Behavioral components of high-fat diet hyperphagia: meal size and postprandial satiety

ZOE S. WARWICK, COLLEEN M. MCGUIRE, KATHLEEN J. BOWEN, AND STEPHEN J. SYNOWSKI
Department of Psychology, University of Maryland Baltimore County, Baltimore, Maryland 21250

Warwick, Zoe S., Colleen M. McGuire, Kathleen J. Bowen, and Stephen J. Synowski. Behavioral components of high-fat diet hyperphagia: meal size and postprandial satiety. Am. J. Physiol. Regulatory Integrative Comp. Physiol. 278: R196–R200, 2000.—Previously, rats fed a high-fat liquid diet (HF) ad libitum consumed more kilocalories and had greater weight gain than rats fed a liquid high-carbohydrate diet (HC) of equivalent energy density (Warwick, Z. S., and H. P. Weingarten. Am. J. Physiol. Regulatory Integrative Comp. Physiol. 269: R30–R37, 1995). The present series of experiments sought to clarify the behavioral expression of HF hyperphagia by comparing HF and HC with regard to meal size and magnitude of postingestive satiety effect. Meal size of HF was greater than HC at 2.3 kcal/ml and also when diets were formulated at 1.15 kcal/ml. In a preload-test meal paradigm, an orally consumed HF preload was less satiating than a calorically equivalent HC preload across a range of preload volumes and intermeal intervals. Sensory-specific satiety was ruled out as an explanation of the relatively weaker postprandial satiety. Meal size of HF tended to be larger than HC, but the difference was not significant. Because chow was consumed concurrent with the self-infused liquid diet, it is difficult to interpret these findings with regard to an independent effect of liquid diet composition on meal size and frequency.

The present series of experiments further explored the hyperphagia elicited by a high-fat diet by measuring the relative meal sizes elicited by HF and HC (experiment 1) and their relative postprandial satiating effects using a preload-test meal paradigm (experiments 2 and 3).

GENERAL METHODS

Subjects and Housing

Male Long-Evans rats (Charles River) were singly housed in hanging wire mesh cages, with a 12:12-h light-dark cycle. Tap water and Purina chow were always available, except as noted.

Solutions, Emulsions, and Liquid Diets

Sucrose solutions were formulated weight per volume using sucrose (Domino brand) and tap water. Corn oil emulsions consisted of corn oil (Mazola, CPC/Best Foods) emulsified in water with 0.6% sodium sterylamine using sucrose (Domino brand) and tap water.
lactylate (Emplex, American Ingredients). Emulsions were prepared weight per volume as described in Ref. 14.

The HC and HF were identical to those used in previous work (15) and were formulated from evaporated milk, sucrose, corn oil emulsion, and water (Table 1).

Testing Conditions

All testing was conducted 4–6 h into the light phase, with chow removed ~15 min before testing.

Experiment 1: Meal Size of HF vs. HC

This study compared meal size of HF to meal size of HC in one-bottle intake tests. To assess the generality of relative meal size of HF and HC, intake of less calorically dense versions of these diets was also measured.

Method. HF and HC (Table 1) were prepared at two caloric densities: 2.3 (standard) and 1.15 kcal/ml (standard formulation diluted 1:1 with water). Ten rats were first trained, as part of an earlier unrelated study, to consume from a spout in individual Plexiglas feeding cages. [During this training, rats consumed sucrose solutions and fat emulsions.] Intake of the HF and HC at both densities was then measured in one-bottle, 30-min tests, with randomized presentation order. The initial test with each diet formulation (first series of 4 tests) served to familiarize rats with the diets, and these intake data were not analyzed. Intake data from the second series of tests were analyzed using two-way ANOVA for repeated measures.

Results. Rats ate a larger meal of HF than of HC in one-bottle tests across both diet densities tested (Fig. 1). These findings were reflected in statistically significant main effects of diet, F(1, 9) = 7.0, P < 0.05, and density, F(1, 9) = 38.4, P < 0.01, with no interaction.

Discussion. Meal size can be conceptualized as reflecting the summation of the intake-excitatory effects of taste ("palatability") and the intake-inhibitory ("satiating") influence of the food's postingestive effects. Differences between HF and HC in either or both of these respects could explain the larger meal size of HF. To determine the mechanism(s) by which HF elicits a larger meal size, it is necessary to isolate taste and postingestive effects on intake, which can be accomplished using the techniques of sham feeding and intragastric feeding, respectively. Previous work (15) found that sham-feeding intake (in which ingested food drains out of the stomach and thus produces minimal postingestive effects) of HF and HC did not differ significantly, although absolute intake of HF was slightly greater.

In light of the significantly larger meal size of HF vs. HC in the present (real feeding) study, the lack of a significant difference in the palatability of HF and HC suggests that a relatively weaker (on a per kcal basis) postingestive inhibitory effect of HF contributes to the larger meal size of HF. Support for this hypothesis comes from two separate studies in which rats were equipped with intragastric catheters and permitted to self-infuse liquid diet directly into their stomach. Because the diet was not tasted in this paradigm, any difference in (infused) intake between HF and HC was attributable to the diets' postingestive effects. In a between-subjects design, rats infusing HF tended to infuse a larger meal than did rats infusing HC (15). A similar finding was noted in a recent study using a within-subjects design (6). However, it should be noted that in both of these studies, the tendency for rats to infuse a larger meal of HF than HC did not attain statistical significance. Thus the significantly larger meal size of HF when rats were real feeding (Fig. 1) suggests that the diets differ in the extent to which their postingestive effects modulate their intake-excitatory effect, i.e., their palatability. In other words, HF elicits a larger meal because the postingestively mediated decline in palatability occurs more slowly than is the case for HC. This inference that HC's postingestive effects are more potent than HF in degrading palatability could be tested in a paradigm combining sham feeding and duodenal infusion (e.g., Ref. 3). The present model predicts that duodenal infusion of HC would suppress sham-feeding intake more than an infusion of HF.

Experiment 2: Postingestive Satiety Effects of HF vs. HC

Ingestion of a meal produces some degree of inhibition of subsequent eating, a state called "satiety." Over time, the satiety produced by a meal dissipates and at some point another meal is begun. Because total kilo-

Table 1. Liquid diets

<table>
<thead>
<tr>
<th>Food</th>
<th>High Fat</th>
<th>High Carbohydrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporated milk, ml</td>
<td>270</td>
<td>270</td>
</tr>
<tr>
<td>Corn oil emulsion (44.4%), ml</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>Sucrose, g</td>
<td>70</td>
<td>195</td>
</tr>
</tbody>
</table>

Brought to volume of 500 ml with water. Both diets = 2.3 kcal/ml. Evaporated milk, Carnation brand; corn oil, Mazola brand, CPC/Best Foods; sucrose, Domino brand. From Ref. 15.
calorie intake by rats consuming HF is greater than that of rats consuming HC (both when the liquid diet was the sole source of nutrition (15) as well as when the liquid diet supplemented maintenance chow (6)), it follows that HF produces less postingestive satiety, per kilocalorie, than HC. If this were not the case, the larger meals of HF (experiment 1) would be followed by proportionally longer intermeal intervals, with the result that fewer meals of HF would be consumed over 24 h and total daily intake of HF would equal HC. A dose-response paradigm was used to directly compare the relative postingestive satiety effects of HF and HC by using a range of preload volumes (experiment 2A). To investigate whether the relative postingestive satiety effects of HF and HC differed as a function of time since ingestion, a range of preload-test meal intervals was used (experiment 2B).

Methods. Fifteen rats were individually housed and trained to associate a buzzer-light conditioned stimulus (CS) with the delivery of food, as described previously (14). After this training, rats reliably initiated feeding in response to the CS, which allowed experimental control over the timing of preload and test meal ingestion. Chow was removed from the home cages 10 min before a test trial, which consisted of a 5-min presentation of the CS, with the preload (either HF or HC) delivered into the food cup during the final minute of the CS. After an interval (the “preload-test meal interval”), the CS was again presented for 5 min, with the test meal delivered during the final minute. The amount of test meal consumed was measured and used to index the relative satiating effect of the preload.

Experiment 2A: Preload Volume Manipulation

HF and HC preloads were given in the following volumes: 2, 4, 6, and 8 ml. The preload-test meal interval was 20 min, and the test meal was 10% sucrose. Two control (no preload) tests were also run. Each rat was tested with both preloads at all volumes; volumes were given in ascending order with the order of preloads within a volume randomized across rats. Only one test session was conducted per day. Chow was available ad libitum after each session. Test meal intake data from the preload test days were analyzed using two-way ANOVA for repeated measures. Test meal intake from the control (no preload) data is presented (Fig. 2), but was not included in the ANOVA so as to avoid a potentially spurious interaction effect.

Results. Intake of a 10% sucrose test meal after the HF preload was greater than test meal intake after an equivalent volume of HC preload, and test meal intake decreased with increasing preload size (Fig. 2). This was reflected in statistically significant main effects of preload type, F(1,14) = 57.8, P < 0.01, and preload volume, F(3,12) = 27.6, P < 0.01. The interaction of preload type and preload volume was also significant, F(3,12) = 3.7, P < 0.05. The difference in intake after the HF and HC preloads increased as preload volume increased: for the 2-ml preload, intake after the HF preload was 6% greater than intake after the HC preload. In contrast, when the preload volume was 8 ml, intake after the HF preload was 54% greater than intake after the HC preload. The functional relationship between preload size and test meal intake was linear for both diets (adjusted r²: HC = 0.31, HF = 0.12); a quadratic function did not explain any additional variance.

Experiment 2B: Preload-Test Meal Interval Manipulation

Rats and testing conditions were as described in experiment 2A, except that the preload-test meal interval was varied as follows: 10, 20, 40, 60, and 120 min and preload volume was always 6 ml. Each rat was tested with both preloads at all intervals, and order of intervals was randomized with the constraint that the same interval was used on consecutive sessions (order of preloads within an interval was randomized).

Results. Intake of a 10% sucrose test meal after HF was greater than intake after HC, and increasing the preload-test meal interval produced a larger test meal after both preload types (Fig. 3). This was reflected in statistically significant main effects ofpreload type, F(1,14) = 45.9, P < 0.01, and preload-test meal interval, F(4,11) = 13.9, P < 0.01, with no interaction.

Discussion. Across a range of preload volumes and preload-test meal intervals, the HF diet produced less postingestive satiety than did an isocaloric quantity of HC. This confirms the prediction made in light of the greater daily intake of HF vs. HC (15), as discussed.

Fig. 2. Experiment 2A: intake of a 10% sucrose test meal after isocaloric (2.3 kcal/ml) HF and HC preloads as a function of preload volume.

Fig. 3. Experiment 2B: intake of a 10% sucrose test meal after isocaloric (2.3 kcal/ml) HF and HC preloads as a function of preload-test meal interval.
of either HF or HC was delivered intragastrically at a rate of ~1 ml/min. Twenty minutes after the start of the intragastric infusion, a test meal of 10% sucrose was offered.

Results. Rats ate significantly more after the HF preload (mean 8.5 ml, SE 0.41) than after the HC preload (mean 6.8 ml, SE 0.80), t(12) = 2.2, P < 0.05.

Experiment 3B: Pure Nutrient Preloads, Evaporated Milk Test Meal

Ten rats were tested using the standard preload-test meal paradigm. Preloads were 17.8% corn oil emulsion (Fat) and 40% sucrose (Suc), both of which had caloric densities of 1.6 kcal/ml. The test meal was evaporated milk. These stimuli were chosen to meet two objectives: to evaluate the effects of pure nutrient preloads (rather than mixtures differing in their relative proportion of macronutrients) and to use a test meal having markedly different sensory properties than either preload. Rats were tested with a range of preload volumes: 2, 4, 6, and 8 ml. The preload-test meal interval was always 20 min.

Results. Intake of the evaporated milk test meal after the Fat preload was greater than test meal intake after an equivalent volume of Suc preload, and test meal intake decreased with increasing preload size (Fig. 4). This was reflected in statistically significant main effects of preload type, F(1,9) = 9.4, P < 0.05, and preload volume, F(3,7) = 21.4, P < 0.01. The difference in intake after the Fat and Suc preloads increased as preload volume increased: for the 2-ml preload, intake after the Fat preload was 6% greater than intake after the Suc preload. In contrast, when the preload volume was 8 ml, intake after the Fat preload was 59% greater than intake after the Suc preload. However, the interaction of preload type and preload volume did not attain statistical significance, F(3,7) = 2.9, P = 0.1.

Discussion. These findings are consistent with the results from experiment 2, as well as previous studies (1, 2, 11, 14, but see 7) in demonstrating that fat produces less postingestive satiety than carbohydrate. With the use of two separate strategies, sensory-specific satiety was ruled out as an explanation for the relatively smaller test meal intake after a high-carbohydrate preload. Although sensory-specific satiety does appear to affect test meal intake when the preload-test meal interval is short (10 min), as shown previously (14), the present data are consistent with previous findings (14) in showing that the sensory-specific satiety effect apparently dissipates within 20 min of preload ingestion.

GENERAL DISCUSSION

The behavioral expression of the hyperphagia elicited by an HF diet relative to an HC diet was investigated by comparing HF and HC with regard to meal size (experiment 1) and satiating effect (experiments 2–3). HF elicited a significantly larger meal size than HC, across both levels of diet density tested. A previous study (15) found no difference in sham intake of HF vs. HC, suggesting that the significantly larger real-fed meal size of HF is attributable to differences in the extent to which the postprandial effects of HF and HC modulate the intake-excitatory effect of taste. In other words, HF elicits a larger meal because its palatability is less rapidly reduced by postingestive feedback. Future studies will test this hypothesis by measuring the impact of HF vs. HC duodenal infusions on sham intake.

HF produced relatively less postprandial satiety than an equivalent quantity of HC. This observation was consistent across a range of methodological manipulations, including preload volume, preload-test meal intervals, and method of preload delivery. Other studies have also found fat to be less suppressive of subsequent intake than carbohydrate in rat (1, 2, 11, 14),
although one study (7) found equivalent intake after fat and carbohydrate preloads.

When consumed long term (16 days), HF elicited greater daily intake and weight gain than HC (15). The present results indicate that the hyperphagia-promoting effect of HF reflects its impact on both of the behavioral components of intake regulation: meal size and postprandial satiety. Meals are bigger, and postprandial satiety is weaker, per kilocalorie, when HF is consumed. These findings predict that rats consuming HF orally would eat larger meals than rats consuming HC; whereas meal frequency might also be greater in HF-fed rats, it is possible that meal frequency would not differ as a function of diet if the larger meal of HF produced satiety equal in magnitude to the smaller HC meal. These predictions can be directly tested by monitoring meal patterns in spontaneously feeding rats.

With regard to the anatomic site(s) that generate intake-suppressive signals, the satiating effects of nutrient loads appear to be mediated both pre- and postabsorptively. When short-term intake was measured, intragastric or duodenal infusion of fat or carbohydrate produced marked intake suppression, whereas the same infusion given intravenously did not (3, 4). Evidence for both pre- and postabsorptive inhibition of intake by infused nutrients comes from a recent study (1) in which rats received either intragastric or intravenous infusions of either lipid or glucose over 3 days. Intragastric infusion produced greater suppression of spontaneous food intake than intravenous infusion, but intravenous infusion did significantly suppress intake relative to baseline. Under both infusion conditions, fat produced less suppression than glucose. Furthermore, areas of the intestine differ with regard to relative sensitivity to the intake-suppressive effects of nutrients. Duodenal infusion of fat (oleic acid) produced greater suppression of intake than the same infusion delivered to the ileum; the opposite pattern was observed when glucose was infused (16). A strength of the present program of research characterizing the behavioral effects of the HF and HC diets is that the role of putatively relevant anatomic site(s) (oral, gastric, duodenal, intestinal) mediating the diet-specific behavioral differences can be investigated using site-specific infusion techniques, with the goal of clarifying the integration of the physiological bases of HF diet hyperphagia with its behavioral manifestation.

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Address for reprint requests and other correspondence: Z. Warwick, Dept. of Psychology, Univ. of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250 (E-mail: warwick@umbc7.umbc.edu).

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REFERENCES


