Interaction of fat availability and sex on postprandial satiety and cholecystokinin after mixed-food meals

Britt Burton-Freeman, Paul A Davis, and Barbara O Schneeman

ABSTRACT

Background: Cholecystokinin (CCK) is associated with fat-induced satiety.

Objective: The primary objective of the present study was to determine, in an acute meal setting, whether the availability of dietary fat for alimentary processing, and hence the stimulation of CCK, affects the postmeal satiety response in men and women.

Design: In a within-subjects design, subjects (8 men, 7 women) consumed 1 of 3 isoenergetic mixed-food test meals 1 wk apart in random order. The test meals contained 30% of energy from fat, of which more than two-thirds was derived from whole almonds, almond oil, or a mix of safflower and corn oils. Visual analogue scales were used to assess indexes of satiety at defined time points up to 6 h after meal consumption. Blood was sampled at corresponding time points for measurement of CCK, glucose, insulin, and triacylglycerol. Subsequent food intake was also assessed.

Results: All meals suppressed hunger and induced a pattern of satiety that was sex-specific and corresponded with the CCK response. Women had higher plasma CCK concentrations and experienced greater satiety after the almond oil and control meals (fat as oil) than after the whole almond meal (fat in whole food structure). Men showed no differential response among meals for CCK and satiety. Plasma triacylglycerol differed by time among meals but not by sex, and no significant differences in glucose and insulin were found.

Conclusions: The satiety response to dietary fat provided in oil or whole food form is influenced by sex and is dependent on the availability of fat to stimulate CCK release in women but not in men.

KEY WORDS Fat availability, almonds, sex, cholecystokinin, satiety

INTRODUCTION

Energy appears to be one of the most important variables responsible for food intake regulation (1, 2). Fat, carbohydrate, and protein are the main sources of energy in the diet and all have important roles in the regulation of short-term food intake. Because fat contributes more than twice the energy that carbohydrate and protein contribute to the diet and because it enhances the palatability of foods, attention has been focused on the role of fat in food intake and body weight regulation.

The principal site for fat-induced satiety is preabsorptive, primarily in the upper one- to two-thirds of the small intestine (3–8). Manipulation of fat exposure to intestinal chemoreceptors by manipulating the fat infusion rate or through a dietary strategy (eg, the inclusion of viscous polysaccharide fibers) augments satiety and reduces food intake and body weight gain (6, 9–11). Fat-induced satiety has been associated with cholecystokinin (CCK) release in both animal and human studies (12–16). Moreover, women appear to be more sensitive than are men to manipulations of dietary fat and CCK release (9, 12), which suggests that outcomes of satiety and food intake control may differ as well.

The aim of the present study was to further our knowledge of the role of fat in the diet of men and women by evaluating the satiety value of fat from a complex food source and from a purified source. Specifically, our main objective was to examine the postmeal, subjective satiety response to mixed meals that deliver dietary fat in forms that influence its availability to stimulate intestinal mechanisms of satiety, namely CCK. The relative effect of fat availability in the context of meals providing fat through a complex food source or a purified source (eg, oil) on measures of satiety, including CCK release, was hypothesized to be more apparent in women than in men and more pronounced with meals providing greater fat availability. Whole almonds and extracted almond oil were incorporated in mixed whole-food meals to provide fat in a complex or an isolated form, respectively.

SUBJECTS AND METHODS

Subjects

The study was approved by the Human Subjects Research Committee of the University of California, Davis. Subjects were recruited in the local Davis and Sacramento areas through newspaper and poster advertisements. Candidates who had any food allergies or intolerances, who were currently modifying their diet or exercise patterns to gain or lose weight, who were exercising excessively, or trained athletes, or who were taking any medications that would affect appetite were excluded. Potential participants were invited to attend an information seminar to learn


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more about the time and effort involved with the study, to confirm self-reported weight and height measures for calculation of body mass index (BMI; in kg/m²), and to complete questionnaires related to diet, exercise, and lifestyle habits, including an assessment of dietary restraint (17). The inclusion criteria for both men and women were as follows: having a BMI of 22–27, being aged 20–50 y, being a moderate to light exerciser, consuming a diet with an average dietary fat intake of 30–35% of total energy, being categorized as an unrestrained eater, and being able to meet the time and effort requirements required for study participation. Eight men and 7 women met the study criteria and were invited to participate in the study. Of these, all completed the study.

Before the beginning of the experimental phase, the study participants were trained individually to keep detailed scale-weighted food records, which were required 3 d before (day 3), the day before (day 1), and the day after (day 1) each study day. Additionally, half-day food records were kept on the test meal study days. All of the subjects liked the foods to be served and anticipated no difficulty in meeting the study requirements for consuming test meals or other required procedures.

### Food records and usual diet

Three-day 24-h food records were collected weekly and were analyzed by using the NUTRITIONIST V (1998, version 1.7) nutrient analysis software package (First Data Bank, San Bruno, CA) to determine the average daily energy, macronutrient, and fiber intakes of the subjects. The dietary information was used primarily to monitor food intake during the study. Food record keeping was scheduled relative to study day (day 0). Subjects kept records 3 d before (day –3), the day before (day –1), and the day after (day 1) each study day. Additionally, half-day food records were kept on the study day; these records reflected everything the subjects consumed after the 6-h study period until midnight. The half-day food records were analyzed to explore changes in food intake after each test meal.

### Test meals and foods

Three isoenergetic test meals were prepared by using commercially available foods to contain approximately one-third of the average daily energy intake of the men (4.1 MJ) and women (3.2 MJ). Test meals included foods such as breakfast cereals, milk, toast, margarine, jelly, muffins, nuts, and juice (Table 1). All 3 test meals contained ~30% of energy from fat, 17% of energy from protein, and 53% of energy from carbohydrate. Whole almonds (AWL) or almond oil (AOL) served as the primary fat source for 2 meals, whereas the control meal (CRL) contained a mixture of safflower and corn oils to provide a dietary fat source with a similar ratio of polyunsaturated to saturated to monounsaturated fatty acids as the meals containing almond fat (ie, 1:1:3.2, respectively). The whole almonds were given “as is” in the AWL meal, whereas the oils were incorporated into muffins in the AOL and CRL meals. Each meal was accompanied with water, which varied slightly in volume depending on the weight of the meal being served. The energy density of the meals was 4.1 kJ/g for men and 3.8 kJ/g for women. The palatability of the meals was rated similarly by the subjects, and all meals were easily consumed.

### Satiety measures (subjective)

VAS booklets were provided to each subject to assess appetite and satiety in response to the 3 test meals. VAS booklets were completed immediately before the test meal breakfast and then 20, 40, 60 (1 h), 90, 120 (2 h), 180 (3 h), 240 (4 h), 300 (5 h), and 360 (6 h) minutes thereafter. The participants rated their hunger, fullness, desire to eat, and prospective consumption on 100-mm line scales. Questions such as, “How hungry do you feel right now?” or “How strong is your desire to eat right now?” preceded a 100-mm line anchored by the opposing phrases “not at all hungry” and “extremely hungry” or “very weak” and “very strong.” Other anchors consisted of the phrases “not at all full” and “extremely full” or “a large amount” and “nothing at all” or “very pleasant” and “not at all pleasant” to access fullness, prospective consumption, and meal like or dislike, respectively. The use and value of these scales for assessing motivation to eat and food preference was reported previously (18, 19).

### Biochemical measures

Blood was drawn before (ie, fasting sample) and at specific time points after test meal consumption corresponding to VAS assessment to investigate the relation between biological mediators of satiety and subjective assessment of satiety. Blood samples were collected in 10-mL EDTA-coated evacuated tubes and were immediately cooled on ice and transferred to a tabletop centrifuge for separation of plasma and red blood cells. Plasma was obtained by spinning samples at 2000 × g for 15 min at room temperature. Two 2-mL portions of plasma were extracted onto cartridges containing octadecylsilica (Sep-Pak; Waters Corporation, Milford, MA) and were frozen at –70 °C for determination of CCK concentrations by radioimmunoassay. Another portion (2 mL) of plasma was stored in microcentrifuge tubes and was frozen at –20 °C for subsequent analysis of glucose, insulin, and triacylglycerol concentrations.

 Plasma CCK concentrations were measured by radioimmunoassay by using the highly specific and selective antibody Ab-92128 (gift from Jens Rehfeld, Rigshospitalet, Copenhagen). Briefly, according to the method of Rehfeld (20), plasma was eluted from Sep-Pak cartridges and was evaporated to dryness in a vacuum centrifuge (SpeedVac Concentrator SVC200H; Savant Instruments, Farmingdale, NY). Samples were incubated with 125I Bolton-Hunter labeled sulfated CCK-8 (Amersham, Arlington Heights, IL) for 4 days at 4 °C. Free and bound isotope were separated by the addition of 0.5 mL 6% charcoal (Sigma, St Louis) suspended in assay buffer without albumin and outdated human plasma (Sacramento Blood Foundation, CA). Plasma insulin was measured by radioimmunoassay according to the basic method described by Yalow and Berson (21), modified by using 0.05-mol/L phosphate buffer containing 0.4% human serum albumin and the precipitation method described by Desbuquois and Aurbach (22), using polyethylene glycol to separate free and antibody-bound insulin. Plasma glucose and triacylglycerols were analyzed in the University of California, Davis, Clinical Nutrition Research Unit analytic core laboratory, NIH#DK35747, by using the glucose oxidase method (kit #315; Sigma Chemical Co, St Louis) and colorimetric enzymatic method that measures triacylglycerols by glycerol release (kit #336, Sigma Chemical Co).
The study used an unblinded, crossover design in which all meals were tested in all subjects, in random order, at least 1 wk apart. The subjects were instructed to keep detailed 24-h food records on days 3, 1, 0 (study day), and 1 of each scheduled test session. On the day of the study session, the subjects arrived at the laboratory between 0700 and 0800 after fasting overnight for ≥8 h. Each subject was scheduled to come in at the same time of the week or weekend within 4 wk. When the subject arrived at the study site, an intravenous catheter was placed in his or her nondominant arm to allow for the drawing of multiple blood samples with minimal disruption or discomfort. After the initial fasting blood draw, the subjects rested for a few minutes, acquainted themselves with their dining area, and then filled out their first set of VASs. After filling out the VASs, the subjects were given one of the 3 test meals to consume in 20 min. Blood was sampled, and VAS booklets were completed for 6 h after meal ingestion according to the schedule described above. At the end of the test session, the catheters were removed, and the subjects were offered a selection of foods (preweighed) from a

### TABLE 1

<table>
<thead>
<tr>
<th>Foods (g)</th>
<th>Men</th>
<th></th>
<th></th>
<th></th>
<th>Women</th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>AWL</td>
<td>AOL</td>
<td>CRL</td>
<td>AWL</td>
<td>AOL</td>
<td>CRL</td>
<td>AWL</td>
<td>AOL</td>
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<tr>
<td>Breakfast cereal</td>
<td>57</td>
<td>57</td>
<td>57</td>
<td>37</td>
<td>43</td>
<td>37</td>
<td>22</td>
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<td>Skim milk</td>
<td>326</td>
<td>407</td>
<td>368</td>
<td>245</td>
<td>306</td>
<td>306</td>
<td>22</td>
<td>11</td>
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<tr>
<td>White bread toast</td>
<td>22</td>
<td>11</td>
<td>25</td>
<td>22</td>
<td>11</td>
<td>11</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>Corn margarine</td>
<td>–</td>
<td>8</td>
<td>8</td>
<td>–</td>
<td>6</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Safflower margarine</td>
<td>–</td>
<td>–</td>
<td>7</td>
<td>–</td>
<td>–</td>
<td>6</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Strawberry jelly</td>
<td>14</td>
<td>8</td>
<td>8</td>
<td>18</td>
<td>7.5</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Egg white</td>
<td>35</td>
<td>55</td>
<td>50</td>
<td>30</td>
<td>35</td>
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<tr>
<td>Egg yolk</td>
<td>18</td>
<td>17</td>
<td>17</td>
<td>19</td>
<td>18</td>
<td>17</td>
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<td>Orange juice</td>
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<td>100</td>
<td>82</td>
<td>149</td>
<td>82</td>
<td>62</td>
<td>149</td>
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<tr>
<td>Muffin (safflower oil)</td>
<td>–</td>
<td>–</td>
<td>110</td>
<td>–</td>
<td>–</td>
<td>110</td>
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<td>–</td>
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<tr>
<td>Muffin (corn oil)</td>
<td>40</td>
<td>–</td>
<td>–</td>
<td>30</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Muffin (almond oil)</td>
<td>–</td>
<td>110</td>
<td>–</td>
<td>–</td>
<td>75</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Almonds</td>
<td>40</td>
<td>–</td>
<td>–</td>
<td>28</td>
<td>–</td>
<td>–</td>
<td>28</td>
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<td>Water</td>
<td>199</td>
<td>226</td>
<td>269</td>
<td>221</td>
<td>216</td>
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<tr>
<td>Total fat (g)</td>
<td>32.3</td>
<td>31.7</td>
<td>32.0</td>
<td>25.0</td>
<td>24.3</td>
<td>24.0</td>
<td>25.0</td>
<td>24.3</td>
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<tr>
<td>(% of energy)</td>
<td>30</td>
<td>30</td>
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<td>30</td>
<td>30</td>
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<td>30</td>
</tr>
<tr>
<td>Saturated fat (g)</td>
<td>4.9</td>
<td>5.2</td>
<td>5.0</td>
<td>4.1</td>
<td>4.3</td>
<td>3.7</td>
<td>4.1</td>
<td>4.3</td>
</tr>
<tr>
<td>(% of energy)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
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<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Polyunsaturated fat (g)</td>
<td>7.5</td>
<td>6.8</td>
<td>7.5</td>
<td>5.7</td>
<td>5.1</td>
<td>5.5</td>
<td>5.7</td>
<td>5.1</td>
</tr>
<tr>
<td>(% of energy)</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Monounsaturated fat (g)</td>
<td>17.1</td>
<td>16.8</td>
<td>17.3</td>
<td>12.9</td>
<td>12.7</td>
<td>12.8</td>
<td>12.9</td>
<td>12.7</td>
</tr>
<tr>
<td>(% of energy)</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Carbohydrate (g)</td>
<td>137</td>
<td>136</td>
<td>137</td>
<td>102</td>
<td>102</td>
<td>102</td>
<td>102</td>
<td>102</td>
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<tr>
<td>(% of energy)</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>Protein (g)</td>
<td>35.5</td>
<td>33.9</td>
<td>33.0</td>
<td>27.4</td>
<td>25.6</td>
<td>26.2</td>
<td>27.4</td>
<td>25.6</td>
</tr>
<tr>
<td>(% of energy)</td>
<td>14</td>
<td>14</td>
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<td>14</td>
<td>14</td>
<td>14</td>
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<tr>
<td>Energy (kJ)</td>
<td>4046</td>
<td>4046</td>
<td>4059</td>
<td>3072</td>
<td>3068</td>
<td>3064</td>
<td>3072</td>
<td>3068</td>
</tr>
<tr>
<td>Energy density (kJ/g)</td>
<td>4.05</td>
<td>4.05</td>
<td>4.05</td>
<td>3.84</td>
<td>3.84</td>
<td>3.84</td>
<td>3.84</td>
<td>3.84</td>
</tr>
</tbody>
</table>

1 Corn Chex; General Mills Inc, Minneapolis.
2 Crystal Cream and Butter Company, Sacramento, CA.
3 Rainbow; The Earthgrains Co, St Louis.
4 Fleischmann’s; ConAgra Foods, Downers Grove, IL.
5 Saffola; Ventura Foods, Inc, City of Industry, CA.
6 Safeway brand; Safeway, Oakland, CA.
7 Large grade AA; Petaluma Farms, Petaluma, CA.
8 Tropicana Products, Inc, Bradenton, FL.
9 Muffin ingredients differed only by fat source and were as follows: flour, baking powder, banana, egg, sugar, skim milk, salt, cinnamon, oil [safflower oil (Saffola; Ventura Foods, Inc), corn oil (Wesson; ConAgra, Irvine, CA), or almond oil (Almond Board of California, Modesto, CA)]. For recipe detail, contact the corresponding author.
10 Whole almonds and almond oil; Almond Board of California.
tray before they left the study site. The tray contained foods such as bananas, oranges, apples, cookies, pretzels, chips, nuts, bagels, granola bars, cheese, juice, and soda. The subjects were required to record the food consumed from the tray along with foods eaten outside the laboratory until midnight of the test day. After the final test meal study day, the subjects were debriefed and compensated for their time and effort in the study.

Data analysis

The sample size was chosen to provide sufficient (≥80%) statistical power, assuming type 1 error of 0.05, to test the primary hypothesis that meals containing fat primarily from a purified compared with a complex food source would impart greater satiety as a result of apparent availability in the intestine to stimulate CCK release. When we calculated power retrospectively by using actual means, variance of means, and within-subjects error, we found that our power to test the hypothesis of subjective satiety relative to meals was >90%.

The subjective satiety response to the 3 test meals was determined from the VAS data and was analyzed by repeated-measures analysis of variance (ANOVA) with test meal, time, and sex as main factors and subject as the blocking variable. The VAS data were first converted to increments above baseline to account for relative baseline variability among subjects. Substrate metabolites and hormonal mediators of satiety (ie, CCK) were analyzed by repeated-measures ANOVA as well. Adjustment in food intake after test meals was assessed by analyzing the subjects’ food records from ≈1330 to midnight of the study day (ie, poststudy food records). Total intake on study days, including the energy from test meals, was compared with usual intake defined by the average energy intake on days −3, −1, and 1, respectively relative to each study day. Differences among treatment means (adjusted) were analyzed by Tukey’s honestly significant difference test and pairwise t tests for appropriate comparisons. Relations between the subjective satiety responses (VAS) and the biological satiety response (CCK) were tested by using linear regression analysis. The level used to determine statistical significance was P < 0.05. All data were analyzed with the PC-SAS GLM procedure (SAS version 6; SAS Institute Inc, Cary, NC). Results are displayed as least-squares means ± SEMs unless noted otherwise.

RESULTS

Subject characteristics

The mean (±SD) ages of the men and the women were 30 ± 13 and 35 ± 8 y, respectively. The mean BMIs of the men and the women were 25 ± 1 and 23 ± 2, respectively. Questionnaires evaluating dietary restraint (Three Factor Eating Questionnaire; 17), potential eating disorders (Eating Attitudes Test; 23), and depression (Depression Inventory; 24) indicated that the subjects were unrestrained eaters (mean score of 6.3 ± 4.7) and had no signs of eating disorders (mean score of 8.8 ± 5.6) or depression (mean score of 0.4 ± 0.1). All subjects complied with the requirements of the study, including maintaining a stable body weight throughout the experimental period.

Food records and usual diets

Collection of weekly food records provided information about the usual diets of the men and women participating in the study as well as their consistency in food intake and feeding patterns during the study. Nutrient and statistical analyses of the food records indicated that energy intake differed between the men and the women (P < 0.03) but not within each sex. Average daily energy intake was 8.3 ± 0.7 MJ for the women and 10.7 ± 0.7 MJ for the men and did not vary significantly from week to week. Macronutrient composition of usual diets expressed as a percentage of energy differed significantly between the men and the women for protein (men, 16%; women, 14%; P < 0.04) and carbohydrate (men, 54%; women, 59%; P < 0.02) and only marginally for fat (men, 29%; women, 26%; P < 0.09) but did not differ significantly over the study. Dietary fiber, sodium, and cholesterol intake per 4.2 MJ were not significantly different between the groups.

To explore compensatory changes that may be attributed to test meal challenges, the subjects were instructed to keep poststudy food records. The poststudy records corresponded to the energy and macronutrient composition of the foods and beverages consumed after each 6-h test meal period until midnight of the same day, −10 h after the study. Energy intake for the poststudy period did not differ significantly among the meals (AOL, 6.5 ± 0.7 MJ; AWL, 8.4 ± 0.7 MJ; CRL, 7.8 ± 0.7 MJ; P = 0.23), nor did macronutrient intake composition. Poststudy energy intake was also not significantly different by sex (8.4 ± 0.6 and 6.7 ± 0.6 MJ for the men and the women, respectively; P = 0.13). Analysis of macronutrient intake composition showed that the men tended to consume a greater percentage of energy from protein than did the women (18% and 13% of energy, respectively; P = 0.06), whereas carbohydrate intake was significantly higher in the women (49% and 59% of energy for the men and women, respectively; P = 0.03).

Energy intake compensation was estimated on the basis of the difference between intake on the study day [sum of test meal energy and poststudy (10 h) energy] and usual intake (average of each subject’s study day–associated 3-d, 24-h food records). Presumably, with accurate compensation for test meal energy, the total energy intake on the study day should not be significantly different from usual intake. For all study days, when test meal energy was included, energy intake on the study days ranged from 5% to 28% above usual intake. However, the difference from usual intake was significant only for the AWL meal in men (28% above usual energy intake; P = 0.03).

Satiety measures (subjective)

Statistical analysis of VAS-based ratings of hunger, fullness, desire to eat, and prospective consumption showed significant test meal (P < 0.001) and time (P < 0.001) effects. In general, the test meals that contained fat in the oil form (AOL, CRL) had a greater suppressive effect on hunger, desire to eat, and prospective consumption (P < 0.001) than did the meal containing fat from an intact source (AWL). Ratings for fullness followed a similar pattern (P < 0.05). In addition to the main effects of test meal and time, a significant test meal–by-sex interaction (P < 0.001) was observed. Baseline ratings of hunger, fullness, desire to eat, and prospective consumption did not differ significantly between the men and the women; however, the postmeal pattern of subjective satiety differed significantly. The difference in pattern of response over time by sex is illustrated graphically for the hunger data only, which are representative of the responses observed for the other assessed appetite and satiety variables (Figure 1). In tabular format (Table 2), the least-squares mean
Measures of subjective satiety in subjects after consumption of the almond oil (AOL), whole almond (AWL), and control (CRL) test meals

TABLE 2

<table>
<thead>
<tr>
<th></th>
<th>Fullness</th>
<th>Hunger</th>
<th>Desire to eat</th>
<th>Amount of food</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Women</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AOL</td>
<td>59.7 ± 2.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-57.3 ± 2.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-58.9 ± 2.4&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-52.3 ± 2.2&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>AWL</td>
<td>47.3 ± 2.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-39.1 ± 2.3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-40.9 ± 2.4&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-33.5 ± 2.2&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>CRL</td>
<td>54.5 ± 2.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-61.9 ± 2.3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-60.4 ± 2.4&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-46.4 ± 2.2&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Men</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AOL</td>
<td>40.3 ± 2.2&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-38.8 ± 2.1&lt;sup&gt;d&lt;/sup&gt;</td>
<td>-40.4 ± 2.2&lt;sup&gt;d&lt;/sup&gt;</td>
<td>-34.5 ± 2.1&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>AWL</td>
<td>40.7 ± 2.1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-42.8 ± 2.1&lt;sup&gt;d&lt;/sup&gt;</td>
<td>-41.4 ± 2.2&lt;sup&gt;d&lt;/sup&gt;</td>
<td>-36.0 ± 2.1&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>CRL</td>
<td>40.2 ± 2.1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-40.0 ± 2.1&lt;sup&gt;d&lt;/sup&gt;</td>
<td>-38.9 ± 2.3&lt;sup&gt;d&lt;/sup&gt;</td>
<td>-36.6 ± 2.1&lt;sup&gt;d&lt;/sup&gt;</td>
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<sup>*</sup> All values are least-squares ± SEM; n = 7 women, 8 men. Values are based on the mean over time for measurements taken 20, 40, 60, 90, 120 (2 h), 180 (3 h), 240 (4 h), 300 (5 h), and 360 (6 h) min after the start of test meal ingestion. Values in a column by sex with different superscript letters are significantly different, P < 0.05. Meal by sex interaction, P < 0.001.
of 337% and 260% from baseline at 20 min, respectively, and continued to rise to peaks of 489% and 496% from baseline at 180 and 120 min, respectively. Return to baseline concentrations occurred between 180 and 240 min for the AWL meal and between 240 and 300 min for the CRL meal, whereas AOL-associated CCK concentrations had not returned to baseline by the last sampling point (360 min).

For men, the postprandial CCK response did not differ significantly by test meal. All test meals produced an increase in plasma CCK, which peaked with a similar magnitude, ≈343% of baseline concentrations, around the 90–120-min sampling points. Return to baseline concentrations occurred around the 180–240-min sampling time for all 3 meals.

Relation between satiety measures (biochemical and subjective)

Evaluation of the subjective measures of satiety (ie, the VAS data) and the biochemical measure of satiety (ie, CCK) in the same model indicated a highly significant relation between hunger, fullness, desire to eat, the amount an individual may want to eat, and plasma CCK concentrations (P < 0.0001). A significant interaction was also observed between plasma CCK and sex for the various VAS satiety ratings (P < 0.0001). For women, every 1-unit change in CCK (pmol/L) resulted in a decline in hunger, desire to eat, and the amount that one wants to eat by ≈4.2 mm on the subjective VASs. Ratings of fullness increased by ≈3.7 mm for every 1-unit change in CCK. For men, every 1-unit change in CCK concentrations resulted in a decline of ≈1.4 mm on the VASs for hunger, desire to eat, and the amount of food one wants to eat. Correspondingly, fullness ratings increased by 1.5 mm on the VAS. As a result of the test meals consumed, the blunted CCK response among women after the AWL meal corresponded with heightened levels of hunger, weaker feelings of fullness, and stronger motivations to eat per unit change in CCK, whereas this same relation was not observed among men.

Other blood and biochemical measures

Plasma concentrations of glucose, insulin, and triacylglycerols were also measured as part of this study. The glucose and insulin responses to the test meals did not differ significantly by meal or sex but did differ by time, as expected (P < 0.0001). Plasma glucose and insulin concentrations peaked at ≈40 min after meal consumption and returned to baseline concentrations by ≈180 min. Plasma concentrations of triacylglycerols did not differ by test meal; however, a significant time effect (P < 0.0001) and a test meal–by-time interaction (P < 0.0008) were observed (Figure 3). Plasma triacylglycerol concentrations peaked at ≈180 min for the 2 meals delivering fat in the oil form (AOL, CRL), whereas peak concentrations after the meal providing fat through whole almonds (AWL) did not occur until ≈300 min. Calculation of the area under the triacylglycerol response curve showed no significant difference in total lipid uptake in the blood among groups, suggesting a delay of absorption rather than a lack of lipid absorption.

DISCUSSION

The primary objective of this project was to examine the postmeal subjective satiety response to mixed whole-food meals that deliver dietary fat in forms that should influence its availability to stimulate intestinal mechanisms of satiety, namely CCK. Secondary objectives included assessment of postprandial lipid, glucose, and insulin responses to the same meals as well as potential behavioral changes in energy intake relative to test meals. In this study, the subjects consumed 3 test meals that were equivalent in energy, macronutrient composition, and ratio of polyunsaturated to saturated fat, whereas this same relation was not observed among men.

In general, the results of the present study support our hypotheses related to subjective measures of satiety, CCK release, and sex. Women showed a differential response to dietary fat accessibility as measured by both CCK release and VAS-based ratings of hunger, fullness, desire to eat, and prospective consumption. In contrast, men showed no differential response in CCK release or in their ratings of hunger and satiety. The meals did, however, suppress appetite and stimulate the release of CCK similarly, which supports the connection between CCK and the satiety response. The lack of distinction of dietary fat changes in these test meals by men compared with women suggests sex-related differences in sensitivity to dietary fat, which was shown in earlier work in our laboratory (9,12). Our previous work suggests that men tend to respond to food bulk, independent of fiber content, rather than variations in macronutrient composition, which is consistent with findings by Rolls et al (26,27) and suggests associations in men between hunger and fullness ratings.
and food volume. In the present study, the solid-to-water weight ratio of all of the meals did not differ, which further supports the notion of gastric bulk as a key signal for men in regulating short-term food intake.

In addition to assessing the biological and subjective satiety responses to the different test meals, we examined behavioral outcomes with respect to actual food intake during the 10-h postprandial period. The objective here was to assess compensatory food intake behavior that may be related to the test meals. In general, the subjects compensated adequately for the energy consumed during the testing period within a normal range of variation. This outcome was somewhat expected when using the instituted 6-h postprandial study paradigm, in which return to baseline status is achieved for variables measured by the end of the test period. Only in the case of men and with the AWL meal did there appear to be undercompensation and, thus, significantly more energy consumed during the AWL test meal day than usual diet intake. The reason or reasons for this lack of compensation on the study day are not readily apparent, because other indicators of the satiety response in this study suggest accurate compensation for the men across all test meals, similar to observations in our previous postprandial satiety studies. Examination of the food intake records for energy the following day (day 1) showed lower energy intake relative to usual diet, suggesting that although compensation was not accurate in the short term, overall compensation and stable energy intake was achieved to maintain body weight. Subjects maintained body weight within 1 kg, on average, throughout the study.

Recently, substantial attention has focused on the lipid, glucose, and insulin response to foods and meals because of the relation of these responses to disease risk, namely diabetes and cardiovascular disease. The test meals all had a similar distribution of protein, fat, carbohydrate, and fiber, and no significant differences were observed in the glucose and insulin responses, as might be expected in healthy, nondiabetic subjects. Although the overall triacylglycerol response did not differ significantly among the test meals, the interaction between time and test meal was significant. This difference was due to a delayed peak in the concentration of triacylglycerols after the AWL meal compared with the test meals containing oil; the peak after the AWL meal occurred ≈2 h after the peak for the other 2 meals. Because the overall response, as indicated by the least-squares means, was not significantly different for the 3 meals, the delay suggests that the fat in whole almonds was more slowly digested and absorbed. However, the accumulation of triacylglycerols in plasma at later time points reflects both appearance and clearance of triacylglycerol-rich particles, and the lower triacylglycerol concentrations during the initial period may reflect less lipid absorption from the meals containing whole almonds. Earlier work showed that fecal fat excretion is higher when peanuts are consumed as whole peanuts rather than as peanut oil (25). More recent work with almonds also showed that subjects provided diets rich in whole almonds excreted significant amounts of lipid (28), a result likely due to the hindrance of intact cell walls for the release of intracellular lipid (29). Thus, in the context of the present study and on the basis of the available data, it appears that the total fat in all meals was absorbed and the differences in plasma concentrations over time were a function of delayed processing. Without the fecal fat analysis, however, this conclusion is tentative.

In summary, the results of the present study indicate that the delivery of dietary fat in a form that changes its availability (eg, as oil or as part of a whole food structure) affects the ability of fat to stimulate intestinal processes mediating satiety, specifically CCK, which is an important determinant of the satiety response to meals in women. The effect of fat availability in the acute meal setting appears to be less important to satiety-related processes in men. These data support the need for continued research in this area to better understand sex-specific differences mechanistically and outcomes behaviorally to assemble diets that provide for optimal food intake control.

Each author contributed to all phases of study, including study design, data collection and analysis, and writing of the manuscript. None of the authors had a conflict of interest with this study or the funding agency.

REFERENCES


