The Effects of Fat and Protein on Glycemic Responses in Nondiabetic Humans Vary with Waist Circumference, Fasting Plasma Insulin, and Dietary Fiber Intake

Elham Moghaddam, Janet A. Vogt, and Thomas M. S. Wolever

Department of Nutritional Sciences, University of Toronto, Toronto, Ontario M5S 3E2 Canada

Abstract

The effects of protein and fat on glycemic responses have not been studied systematically. Therefore, our aim was to determine the dose-response effects of protein and fat on the glycemic response elicited by 50 g glucose in humans and whether subjects’ fasting plasma insulin (FPI) and diet influenced the results. Nondiabetic humans, 10 with FPI ≥40 pmol/L and 10 with FPI >40 pmol/L, were studied on 18 occasions after 10 14-h overnight fasts. Subjects consumed 50 g glucose dissolved in 250 mL water plus 0, 5, 10, or 30 g fat and/or 0, 5, 10, or 30 g protein. Each level of fat was tested with each level of protein. Dietary intake was measured using a 3-d food record. Gram per gram, protein reduced glucose responses −2 times more than fat (P < 0.001) with no significant fat × protein interaction (P = 0.051). The effect of protein on glycemic responses was related to waist circumference (WC) (r = −0.56, P = 0.011) and intake of dietary fiber (r = −0.60, P = 0.005) but was unrelated to FPI or other nutrient intakes. The effect of fat on glycemic responses was related to FPI (r = 0.49, P = 0.029) but was unrelated to WC or diet. We conclude that, across the range of 0–30 g, protein and fat reduced glycemic responses independently from each other in a linear, dose-dependent fashion, with protein having −3-times the effect of fat. A large protein effect was associated with high WC and high dietary-fiber intake, whereas a large fat effect was associated with low FPI. These conclusions may not apply to solid meals. Further studies are needed to determine the mechanisms for these effects. J. Nutr. 136: 2506–2511, 2006.

Introduction

It is generally accepted that adding fat and protein to carbohydrate reduces glycemic responses by delaying gastric emptying and stimulating insulin secretion (1,2). These effects have a number of possible implications for human nutrition, such as supporting the role of high protein or high fat diets in the management of diabetes (3,4) or being a source of criticism for the application of the glycemic index to mixed meals (1,5). However, the effects of fat and protein on postprandial responses have not been studied systematically and their effects in mixed meals cannot be predicted reliably. Normal meals contain both fat and protein, but it is not known if there is an interaction between their effects. Also, there is evidence that fat and protein may not have the same effects in all situations. For example, studies in normal humans suggest that the dose-response is not linear (6–8); thus, adding more fat and/or protein to a carbohydrate meal that already contains some may have little or no effect. The glucose-lowering effects of fat and protein are attenuated or absent in subjects with diabetes (9,10), suggesting that the same may occur in insulin-resistant subjects without diabetes. A high-fat diet potentiates the effect of oral glucose on gastric inhibitory polypeptide secretion (11) and influences gastrointestinal transit (12,13), suggesting that the acute glucose-lowering effects of fat may be influenced by habitual fat intake.

Thus, the aims of this pilot, dose-finding study were to determine the dose-response effects of 0–30 g protein and fat, alone and in combination, on the glycemic response elicited by 50 g glucose in nondiabetic humans and to see whether the effects were influenced by subjects’ insulin sensitivity and diet.

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2 T.M.S.W. is President and part-owner of Glycemic Index Testing, Inc., a corporation that provides laboratory services and educational and promotional activities related to the glycemic index, and President and part-owner of Glycemic Index Laboratories, Inc., a corporation that does contract research. T.M.S.W. is the coauthor of a range of books on glycemic index under the general title of The Glycemic Index: A Physiological Classification of Dietary Carbohydrate, published by CABI, UK. The other authors declare no conflicts of interest.

* To whom correspondence should be addressed. E-mail: thomas.wolever@utoronto.ca.

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Materials and Methods

Healthy men and nonpregnant, nonlactating women aged 18–60 y, recruited from the University of Toronto campus, were screened by having their height, weight, waist circumference (WC), blood pressure, fasting plasma insulin (FPI) and glucose, serum total and HDL cholesterol and triglycerides measured (14,15); and LDL cholesterol calculated (16). Exclusion criteria were: history of diabetes; use of diuretics, corticosteroids or β-blockers; BMI > 30 kg/m²; fasting glucose ≥7.0 mmol/L; or triglycerides ≥ 10.0 mmol/L. Ten (10) hyperinsulinemic (hyperl) subjects and 10 controls completed the study. We classified subjects by FPI, because in nondiabetic subjects, FPI is related to insulin sensitivity as measured by the euglycemic, hyperl clamp (17) or the minimal model (18). Hyperl was defined as FPI > 40 pmol/L, representing ~75th percentile of FPI in healthy volunteers in our hands (14,19). The protocol was approved by the University of Toronto Research Ethics Board, and all subjects gave their informed consent to participate by signing the approved consent form.

Subjects were studied on 18 mornings after 10 14-h overnight fasts. On each day, subjects gave a fasting capillary finger-prick blood sample, consumed a liquid test meal within 10 min, and gave further capillary blood samples at 15, 30, 45, 60, 90, and 120 min after starting to eat. Blood (2–3 drops) was placed into fluoro-oxalate tubes, mixed by rotation, and frozen prior to analysis of whole blood glucose using a YSI Model 2300 STAT analyzer.

The 16 different test meals consisted of 50 g anhydrous glucose (Sigma Chemical); 250 mL tap water; 0, 5, 10, or 30 g of fat (0, 5, 10, or 10 g corn oil; Mazola, ACH Food); and 0.5, 10, or 30 g protein (0–5.6, 11.1, or 33.3 g soy protein concentrate; Supro, Swiss Herbal Remedies; 90 g protein, 0 g carbohydrate, and 2.7 g fat/100 g) blended to a smooth drink prior to consumption. Subjects took 250 mL water with each test meal. Test meals were administered according to a randomized block design; each block consisted of 1 level of fat (g of fat, 0, 5, 10, or 30, respectively, added to 50 g glucose [F0, F5, F10, or F30]) with each of the 4 levels of protein (g of protein, 0, 5, 10, or 30, respectively, added to 50 g glucose [P0, P5, P10, and P30]). The order of the blocks and the order of tests within blocks were randomized. Glucose alone (F0P0) was added to 2 other blocks so that each subject tested F0P0 3 times.

Nutrient intakes were estimated using 3-d diet records (2 weekdays and 1 weekend day), filled out during the experimental period, and analyzed using Food Processor SQL edition, version 9.3.1m (ESHA Research).

Results are presented as means ± SEM. Insulin sensitivity was estimated using the homeostasis assessment model (HOMA); 20). Body fat percentage was estimated from sex, age, BMI, and ethnicity using regression equations developed in different ethnic populations (21). Adjustment of screening parameters for sex was done by the residuals method using dummy variables (1 = female; 0 = male). Peak rise (PR) was the maximum glucose concentration achieved minus fasting glucose. Incremental areas under the curve (AUC), ignoring area below fasting, were calculated as previously described (22). AUC after each test meal was expressed as a percentage of the mean AUC after F0P0 in each subject and the resulting values termed relative glycemic response (RGR). RGR was the primary outcome. RGR, AUC, and PR values were subjected to ANOVA for 3-factor experiments with repeated measures on 2 factors (23), examining for the main effects of FPI (control vs. hyperl), fat dose, protein dose, fat × protein interaction, and FPI × fat × protein interaction. The shape of the dose-response relations was assessed by testing if there was significant reduction of residual variation when a term for dose 2 of fat (or protein) was added to the linear regression model (Prism 4 for Windows, GraphPad Software). A significant effect would indicate that a nonlinear (quadratic) model fit the data significantly better than a linear model. The ability of fat (or protein) to reduce postprandial glucose in each subject was defined as the slope of the regression line of RGR on dose of fat (or protein). The regression equations were based on 16 points in each subject (4 × 4 levels of fat and protein). It was considered valid to pool the data in this way because there was no significant fat × protein or FPI × fat × protein interaction and no significant evidence of a nonlinear dose-response relation. Correlations between these slopes and other variables were determined by simple and multiple linear regression analysis (Lotus 123 97 Edition, Lotus Development). Differences were considered significant if 2-tailed P < 0.05. The significance of differences between individual means was assessed using Tukey’s test to control for multiple comparisons.

Results

Hyperl subjects were similar to control with respect to sex, ethnicity, age, height, weight, BMI, and percent body fat (Table 1). The 2 groups had similar fasting glucose, but WC, FPI, and HOMA were significantly higher in hyperl than controls. Mean HOMA in hyperl, 14 pmol × mmol, was similar to multi-ethnic, first-degree relatives of people with type 2 diabetes with normal (n = 240) or impaired (n = 191) glucose tolerance, 12, and 16 pmol × mmol, respectively (24). Hyperl had significantly lower HDL cholesterol and higher total and LDL cholesterol, triglycerides, and total: HDL cholesterol ratio than controls. None of the control or hyperl subjects had the metabolic syndrome using the National Cholesterol Education Program Adult Treatment Panel III definition (25). One hyperl subject had metabolic syndrome according to the International Diabetes Federation consensus definition (26).

Mean blood glucose after the different test meals did not differ significantly between control and hyperl subjects (Fig 1); however, AUC, RGR, and the PR differed significantly between the individual test meals (Table 2). There were significant main effects of fat and protein on AUC, RGR, and PR (Table 3). AUC, RGR, and PR after 30 g fat were significantly less than after 5 g.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Details of subjects studied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controls, FPI ≤40 pmol/L</td>
<td></td>
</tr>
<tr>
<td>Sex [males:females], n</td>
<td>4:6</td>
</tr>
<tr>
<td>Ethnicity (SA:AC:OT, n:n:n)</td>
<td>2:6:2</td>
</tr>
<tr>
<td>Age, y</td>
<td>24.5 ± 1.0</td>
</tr>
<tr>
<td>Height, cm</td>
<td>169 ± 2</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>26.7 ± 2.5</td>
</tr>
<tr>
<td>Body fat, %</td>
<td>21.5 ± 0.7</td>
</tr>
<tr>
<td>WC, cm</td>
<td>25.3 ± 0.9</td>
</tr>
<tr>
<td>Fasting plasma glucose, mmol/L</td>
<td>76.7 ± 1.3</td>
</tr>
<tr>
<td>FPI, pmol/L</td>
<td>4.74 ± 0.10</td>
</tr>
<tr>
<td>HOMA, pmol × mmol</td>
<td>27 ± 3</td>
</tr>
<tr>
<td>Systolic blood pressure, mm Hg</td>
<td>4.3 ± 0.5</td>
</tr>
<tr>
<td>Diastolic blood pressure, mm Hg</td>
<td>110 ± 1</td>
</tr>
<tr>
<td>Serum total cholesterol, mmol/L</td>
<td>59 ± 1</td>
</tr>
<tr>
<td>Serum HDL cholesterol, mmol/L</td>
<td>3.83 ± 0.12</td>
</tr>
<tr>
<td>Serum LDL cholesterol, mmol/L</td>
<td>1.58 ± 0.10</td>
</tr>
<tr>
<td>Total-HDL cholesterol ratio</td>
<td>1.85 ± 0.11</td>
</tr>
<tr>
<td>Serum triglycerides, mmol/L</td>
<td>2.54 ± 0.20</td>
</tr>
<tr>
<td>Values adjusted for sex (significant effect of sex).</td>
<td></td>
</tr>
</tbody>
</table>

Effect of fat and protein on glycemic responses

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2 Abbreviations used: AUC, incremental area under the curve; F0, F5, F10, F30, g of fat (0, 5, 10 or 30, respectively) added to 50 g glucose; FPI, fasting plasma insulin; GLP-1, glucagon-like peptide-1; HOMA, homeostasis assessment model (an index of insulin resistance); hyperl, hyperinsulinemic FPI (≥40 pmol/L); P0, P5, P10, P30, g of protein (0, 5, 10 or 30, respectively) added to 50 g glucose; PR, peak rise; RGR, relative glycemic response; WC, waist circumference.

3 Values = means ± SEM. * Different from controls, P < 0.05. SA = South Asian; EA = East Asian; C = Caucasian.
AUC, RGR, and PR after 30 g protein were significantly less than after 0, 5, and 10 g (Fig. 2). Dose of fat was linearly correlated with RGR \((r = -0.33, P = 0.0025)\) and the nonlinear (quadratic) model was not a significantly better fit \((P = 0.56)\). Similarly, dose of protein was correlated with RGR \((r = -0.70, P < 0.0001)\) and the quadratic model was not significantly better \((P = 0.94)\). Mean changes in glycemic response per g protein were 2–3 times greater than those per g fat \((P < 0.001; \text{Fig. 2})\).

There were no significant differences in AUC, RGR, or PR between control or hyper[I] subjects (Table 3). Although there were significant fat \times subject and protein \times subject interactions, the group \times fat, group \times protein, and group \times fat \times protein interactions were not significant, indicating that differences between subjects were not explained by their classification into control and hyper[I] groups.

The ability of fat or protein to reduce glycemic responses is termed fat slope or protein slope, respectively. Fat and protein slopes in all 20 subjects were not related to each other whether expressed as RGR \((r = -0.11, P = 0.65)\) or AUC \((r = -0.23, P = 0.33)\). Fat slope was related to FPI but not WC, whether expressed in relative \((\Delta \text{RGR/g fat, Fig. 3})\) or absolute terms \((\Delta \text{AUC/g vs. FPI, } r = 0.52, P = 0.018; \Delta \text{AUC/g vs. WC, } r = 0.27, P = 0.25)\). The correlations between HOMA and \(\Delta \text{RGR/g fat (} r = 0.44, P = 0.051)\) and between HOMA and \(\Delta \text{AUC/g fat (} r = 0.48, P = 0.034)\) were weaker than those for FPI. Protein slope was related to WC when expressed as \(\Delta \text{RGR/g (Fig. 3)}\) but not as \(\Delta \text{AUC/g (} r = -0.30, P = 0.19)\); protein slope was not related to FPI (Fig. 3) or HOMA. Fat and protein slopes were not related to percent body fat.

Fat slope was not related to dietary fat intake. Protein slope, expressed as \(\Delta \text{RGR/g, was significantly related to dietary fiber intake, whether expressed in g (} r = -0.67, P = 0.0014)\) or g/kJ (Fig. 4). In a multiple regression model, 75% of the variation in protein slope was explained by fiber \((F, g/kJ)\) and WC \((cm)\) as follows: \(\Delta \text{RGR/g protein} = 1.59 - 0.34 \times F - 0.028 \times WC.\) The effects of \(F\) and WC were independent and significant (both \(P < 0.0001\)).

### Table 2

AUC, RGR, and peak rises in whole blood glucose in nondiabetic humans after they consumed 50 g glucose plus different levels of fat and protein.

<table>
<thead>
<tr>
<th>Fat, g</th>
<th>Protein, g</th>
<th>AUC, mmol × min/L</th>
<th>RGR, %</th>
<th>Peak Rise, mmol/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>301 ± 21*</td>
<td>100 ± 2*</td>
<td>4.5 ± 0.2*</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>314 ± 25*</td>
<td>106 ± 6*</td>
<td>4.7 ± 0.3*</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>297 ± 26*</td>
<td>100 ± 6*</td>
<td>4.3 ± 0.3*</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
<td>292 ± 24*</td>
<td>99 ± 5*</td>
<td>4.4 ± 0.3*</td>
</tr>
<tr>
<td>0</td>
<td>5</td>
<td>283 ± 23*</td>
<td>96 ± 5*</td>
<td>4.2 ± 0.3*</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>307 ± 21*</td>
<td>106 ± 6*</td>
<td>4.5 ± 0.3*</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>261 ± 24*</td>
<td>91 ± 7*</td>
<td>3.9 ± 0.3*</td>
</tr>
<tr>
<td>30</td>
<td>5</td>
<td>261 ± 26*</td>
<td>88 ± 7*</td>
<td>3.8 ± 0.4*</td>
</tr>
<tr>
<td>0</td>
<td>10</td>
<td>276 ± 18*</td>
<td>94 ± 5*</td>
<td>4.2 ± 0.3*</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>287 ± 28*</td>
<td>98 ± 8*</td>
<td>4.2 ± 0.4*</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>257 ± 21*</td>
<td>87 ± 5*</td>
<td>3.9 ± 0.3*</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>217 ± 24*</td>
<td>72 ± 6*</td>
<td>3.1 ± 0.3*</td>
</tr>
<tr>
<td>0</td>
<td>30</td>
<td>199 ± 17*</td>
<td>68 ± 4*</td>
<td>3.1 ± 0.2*</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>192 ± 19*</td>
<td>63 ± 3*</td>
<td>3.0 ± 0.2*</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>182 ± 20*</td>
<td>61 ± 5*</td>
<td>2.9 ± 0.2*</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>166 ± 19*</td>
<td>57 ± 2*</td>
<td>2.3 ± 0.2*</td>
</tr>
</tbody>
</table>

\(\Delta\) LSD \(P < 0.05\).

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**Figure 1** Blood glucose responses after 50 g oral glucose plus 0, 5, 10, or 30 g fat and 0, 5, 10, or 30 g protein in nondiabetic humans with FPI ≤ 40 pmol/L (control) and FPI > 40 pmol/L (hyper[I]). Values are means ± SEM, \(n = 10\). Error bars not shown if they are smaller than the symbol or overlap other bars or symbols.

**Figure 3** Blood glucose responses after 50 g oral glucose plus 0, 5, 10, or 30 g fat and 0, 10, or 30 g protein in nondiabetic humans with FPI ≤ 40 pmol/L (control) and FPI > 40 pmol/L (hyper[I]). Values are means ± SEM, \(n = 10\). Error bars not shown if they are smaller than the symbol or overlap other bars or symbols.

**Figure 4** Blood glucose responses after 50 g oral glucose plus 0, 5, 10, or 30 g fat and 0, 10, or 30 g protein in nondiabetic humans with FPI ≤ 40 pmol/L (control) and FPI > 40 pmol/L (hyper[I]). Values are means ± SEM, \(n = 10\). Error bars not shown if they are smaller than the symbol or overlap other bars or symbols.

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### Table 3

Results of ANOVA for AUC, RGR, and PR values in whole blood glucose in nondiabetic humans \((n = 10 \text{ controls and } n = 10 \text{ hyper[I]) who consumed test meals consisting of 50 g glucose plus different levels of fat and protein.}\)

<table>
<thead>
<tr>
<th></th>
<th>AUC</th>
<th>RGR</th>
<th>PR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat</td>
<td>0.029</td>
<td>0.017</td>
<td>0.0018</td>
</tr>
<tr>
<td>Protein</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Group(^1)</td>
<td>0.53</td>
<td>0.93</td>
<td>0.39</td>
</tr>
<tr>
<td>Subjects(^2)</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

**Main effects**

**Interactions**

Fat \times protein: 0.71, 0.51, 0.11

Fat \times group: 0.78, 0.71, 0.74

Protein \times group: 0.80, 0.92, 0.72

Fat \times protein \times group: 0.11, 0.34, 0.11

Fat \times subjects: 0.001, 0.010, <0.001

Protein \times subjects: <0.001, <0.001, <0.001

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**Note:**

1. Control group vs. hyper[I] group.
2. Individual subjects vs. each other, \(n = 20\).
Figure 2  Main effects of fat (black circles and bars) and protein (white circles and bars) on glucose responses expressed as AUC (A), RGR (B), and PR (C) after nondiabetic humans consumed 50 g glucose plus different levels of fat and protein. Means not sharing a common superscript letter differ, P < 0.05 (\textsuperscript{*} for comparisons of different levels of fat and \textsuperscript{**} for comparisons of different levels of protein). Insets: slopes of regression lines of AUC, RGR, and PR on g of fat or protein. *Mean slope for protein differs from slope for fat, P < 0.001. Values are means ± SEM, n = 20.

Discussion

The results showed that both protein and fat reduced the glycemic response elicited by oral glucose in normal humans. The effects of protein and fat were independent of each other, but gram-for-gram, protein had a 2 to 3 times larger effect than fat. Fat reduced glycemic responses to a greater extent in subjects with low FPI, whereas protein had more effect in subjects with a high WC and a high intake of dietary fiber.

Previous studies suggest that adding fat and protein to carbohydrate reduces glycemic responses nonlinearly, with the glycemic impact reaching a plateau as more and more protein and fat are added (6,8). However, we found no evidence for a nonlinear dose response over the range of doses used (0–30 g). This may have been due in part to a lack of statistical power or to differences in study design. We previously found that adding margarine to bread reduced glucose PR in a significantly nonlinear fashion (8); by contrast, in this study, liquid test meals were used. Because of differences in how solids and liquids empty from the stomach (27), the shape of the dose-response curve for added fat may differ for solid and liquid meals.

A number of our conclusions are based on using linear regressions as quantitative estimates of the effects of fat and protein on glycemic responses in individual subjects. The linear model was considered valid because there was no evidence for nonlinear relations. The validity of pooling the results for the different levels of 1 nutrient (i.e. protein or fat) to determine the effect of the other (i.e. fat or protein) depends on there being no nutrient × nutrient interaction. The fat × protein interaction was not significant, but interactions are more difficult to detect than main effects, and the lack of significant difference does not mean that no effect exists. Thus, we cannot rule out the existence of a fat × protein interaction; but, if it exists, it is likely to be small, and a larger number of subjects will be required to detect it.

The effect of fat on glycemic responses did not differ in hyper[I] vs. control subjects, but there was a significant correlation between the fat effect and FPI in individual subjects. This suggests that our definition of hyper[I], i.e. FPI >40 pmol/L, was too low and that an abnormal fat effect may occur only when FPI > 80 pmol/L, which is the mean FPI in people with newly discovered diabetes (24). This is consistent with studies showing that fat has no effect on glycemic responses in subjects with diabetes (9). Taken together, the results suggest that insulin resistance rather than diabetes per se may be responsible for the lack of fat effect. Our finding that fiber intake and WC modulated the glucose-lowering effect of protein may help explain the inconsistent effects of protein reported in the literature (6,7), although other factors, such as protein digestibility (28) and differences in the ability of specific amino acids to stimulate insulin (29), may also be important.

Adding fat and protein to carbohydrate is thought to reduce glycemic responses by similar mechanisms (1,2), namely, delayed gastric emptying (3,30), mediated by gut hormones such as gastric inhibitory polypeptide and glucagon-like peptide-1 (GLP-1) (31–34), and increased insulin secretion mediated by direct effects of fatty and amino acids (35,36) and/or by the hormones of the entero-insulin axis (37). However, the lack of correlation between fat slopes and protein slopes in the different subjects and the 2–3 times greater effect of protein than fat, suggest that the mechanisms by which fat reduces glycemic responses differ from those for protein.

We expected the glucose-lowering effects of both fat and protein to be smaller in hyper[I] subjects than controls, because these effects are thought to be mediated by gut hormones that are reduced in insulin resistance and obesity (38–40). Also, we anticipated that any effects related to FPI would also be related to WC, a marker of abdominal obesity, because insulin...
resistance and hyperinsulinemia are closely associated with abdominal obesity (41). Thus, our findings that the fat slopes were positively related to FPI but not WC, whereas the protein slopes were negatively related to WC but not FPI, were unexpected. Indeed, this suggests that abdominal obesity and hyperinsulinemia have distinct metabolic implications, an idea that has been proposed from the positive association between FPI and increased risk of cardiovascular disease independent of variation in WC (41). Our results are hard to explain but could be consistent with the hypothesis that fat reduces glucose responses via GLP-1 mediated effects on gastric emptying, whereas protein reduces glucose due to amino-acid mediated effects on insulin secretion. However, the results of this pilot study do not allow anything but speculation as to the mechanisms involved, and further studies are needed to investigate how fat and protein affect postprandial responses in normal and hyper[I] subjects.

The results did not support our hypothesis that the acute glucose-lowering effect of fat is reduced by a high fat intake. However, unexpectedly, there was a strong relation between dietary fiber intake and protein slope, such that a high fiber intake was associated with a larger protein effect (Fig. 4). A potential explanation, based on animal studies, is that a high fiber diet upregulates GLP-1 secretion, due to colonic short chain fatty acids produced by the colonic fermentation of dietary fiber (42). Because GLP-1 increases β-cell mass (43), a high fiber intake may be associated with increased insulin secretion in response to protein ingestion. However, it is not known if fiber has these effects in humans.

We conclude that, across the range of 0–30 g protein and fat reduce the glycemic response elicited by oral glucose independently from each other, with a linear dose response and a 2–3 times greater effect from protein than fat. High fiber intake and high WC were associated with an increased effect of protein, whereas a high FPI was associated with a reduced effect of fat. These conclusions may not apply to solid meals. Further studies are needed to determine the mechanisms for these effects.

Literature Cited

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