Relation between estimates of cornstarch digestibility by the Englyst in vitro method and glycemic response, subjective appetite, and short-term food intake in young men¹⁻³

G Harvey Anderson, Clara E Cho, Tina Akhavan, Rebecca C Mollard, Bohdan L Luhovyy, and E Terry Finocchiaro

ABSTRACT

Background: Starch composition and rate of digestion are determinants of blood glucose concentrations and food intake (FI).

Objective: Our objective was to describe relations between estimates of digestibility of starchy by the in vitro Englyst method and their effect on blood glucose concentrations, subjective appetite, and FI in young men.

Design: Subjects consumed 5 soups containing 50 g maltodextrin, whole-grain, high-amylase, regular cornstarch, or no added starch at 1-wk intervals. Ad libitum FI was measured at 30 min (experiment 1) or 120 min (experiment 2) later, which were the estimated times of digestion of a rapidly digestible starch (RDS) and slowly digestible starch, respectively. Blood glucose concentrations and appetite were measured pre- and postmeal.

Results: At 30 min, FI was reduced by maltodextrin only [86% RDS, 12% resistant starch (RS); P < 0.05], but at 120 min FI was reduced by whole-grain (24% RDS, 66% RS), high-amylase corn (40% RDS, 48% RS), and regular corn (27% RDS, 39% RS) (P < 0.0001). The premeal blood glucose concentration at 30 and 120 min was highest and lowest after maltodextrin treatment, respectively (P < 0.0001). After the meal, the blood glucose area under the curve at 30 min was lower after all starch treatments (P < 0.05), but at 120 min the blood glucose area under the curve was lower only after the regular cornstarch treatment (P < 0.05). Premeal appetite decreased by all treatments (P < 0.05).

Conclusion: The in vitro estimates of starch digestibility by the Englyst method predicted the effects of starch composition on blood glucose concentrations and FI in young men 30 and 120 min after consumption. This trial was registered at clinicaltrials.gov as NCT00980941 for experiment 1 and NCT00988689 for experiment 2.

INTRODUCTION

The starch composition of food and its rate of digestion are determinants of blood glucose, satiety, and energy intake (1, 2). In general, granular starches that are relatively high in amylose content tend to be more resistant to digestion, whereas starch granules with higher amylpectin content tend to be more digestible. Other factors influencing digestion of native starches include the starch source, their granular structure, and the degree of isolation and processing. The isolation and purification of starch from whole-grain flour to starch, rather than from the kernel, could also affect digestibility and the physiologic effect of starches (3).

Studies (4–8) showed that higher intakes of fiber, including slowly digested and resistant starches (RSs), are associated with increased satiety, reduced hunger and/or reduced body weight, a reduced glycemic response, and insulin resistance. Because of these associations, both in vivo and in vitro methods have been used to estimate the effect of composition and structures of starchy on rates of digestion. In vivo studies in humans showed that meals high in amylose compared with meals low in amylose starch resulted in lower glucose and insulin responses (9, 10) and induced greater satiety for 2–6 h (9, 11), suggesting an association between RS content, lower glycemic response, and reduced food intake (FI). However, in other short-term studies (12, 13), carbohydrates that produce higher glycemic responses were associated with lower FI 1–2 h after consumption. Thus, although both in vivo and in vitro methods focused on glucose release from starchy as a measure of digestibility, the relevance of the blood glucose response to physiologic mechanisms including those controlling FI and satiety remains uncertain (14).

Because of the expense of in vivo physiologic assays for the assessment of starch digestibility in humans, in vitro methods are desired but may have limited applications because their physiologic relevance is uncertain. The in vitro method developed by Englyst and Cummings (ie, the Englyst method) (15) crudely mimics the physiologic conditions for starch digestion in the stomach and small intestine (16). The physiologic relevance of the Englyst method has been shown because the in vitro estimates of digestibility of carbohydrates correspond to their glycemic index in humans (17–19). However, to our knowledge, there has been no report of the relations between the Englyst estimates of readily digestible starch (RDS), slowly digestible starch (SDS), and RS and the in vivo effects of starchy on the short-term glycemic response, satiety, and FI in humans.

¹ From the Department of Nutritional Sciences, Faculty of Medicine, University of Toronto, Toronto, Canada (GHA, CEC, TA, RCM, and BLL), and the National Starch LLC, Bridgewater, NJ (ETF).
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³ Address reprint requests and correspondence to GH Anderson, Department of Nutritional Sciences, Faculty of Medicine, University of Toronto, 150 College Street, Toronto, Ontario, MSS 3E2, Canada. E-mail: harvey.anderson@utoronto.ca.

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The hypothesis of this study was that the Englyst estimates of starch digestibility predict glucose and FI responses in vivo in humans. Therefore, the objective was to compare the in vitro Englyst estimates of RDS, SDS, and RS of 4 types of commercially available cornstarches representing a range of digestion profiles with their effects on FI at 30 and 120 min after consumption and to assess the pre- and postmeal glycemic and subjective appetite responses in healthy young men.

SUBJECTS AND METHODS

Subjects

Healthy men, aged 20–30 y, with a body mass index (BMI; in kg/m²) of 20–24.9 were recruited through advertisements placed around the University of Toronto campus. Recruitment for experiment 1 began in December 2007 and recruitment for experiment 2 began in June 2008. Women, smokers, breakfast skippers, individuals with diabetes or other metabolic diseases, and those scoring ≥11 on an eating habits questionnaire (20) were excluded from the study. Sixteen and 17 subjects participated in experiments 1 and 2, respectively. The sample size was determined by a power analysis for a within-subject design from a previous study (12) to be sufficient to detect a treatment effect on FI of 150 kcal with a power of 0.80 and an α < 0.05. Study procedures were approved by the University of Toronto Health Sciences Research Ethics Board.

Study design

Two experiments were conducted, in which FI was measured after consumption at 30 min in experiment 1 and 120 min in experiment 2. The times selected for measurement of FI corresponded to Englyst estimates of the release of glucose from RDS (≤30 min) and RDS and SDS (≤120 min), respectively. Subjects were given the treatments in a randomized order at weekly intervals for ~5 wk.

The 4 starch treatments consisted of 50 g dry weight (adjusted for moisture content) of whole-grain [a minimally processed, high-amylose starch (Hi-maize whole-grain flour; National Starch LLC, Bridgewater, NJ)], high-amylose corn [a stabilized, heat-moisture-treated, high-amylose starch (Hi-maize 260 starch; National Starch LLC)], regular corn [a high-amyllopectin granular starch (MELOJEL starch; National Starch LLC)], and maltodextrin [a highly processed, nongranular starch (STAR-DRI 100 maltodextrin; Tate & Lyle, Decatur, IL)]. Each starch treatment was added to tomato soup containing 30 g tomato paste (Unico Tomato Paste 100% Pure; Unico, Concord, Canada) (Table 1). A control treatment consisted of tomato soup containing 30 g tomato paste alone.

Starches were chosen to have a wide range in RDS and RS. Because the tomato paste contained small amounts of RDS and RS, these quantities were added to the starches to estimate the total starch consumed in the soup. The caloric content of the treatments was estimated from the starch digested within 20 min (RDS and 120 min (RDS and SDS) and from the protein and fat, with the assumption that they were fully digested at 30 min.

A proximate analysis and total dietary fiber (by the Association of Official Analytical Chemists method 991.43) (21) of the starches and tomato paste were determined. A modified version of the Englyst RS method (22) was used to analyze the starches for RDS, SDS, and RS content. Three minor modifications were made to the RS assay: 1) A commercial source of amyloglucosidase (AMG) was used to replace the original AMG 400, which is no longer available; 1 mL AMG enzyme (300 L AMG; Novozymes, Franklinlton, NC) was added to centrifuged 12 g pancreatin in solution. 2) Invertase (40 mg) (Sigma I4504, Grade VII from Baker’s yeast, 355 U/mg; Sigma, St Louis, MO) was added, replacing 4 mL of the original liquid enzyme (3000 EU/mL). 3) Guar gum (Sigma G-4129) was prehydrated in 0.05 M HCl solution (0.5% wt:vol) with 0.5% pepsin before being added to the digestion tubes. Because thermally stable α-amylase and pullulanase (debranching) enzymes were not added in the modified method, total starch and RS type were not measured.

All treatments were isovolumetric (300 mL) and contained 30 g tomato paste, 1 mL pepper (Verona, Montreal, Canada), 2 g salt (Sifto table salt; Sifto, Mississauga, Canada) and 2 mL garlic herbs (McCormick Garlic and Herb Seasoning; McCormick,

### TABLE 1

Composition of tomato soups including starch and tomato paste

<table>
<thead>
<tr>
<th>Soups</th>
<th>Control</th>
<th>Whole-grain (Hi-maize)</th>
<th>High-amylose (Hi-maize 260)</th>
<th>Regular cornstarch (MELOJEL)</th>
<th>Maltodextrin (STAR-DRI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapidly digestible starch (g)</td>
<td>1</td>
<td>10</td>
<td>19</td>
<td>13</td>
<td>41</td>
</tr>
<tr>
<td>Slowly digestible starch (g)</td>
<td>0</td>
<td>4</td>
<td>6</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>Resistant starch (g)</td>
<td>3</td>
<td>27</td>
<td>23</td>
<td>19</td>
<td>6</td>
</tr>
<tr>
<td>Total carbohydrate (g)</td>
<td>4</td>
<td>41</td>
<td>48</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Protein (g)</td>
<td>1</td>
<td>6</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Fat (g)</td>
<td>0</td>
<td>4</td>
<td>&lt;0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Energy at 30 min (kcal)</td>
<td>10</td>
<td>96</td>
<td>87</td>
<td>59</td>
<td>171</td>
</tr>
<tr>
<td>Energy at 120 min (kcal)</td>
<td>10</td>
<td>112</td>
<td>109</td>
<td>124</td>
<td>175</td>
</tr>
<tr>
<td>Fiber (g)</td>
<td>1</td>
<td>16</td>
<td>29</td>
<td>&lt;1.5</td>
<td>1</td>
</tr>
<tr>
<td>Volume (mL)</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

1 Hi-maize, Hi-maize 260, and MELOJEL are manufactured by National Starch LLC, Bridgewater, NJ. STAR-DRI is manufactured by Tate & Lyle, Decatur, IL.

2 Energy (kcal) of soups digested by 20 min is the sum of rapidly digestible starch + protein + fat, and energy (kcal) of soups digested by 120 min is the sum of rapidly and slowly digestible starches + protein + fat.
London, Canada). The treatments were prepared by adding starches to the tomato paste and flavoring in 150 mL water at room temperature. Immediately before consumption, warm water at 80–83°C was added to a total volume of 300 mL, and the treatment was served at 55–58°C. To remove aftertaste, an additional 100 mL water was served in a separate glass for consumption after the soup was consumed.

Protocol

As previously reported (12, 13, 23), subjects chose a time between 1100 and 1400 to participate after a fast of 10–12 h followed by a standard breakfast (300 kcal) 4 h before arriving at the same time and day of the week for each session. The breakfast consisted of a single serving of ready-to-eat cereal (Honey Nut Cheerios; General Mills, Mississauga, Canada), 250 mL 2% milk (Sealtest, Markham, Canada), 250 mL orange juice (Tropicana, Bradenton, FL) and, if desired, either tea or coffee without additions. Subjects were asked not to eat between breakfast and the study session, but water was allowed up to 1 h before the session.

During the sessions, blood glucose concentrations were measured by a glucose meter (Accu-Chek Compact Plus; Roche Diagnostics, Laval, Canada) that was standardized against commercial human serum at 2 concentrations of 6.3 and 10.0 mmol/L glucose (Assayed Human Multi-Sera; Randox Laboratories Canada Ltd, Mississauga, Canada). In a comparison of the variation of the estimated glucose concentrations in the standards, the 11 glucose meters used in these experiments had a CV of 3%, similar to the variation of the estimates of 11 measures of the solutions by an YSI 2300 STAT PLUS glucose analyzer (YSI Inc, Yellow Springs, OH). Blood samples were obtained by finger prick by a Monjector Lancet Device (Sherwood Medical, St Louis, MO). The first drop of blood was wiped off, and the second drop was placed on the glucose-meter strip.

On arrival for the sessions, subjects completed questionnaires assessing their sleep, stress, and compliance with fasting and pattern of activity. If they reported substantial deviations from their usual pattern, they were asked to reschedule. Before treatment, subjects completed a motivation-to-eat visual analog scale to measure subjective appetite (24, 25), as used in previous studies (12, 13, 23). A baseline measurement of the blood glucose concentration was taken. A value >6 mmol/L was interpreted to suggest that the subject had not fasted or was insulin resistant (13), and the subject was rescheduled. After these baseline measures, subjects consumed the treatment within 5 min.

In experiment 1, the premeal blood glucose concentration and subjective appetite were measured at 15 and 30 min after consumption of the treatment. At 30 min, the subjects were provided 20 min to eat an ad libitum pizza meal, and FI was measured. Subjects rated the palatability of the meal, and postmeal blood glucose samples and subjective appetite were measured at 50, 65, 80, 95, 110, 140, and 170 min. In experiment 2, the premeal blood glucose concentration and subjective appetite were measured at 0, 15, 30, 45, 60, 90 and 120 min, and FI was measured at 120 min. At the end of the meal, subjects rated its palatability, and postmeal blood glucose samples and subjective appetite were measured at 140, 155, 170, 185 and 200 min.

Subjects were instructed to eat until they were comfortably full. Three varieties (Pepperoni, Deluxe, and Three Cheese) of Deep ‘N Delicious pizza (McCain Foods, Florenceville, Canada) were offered to subjects according to their preference at screening, and their same choices were provided at all sessions. The pizzas had an average of 10.0 g protein, 7.6 g fat, 26.6 g carbohydrates, and 226 kcal/100 g. Each cooked pizza (8 min at 227°C and cut in quarters) was weighed before serving. Fresh pizzas trays replaced the previous tray at 8-min intervals until the subjects declined further trays. Each tray contained 2 pizzas of their first choice and one pizza each of their second and third choices.

Statistical analyses

The average subjective appetite score was calculated from the motivation-to-eat visual analog scale questionnaire as follows: appetite score = [desire to eat + hunger + (100 – fullness) + prospective consumption]/4 (24). The energy intake from the pizza meal was calculated from the weight consumed and the compositional information provided by the manufacturer. The cumulative energy intake was calculated from the sum of calories from the treatment and pizza test meal. The percentage of energy compensation was calculated as [(kcal consumed at the test meal after control treatment – kcal consumed at the test meal after starch treatment)/(kcal of starch treatment – kcal of control treatment)] × 100%. Pre- and postmeal net incremental area under the curves (AUCs) (13, 23, 26) for blood glucose concentration and average appetite were calculated for 0–30 and 30–170 min, respectively, in experiment 1, and 0–120 and 120–200 min, respectively, in experiment 2.

SAS version 8.2 (SAS Institute, Cary, NC) was used for statistical analyses. Two-way repeated measures analysis of variance (ANOVA) determined the effects of treatments, time, and time-by-treatment interaction on blood glucose and average-appetite scores over the time of the experiment. A statistically significant interaction was followed by one-way repeated measures ANOVA, and the Tukey-Kramer post hoc test was used to describe mean differences between treatments at each time point. The effects of treatments on FI at the meal, cumulative FI, and percentage of energy compensation at 30 min (experiment 1) and 120 min (experiment 2) and on blood glucose and average-appetite AUCs were determined by one-way repeated measures ANOVA followed by the Tukey-Kramer post hoc test. Correlation analyses between treatments and outcome measures were performed by using Pearson’s correlation coefficient. All results are presented as means ± SEMs. Statistical significance was concluded with \( P < 0.05 \).

RESULTS

Subject characteristics

In experiment 1, subjects \((n = 17)\) had a mean ± SEM age of 20.2 ± 0.1 y, weight of 71.3 ± 1.5 kg, and BMI of 22.5 ± 0.3. In experiment 2, subjects \((n = 16)\) had a mean age of 20.9 ± 0.3 y, weight of 70.4 ± 1.2 kg, and BMI of 22.5 ± 0.4.

Blood glucose

In both experiments, there was an effect of treatment \((P < 0.001)\), time \((P < 0.0001)\), and time-by-treatment interaction \((P < 0.0001)\) on blood glucose concentrations that was explained
by the differences in treatment effect over time. In experiment 1, 
blood glucose concentrations premeal (at 15 and 30 min) and 
immediate postmeal (at 50 min) were higher after the malto-
dextrin treatment than after the other starch treatments and the 
control treatment ($P < 0.0001$) (Figure 1A). Postmeal blood 
glucose concentrations 65 min after the whole-grain treatment 
were lower than after the high-amylose treatment ($P = 0.02$). At 
80 min, postmeal blood glucose concentrations were lower after 
regular cornstarch, whole-grain, and maltodextrin treatments 
than after the high-amylose treatment ($P = 0.003$). The control 
treatment resulted in intermediate concentrations. At 170 min, 
postmeal blood glucose concentrations after the regular corn-
starch and whole-grain treatments were lower than after the 
control treatment ($P < 0.05$).

In experiment 2, the premeal blood glucose concentration 
60 min before the meal was highest after the maltodextrin 
treatment ($P < 0.0001$) (Figure 1B). Immediately before the 
meal at 120 min, the premeal blood glucose concentration was 
lower after the maltodextrin treatment than after the regular 
cornstarch and high-amylose treatments ($P < 0.0001$) but not 
different from the whole-grain or control treatments. The blood 
glucose concentration at 120 min after the regular cornstarch 
treatment was sustained above the baseline, but the blood glu-
cose concentration fell below baseline after the maltodextrin 
treatment ($P < 0.05$). The postmeal blood glucose concentra-
tions at 170, 185, and 200 min were highest after the whole-
grain and control treatments.

In both experiments, all starch treatments resulted in higher 
premeal blood glucose AUCs than the control treatment ($P < 
0.0001$). Maltodextrin and whole-grain treatments resulted in 
the highest and lowest blood glucose AUCs, respectively. In 
experiment 1, all starch treatments resulted in lower postmeal 
blood glucose AUCs (30–170 min) compared with the control 
treatment ($P < 0.0001$). The postmeal blood glucose AUC was 
most reduced after the maltodextrin treatment (Figure 2A). In 
experiment 2, only the regular cornstarch treatment resulted in a 
significantly lower postmeal blood glucose AUC (120–200 min) 
compared with the control treatment ($P < 0.0001$) (Figure 2B). 
Postmeal blood glucose AUCs were not different between the 
regular cornstarch and high-amylose treatments but both post-
meal blood glucose AUCs were lower than after whole-grain or 
maltodextrin treatments.

**FIGURE 1.** Mean ($\pm$SEM) effect of cornstarch treatments on blood glucose concentration. A: Experiment 1. B: Experiment 2. Treatments were maltodextrin, regular cornstarch, high-amylose, whole-grain, and a control, served as tomato soup. Values with different superscript letters are 
significantly different at each measured time: 2-factor ANOVA, time-by-treatment interaction ($P < 0.01$) followed by one-factor ANOVA, Tukey-Kramer 
post hoc test ($P < 0.05$). $n = 17$ in experiment 1; $n = 16$ in experiment 2.
Average appetite

In experiment 1, premeal appetite (0–30 min) was affected by time ($P = 0.0003$) and treatment ($P = 0.03$), but there was no time-by-treatment interaction ($P = 1.0$). After consumption of the treatments at 15 min, premeal average-appetite scores were reduced from baseline (70.5 mm) by an average of 6.7 mm for all treatments. Average-appetite scores over the 30-min premeal period for the treatments were as follows: 76.0 ± 1.8, 70.8 ± 1.5, 70.5 ± 2.0, and 75.1 ± 2.0 mm for the regular cornstarch, maltodextrin, whole-grain, and high-amylose treatments, respectively. The average-appetite score after the control treatment averaged 72.1 ± 2.0 mm.

Postmeal appetite (50–170 min) was affected by time ($P = 0.0002$) and treatment ($P < 0.0001$), but there was no time-by-treatment interaction ($P = 1.0$). After the meal (50 min), there was an average reduction in appetite scores of 53.7 mm from right before subjects consumed the meal. This was followed by an average increase of 18.0 mm at 120 min, which was above the baseline appetite score (72.5 mm). Over the premeal period, the regular cornstarch treatment led to significantly lower average-appetite scores (67.6 ± 1.8 mm), indicating greater appetite suppression compared with the control treatment (72.8 ± 1.8 mm) ($P < 0.05$), whereas high-amylose (71.3 ± 1.8 mm), whole-grain (68.8 ± 1.8 mm), and maltodextrin (71.5 ± 1.9 mm) treatments resulted in intermediate average-appetite scores.

In experiment 2, premeal appetite (0–120 min) was affected by time ($P < 0.0001$) and treatment ($P = 0.01$), with no time-by-treatment interaction ($P = 1.0$). At 15 min after treatment consumption, appetite scores were reduced by an average of 10.9 mm from baseline and then increased by 17.7 mm at 120 min, which was above the baseline appetite score (72.5 mm). Over the premeal period, the regular cornstarch treatment led to significantly lower average-appetite scores (67.6 ± 1.8 mm), indicating greater appetite suppression compared with the control treatment (72.8 ± 1.8 mm) ($P < 0.05$), whereas high-amylose (71.3 ± 1.8 mm), whole-grain (68.8 ± 1.8 mm), and maltodextrin (71.5 ± 1.9 mm) treatments resulted in intermediate average-appetite scores.

The postmeal average appetite (140–200 min) was affected by time ($P = 0.0001$) and treatment ($P < 0.0001$) with no time-by-treatment interaction ($P = 0.81$). Postmeal average-appetite scores after the meal (140 min) for all treatments were reduced from premeal values (79.2 mm) immediately before meal consumption by an average of 65.3 mm and then increased by an average of 10.9 mm to 200 min. Over the postmeal period, the whole-grain treatment (22.1 ± 1.4 mm) resulted in significantly higher average-appetite scores, indicating less suppression than after the meal for maltodextrin (17.7 ± 1.0 mm), high-amylose (17.4 ± 1.1 mm), and the control (18.7 ± 1.1 mm) ($P < 0.05$). After the meal, the regular cornstarch (21.5 ± 1.4 mm)
treatment also resulted in significantly higher average-appetite ratings than after maltodextrin and high-amylose treatments ($P < 0.05$).

Pre- and postmeal average-appetite AUCs were not different between starch treatments and/or the control treatment in experiment 1 (Table 2). Similarly, in experiment 2, premeal AUCs were not different; however, the whole-grain treatment resulted in a greater postmeal average-appetite AUC (120–200 min) ($P < 0.05$), indicating a lower suppression of appetite that was consistent with lower FI at the meal (Table 2).

### Food intake

In experiment 1, FI at 30 min was lower after the maltodextrin treatment, which contained the most RDS, compared with the control treatment ($P < 0.05$), but there were no significant differences between starch treatments (Table 3). Cumulative energy intake and caloric compensation did not differ between treatments (Table 3).

In experiment 2, all starch treatments, except maltodextrin, reduced FI compared with the control, with the lowest FI occurring after the whole-grain treatment ($P < 0.0001$). Maltodextrin treatment resulted in lower postmeal average-appetite AUC (120–200 min) ($P < 0.05$), indicating a lower suppression of appetite that was consistent with lower FI at the meal (Table 2).

### Table 2

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Premeal</th>
<th>Postmeal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min - min</td>
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</tr>
<tr>
<td>Control</td>
<td>−185.3 ± 41.3</td>
<td>−5939.7 ± 610.4</td>
</tr>
<tr>
<td>Whole-grain</td>
<td>−122.8 ± 90.1</td>
<td>−5033.5 ± 758.0</td>
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<tr>
<td>High-amylose</td>
<td>−137.0 ± 67.2</td>
<td>−6199.9 ± 469.0</td>
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<tr>
<td>Regular cornstarch</td>
<td>−165.9 ± 61.1</td>
<td>−6461.6 ± 512.6</td>
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<tr>
<td>Maltodextrin</td>
<td>−126.1 ± 53.0</td>
<td>−5673.1 ± 452.4</td>
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<td>$P$</td>
<td>NS</td>
<td>NS</td>
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**Experiment 2**

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<tr>
<td>Control</td>
<td>104.5 ± 480.0</td>
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<td>Whole-grain</td>
<td>−657.0 ± 368.0</td>
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<td>−73.1 ± 390.8</td>
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<td>−212.2 ± 474.3</td>
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<td>−64.8 ± 426.8</td>
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<td>$P$</td>
<td>NS</td>
<td>&lt;0.05</td>
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1 All values are means ± SEMs ($n = 17$ in experiment 1; $n = 16$ in experiment 2). Values in the same column with different superscript letters are significantly different from each other, $P < 0.01$ (one-factor ANOVA, Tukey-Kramer post hoc test).

2 Premeal: 0–30 min; postmeal: 30–170 min.

3 Premeal: 0–120 min; postmeal: 120–200 min.

### Table 3

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Food intake$^2$</th>
<th>Cumulative energy intake$^2$</th>
<th>Caloric compensation$^4$</th>
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<tr>
<td></td>
<td>kcal</td>
<td>kcal</td>
<td>%</td>
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<tr>
<td><strong>Experiment 1</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Control</td>
<td>1187.7 ± 64.8$^a$</td>
<td>1198.2 ± 64.8</td>
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<tr>
<td>Whole-grain</td>
<td>1123.3 ± 76.8$^{b,b}$</td>
<td>1219.3 ± 76.8</td>
<td>75.3 ± 82.7</td>
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<tr>
<td>High-amylose</td>
<td>1101.3 ± 79.0$^{b,b}$</td>
<td>1188.3 ± 79.0</td>
<td>112.9 ± 80.8</td>
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<tr>
<td>Regular cornstarch</td>
<td>1144.1 ± 58.5$^{b,b}$</td>
<td>1203.1 ± 58.5</td>
<td>90.0 ± 112.2</td>
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<tr>
<td>Maltodextrin</td>
<td>1006.1 ± 78.9$^b$</td>
<td>1177.1 ± 78.9</td>
<td>113.1 ± 32.1</td>
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<tr>
<td>$P$</td>
<td>&lt;0.05</td>
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<td>NS</td>
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<tr>
<td><strong>Experiment 2</strong></td>
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<tr>
<td>Control</td>
<td>1510.6 ± 61.1$^a$</td>
<td>1521.1 ± 61.1$^{a,b}$</td>
<td>—</td>
</tr>
<tr>
<td>Whole-grain</td>
<td>1242.8 ± 74.6$^c$</td>
<td>1355.1 ± 74.6$^e$</td>
<td>263.0 ± 32.8$^a$</td>
</tr>
<tr>
<td>High-amylose</td>
<td>1373.7 ± 62.8$^b$</td>
<td>1483.0 ± 62.8$^b$</td>
<td>138.5 ± 24.1$^b$</td>
</tr>
<tr>
<td>Regular cornstarch</td>
<td>1362.3 ± 63.8$^b$</td>
<td>1486.1 ± 63.8$^b$</td>
<td>130.9 ± 26.1$^{a,c}$</td>
</tr>
<tr>
<td>Maltodextrin</td>
<td>1424.0 ± 74.6$^{b,b}$</td>
<td>1598.9 ± 74.6$^b$</td>
<td>52.7 ± 19.4$^c$</td>
</tr>
<tr>
<td>$P$</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

1 All values are means ± SEMs ($n = 17$ in experiment 1; $n = 16$ in experiment 2). Values in the same column with different superscript letters are significantly different from each other, $P < 0.05$ (one-way ANOVA, Tukey-Kramer post hoc test).

2 Energy consumption in a test meal was measured after treatments at 30 min in experiment 1 and 120 min in experiment 2.

3 Energy from treatment + energy from test meal.

4 Defined as follows: [(kcal consumed at the test meal after control treatment – kcal consumed at the test meal after starch treatment)/(kcal of starch treatment – kcal of control)] × 100%.

### DISCUSSION

The results of the 2 experiments show that the in vitro classification of starch digestibility by the Englyst method predicted the effect of starches on premeal glycemic response and FI in young men. However, associations between the physiologic and analytic values depended on the time of measurement. RDS content correlated with a higher blood glucose concentration and lower FI at 30 min but with a lower blood glucose concentration and higher FI at 120 min. In contrast, higher RS was correlated with reduced FI at 120 min. Blood glucose AUCs before the meals were consistent with in vitro classification of starch digestibility, but the blood glucose concentration immediately before the meal was the most reliable predictor of the effect of starch on FI.

In vivo digestion rates were predicted by the in vitro digestion system of the Englyst method because there was a positive relationship between the amount of starch classified as RDS and as RDS and SDS and premeal blood glucose AUC to 30 min (RDS: $r = 0.84$, $P < 0.0001$; RDS and SDS: $r = 0.83$, $P < 0.0001$) and 120 min (RDS: $r = 0.80$, $P < 0.0001$; RDS and SDS: $r = 0.80$, $P < 0.0001$), respectively. Similarly, the Englyst method predicted the lack of digestibility of RS to 120 min because RS did not correlate with the premeal blood glucose AUC ($r = −0.14$, NS). The energy content of the treatments correlated strongly with premeal glucose AUC, which is explainable because the digestible energy content of the treatments was based primarily on their digestible carbohydrate to 30 min ($r = 0.67$, $P < 0.0001$) and 120 min ($r = 0.75$, $P < 0.0001$). However, the energy content was not correlated with FI at 30 min ($r = −0.20$, $P = 0.20$).
Although the Englyst method predicted the effects of the starch composition on blood glucose concentrations within 30 and 120 min as measured by AUC, it did not predict the relation of blood glucose concentrations over time with FI. However, the blood glucose concentration immediately before the meal was a predictor of FI. Lower FI was associated with higher RDS ($r = -0.20, P < 0.06$) in the starches and with a higher blood glucose concentration ($r = -0.25, P < 0.05$) immediately before the meal at 30 min. In contrast, at 120 min, lower FI was associated with the higher RS content ($r = -0.29, P = 0.01$) of the treatments. Thus, as previously noted, the effect of carbohydrate ingestion on FI cannot be judged by the AUC of blood glucose alone (14), and the concentration of blood glucose immediately before eating is the more important factor predicting FI (27). Therefore, the relation between the glycemic index of foods and their effect on food intake depends on the duration of time between ingestion and the next eating occasion.

Previous studies (5, 28, 29) suggested that the inverse association of RS with FI and/or satiety can be explained by fermentation in the colon. However, there is little evidence that this is a significant factor within 2 h of consumption (30). Thus, it may be that RS provides satiety signals similar to those proposed for insoluble wheat fiber (31). Insoluble wheat fiber consumed in a breakfast cereal reduces FI up to 75 min later (23, 32), independent of the glycemic effect of the digestible carbohydrate and, when consumed in a low-energy breakfast cereal, prevented caloric compensation for the reduced energy intake of the breakfast at a lunch-time meal (26). In the current study, a short-term satiety signal arising from RS was suggested because caloric compensation at 120 min for the whole-grain, regular cornstarch, and high-amyllose treatments, which are high in RS, averaged >100% compared with 53% for maltodextrin. Although significant effects were not shown between treatments on the premeal average appetite, this may be explained by the variability of subjective appetite measures and the relatively low intakes of RS. Recently, RS (8 g) was reported to increase satiety to 120 min when added to low-fiber equi-caloric muffins and was somewhat stronger than a similar satiety effect of insoluble fiber from corn bran (5).

Postmeal blood glucose concentrations and subjective appetite were measured because lower glycemic responses have been observed after meals of high-fiber, low-glycemic carbohydrates and also after a later meal (33). In both of the current experiments, higher FI at the test meals led to higher postmeal blood glucose as measured by the AUC (experiment 1: $r = 0.28, P < 0.01$) or concentrations (experiment 2: 170 min, $r = 0.26, P < 0.05$; 185 min, $r = 0.35, P < 0.01$; and 200 min, $r = 0.23, P < 0.05$) and more negative postmeal appetite ratings as measured by the AUC (experiment 1: $r = -0.26, P < 0.01$; experiment 2: $r = -0.49, P < 0.0001$), indicating less hunger. However, the effect of RS on glycemic and appetite responses to a later meal is unclear because the current results are confounded by the interaction of the premeal treatments with FI at the test meal. Measurements after a meal of fixed calories and carbohydrate content will be required to delineate the effect of premeal starch composition, including RS, on postmeal appetite and blood glucose, an approach previously used to show that the premeal consumption of insoluble fiber reduced postmeal blood glucose but not average appetite (23).

Because estimates of the digestibility of these starches by the Englyst method predicted their effect on blood glucose concentrations and FI, the results have practical implications for the development of food products for the control of glycemic responses by using starch ingredients. For example, a soup containing primarily RDS and consumed immediately before a meal would be expected to lead to earlier satiation at the meal (12, 14), whereas in a soup intended to be a meal, the preferred starch would be one high in SDS and RS to delay the return of hunger after the meal (23, 26). Although the ultimate test of the physiologic functionality of food products requires studies in humans, the Englyst method is less expensive, and therefore its application should encourage the use of physiologic and food functionality of starches in guiding food formulations.

In conclusion, in vitro characterization of starch digestibility by the Englyst method is a valid surrogate for estimating pre- and postmeal glycemic responses and subsequent FI at 30 and 120 min after consumption of starches by young adult men. Thus, the Englyst method of measuring digestibility of starch components has the potential to evaluate physiologic functionality of ingredient starches and the foods to which they are added for the purpose of glycemic and possibly FI control.

The authors’ responsibilities were as follows—GHA: conceived of and designed the study and participated in writing the manuscript; CEC: conducted experiments, collected data, assisted in data analysis, and assisted in writing the manuscript; TA: contributed to the study design, conducted data analysis, and assisted in writing the manuscript; RCM and BLL: contributed to the study design, assisted in data analysis; and assisted in writing the manuscript; and ETF: supervised analysis of the starch treatments by the Englyst in vitro method and reviewed the manuscript. ETF is employed by National Starch as the Director of Nutrition Research and Development and was not involved in the gathering or analysis of data. GHA, CEC, TA, RCM, and BLL reported no conflicts of interest.

REFERENCES