true, this could potentially explain the disconnect we found between ghrelin and glucose concentrations with hunger ratings and food intake.

It has also been suggested that insulin is an inhibitor of ghrelin release [36]. In the current study, we found no consistent indication that insulin had an effect on ghrelin concentrations. In fact, insulin and ghrelin were both at or near their highest point after the buffet in all conditions, which contradicts the notion that insulin suppresses ghrelin. It is possible that there is a time lag in the effect of insulin on suppression of ghrelin [37], but the study design we used does not provide for an opportunity to examine this possibility.

4.3. Strengths and limitations

There are several strengths to the current study including the double-blind and within-subject design. Because acute energy balance can affect subjective measures of hunger and satiety as well as actual food intake, we determined energy requirements for each individual subject and provided all food for the day before the 3 testing conditions and also a standardized breakfast the day of each test. Thus, between- and within-subject differences in energy balance across the 3 conditions were minimized. Because of the short study duration, it is unclear what long-term effects the additional CHO and the exercise energy expenditure would have on energy intake. Furthermore, because our study sample was composed of lean college-aged men, our results are likely not applicable to overweight, obese, or female populations.

We considered matching the energy consumed from the CHO beverage with the net cost of the exercise bout, essentially creating a condition of exercise without any acute energy deficit. However, difficulties in accurately determining resistance exercise energy expenditure limit the ability to design such a study, as well as the fact that rarely would a person exercise for 80 minutes without some degree of energy deficit. We believe that the amount of supplemental CHO consumed led to only partial energy replacement based on estimates of the energy cost of the exercise. However, we recognize that the formula we used was only an estimate; and it is therefore possible that the magnitude of energy deficit may have been higher or lower than we surmise.

We used the VAS approach to determine subjective measures of hunger during the protocol. The hunger ratings were not different among trials, but peaked just before eating the buffet meal, with an average hunger rating of around 65. However, we did not measure hunger ratings after the overnight fast just before the breakfast, which might be expected to be the peak level of hunger [38]. We therefore cannot ascertain how the level of hunger before the buffet relates to subjects' maximum level of hunger after the overnight fast. It has been shown that a rating of around 75 to 80 is typical after an overnight fast [38], suggesting that our subjects' hunger rating of 65 before the buffet meal reflected a fairly high level of hunger for participants.

The amount of fluid provided each study participant was consistent across all 3 trials. It is possible that the increase in fluid per se could have an effect on ghrelin, hunger, or food intake. It has been demonstrated that food intake and hunger do not differ when noncaloric or caloric beverages are consumed 30 and 60 minutes before a meal [33]. Moreover, fluid consumption compared with no fluid does not affect food intake or hunger ratings 30 and 60 minutes later [33]. The effect of fluid intake on ghrelin levels is not known; however, intragastric infusion of water has no effect on ghrelin concentrations [39]. Given the nature of our study design in which we did not include a no-fluid condition, we cannot discern any possible effects that the fluid and electrolytes might have had on ghrelin levels, hunger, and buffet intake.

4.4. Conclusion

Vigorous resistance exercise, with or without partial energy replacement by way of CHO supplementation, attenuated the postexercise rise in plasma ghrelin concentrations as the time interval increased from the preexercise meal. However, the lower plasma ghrelin concentrations did not decrease subjective feelings of hunger relative to the no-exercise condition; nor was absolute postexercise ad libitum energy intake lower in the exercise compared with the no-exercise conditions. However, when accounting for the cost of the exercise, relative energy intake was lower for the 2 exercise conditions compared with rest, leaving open the possibility that the lower plasma ghrelin may be related to reduced relative energy intake after resistance exercise.

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