

Food Viscosity Influences Caloric Intake Compensation and Body Weight in Rats

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Abstract

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Objective: To determine the effects of food viscosity on the ability of rats to compensate for calories in a dietary supplement.

Research Methods and Procedures: In a series of four experiments, rats consumed dietary supplements equated for caloric and nutritive content but differing in viscosity. Experiments 1 to 3 examined the ability of the rats to compensate for the calories consumed in low- compared with high-viscosity premeals by reducing intake of a subsequent test meal. Caloric compensation was assessed with a wide range of premeal viscosity levels and with two different non-nutritive thickening agents. Experiment 4 assessed the effects of consuming daily a low-viscosity compared with an equicaloric high-viscosity dietary supplement on longer term body weight gain.

Results: Consuming a lower viscosity premeal was followed by significantly more caloric intake (i.e., less caloric compensation) compared with consuming premeals with higher viscosity levels. This effect was not specific to one thickening agent. Furthermore, rats given a low-viscosity supplement daily gained significantly more weight over a 10-week period compared with rats given a high-viscosity supplement.

Discussion: The results of these experiments suggest that food viscosity may be an important determinant of short-term caloric intake and longer term body weight gain.

Key words: calories, eating, rheology, learning, environment

Introduction

Caloric compensation involves the ability to adjust for excess calories consumed on one occasion by reducing intake at other times (1,12). Failure of caloric compensation could, therefore, result in positive energy balance and increased tendencies toward overweight and obesity (22). Viscosity, which is defined as resistance of a substance to flow, may be one property of food that influences caloric compensation. According to some reports, calories consumed in liquid form produce compensation in humans that is incomplete relative to that produced when calories are consumed in solid foods (e.g., 5,7,15). However, other studies have not found this relationship (e.g., 21,23).

At least some of the variability of the findings may be due to the lack of control over important factors that could reduce the effectiveness of viscosity manipulations or that could make it difficult to detect the effects of those manipulations on food intake. For example, the magnitude of the viscosity manipulation has been quite varied, with little universally accepted definition of what constitutes a high- or low-viscosity diet. As a consequence, the low level of viscosity in some studies has sometimes been higher than the high level of viscosity used in other studies. The method of altering viscosity has also varied across studies, and some studies have confounded manipulations of viscosity with manipulations of energy density. In addition, a recent review proposed that such divergent results may be based on procedural differences such as those related to the timing of tests for caloric compensation (1). Finally, the effects of exposure to differences in diet, meal patterns, attitudes about food and eating, and other social, cultural, and learned factors can complicate interpretation of some human studies.

The purpose of the present research is to use the control that is afforded by a rat model of appetitive and consummatory behavior to study the effects of food viscosity on short-term caloric compensation and longer term body

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weight gain. Several earlier studies reported that rats tended to gain more weight and body fat when fed high-calorie liquid diets given either in addition to or instead of solid food (e.g., 14,16,17). However, because the rats were typically allowed free access to the diets used in these studies, instead of caloric compensation, differences in body weight and composition could have been due to differences in the palatability of the diets, in the amount of the diets consumed, and, in some cases, the macronutrient or energy content of the diets. In the present studies, rats consumed fixed amounts of dietary supplements that varied in viscosity but were equated with respect to nutritive and caloric content.

If rats compensate less well for calories contained in relatively low- compared with relatively high-viscosity foods, then rats that receive a low-viscosity premeal (LV)¹ should consume more calories in a subsequent test meal than rats that receive an equicaloric high-viscosity premeal. In Experiment 1, rats were given a premeal consisting of 10 grams of Chocolate Ensure Plus. For one group, 3% guar (a non-metabolizable gum) was added to the Ensure Plus, whereas 3% water was added for the other group. This procedure produced marked differences in the viscosity of the two premeals while holding constant caloric and nutritive content. After all of the rats had consumed all of their respective premeals, they were given free access to one of three different test meals, including their normal laboratory chow. Differences in test meal intake served as the index for differences in caloric compensation after each premeal. With this research design, the effects of the viscosity of the supplement on caloric compensation were measured under conditions that controlled for the palatability, energy and nutrient content, and amount of dietary supplement consumed. Experiments 2 and 3 used this basic approach to assess caloric compensation after intake of different viscosity premeals compared with Experiment 1 and to determine whether differences in caloric compensation could be observed when methylcellulose instead of guar was used as a thickening agent.

Experiment 4 assessed the effects on longer term body weight gain of the viscosity of a dietary supplement consumed each day for 10 weeks. Previously, Labore et al. (9) reported that over a 6-week period, rats fed ad libitum (ad lib) a pureed diet of meat, beans, starch, and water gained more weight than rats given a non-pureed form of the same diet. However, animals given the pureed diet also ate more, so the effects of diet form per se could not be determined. In Experiment 4, rats ate the same fixed amount of equicaloric low- or high-viscosity Ensure Plus as a supplement to their normal diet of laboratory chow. Thus, in Experiment 4, differences in body weight gain could not be attributed to differences in the amount of supplement consumed.

Research Methods and Procedures

Subjects

The subjects were male Sprague-Dawley rats, obtained from Harlan, Inc. (Indianapolis, IN). In each experiment, all rats were assigned to treatment conditions that were matched on body weight. All rats had free access to water throughout the study. They were maintained on a 12-/12-hour light/dark cycle, with the light phase beginning at 7 AM daily. All rats were naïve, with the exception of the rats used in Experiment 1. These rats were assigned to Experiment 1 treatment conditions matched not only on body weight but also on prior experimental history. All rats were treated in accord with the *Guide for the Care and Use of Laboratory Animals*.

Viscosity Manipulations and Measurement

In all studies, rats were given premeals or daily supplements that consisted of 97% Ensure Plus and 3% of either distilled water, a non-nutritive and non-metabolizable thickening agent, or a mixture of water and thickening agent, by weight. With this procedure, large differences in viscosity could be achieved while holding constant both the caloric density (1.32 kcal/g) and the nutritive content of the premeals or supplements. In all experiments, these mixtures were blended for ~60 seconds using a standard kitchen blender set at medium speed. After being refrigerated for up to 48 hours, the mixtures sat at room temperature for ~1 hour before being stirred briefly by hand to remove air bubbles. Viscosity measurements were then recorded using a Brookfield digital viscometer (Model LVDV-1+ set at 50 rpm with a no. 7 spindle, Brookfield Engineering Laboratories, Stoughton, MA).

A viscosity reading of ~56 centipoises (cps), which is similar to chocolate milk, was obtained with a mixture of 97% Ensure Plus, 3% water, and no thickening agent. A mixture containing 3% guar and no water yielded a viscosity reading of ~56,000 cps, similar to chocolate pudding. These were the lowest and highest viscosity levels used in the present studies. Intermediate viscosity levels were produced by varying the relative concentrations of thickening agent and distilled water that were added to Ensure Plus. A mixture of 0.5% water, 2.5% guar, and 97% Ensure Plus produced a reading of ~16,700 cps. A reading of ~16,100 cps was obtained with 0.5% water, 2.5% methylcellulose, and 97% Ensure Plus. The viscosities of these two mixtures were both comparable to a thick chocolate shake. A thinner chocolate shake-like mixture of ~3600 cps was produced with a concentration of 1.5% guar and 1.5% water.

¹ Nonstandard abbreviations: LV, low-viscosity premeal; cps, centipoise(s); ad lib, ad libitum.

Procedures (Experiments 1 to 3)

To reduce potential neophobia during later experimental manipulations, each rat was given an overnight exposure to 10 grams of the mixtures that would subsequently be presented as premeals or test meals. The rats had free access to laboratory chow (Laboratory Rodent Diet; Constant Nutrition 5001, PMI Nutrition International, Brentwood, MO) and water during these exposure sessions. All rats consumed all of the mixtures that were presented. After overnight exposures, food rationing was used to gradually reduce the rats to 85% of their ad lib body weights. On the test day, the rats were given a 10-gram premeal for 1 hour instead of their normal food ration. The premeal was presented in small metal cups that were fastened inside the cages of each rat. Water was always available. In all experiments, all rats consumed all of their premeal in the time allotted. The premeal was followed by a 1-hour period when the rats had no further access to food. The 50-gram test meal began at the conclusion of this period. Amount of the test meal consumed, adjusted for spillage, was recorded for up to 4 hours. Guar was used as thickening agent in all premeals except as described below for Experiment 2.

Experiment 1. The rats (mean weight 390 grams) were divided into two groups of 24 each that differed with respect to whether they received a low- (~56 cps) or high- (~56,000 cps) viscosity Ensure Plus premeal. These two groups were further subdivided into three groups of eight rats each, with each of the three groups receiving a different test meal. One of these test meals was the low-viscosity mixture used for the premeal, another was the high-viscosity premeal mixture, and the third test meal was standard laboratory chow.

Experiment 2. The rats (mean weight 325 grams) were assigned to three groups of eight each. The treatment of the groups differed only with respect to the viscosity of the premeals they were given, ~16,600, 3600, and 56 cps, respectively. The test meal was 50 grams of laboratory chow for all rats.

Experiment 3. Rats (mean weight 327 grams) were assigned to one of four premeal treatment conditions. Nine rats received a premeal for which guar was used to produce a viscosity level of ~16,600 cps. Nine rats received a premeal with a viscosity level of 16,100 cps, which used methylcellulose as the thickening agent. An additional eight rats were given a lower viscosity, 56-cps premeal that contained neither guar nor methylcellulose. The remaining nine rats received no premeal. The test meal was 50 grams of laboratory chow for all rats.

Procedure (Experiment 4). The rats were assigned to three groups that differed with respect to the types of daily supplements they received. Group low viscosity ($n = 8$; mean weight = 435 grams) received 15 grams daily of low-viscosity (56 cps) Ensure Plus. Group high viscosity ($n = 7$; mean weight = 437 grams) received the same amount of Ensure Plus in high-viscosity (55,600 cps) form.

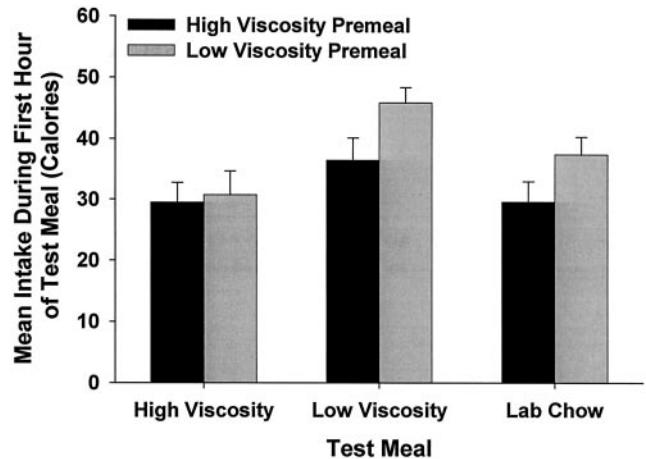


Figure 1: Caloric intake of high- or low-viscosity Ensure Plus or laboratory chow test meal for rats given a premeal of low- or high-viscosity Ensure Plus. Data depicted yielded a significant main effect of premeal viscosity ($p < 0.05$). The premeal \times test meal interaction was nonsignificant. Error bars represent SE of the mean.

For these two groups, metal cups containing the supplements were fastened on to the inside front wall of the home cage of each rat on each day of the study. For a third, no supplement group ($n = 6$; mean weight = 433 grams), an empty cup was fastened in the cage of each rat. The rats were also given ad lib food and water throughout the experiment. The supplements were replenished, and all rats were weighed daily at 11 AM for 10 weeks. Each rat consumed all of its supplement on each day.

Results

Experiment 1

Figure 1 shows that rats given the LV ate more calories during 0 to 1 hours of testing than did rats given the high-viscosity premeal. This difference was most pronounced for rats that received either the low-viscosity or the laboratory chow test meals, respectively. ANOVA yielded a significant main effect of premeal [$F(1,42) = 5.24$, $p < 0.05$] that did not interact significantly with type of test meal [$F(2,42) < 1$]. This result confirmed that rats given the LV consumed more calories during the 1st hour of testing than did rats given the high-viscosity premeal. No significant main effect or interaction involving premeal was obtained during either the 1- to 2- or 2- to 4-hour test periods.

The results of Experiment 1 provided evidence that food viscosity can influence caloric compensation in the rat. Consuming 10 grams of a low-viscosity food had less of a suppressive effect on subsequent caloric intake than did consuming 10 grams of a higher viscosity food despite the fact that the two foods were equivalent in energy content

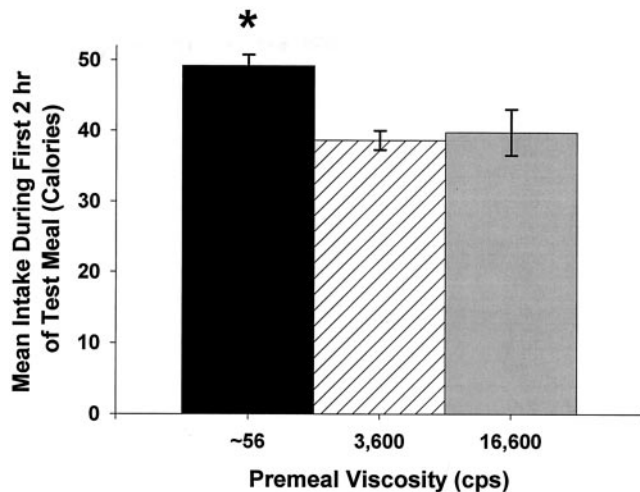


Figure 2: Effects of premeal viscosity on mean caloric intake during first 2 hours of the test meal. (*) significant ($p < 0.05$) difference from 3600- and 16,600-cps premeals. Error bars represent SEM.

and other nutrient properties. This effect of food viscosity did not vary significantly based on type of test meal. This generality reduces the possibility that the intake differences found in this experiment are based on the similarity or dissimilarity of the sensory or hedonic properties of the premeal relative to the test meal.

Experiment 2

The purpose of Experiment 2 was to determine whether this finding would also be obtained in comparison with high-viscosity premeals that were of lower viscosity (16,600 and 3600 cps, respectively) than the high-viscosity premeal used in Experiment 1. Because the effects of premeal viscosity on intake during testing did not depend on type of test meal in Experiment 1, only laboratory chow was used as a test meal for Experiment 2.

An unexpected delay prevented measurement of food intake during the first hour of the test meal. Figure 2 shows that, during the first 2 hours of testing, rats given the LV (56 cps) consumed more calories than rats given either of the higher viscosity (3600 or 16,600) premeals. An ANOVA revealed a significant main effect of premeal for the 0- to 2-hour period [$F(2,21) = 39.95, p < 0.01$]. Newman-Keuls tests confirmed that rats that consumed either the 3600- or 16,400-cps premeals ate significantly fewer calories during the subsequent 0- to 2-hour test period than did the rats that consumed the lower viscosity (56 cps) but equicaloric premeal. Test meal intake did not differ significantly among rats given the 3600-cps and those given the 16,600-cps premeals. No significant main effects or interactions involving premeal viscosity were obtained at the 2- to 4- or 4- to 24-hour intake test periods.

The results of Experiment 2 confirmed the findings of Experiment 1 by showing that calories consumed in a rel-

atively LV are compensated for less well during a subsequent intake test than are calories consumed in higher viscosity premeals. This outcome was obtained when intake of rats given the LV was compared with that of rats given premeals of substantially lower viscosity (i.e., 3600 and 16,600 cps, respectively) than the high-viscosity premeals used in Experiment 1 (56,000 cps). Moreover, the lack of difference between the 3600- and 16,600-cps premeals indicates that the function relating viscosity level to subsequent caloric compensation may be nonlinear.

Experiment 3

Experiment 3 compared caloric compensation after premeals that differed with respect to whether guar or methylcellulose was used as a thickening agent. Both guar and methylcellulose are hydrocolloids that increase viscosity by absorbing water. However, guar is a naturally occurring dietary fiber, whereas methylcellulose is considered semi-synthetic because of the added methyl ester group. Experiment 3 also included an additional group that received no premeal before intake testing. This group provided a means of assessing the degree to which calories consumed during the premeal were compensated for during the test meal.

Figure 3A shows that rats given no premeal and those given the LV consumed a similar amount of calories. Moreover, both of these groups consumed more calories than rats given either of the high-viscosity (guar or methylcellulose) premeals during that period. ANOVA revealed a main effect of group during the first 2 hours of testing [$F(3,31) = 7.34, p < 0.01$] but not during the last 2 hours. Newman-Keuls tests showed that during the first 2 hours, both the no premeal and LV groups consumed significantly ($p < 0.01$) more calories than the groups given the high-viscosity premeals prepared with either guar or methylcellulose. These latter groups did not differ significantly from one another. The results indicate that consuming a high-viscosity premeal, independently of whether guar or methylcellulose is used to increase viscosity, produces greater subsequent caloric compensation than does consuming an equicaloric LV.

Figure 3B depicts the total caloric intake for each premeal treatment condition when the calories consumed during the premeal were added to those consumed during the first 2 hours of testing. Recall that all rats consumed the same number of calories during the premeal (13.3) except for the rats that were given no premeal. Figure 3B shows that during the first 2 hours of testing, rats given either of the high-viscosity premeals ate a total number of calories quite similar to the no premeal group. This outcome indicates that rats in the two high-viscosity conditions showed virtually complete compensation for the calories they consumed in their premeals. In contrast, the total amount of calories consumed by the rats in the LV group during the same period exceeded the amount consumed by the rats given each of the other premeal treatments. This suggests that rats given the LV compensated significantly less well for

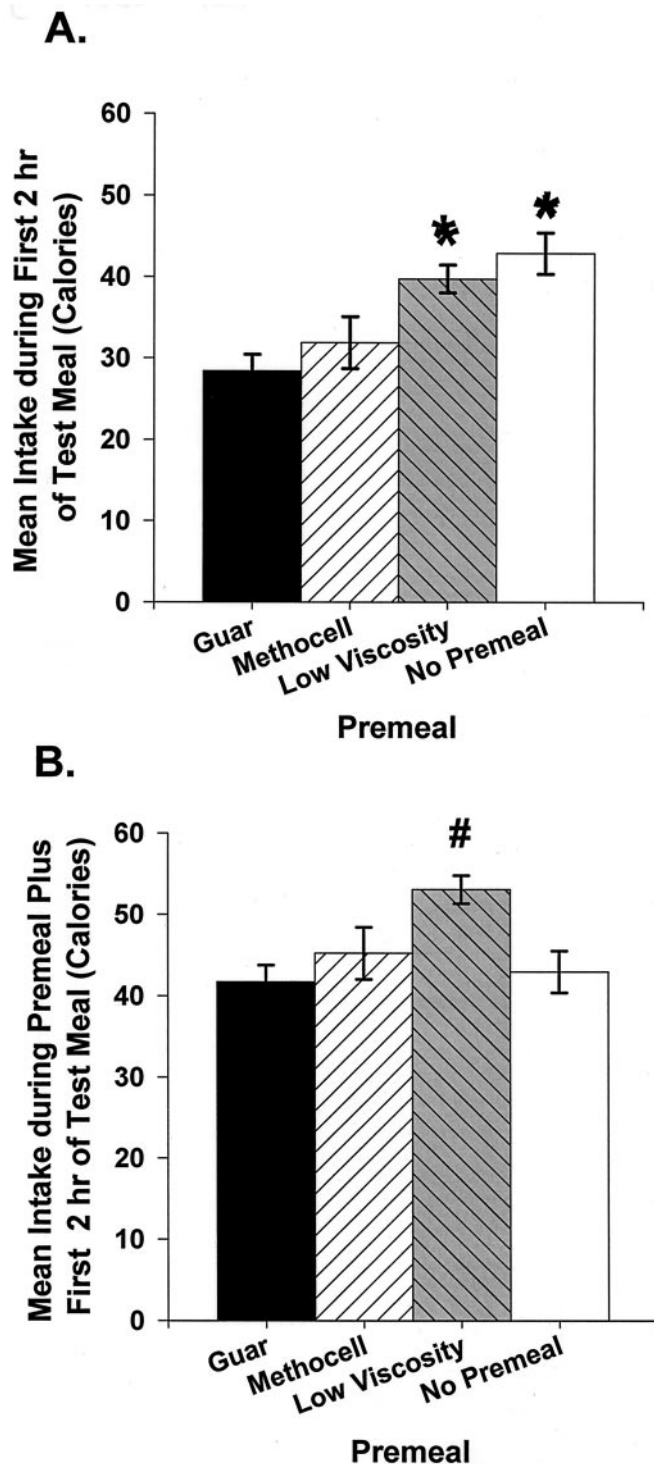


Figure 3: (A) Mean caloric intake of laboratory chow during the test meal and (B) mean total calories consumed during the premeal and test meal for rats given a premeal thickened with methylcellulose, guar, a lower viscosity premeal that was not thickened, or no premeal. (*) Significant ($p < 0.05$) difference from guar and methylcellulose premeal conditions. (#) Significant ($p < 0.05$) difference from guar, methylcellulose, and no premeal conditions. Error bars represent SEM.

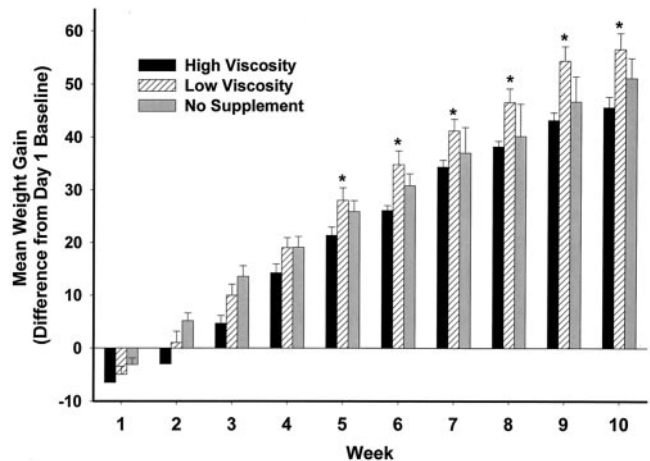


Figure 4: Mean cumulative weight gain by rats given daily high- or low-viscosity dietary supplements or no supplements. Comparison of high- and low-viscosity supplement conditions yielded a significant ($p < 0.05$) main effect. (*) Significant ($p < 0.05$) difference between the low- and high-viscosity supplement conditions. Comparison of low-viscosity and no supplement conditions yielded a significant ($p < 0.05$) supplement \times weeks interaction. Error bars represent SEM.

calories contained in their premeal compared with the rats given the higher viscosity premeals.

An ANOVA comparing total caloric intake for each premeal treatment condition when premeal caloric intake was added to caloric intake during the first 2 hours of testing yielded a significant main effect of premeal treatment [$F(3,31) = 4.30$, $p < 0.05$]. Newman-Keuls tests showed that rats given the LV consumed significantly more total calories compared with rats given each of the other premeal treatments (all $p < 0.05$). Total caloric intake for these latter three premeal treatment conditions did not differ significantly. A separate ANOVA comparing total caloric intake over the 2- to 4-hour test period failed to reveal a significant effect of premeal.

The results of Experiment 3 confirmed our earlier findings that consuming an LV interfered with subsequent short-term caloric compensation more than consuming a high-viscosity premeal regardless of whether guar or methylcellulose was used as a thickening agent. Similar to Experiments 1 and 2, significant effects of viscosity were observed only within the first 2 hours of the test period. This suggests that the effects of premeal viscosity on intake do not extend much beyond the next meal after the premeal is consumed. Whether or not these short-term effects translate into significant effects on body weight gain over the longer term is unknown. Experiment 4 investigated this possibility.

Experiment 4

Figure 4 presents mean body weight gain per week relative to Day 1 baseline for rats in each supplement condition. As can be seen in that figure, body weights for each of the

supplement conditions fell below baseline immediately after the experiment began. This presumably occurred in response to changes in handling, weighing, and to the introduction of the food cups in the home cage that occurred as part of the experimental regimen. By Week 3, body weights for all groups were above baseline. Figure 4 indicates that weight gain for the rats in the low-viscosity supplement condition was greater than for the rats that received the high-viscosity supplement and also, to a lesser degree, greater than for the rats in the no supplement control group.

ANOVA with supplement condition as a between-subjects factor and weeks as a within-subjects factor yielded a significant main effect of weeks [$F(10,180) = 464.8, p < 0.01$] and a significant weeks \times supplement interaction. [$F(20,180) = 2.33, p < 0.05$]. Separate ANOVAs were used to compare each supplement pair. Comparison of the high-viscosity and no supplement conditions failed to obtain a significant main effect of supplement or a significant supplement \times weeks interaction. Thus, weight gain for these two treatments was identical statistically. In contrast, when the low- and high-viscosity supplement conditions were compared, a significant main effect of supplement [$F(1,13) = 8.44, p < 0.01$] and a significant supplement \times weeks interaction [$F(10,130) = 4.10, p < 0.01$] was obtained. These findings confirmed that rats given the low-viscosity supplement gained more weight over the course of the study than did rats that received the high-viscosity supplement. Moreover, simple main effects analyses showed that the difference in weight gain between these groups was significant on each week beginning in Week 5 ($ps < 0.05$). This supplement \times weeks interaction was also significant when the low-viscosity and no supplement conditions were compared [$F(10,120) = 2.48, p < 0.05$]. This result indicates that the magnitude of the differences between these conditions changed significantly over the course of 10 weeks. However, simple main effects analysis obtained no significant differences between these conditions on any individual week.

Discussion

The results from this series of experiments indicate that viscosity may play a role in the modulation of short-term food intake and longer term body weight in rats. Experiments 1 to 3 found that caloric intake during a test meal was significantly higher for rats given an LV compared with a high-viscosity premeal even though both premeals were equated with respect to caloric and nutritive content. This effect of viscosity did not depend on the specific thickening agent used because both guar and methylcellulose produced similar effects on caloric compensation. Furthermore, enhanced test meal intake after an LV was observed in comparison with a wide range (3600 to 56,000 cps) of higher viscosity premeals. In all studies, the amount of LV and high-viscosity premeal or supplements that was consumed

was the same. In addition, Experiment 4 found that daily consumption of low-viscosity supplements over a 10-week period enhanced longer term weight gain compared with calorically and nutritively equivalent supplements of higher viscosity. The results of these studies are consistent with the hypothesis that the viscosity of the supplements influenced the ability to compensate for the calories that the supplements contained.

It is possible that differences in caloric compensation were based not on differences in viscosity per se but on other effects produced by the use of dietary fibers as thickening agents. For example, if consuming guar produced malaise or other aversive gastrointestinal consequences, this might have reduced food intake and body weight gain for rats given high-viscosity supplements. However, there are reasons to discount the idea. Guar is on the list of food additives that are "generally regarded as safe" by the U.S. Food and Drug Administration (4), and there appears to be no evidence that mixing low concentrations of guar with food produces illness. Moreover, studies of conditioned taste aversion show that rats will strongly avoid novel flavors that are followed, on even a single occasion, by mild illness (8). Yet, none of the rats in the present studies showed any tendency to avoid eating novel supplements after their first opportunity to consume them, regardless of whether they included thickening agents. This was the case even in Experiment 4, in which rats rapidly consumed a high-viscosity supplement that contained 3% guar (the maximum concentration used in our studies) on 70 different occasions. Thus, it seems unlikely that malaise contributed to the results of the present experiments.

Rather than inducing malaise, it has been suggested that high-viscosity or high-fiber foods are particularly effective at inducing satiety. For example, foods made high in viscosity by the addition of guar have been reported to delay gastric emptying and intestinal transit of nutrients (e.g., 19,20, but see 2,25)—responses that have been associated with both reduced food intake and heightened feelings of satiety (e.g., 3,11).

If calories consumed in high-viscosity form are more satiating, then eating high-viscosity supplements should have suppressed subsequent caloric intake and body weight gain, not only relative to rats that ate low-viscosity supplements both also compared with rats that received no supplement at all. However, the results of Experiment 3 showed that the total caloric intake during the premeal and test meal was the same for rats given a high-viscosity premeal and for control rats that received no premeal. Because total caloric intake was the same, it is difficult to conclude that the high-viscosity premeal produced greater satiation than the no premeal condition.

In contrast, rats showed much less compensation for the calories contained in the LV. Total intake for these rats (premeal + test meal) exceeded that for both the high-

viscosity premeal group and the no supplement control. This pattern of results suggests that consuming a low-viscosity supplement reduced subsequent caloric compensation. In Experiment 4, the tendency for faster weight gain by rats that consumed the low-viscosity supplement compared with no supplement is also consistent with this conclusion. Rather than high-viscosity foods being more effective inducers of satiety, the present results agree with the view that calories may be less able to induce satiety when they are consumed in low-viscosity form (12). It may be that less viscous calorie sources produce less stimulation of oroesophageal or gastrointestinal receptors or less activation of enzymatic and hormonal cascades that occur in conjunction with the absorption of the nutrients. It seems likely that the ability to achieve tight compensatory control of caloric intake regulation might involve these types of receptors or processes.

Recently, we proposed that such compensatory control may depend, in part, on the ability of food viscosity cues to signal the caloric or nutritive density of food (6). Based on the idea that the viscosity and caloric content of foods are usually directly correlated, animals, including humans, could use food viscosity cues to anticipate and, thus, prepare for the introduction of calories to the gastrointestinal tract (also see 26). New findings that show that sensory information about food viscosity is distinctly represented in the primate brain encourage the idea that animals could use viscosity as a predictive cue (18). Within this scheme, low-viscosity cues would tend to evoke weaker anticipatory responses than would higher viscosity cues because low-viscosity cues predict the delivery of a relatively low amount of calories. Accordingly, when high calories are consumed in low-viscosity form, low-viscosity cues might evoke anticipatory responses that are inadequate to optimally prepare, and, perhaps, compensate, for the arrival of an energy rich substance. This analysis is encouraged by the results of recent studies with rats (9) and humans (10) that compared the effects of texture modifications of diets that would also alter viscosity on several anticipatory physiological reflexes that have been linked to intake regulation. In both sets of studies, consumption of the different textured diets produced significant differences in several indices of hormonal or metabolic activity.

There has been recent interest in the role of environmental factors as contributors to current trends toward body weight gain and obesity in the population of the United States (e.g., 13). Intake of caloric beverages has risen dramatically, coinciding with the dramatic rise in obesity in the United States during the last 20 to 25 years (24). The findings of the present studies lend support to earlier suggestions (e.g., 7,12) that significant increases in numbers of calories that are consumed in the form of beverages may have particularly detrimental effects on the regulation of food intake and body weight. Thus, one approach to ame-

liorating the obesity epidemic may be to reduce the number of calories that are consumed in low-viscosity form.

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