Original Research Communications

Sucrose compared with artificial sweeteners: different effects on ad libitum food intake and body weight after 10 wk of supplementation in overweight subjects[1–3]

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ABSTRACT

Background: The role of artificial sweeteners in body-weight regulation is still unclear.

Objective: We investigated the effect of long-term supplementation with drinks and foods containing either sucrose or artificial sweeteners on ad libitum food intake and body weight in overweight subjects.

Design: For 10 wk, overweight men and women consumed daily supplements of either sucrose [*n* = 21, body mass index (BMI; in kg/m^2) = 28.0] or artificial sweeteners (*n* = 20, BMI = 27.6). On average, sucrose supplements provided 3.4 MJ and 152 g sucrose/d and sweetener supplements provided 1.0 MJ and 0 g sucrose/d.

Results: After 10 wk, the sucrose group had increases in total energy (by 1.6 MJ/d), sucrose (to 28% of energy), and carbohydrate intakes and decreases in fat and protein intakes. The sweetener group had small but significant decreases in sucrose intake and energy density. Body weight and fat mass increased in the sucrose group (by 1.6 and 1.3 kg, respectively) and decreased in the sweetener group (by 1.0 and 0.3 kg, respectively); the between-group differences were significant at $P < 0.001$ (body weight) and $P < 0.01$ (fat mass). Systolic and diastolic blood pressure increased in the sucrose group (by 3.8 and 4.1 mm Hg, respectively) and decreased in the sweetener group (by 3.1 and 1.2 mm Hg, respectively).

Conclusions: Overweight subjects who consumed fairly large amounts of sucrose (28% of energy), mostly as beverages, had increased energy intake, body weight, fat mass, and blood pressure after 10 wk. These effects were not observed in a similar group of subjects who consumed artificial sweeteners. *Am J Clin Nutr* 2002;76:721–9.

KEY WORDS Aspartame, acesulfame-K, cyclamate, saccharin, obesity, fat-free mass, fat mass, appetite, bone mineral content, artificial sweeteners, sugar, sucrose, weight control, weight management, weight reduction

INTRODUCTION

Today, there is still no consensus on the usefulness of substituting artificial sweeteners for sucrose to obtain better weight control (1). Considering the worldwide increase in the prevalence of obesity (2), it seems important to clarify whether artificial sweeteners can help regulate body weight or not. It has been suggested that eliminating sucrose from the diet will increase the relative dietary fat content (3, 4), which will then result in increased energy intake and body weight over the long term (5, 6). Most of the published studies on artificial sweeteners are short-term studies lasting from a few hours to 1–2 d (7–17). A few of these studies found a stimulating effect of artificial sweeteners on appetite (7, 9, 10), whereas most of the other studies did not find this effect (8, 11–17). However, short-term studies are not very informative because appetite regulation and macronutrient balance probably do not correct for the missing energy and sucrose until the individual has consumed the diet for several days (4).

Therefore, epidemiologic studies or studies lasting for weeks or months are of greater interest. Long-term intervention studies without energy restriction are scarce, and those that have been done did not last for > 3 wk (18–20). These studies suggested that increased intake of artificial sweeteners either has no effect or decreases energy intake and body weight compared with sucrose consumption. Epidemiologic studies, on the other hand, found an inverse relation between the intake of sucrose and body weight in adults (21) and children (22, 23), suggesting that sucrose may help prevent overweight. These epidemiologic data were recently supported by the long-term, multi-center trial CARMEN, in which a diet low in fat and high in simple sugars, consumed ad libitum for 6 mo, reduced body weight and fat mass in overweight subjects (6). Furthermore, normal-weight to moderately overweight Scottish men lost more body weight and fat mass with a fat-reduced diet than with a fat- and sucrose-reduced diet (24).

Regarding artificial sweeteners, a long-term epidemiologic study reported a positive relation between saccharin intake and weight change in adults (25) and a positive relation between intake of carbonated soft drinks and body mass index (BMI; in kg/m^2)

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[2] Supported by the Danish Research and Development Programme for Food Technology 1990–1994 and Danisco Sugar. Coca Cola (Nordic and Eurasia Divisions) generously provided soft drinks for the study.

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TABLE 1
Subject characteristics before the intervention[1]

	Sucrose group (n = 21)	Sweetener group (n = 20)
Age (y)	33.3 ± 2.0	37.1 ± 2.2
Body wt (kg)	82.5 ± 1.7	79.2 ± 2.0
Height (cm)	171.6 ± 1.6	169.5 ± 1.6
BMI (kg/m^2)	28.0 ± 0.5	27.6 ± 0.5
Fat mass		
(kg)	29.1 ± 1.0	27.9 ± 1.0
(%)	35.2 ± 0.9	35.2 ± 0.9
Fat-free mass		
(kg)	53.5 ± 1.4	51.3 ± 1.5
(%)	64.8 ± 0.9	64.8 ± 0.9
Waist-to-hip ratio	0.79 ± 0.02	0.77 ± 0.01
Sagittal height (cm)	20.8 ± 0.5	20.3 ± 0.4
Systolic BP (mm Hg)	119.0 ± 2.5	115.8 ± 1.9
Diastolic BP (mm Hg)	72.6 ± 2.1	72.8 ± 2.0
Physical activity (h/wk)	12.5 ± 2.1	9.5 ± 1.7
Physical activity level[2]	3.0 ± 0.2	3.0 ± 0.3

[1] $\bar{x}$ ± SEM. BP, blood pressure. Body composition was calculated with bioelectric impedance (30). There were no significant differences between the groups (unpaired t test).
[2] Rated from 1 to 5, with 1 = low and 5 = high.

in 12–16-y-old children (26). This may suggest that artificial sweeteners do not prevent weight gain, although cause and effect cannot be determined from these studies. In contrast, long-term intervention studies with energy restriction have shown that the inclusion of artificial sweeteners can increase compliance, improve quality of life, and help maintain weight loss (27). Persons who are concerned about their weight but are not following a diet typically use artificial sweeteners because they wish to reduce their daily energy intake without changing the rest of their diet; with this approach, they hope to maintain or reduce their body weight. Whether this actually happens or not has not been adequately investigated yet. Therefore, the purpose of the present study was to monitor changes in ad libitum energy and macronutrient intakes, body weight, and body composition during 10 wk of supplementation with either sucrose or artificial sweeteners.

SUBJECTS AND METHODS

Experimental design

The study had a parallel design with 2 intervention groups. For 10 wk, one group received supplemental drinks and foods containing sucrose while the other group received similar drinks and foods containing artificial sweeteners. Subjects were not informed about the true purpose of the study, but were all told that they would receive supplements containing artificial sweeteners, some of which would be newly developed. A 2-wk pilot study (n = 4) was performed before the intervention to test the supplements, evaluate the comprehensibility of the different questionnaires, and practice the measurement procedures.

Several measurements were performed before, during, and at the end of the 10-wk intervention period. At weeks 0, 2, 4, 6, 8, and 10, we measured body weight, fat mass, and fat-free mass. At weeks 0, 5, and 10, subjects completed 7-d dietary records, 7-d diaries (for monitoring hunger, fullness, palatability of the food, and well being), 24-h urine collections, and diurnal appetite scores. At weeks 0 and 10, dual-energy X-ray absorptiometry (DXA) scans were performed and the waist-to-hip ratio, sagittal height (height of abdomen when lying in a supine position), and blood pressure were measured. In addition, subjects completed a 3-factor questionnaire about eating behavior (28) and a questionnaire about habitual physical activity. After the intervention, subjects also completed a questionnaire about the experimental diet. Once each week throughout the intervention, subjects came to the research department to collect their drinks and foods and to deliver their diaries, questionnaires, urine samples, and other materials.

Subjects

Subjects for the study were recruited with posters and with advertisements in newspapers and magazines. The inclusion criteria were: 20–50 y old, overweight [BMI of 25–30 or > 10% overweight according to weight-and-height tables (29)], healthy, not dieting, and not pregnant or lactating. We received ≈300 telephone calls from interested potential subjects and we provided written and oral information about the study to 100 of them. Forty-two subjects enrolled in the study and 41 of them (35 women and 6 men; n = 21 for the sucrose group and n = 20 for the sweetener group) completed the study. The subjects were randomly assigned to the 2 intervention groups, which were matched for sex, age, weight, height, BMI, fat mass, fat-free mass and usual amount of physical activity (**Table 1**). The study was approved by the Municipal Ethical Committee of Copenhagen and Frederiksberg as being in accordance with the Helsinki II Declaration. All subjects gave their written consent after the experimental procedure had been explained to them orally and in writing.

Experimental diets

Subjects were instructed to consume a specific minimum amount of either sucrose-sweetened or artificially sweetened drinks and foods every day during the 10-wk intervention period. A minimum amount was prescribed to ensure that subjects would consume at least this amount and not less. In the sucrose group, ≈70% of the sucrose came from drinks and ≈30% came from solid foods. About 80% by wt of the supplements were beverages and ≈20% by wt were solid foods. This distribution corresponds to the population's intake of artificially sweetened foods (31, 32).

The beverages consisted of several soft drinks (Coca Cola, Fanta, and Sprite, all from Coca-Cola Tapperierne A/S, Fredericia, Denmark) and flavored fruit juices (orange, raspberry, "sport," and mixed). The caps on all the soft drinks were changed and all labels were removed for our study, because the pilot study showed that subjects could guess which drinks were "light" from the color of the caps. The solid foods consisted of yogurt (strawberry, Peach Alexander, and cherry for the sucrose group or strawberry-rhubarb, Peach Melba, and forest berries for the sweetener group), marmalade (orange, raspberry, or black currant), ice cream (strawberry, pistachio, or vanilla), and stewed fruits (apricots, prunes, or apples). Great efforts were made before the intervention to find the most palatable artificially sweetened food products on the market for which a matching sucrose-containing product existed. Subjects were invited to taste all the products in their respective diet group before the intervention started, so that they could select the ones they wanted to consume during the intervention. To keep the fat intake from the provided foods as similar as possible for the 2 groups, subjects in the sweetener group were given additional butter or corn oil every week. This was necessary because some of the artificially sweetened products were fat-reduced.

The amounts of supplemental drinks and foods to be consumed were calculated on the basis of a sucrose intake of ≈2 g/kg body wt daily. This corresponded to 23% of energy for an 80-kg person with an energy intake of 12 MJ/d (ie, it was a rather high sucrose intake). To ensure that each subject received the correct sucrose intake, subjects were assigned to 3 different intake levels according to their initial body weight, as follows: level 1, 60–75 kg; level 2, 75–90 kg; and level 3, > 90 kg. Subjects on levels 1, 2, and 3 received drinks and foods containing a total of 125, 150, or 175 g sucrose/d, respectively. This corresponded to a total energy intake from the sucrose supplements of 2738, 3285, or 3833 kJ/d, respectively. The sweetener group received an equivalent amount (by weight) of drinks and foods, resulting in an average intake of artificial sweeteners of 0.48, 0.57, or 0.67 g/d and an average energy intake of 694, 832, or 971 kJ/d on levels 1, 2, and 3, respectively. The percentage contributions of the different artificial sweeteners were 54% from aspartame, 22% from acesulfame K, 23% from cyclamate, and 1% from saccharin. The average daily intakes of the different sweeteners in the sweetener group were far below the acceptable daily intakes.

In addition to the experimental diet, subjects were free to consume their own diet ad libitum until they felt pleasantly satisfied. To monitor any changes in food intake, subjects completed 7-d weighed dietary records, along with 24-h urine collections, during weeks 0, 5, and 10. Digital food scales with an accuracy of 1 g were used (Soehnle 8020 and 8009; Soehnle-Waagen GmbH & Co, Murrhardt, Germany). A 7-d dietary record was also completed 1–2 mo before the intervention to get the subjects accustomed to the method. The computer database of foods from the National Food Agency of Denmark (Dankost 2.0) was used to calculate the energy and nutrient intakes (33).

Measurements

Anthropometry

All measurements except the DXA scans were done in the morning after the subjects had fasted from 2200 the previous night. For all measurements, the same device was used every time. Body weight was measured to the nearest 0.1 kg with a digital scale (Seca model 708; Seca Mess und Wiegetechnik, Vogel & Halke GmbH & Co, Hamburg, Germany) after the subject voided. Body composition was subsequently estimated with the bioelectrical impedance method by using an Animeter (HTS-Engineering Inc, Odense, Denmark). Fat mass (FM) and fat-free mass (FFM) were calculated as described previously (33). Height was measured to the nearest 0.5 cm at the screening visit by using a wall-monitored stadiometer. Waist and hip circumferences were measured with a tape measure. Sagittal height was measured in the supine position to the nearest 0.5 cm. Blood pressure was also measured in the supine position after 10 min of rest with an automatically inflating cuff (UA-743, A&D Company Ltd, Tokyo).

Whole-body DXA scans were performed with a Hologic 1000 W DXA scanner (Hologic Inc, Waltham MA) at Rigshospitalet in Copenhagen. The scanner uses an X-ray source with 2 photon-energy levels (45 and 105 keV), and the difference in energy makes it possible to determine the calcium content of the bones. The X-ray dose received from a whole-body scan is a maximum of 0.01 mSv (34). Each scan took 10–20 min. During the scan, bone mineral content, bone area, and bone mineral density were determined. Because the scans were performed when subjects were not fasting and at different times during the day, DXA data on body composition were not used.

Urine samples

Subjects collected 24-h urine samples during the sixth day and night of every dietary record period (weeks 0, 5, and 10) to validate the dietary records. During these 24-h periods, subjects ingested a paraaminobenzoic acid (PABA) pill with the 3 main meals (a total of 240 mg PABA/d) to serve as an indicator of complete urine collection (35). Urine samples containing < 85% recovered PABA were excluded from further analyses. The volume and density of each 24-h urine collection were determined and a 2-mL sample was frozen at −20 °C until further analyses. The nitrogen content was determined in 30 μL urine on a nitrogen analyzer (NA 1500 Carlo Erba; Fisons Instruments, Milano, Italy). PABA was determined spectrophotometrically (Bodenseewek Perkin-Elmer & Co GmbH, Überlingen, Germany).

The analyzed urinary nitrogen was converted to protein equivalents by multiplying by 6.25. It is estimated that 81% of ingested protein is excreted in urine (36). Urinary protein was therefore converted to ingested protein with the formula:

$$\text{Ingested protein (g)} = \text{urinary protein (g)} / 81 \times 100 \qquad (1)$$

Dietary protein recovery was subsequently calculated as the index:

$$\text{Dietary protein from 24-h urine collections (g)} / \text{dietary protein from 7-d dietary records (g)} \times 100\% \qquad (2)$$

Questionnaires

To monitor each subject's well-being during the intervention period, 7-d diaries and week diaries were used. The 7-d diaries were completed every day during each of the 7-d dietary record periods. They contained a visual analogue scale for monitoring each of the following: hunger, fullness, palatability of the food, and well being. The scales consisted of 10-cm, unmarked, unipolar, horizontal lines with words anchored at each end, expressing the most positive (ie, good or pleasant) or the most negative (ie, bad or unpleasant) ratings (37). The week diaries were used in the weeks without 7-d dietary records and were only used for recording comments about events such as illness, menstruation, altered diet, medication, or altered physical activity pattern.

Subjective appetite sensations (hunger, satiety, prospective consumption, fullness, and desire to eat something sweet, salty, fat-rich, or savory) were registered under free-living conditions by using a visual analogue scale. Subjects were instructed to complete the visual analogue scale just before and 1, 2, and 4 h after each main meal on day 4 of each 7-d dietary record period. The data were subsequently analyzed by using a mean value for the day, because subjects recorded the scores at different time points during the day as a result of different meal patterns.

A Three-factor Eating Questionnaire on dietary habits and eating behavior (translated from Stunkard and Messick, 28) was completed by the subjects before and after the intervention period. On the basis of the subjects' answers to 51 questions on dietary habits, eating behavior and patterns, slimming diets, and thoughts on food, they received scores for 3 categories of eating behavior: FI, cognitive control of eating behavior; FII, disinhibition of control; and FIII, susceptibility to hunger. If the individual has normal attitudes about foods and body weight, a low score is obtained for all 3 categories.

Before and after the intervention period, subjects recorded information about their physical activity, namely the amount (hours of activity/wk) and intensity (rated 1–5, for low to high). The information was used to match the 2 study groups before the intervention and to monitor any changes after the 10-wk intervention.

TABLE 2
Average daily dietary intakes from the supplements in the sucrose and sweetener groups during week 5 and week 10 of supplementation[1]

	Week 5	Week 10	P (ANOVA) Diet × time effect	Diet effect	Time effect
Energy (kJ)					
Sucrose	3445 ± 52[2]	3349 ± 66	NS	0.0001	0.009
Sweetener	1019 ± 51	963 ± 44			
Carbohydrate					
(% E)					
Sucrose	89 ± 0	89 ± 0	NS	0.0001	NS
Sweetener	55 ± 2	52 ± 2			
(g)					
Sucrose	180 ± 3	176 ± 3	NS	0.0001	0.01
Sweetener	34 ± 3	31 ± 3			
Fat					
(% E)					
Sucrose	10 ± 0	10 ± 0	NS	0.0001	NS
Sweetener	34 ± 1	35 ± 1			
(g)					
Sucrose	9 ± 0	9 ± 0	NS	NS	NS
Sweetener	9 ± 0	9 ± 0			
Sucrose					
(% E)					
Sucrose	76 ± 1	77 ± 1	—	—	—
Sweetener	0 ± 0	0 ± 0			
(g)					
Sucrose	153 ± 3	151 ± 3	—	—	—
Sweetener	0 ± 0	0 ± 0			
Protein					
(% E)					
Sucrose	4 ± 0	4 ± 0	NS	0.0001	NS
Sweetener	16 ± 1	16 ± 1			
(g)					
Sucrose	9 ± 0	9 ± 0	NS	NS	NS
Sweetener	9 ± 0	9 ± 0			
Dietary fiber (g)					
Sucrose	3 ± 1	3 ± 1	NS	0.004	NS
Sweetener	5 ± 1	5 ± 1			
Total wt of food (g)					
Sucrose	1652 ± 38	1621 ± 43	NS	NS	NS
Sweetener	1589 ± 45	1564 ± 48			
Energy density (kJ/g)					
Sucrose	2.1 ± 0.0	2.1 ± 0.0	NS	0.0001	NS
Sweetener	0.6 ± 0.0	0.6 ± 0.0			

[1] % E, percentage of energy. At week 5, $n = 20$ in each group. At week 10, $n = 21$ in the sucrose group and $n = 20$ in the sweetener group.
[2] $\bar{x}$ ± SEM.

A questionnaire regarding the supplements was completed by the subjects after the intervention to investigate whether all subjects believed that they had been consuming artificial sweeteners. The subjects answered questions indicating how much of each of the following substances was in the supplements, in their opinion: salt, sucrose, protein, vitamin C, artificial sweetener, carbohydrate, fat, or other. They chose from the following possible responses: nothing (0), a little (1), medium (2), much (3), or do not know. Only the results on sucrose and artificial sweetener are reported here.

Statistical analyses

All results are given as means ± SEM. Initial group differences were tested by using an unpaired *t* test (Table 1). Other differences between groups and times were tested by using parametric analysis of variance with the general linear model procedure in SAS. The factors were diet, time, and diet × time with subject (group) as an error term for group effects. When the interaction of diet and time was significant, Tukey's post hoc tests were applied. Linear and stepwise regression analyses were performed. The significance level was set at $P < 0.05$. STATGRAPHICS software version 4.2 (Graphic Software Systems Inc, Rockville, MD) and SAS version 6.12 (SAS Institute, Cary, NC) were used in the statistical calculations.

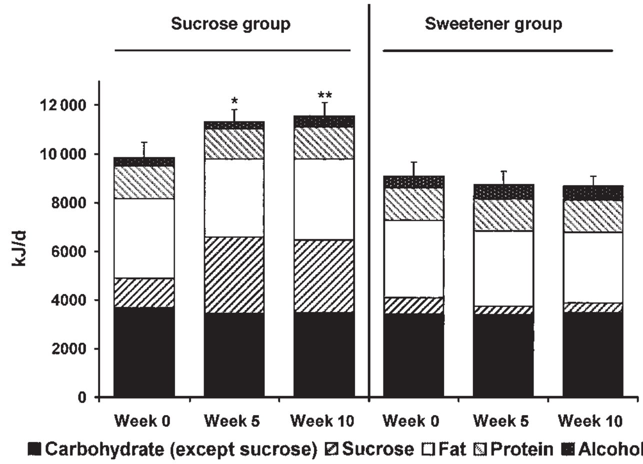

FIGURE 1. Mean (± SEM) energy and macronutrient intakes from the ad libitum diet (including supplements) before (week 0) and during week 5 and week 10 of an intervention in which overweight subjects consumed supplements containing either sucrose or artificial sweeteners daily. For total energy intake, there was a significant time × diet interaction ($P < 0.05$) and diet effect ($P < 0.01$) by analysis of variance; the between-group difference was significant at week 5 (*$P < 0.001$) and week 10 (**$P < 0.0001$) by Tukey's post hoc tests. At weeks 0 and 10, $n = 21$ in the sucrose group and $n = 20$ in the sweetener group. At week 5, $n = 20$ in each group.

RESULTS

Dietary intake

The subjects' intakes of energy and macronutrients from the supplemental drinks and foods corresponded well to the planned intakes (**Table 2**). Thus, energy intake from the sucrose supplements was about 3 times higher than that from the sweetener supplements (diet effect: $P < 0.0001$). Significantly higher amounts of total carbohydrate and sucrose (g and percent of energy) were consumed from the sucrose supplements, whereas significantly higher amounts of fat and protein (percent of energy) were provided in the sweetener supplements. The intakes of fat and protein in absolute amounts and the total weight of foods and drinks did not differ significantly between the 2 groups (Table 2). The average intake of sweetened drinks was ≈1285 g/d. This was determined by multiplying the total average weight of foods and drinks consumed (1600 g/d) by the percentage of this total weight that was contributed by drinks (80%).

Records of ad libitum food intake (including supplements) showed that total energy intake increased significantly in the sucrose group (by 1.5 MJ/d) but remained constant in the sweetener group compared with habitual energy intake (week 0) (**Figure 1**, **Table 3**). The average difference between the 2 groups

TABLE 3
Average daily energy and macronutrient intakes in the sucrose and sweetener groups before (week 0) and during week 5 and week 10 of the supplementation[1]

	Week 0	Week 5	Week 10	*P* (ANOVA) Diet × time effect	Diet effect	Time effect
Energy (kJ/d)						
Sucrose	9835 ± 616[a,2]	11202 ± 517[a,b,3]	11452 ± 551[b,4]	0.03	0.002	NS
Sweetener	9095 ± 563	8713 ± 542	8656 ± 416			
Carbohydrate						
(g/d)						
Sucrose	288 ± 23[a]	388 ± 17[b,4]	381 ± 16[b,4]	0.0001	0.0001	0.0004
Sweetener	241 ± 15	221 ± 15	229 ± 12			
(% E)						
Sucrose	49 ± 2[a]	59 ± 1[b,4]	57 ± 1[b,4]	0.0001	0.0001	0.0001
Sweetener	45 ± 1	43 ± 1	45 ± 1			
Sucrose						
(g/d)						
Sucrose	72 ± 16[a,5]	185 ± 9[b,4]	177 ± 6[b,4]	0.0001	0.0001	0.0001
Sweetener	39 ± 6[a]	21 ± 3[b]	24 ± 4[a,b]			
(% E)						
Sucrose	11 ± 2[a,6]	28 ± 1[b,4]	27 ± 1[b,4]	0.0001	0.0001	0.0001
Sweetener	7 ± 1[a]	4 ± 0[b]	4 ± 1[b]			
Dietary fiber (g/d)						
Sucrose	20 ± 2	20 ± 2	20 ± 1	NS	NS	NS
Sweetener	19 ± 2	19 ± 2	21 ± 2			
Fat						
(g/d)						
Sucrose	86 ± 6	84 ± 6	87 ± 5	NS	NS	NS
Sweetener	84 ± 7	81 ± 6	77 ± 5			
(% E)						
Sucrose	33 ± 2[a]	28 ± 1[b,4]	29 ± 1[b,5]	0.005	0.005	0.007
Sweetener	34 ± 1	35 ± 1	33 ± 1			
Saturated (g/d)						
Sucrose	33 ± 3	34 ± 3	37 ± 2	NS	NS	NS
Sweetener	31 ± 3	32 ± 2	30 ± 2			
Monounsaturated (g/d)						
Sucrose	23 ± 2	21 ± 2	22 ± 1	NS	NS	NS
Sweetener	26 ± 4	22 ± 2	20 ± 1			
Polyunsaturated (g/d)						
Sucrose	9 ± 1	10 ± 1	9 ± 1	NS	NS	NS
Sweetener	10 ± 1	10 ± 1	9 ± 1			
Protein						
(g/d)						
Sucrose	80 ± 5	74 ± 4	77 ± 4	NS	NS	NS
Sweetener	78 ± 4	78 ± 5	77 ± 4			
(% E)						
Sucrose	14 ± 1[a]	11 ± 0[b,4]	11 ± 0[b,4]	0.0001	0.0001	0.0006
Sweetener	15 ± 1	15 ± 0	15 ± 0			
Alcohol						
(g/d)						
Sucrose	11 ± 2	9 ± 1	16 ± 3	NS	0.02	NS
Sweetener	16 ± 3	20 ± 4	20 ± 3			
(% E)						
Sucrose	4 ± 1	2 ± 0	4 ± 1	NS	0.002	NS
Sweetener	5 ± 1	7 ± 1	7 ± 1			
Total wt of food (g/d)						
Sucrose	2991 ± 199	3599 ± 168	3590 ± 196	NS	NS	0.0001
Sweetener	3154 ± 219	3628 ± 169	3780 ± 190			
Energy density (kJ/g)						
Sucrose	3.4 ± 0.2	3.1 ± 0.1[4]	3.3 ± 0.1[4]	0.03	0.0004	0.0001
Sweetener	3.0 ± 0.2[a]	2.4 ± 0.1[b]	2.3 ± 0.1[b]			

[1] % E, percentage of energy. At weeks 0 and 10, $n = 21$ in the sucrose group and $n = 20$ in the sweetener group. At week 5, $n = 20$ in each group. Values in the same row with different superscript letters are significantly different, $P < 0.05$.

[2] $\bar{x} \pm$ SEM.

[3–6] Significant difference between the sucrose and sweetener groups (ANOVA with Tukey's post hoc tests): [3] $P < 0.001$, [4] $P < 0.0001$, [5] $P < 0.01$, [6] $P < 0.05$.

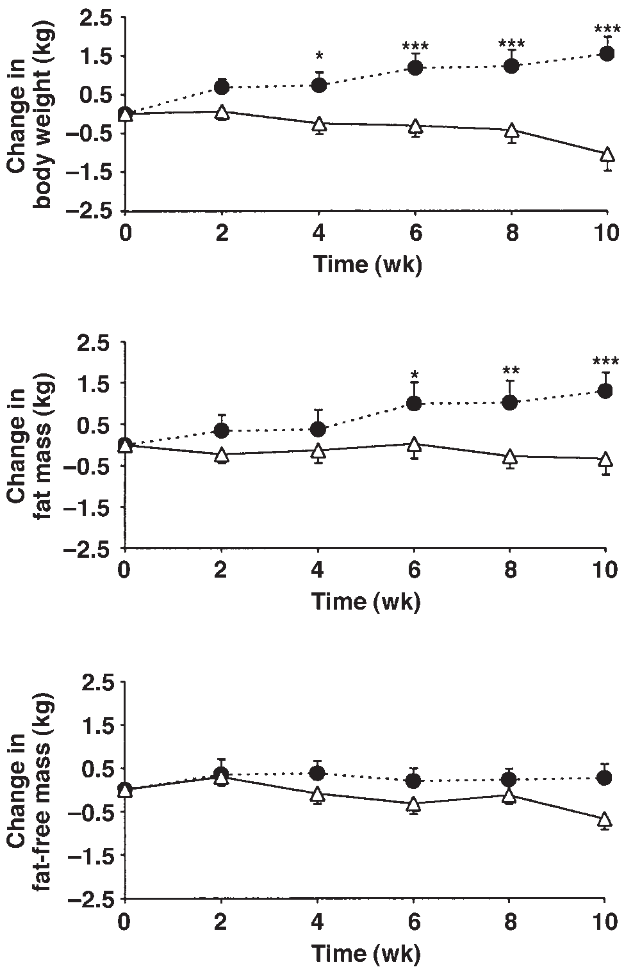

FIGURE 2. Mean (± SEM) changes in body weight, fat mass, and fat-free mass during an intervention in which overweight subjects consumed supplements containing either sucrose (●; $n = 21$) or artificial sweeteners (△; $n = 20$) daily for 10 wk. The diet × time interactions were significant for changes in body weight ($P < 0.0001$) and fat mass ($P < 0.05$) by analysis of variance with Tukey's post hoc tests. At specific time points for changes in body weight and fat mass, there were significant differences between the sucrose and sweetener groups: *$P < 0.05$, **$P < 0.001$, and ***$P < 0.0001$ (general linear model with least squares means and adjustment for multiple comparisons).

was 2.6 MJ/d during the intervention and 185 MJ for the entire 70-d period. The total weight of foods and drinks consumed increased in both groups from week 0 to week 5, but was not significantly different between the groups. The energy density of the diet was significantly lower in the sweetener group than in the sucrose group during the intervention, and energy density decreased significantly in the sweetener group from week 0 to week 5. Total carbohydrate intake in grams increased significantly in the sucrose group, mainly because of the increased sucrose intake, but did not change significantly in the sweetener group. Carbohydrate intake as percent of energy increased significantly in the sucrose group (from 49% before the intervention to 58% during the intervention) but remained constant in the sweetener group (45% before and 44% during the intervention) (diet × time interaction: $P < 0.0001$). Intakes of fat and protein (g) did not differ significantly between the 2 groups, but the percentage of energy from fat decreased significantly in the sucrose group (from 33% to 28%) and remained unchanged in the sweetener group (34% E; diet × time interaction: $P = 0.005$). The percentages of energy as protein and alcohol were higher in the sweetener group than in the sucrose group during the intervention, and alcohol intake (g) was slightly higher in the sweetener group than in the sucrose group (diet effect: $P = 0.02$).

Validation of protein intake

Urinary protein excretion was estimated in 91 urine samples after excluding 32 samples (17 from the sucrose group and 15 from the sweetener group) that were incomplete, as indicated by a recovery of < 85% of PABA. Data were available from 15 subjects in each group at each time point (with the exception of the sucrose group at week 10, which had $n = 16$). Protein intake, as estimated from the urine samples, decreased significantly from week 0 (96 ± 6 g) to week 5 (76 ± 5 g) and week 10 (81 ± 5 g) in the sucrose group but did not change significantly in the sweetener group (week 0: 85 ± 6 g; week 5: 90 ± 5 g; and week 10: 90 ± 5 g). The differences between urinary protein and self-reported dietary protein ranged from 1 to 13 g/d with no significant differences between groups or times. Dietary protein recovery ranged from 103% to 119%, also with no significant differences between groups or times. Urinary protein correlated significantly with dietary protein at all 3 time points, with the strongest correlations in weeks 5 and 10 (week 0: $r = 0.39$, $P < 0.05$; week 5: $r = 0.52$, $P < 0.01$; and week 10: $r = 0.53$, $P < 0.01$).

Body weight and composition

Body weight and FM increased in the sucrose group and decreased in the sweetener group during the 10-wk intervention (diet × time interactions for body wt and FM, $P < 0.0001$ and $P < 0.05$, respectively) (**Figure 2**). For the sucrose group, the total weight gain at week 10 averaged 1.6 kg, of which 1.3 kg was a gain in fat mass (**Table 4**). For the sweetener group, the total weight loss at week 10 averaged 1.0 kg, of which 0.7 kg was FFM and 0.3 kg was FM.

There were no significant differences between groups in the changes in waist-to-hip ratio or sagittal height (Table 4). The results of the DXA scans showed no significant differences in bone mineral content, bone area, and bone mineral density when expressed as total values or when subdivided into the different limbs and regions of the body (data not shown).

Blood pressure

After 10 wk of supplementation, systolic and diastolic blood pressure had increased in the sucrose group but decreased in the sweetener group, resulting in significant between-group differences of 6.9 and 5.3 mm Hg, respectively (Table 4). The changes in systolic blood pressure were positively correlated with the changes in body weight ($r = 0.41$, $P < 0.01$), FM ($r = 0.39$, $P < 0.05$), sucrose intake in g and percent of energy ($r = 0.43$ and 0.40, $P < 0.01$ for both), and total energy ($r = 0.33$, $P < 0.05$). Changes in diastolic blood pressure were positively correlated with sucrose intake in g and percent of energy ($r = 0.39$ and 0.38, $P < 0.05$) and total energy intake ($r = 0.34$, $P < 0.05$). Stepwise multiple regression analyses including these variables showed that only changes in FM and sucrose intake in g remained significant predictors of changes in systolic blood pressure. For changes in diastolic blood pressure, only the change in sucrose intake in g was retained in the regression model.

TABLE 4
Changes in anthropometric data, blood pressure, and physical activity in the sucrose and sweetener groups after 10 wk of supplementation[1]

	Sucrose group (n = 21)	Sweetener group (n = 20)	Difference between groups[2]
Body wt			
(kg)	1.6 ± 0.4[3]	−1.0 ± 0.4[4]	2.6 (1.3, 3.8)
(%)	1.8 ± 0.5	−1.4 ± 0.6[4]	3.2 (1.7, 4.8)
Fat mass (kg)	1.3 ± 0.5	−0.3 ± 0.4[5]	1.6 (0.4, 2.8)
Fat-free mass (kg)	0.3 ± 0.3	−0.7 ± 0.2[6]	1.0 (0.1, 1.8)
BMI (kg/m^2)	0.5 ± 0.2	−0.4 ± 0.2[4]	0.9 (0.5, 1.4)
Waist-to-hip ratio	0.00 ± 0.01	0.01 ± 0.00	0.00 (−0.01, 0.02)
Sagittal height (cm)	0.2 ± 0.1	−0.1 ± 0.2	0.34 (−0.13, 0.81)
Systolic BP (mm Hg)	3.8 ± 2.0	−3.1 ± 1.3[5]	6.9 (2.0, 11.9)
Diastolic BP (mm Hg)	4.1 ± 1.7	−1.2 ± 1.3[6]	5.3 (1.1, 9.6)
Physical activity (h/wk)	−0.4 ± 1.8	0.1 ± 2.1	−0.5 (−6.1, 5.1)
Physical activity level[7]	0.1 ± 0.2	0.4 ± 0.3	−0.3 (−1.0, 0.5)

[1] BP, blood pressure.
[2] Mean difference (sucrose group − sweetener group) with 95% CI in parentheses.
[3] $\bar{x}$ ± SEM.
[4–6] Significantly different from sucrose group (unpaired t test): [4] $P < 0.001$, [5] $P < 0.01$, [6] $P < 0.05$.
[7] Rated from 1 to 5, with 1 = low and 5 = high.

Diaries and questionnaires

The 7-d food diaries completed 3 times during the intervention showed no significant differences between the 2 groups' ratings of hunger, fullness, palatability of the food, and general well-being (data not shown). Furthermore, mean scores for postprandial appetite sensations on day 4 of each dietary record showed no significant differences between the 2 groups during the intervention (data not shown). There were also no significant between-group differences in the changes in the amount of physical activity or level of physical activity, as recorded by the subjects, after the 10-wk intervention (Table 4).

The Three-factor Eating Questionnaire showed that about half of the subjects in each group had controlled eating behavior before the intervention (FI). For all 3 factors, the number of positive subjects (those with values above the mean score) had decreased in the sucrose group (by 2–3 subjects) and increased in the sweetener group (by 1–3 subjects) after the intervention (**Table 5**). There were no significant differences between the 2 groups in the average scores of the positive subjects before or after the intervention.

The questionnaire administered after the intervention showed that to some extent, subjects were aware of the true content of the supplements. Subjects chose from the following possible responses to indicate how much sucrose and artificial sweeteners they thought were in their supplements: nothing (0), a little (1), medium (2), much (3), or do not know. Subjects in the sucrose group thought that their supplements contained a little to a medium amount of sucrose (mean score: 1.6 ± 0.3), whereas subjects in the sweetener group thought that there was almost no sucrose in their supplements (0.3 ± 0.1) ($P < 0.001$). Regarding artificial sweeteners, subjects in the sucrose group thought that their supplements contained a little to a medium amount (1.8 ± 0.3), whereas subjects in the sweetener group thought that their supplements contained a medium amount to much artificial sweetener (2.6 ± 0.1) ($P < 0.05$).

DISCUSSION

To our knowledge, this is the first long-term intervention study that has compared the effects of artificial sweeteners and sucrose, without any energy restriction, on energy intake and body weight in overweight subjects. Interestingly, we found that energy intake, body weight, FM, and blood pressure increased after 10 wk of supplementation with sucrose, whereas a decrease or no change in these variables was seen with supplementation with artificial sweeteners. These findings were not expected on the basis of previous intervention and observational studies (6, 21, 25, 38). Furthermore, the macronutrient composition of the diet in the sucrose group matched the dietary recommendations for total fat (28% of energy) and carbohydrate (58% of energy) more closely than that in the sweetener group (34% and 44% of energy from fat and carbohydrate, respectively) (39). A weight gain in the sucrose group and a weight loss in the sweetener group were therefore not expected, to the contrary, we expected a weight gain in the sweetener group and a weight loss in the sucrose group.

One likely reason for the increases in energy intake and body weight in the sucrose group is the fact that ≈70% of the sucrose

TABLE 5
Results of the Three-factor Eating Questionnaire (28) completed by the subjects before and after the 10-wk intervention[1]

Factor	$\bar{x}$ for both groups combined (n = 41)	Sucrose group (n = 21) Positive subjects[2]			Sweetener group (n = 20) Positive subjects[2]		
		n	$\bar{x}$	Range	n	$\bar{x}$	Range
FI							
Before	7.7	10	10.3	(8–15)	8	11.5	(9–14)
After	7.9	7	12.1	(9–16)	10	12.0	(8–17)
FII							
Before	8.7	9	11.1	(9–14)	13	10.4	(9–12)
After	8.4	7	10.9	(9–12)	14	10.8	(9–13)
FIII							
Before	6.1	10	8.6	(7–12)	6	8.5	(7–11)
After	6.0	7	9.4	(7–13)	9	8.8	(7–10)

[1] FI, cognitive control of eating behavior (restraint eating); FII, disinhibition of control; FIII, susceptibility to hunger. There were no significant between-group differences in the average scores for positive subjects before or after the intervention by unpaired t test.
[2] Positive subjects were those with values above the mean score.

came from fluids. Energy obtained from fluids was shown to be less satisfying than energy from solid foods (40). Thus, energy from liquids may not be fully compensated for, making it is easier to overconsume energy when drinking liquids than when eating solids (40). This is in agreement with a recent prospective study in children that reported that the intake of sugar-sweetened drinks increased the risk of becoming overweight (41). These findings and the current results are not in agreement with data from the CARMEN intervention study (6), but we believe that a difference in the amount of sugars from fluids as compared with solids may explain the different outcomes of these studies.

A second possible reason for overconsumption of energy during sucrose supplementation may be that overweight subjects are less sensitive to dietary manipulations and cannot adjust their energy intake to match their energy needs as effectively as can lean subjects (42). Thus, a similar study performed in lean subjects might not have produced the same results. A third possible reason for the current results is that subjects consumed rather large amounts of sucrose per day (28% of energy), with an average intake of sweetened drinks of ≈1285 g/d. Smaller amounts may not have produced the effects we observed here. Finally, after the intervention, the number of subjects with controlled eating behavior decreased in the sucrose group and increased in the sweetener group. This may also have caused the higher energy intake in the sucrose group compared with the sweetener group, although we cannot determine what is cause and effect here.

The increase in total energy intake compared with habitual energy intake in the sucrose group was 1.5 MJ/d. The supplemental drinks and foods supplied 3.4 MJ/d, and subjects in the sucrose group reduced their energy intake from their own foods (ie, all foods other than supplemental foods) by 1.9 MJ/d, (ie, 56% of the supplemental amount). This implies that the large amount of sucrose consumed by the sucrose group (28% of energy) did satisfy the subjects' appetites to some degree, but not to the extent that subjects reduced their energy intake from their own foods by an equal amount and thereby maintained body weight. We found no differences in appetite sensations between the 2 study groups. This result could be explained by either similar sensations of hunger and satiety in the 2 groups, a lack of sufficient sensitivity of the method (43), or lack of appetite control in overweight subjects, as discussed above (42).

In the sucrose group, subjects reduced their intakes of sucrose and total carbohydrate from their own foods, which compensated partially for the supplemental sucrose. Thus, from week 0 to week 10, sucrose intake from the subjects' own foods decreased by 46 g [72 g (from own food in week 0) + 151 g (from sucrose supplement in week 10) − 177 g (total intake in week 10)] or 64%, and total carbohydrate intake from their own foods decreased by 83 g (288 g + 176 g − 381 g) or 29%. Interestingly, sucrose and total carbohydrate intakes from the subjects' own foods also decreased in the sweetener group. Thus, from week 0 to week 10, intake of sucrose from the subjects' own foods decreased by 15 g (39 g − 24 g) or 38%, and total carbohydrate decreased by 43 g (241 g + 31 g − 229 g) or 18%. Therefore, this diet did not stimulate either sucrose or carbohydrate intake as was suggested previously (7, 10) but instead had the opposite effect.

An increase in energy intake of 1.5 MJ/d for 70 d (= 105 MJ in total) would result in a weight gain of 3.1 kg, if one assumes that an average of 34 MJ is required to make 1 kg body tissue (containing a combination of FM and FFM) (44), if all other factors are held constant. We only observed half that amount of weight gain (ie, 1.6 kg or 52% of the predicted weight gain). Thus, 48% of the extra energy intake in the sucrose group must have been used for other energy-demanding processes in the body (eg, facultative thermogenesis or de novo lipogenesis). This value corresponds to the estimated 49% of energy that was used for thermogenesis after 3 wk of carbohydrate overfeeding in lean young men (45).

It was suggested from short-term studies that artificial, nonenergetic sweeteners can increase appetite through cephalic stimulation (eg, the taste, smell, and sight of food) and that aspartame in particular may have a paradoxical stimulating effect on appetite (7, 9, 10). We were not able to confirm such an effect in this long-term study, and our findings were therefore in agreement with several previous short-term studies (8, 11–17). Body weight actually decreased by 1.0 kg in the sweetener group, and although 70% of this resulted from a loss of FFM (probably glycogen and water), 0.3 kg of FM was also lost. This weight loss may have been caused by the low-energy sweetener supplements replacing higher-energy foods and drinks, leading to a lower overall energy density in the subjects' diets. The decrease in energy intake in the sweetener group (439 kJ/d) was not significant. However, 439 kJ/d (= 30.7 MJ) over 70 d would give rise to a weight loss of 0.9 kg (assuming 34 MJ/kg weight loss). This calculated weight loss is very close to the observed weight loss of 1.0 kg.

Systolic and diastolic blood pressure increased in the sucrose group but decreased in the sweetener group. This was related to changes in FM and sucrose intake. The correlation with sucrose intake could indicate an effect of sucrose per se on the sympathetic nervous system, as suggested previously (38, 46).

All subjects were told that they received supplements containing artificial sweeteners. At the end of the study, the questionnaire on supplements revealed that subjects in the sweetener group believed this, but subjects in the sucrose group had guessed to some extent the true contents of their supplements. In theory, this could have influenced the subjects' eating behavior so that subjects in the sucrose group would have eaten less of their own foods and subjects in the sweetener group would have eaten more of their own foods. However, the data show that this was apparently not the case, perhaps because of a lack of control over eating behavior.

In conclusion, predominantly female overweight subjects who were given supplemental drinks and foods containing sucrose for 10 wk experienced increases in total energy intake, body weight, FM, and blood pressure. This was not observed in a similar group of subjects given similar drinks and foods containing artificial sweeteners. The most likely reason for these differences between the groups was the use of large amounts of beverages, giving rise to overconsumption of energy on the high-sucrose diet. Therefore, overweight individuals may want to consider choosing beverages containing artificial sweeteners rather than sucrose to prevent weight gain.

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