Delayed gastric emptying rate as a potential mechanism for lowered glycemia after eating sourdough bread: studies in humans and rats using test products with added organic acids or an organic salt

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ABSTRACT  The possible effects of organic acids or an organic salt on the rate of gastric emptying was studied to identify the cause for reduced postprandial responses of blood glucose and insulin to foods containing such components, eg, sourdough bread. Paracetamol was included in bread products with added lactic acid or sodium propionate and used as a marker for the rate of gastric emptying in healthy subjects. In parallel, postprandial glycemia, insulinemia, and satiety were evaluated. The influence of lactic acid, propionic acid, and sodium propionate was also studied in rats after they were tube-fed with glucose solutions. The bread products with lactic acid or sodium propionate both lowered blood glucose and insulin responses. The bread with sodium propionate also prolonged satiety. The reason for the lowered metabolic responses with sodium propionate was probably a lowered gastric emptying rate, as judged from reduced blood paracetamol concentrations; there was no such effect observed with bread with added lactic acid. A similar amount of lactic acid in solution tube-fed to rats did not affect the disappearance of glucose from the stomach. In contrast with the finding in humans, sodium propionate had no effect on the rate of gastric emptying in rats whereas an equimolar solution of propionic acid reduced gastric emptying rate in rats. Possibly, less of this acid was produced in the gastric contents after a bolus load of a sodium propionate solution (in rats) than in an eating situation. Also, the pH and/or the osmolarity may be important, and when provided in excessive amounts, lactic acid reduced the gastric emptying rate in rats. A hydrochloric acid solution of similar pH was much less effective in this respect. Am J Clin Nutr 1996;64:886–93.

KEY WORDS  Lactic acid, sodium propionate, bread, starch, glycemic and insulinenic responses, gastric emptying, satiety, humans, rats

INTRODUCTION

Glycemic index (GI) is a concept used to rank foods on the basis of their acute glycemic effect (1). Most breakfast cereals (2, 3), bread products (3), and potatoes (4) elicit responses comparable with that of a similar load of glucose, whereas intact cereal grains (5), pasta (6), and legumes (7) display low-GI features. Hence, in several long-term studies (8–14), diets characterized by a low GI were reported to lower average blood glucose, glycated hemoglobin, fructosamine, urinary C-peptide, serum cholesterol, and triacylglycerols in diabetic subjects. The metabolic benefits related to a low-GI diet in healthy individuals have been less acknowledged. According to Reaven (15), hyperglycemia linked to insulin resistance and subsequent hyperinsulinemia is a key feature of disorders linked to the metabolic syndrome (eg, diabetes, hyperlipidemia, and hypertension). Thus, evidence of improved glucose tolerance (8, 9, 12) and also lowered concentrations of serum cholesterol (9, 13, 14) and triacylglycerols (10, 11, 14) after a diet characterized by low-GI foods indicates that such a diet has the potential to reduce the incidence of cardiovascular disease (16).

Recently, a lowering of postprandial blood glucose and insulin responses was noted with sourdough compared with ordinary bread (17, 18), suggesting an effect of the organic acids formed during the fermentation process. In addition, bread with the added sodium salt of propionic acid also lowered postprandial glucose and insulin responses (18). These findings support efforts to produce bread with a low GI. Improved glucose tolerance to starch in the presence of organic acids has also been reported with fermented vegetables (19) and lettuce dressed with vinegar (20). However, the mechanism connected with the metabolic events is not clearly understood. One theory is that sodium propionate acts as an amylase inhibitor, thus reducing the rate of digestion (21). However, others have failed to show an inhibitory effect of sodium propionate in vitro (18). Another possibility concerns the potential influence of organic acids or salt on the rate of gastric emptying, which is also the topic of the present study.

The purpose of the present work was thus to study whether a delayed gastric emptying rate could explain the reduced postmeal glucose and insulin responses seen with bread products containing organic acids or an organic salt. In a study in

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healthy subjects paracetamol was included in bread products with added lactic acid or sodium propionate and used as an indirect marker for the rate of gastric emptying. It is known that paracetamol is rapidly absorbed in the upper part of the small intestine. Thus, the absorption and postprandial appearance of paracetamol in peripheral blood is dependent on the rate of gastric emptying. In addition, postprandial glucose and insulin responses were evaluated. Because it has been suggested that certain foods that contribute to stomach distension are linked to a feeling of fullness (22), satiety was also measured for the bread meals.

A rat experimental model was also used to study the influence of different loads of organic acids on the rate of gastric emptying and to make a comparison with an inorganic acid (hydrochloric acid), which was not possible to perform with bread products. Test solutions containing glucose and different loads of lactic acid, propionic acid, hydrochloric acid, or sodium propionate were infused by orogastric intubation, and the gastric emptying rate was determined as the amount of glucose remaining in the stomach after 15 min.

MATERIALS AND METHODS

Bread products

Hull-less, intact barley kernels (no. 8775) were provided by Svalöf Weibull AB (Svalöv, Sweden) and commercial white wheat flour was obtained from Kungsörnen AB (Järna, Sweden). Before baking, the barley kernels were milled to pass through a 0.8-mm screen.

Three bread products were made from the same basic recipe with 80% whole-meal barley flour and 20% white wheat flour. To provide for indirect measurement of gastric emptying rate, all bread products were baked with a low concentration of paracetamol (1.0 g/test meal). Two of the bread products were baked with the addition of either lactic acid or sodium propionate. Lactic acid was added in the amount corresponding to that formed during sourdough fermentation. On a molar basis, the load of added sodium propionate was approximately three times higher than the acid load of added lactic acid. The third bread contained no such additives and was used as a reference.

Recipes

Whole-meal bread (basic recipe)

The bread was prepared by using 3280 g water, 2960 g whole-meal barley flour, 740 g white wheat flour, 200 g yeast, 50 g NaCl, 50 g sucrose, 47 g paracetamol, and 37 g monoglycerides. The dough was proofed for 50 min, divided into pieces of 600 g, and given a second proofing for 20 min (38 °C, 75% humidity). Baking was performed at 200 °C for 30 min.

Bread with lactic acid

The bread was baked from the basic recipe with the addition of 81 g lactic acid (solution added was 72% by wt). The water content was corrected for the amount of added liquid.

Bread with sodium propionate

One hundred eighty-five grams sodium propionate was added to the basic recipe and the bread was baked as described above.

Before being cut into slices, all bread products were stored at room temperature over night. The crust was removed and three to four slices were wrapped in aluminium foil, put into plastic bags, and stored in a freezer until used.

Chemical analysis

A portion from each bread was air dried and milled (Cyclotec, Tecator, Sweden) to < 0.8 mm before analysis. The flours and bread products were analyzed for starch according to Holm et al (23) with some modifications. Instead of suspending the sample in distilled water before boiling with Termamyl (Novo Nordisk A/S, Bagsvaerd, Denmark), a phosphate buffer (0.1 mol/L, pH 6) was used. This was done to ensure an optimal pH during incubation with the thermostable α-amylase also when analyzing bread products supplemented with an organic acid or salt. It was noted that the recovery of starch decreases by ~30% after addition of acetic acid to bread (pH 4.5). Thus, addition of the phosphate buffer is recommended to make the starch assay more generally applicable. Further, protein (by the Kjeldahl method) and fat (24) contents were determined in the reference bread. The products were also characterized with respect to pH and acid equivalents (25). Samples for measuring the amount of lactic acid, propionic acid, and ethanol were prepared and stored as described by Lönnér and Preve-Åkesson (25). The amount of lactic acid was determined enzymatically (Boehringer Mannheim, GmbH Biochemica, Mannheim, Germany) and the amounts of acetic acid, propionic acid, and ethanol were determined with a Varian 3400 gas chromatograph (Varian Associates, Inc, Palo Alto, CA). Finally, to ensure the recovery of paracetamol in the baked breads, the concentration was confirmed by use of an enzymatic kit (Cambridge Life Sciences Plo, Cambridge, United Kingdom). In the reference bread, 98% of added paracetamol was recovered after baking and in the case of the products containing lactic acid or sodium propionate 98% and 99% were recovered, respectively. The composition of the bread products is shown in Table 1.

Blood glucose, insulin, and paracetamol responses in healthy subjects

Twelve healthy volunteers, eight women and four men aged 24–56 y, who had normal body mass indexes (in kg/m²; 21.7 ± 1.9) and were taking no medications participated in the study. The bread products were provided in amounts corresponding to 50 g available starch and served with 7 g butter and 23 g cheese (10% fat, wet wt). Also included was a small amount of apricot purée (7.0 g) eaten as jam with the breads. In addition, 250 mL water and 150 mL coffee or tea was served with each meal. All test meals contained 51.5 g carbohydrates, 17.6 g protein, and 11.1 g fat, providing 1585 kJ. The subjects were served the test products as a breakfast in random order (three separate occasions) after an overnight fast. The tests were performed ~1 wk apart and commenced at the same time in the morning. All meals were consumed steadily over a 12–14-min period.

Finger-prick capillary blood samples were taken before the meal (0 min) and at 30, 45, 70, 95, 120, and 180 min after the meal for analysis of glucose, and after 30, 45, 95, and 120 min for analysis of insulin. Blood glucose concentration was determined with a glucose oxidase peroxidase reagent and serum insulin concentration with an enzyme immunoassay kit (Boehringer Mannheim). In addition, serum paracetamol was mea-
sured with an enzyme kit (Cambridge Life Sciences Plc) at the following time points: before the meal (0 min) and at 15, 30, 45, 70, and 95 min after the meal.

Approval for the studies was given by the Ethics Committee of the Faculty of Medicine at Lund University and by the Ethics Committee for Evaluation of Animal Experiments at Lund University.

Satiety score
Satiety after the test meals above was estimated numerically according to Haber et al (26). Assessments were done before the meal (0 min) and at 15, 45, 95, 120, and 180 min after the meal by using a scoring system graded from −10, for extreme hunger, to +10, for extreme satiety. The area under the satiety curve was calculated above zero.

Measurement of the gastric emptying rate in rats
Fasting male Sprague-Dawley rats (162 ± 3 g) were given a test solution (2.5 mL) containing glucose (100 mg) and different loads of lactic acid, propionic acid, or sodium propionate. For comparison, hydrochloric acid was also tested. A glucose solution with no additives was used as a reference. The test solutions were infused by orogastric intubation under light anesthesia. Fifteen minutes after intubation the rat was killed with carbon dioxide, its stomach was clamped at the cardio and pylorus, and removed and frozen. Gastric emptying rate was measured by determining the amount of glucose remaining in the stomach with a glucose oxidase peroxidase reagent.

Series 1
One test group (n = 9) was tube-fed with a glucose solution containing 13 mmol lactic acid/L (pH adjusted to 4.0 with sodium hydroxide). The acid load of lactic acid and the pH were chosen to match the properties of the lactic acid bread included in the human study described above. Another test group (n = 6) was given an elevated concentration of lactic acid, 133 mmol/L (pH 2.4). A control group (n = 7) was given only glucose (pH 5.7).

Series 2
In a second series of experiments a test group (n = 10) was tube-fed a glucose solution containing 43 mmol sodium propionate/L (pH adjusted to 5.7 with hydrochloric acid), which corresponded to the concentration reached in the propionate bread included in the human study. A second group (n = 10) was given an equimolar acid load (43 mmol/L) of propionic acid (pH 3.3). Hydrochloric acid (8 mmol/L, pH 2.4) was tube-fed to a third group. The last group (n = 10) was used as a control and received a solution containing only glucose.

Statistical methods
The results are expressed as means ± SEMs. One-way analysis of variance followed by the Duncan procedure for multiple comparisons was used to determine significant differences in the amount of glucose remaining in the stomach of tube-fed rats. In the human study, the significance of differences was assessed by the Wilcoxon matched-pair, signed-ranking test. The SPSS/PC+ advanced statistics program (version 2.0; SPSS, Chicago) was used. A value of $P < 0.05$ was considered significant.

RESULTS
Postprandial blood glucose and insulin responses in healthy subjects
In the initial postprandial phase (30 min), the bread with added lactic acid or sodium propionate resulted in significantly lower blood glucose increments ($P < 0.05$) than did the wholemeal barley reference bread (Figure 1). These two bread products also reduced the incremental areas under the curve compared with the reference bread. The reduction was ≈26% with the bread with lactic acid and 37% with the bread with propionate. The same differences were obtained when the calculations of the glucose areas under the curve were based on the 0–45-min, 0–95-min, or 0–120-min postprandial periods, respectively (Table 2).

The insulin responses were closely associated with the glucose responses (Figure 2). Compared with the reference bread, significantly lower insulin concentrations ($P < 0.05$) were found at 0–45 min with the propionate bread, and at 45–95 min with the lactic acid bread. Also, reduced incremental areas (based on 45, 95, and 120 min, respectively) were measured with these breads (Table 3).

Blood paracetamol responses
No significant differences in postprandial paracetamol blood concentrations ($P < 0.05$) were noted between the lactic acid bread and the reference bread at any time point from 0 to 95 min (Figure 3), and the calculated areas under the curves (0–95 min) were similar (5.1 ± 0.4 and 5.1 ± 0.2 mmol·min/L, respectively). In contrast, the paracetamol concentrations after the propionate bread (0–70 min) were consistently lower than after the reference bread, also resulting in a reduced total area (0–95 min) under the curve (3.7 ± 0.3 mmol·min/L).

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TABLE 1
Composition of the bread products

<table>
<thead>
<tr>
<th>Bread products</th>
<th>pH</th>
<th>Acid equivalents$^1$</th>
<th>Lactic acid$^2$</th>
<th>Propionic acid$^2$</th>
<th>Ethanol</th>
<th>Starch</th>
<th>Protein</th>
<th>Fat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mol/kg dry wt</td>
<td>mol/kg dry wt</td>
<td>mol/kg dry wt</td>
<td>g/kg dry wt</td>
<td>g/kg dry wt</td>
<td>g/kg dry wt</td>
<td>g/kg dry wt</td>
</tr>
<tr>
<td>Whole-meal bread$^3$</td>
<td>5.8</td>
<td>9.6</td>
<td>0.00</td>
<td>0.00</td>
<td>70</td>
<td>642</td>
<td>126</td>
<td>42</td>
</tr>
<tr>
<td>+ Lactic acid</td>
<td>3.9</td>
<td>27.2</td>
<td>0.17</td>
<td>0.00</td>
<td>70</td>
<td>630</td>
<td>126$^4$</td>
<td>42$^4$</td>
</tr>
<tr>
<td>+ Sodium propionate</td>
<td>6.1</td>
<td>9.5</td>
<td>0.00</td>
<td>0.56</td>
<td>20</td>
<td>598</td>
<td>126$^4$</td>
<td>42$^4$</td>
</tr>
</tbody>
</table>

$^1$ Milliliters 0.1 mol NaOH/L consumed in 10 g bread (dry wt).
$^2$ Includes minor amounts, 0.8–1.0 g/kg acetic acid (dry wt) formed during baking.
$^3$ Whole-meal barley flour and white wheat flour (80:20) reference product.
$^4$ Based on analysis of the whole-meal bread reference.
Satiety

The satiety scores with the lactic acid bread could not be distinguished from those for the reference bread at any time point after the meal (Figure 4). The calculated area under the satiety curve from 0 to 180 min for the lactic acid bread (267.1 ± 72.9) did not significantly deviate from the corresponding area for the reference bread (304.2 ± 73.4). However, in the initial phase (15–45 min), higher satiety scores were registered for the bread with added sodium propionate compared with the reference bread (P < 0.05). Also, the area under the satiety curve (0–180 min) was significantly higher for the sodium propionate bread (438.4 ± 93.1) than for the reference bread (P < 0.05).

Rat experiments

Series 1

The results are shown in Table 4. Similar amounts of glucose remained in the stomachs of the control rats and rats tube-fed with a low acid load of lactic acid. However, considerably more glucose (P < 0.05) remained after tube-feeding with a high load of lactic acid.

Series 2

The amount of glucose remaining in the stomach of rats given propionic acid was slightly higher (P < 0.05) than that noted in those given the glucose reference. In contrast, the glucose content after tube-feeding with sodium propionate or hydrochloric acid could not be distinguished from that after the glucose reference solution.

DISCUSSION

Bread products with added lactic acid (pH 3.9) or sodium propionate (pH 6.1) were shown to flatten the postprandial blood glucose and insulin rise. This agrees with results from previous work (18), in which bread products of similar composition lowered the metabolic responses to a similar extent. In that study lowered glycemia was also noted with a sourdough bread containing mainly lactic acid (18). A fermentation process that generates organic acids should thus be useful in improving glucose tolerance to starch, and hence, be beneficial in the management of diabetes. The bread product with a high amount of added sodium propionate showed an extraordinary

![Diagram](https://academic.oup.com/ajcn/article-abstract/64/6/886/4655249/18x2.png)

**FIGURE 1.** Incremental blood glucose responses in healthy subjects after ingestion of breakfast meals with whole-meal bread (WMB), WMB with added lactic acid (WMB-la), and WMB with added sodium propionate (WMB-p). Values are means; n = 12. Values with different letters are significantly different, P < 0.05.

**TABLE 2**

<table>
<thead>
<tr>
<th>Fasting blood glucose</th>
<th>Area under curve</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–45 min</td>
</tr>
<tr>
<td>Whole-meal bread</td>
<td>4.5 ± 0.1</td>
</tr>
<tr>
<td>+ Lactic acid</td>
<td>4.6 ± 0.1</td>
</tr>
<tr>
<td>+ Sodium propionate</td>
<td>4.6 ± 0.1</td>
</tr>
</tbody>
</table>

* 𝑥 ± SEM; n = 12. Values with different superscript letters are significantly different, P < 0.05.

* Reduction in postprandial blood glucose area (0–95 min) as a percentage of the reference product value.
FIGURE 2. Incremental serum insulin responses in healthy subjects after ingestion of breakfast meals with whole-meal bread (WMB), WMB with added lactic acid (WMB-la), and WMB with added sodium propionate (WMB-p). Values are means; \( n = 12 \). Values with different letters are significantly different, \( P < 0.05 \).

ability to reduce the metabolic responses; the 95-min postprandial glucose and insulin areas were reduced by \( \approx 40\% \) (18). This agrees with the results of Todesco et al (21), who reported a 48% reduction of the glucose area (120 min) with a similar product. In the baking industry propionate is commonly used to inhibit mold and bacterial growth. On the basis of the favorable metabolic effects noted, we conclude that the sodium salt of propionic acid may have potential in developing low-GI bread with less acidic characteristics than a fermented product or a product with the added corresponding acids.

The hypothesis tested in the present study was that a delayed gastric emptying rate might be the cause for the metabolic effects seen with lactic acid and sodium propionate, respectively. In the human study, paracetamol was included in the bread products and used as a marker for indirect measurement of the rate of gastric emptying. This procedure was validated previously against a direct method using radionuclide-labeled indium and found to give results in good agreement (27). However, the paracetamol procedure must be used with caution, and when postprandial glycemic response to spaghetti was studied in relation to gastric emptying (28), the paracetamol method might have been inadequate. In fact, it was reported (6) that the slow behavior of pasta products is related to a restricted enzymic availability due to the compact food structure. Thus, it is likely that the delayed absorption of paracetamol (included in the spaghetti) followed not only from a delayed gastric emptying rate, but also from a slow release of paracetamol and starch in the small intestine. Further, when gastric emptying was evaluated as a potential mechanism for the low-GI features in the presence of purified viscous fibers (29, 30), it is possible that the absorption of paracetamol in the small intestine was also affected by the action of these fibers, suggesting that this marker for gastric emptying is not generally applicable.

In the present work, paracetamol, organic acids, and a salt were included in a whole-meal bread product, which was characterized previously by a high GI (GI = 98, white bread reference) (17). The bread with added lactic acid (in an amount that could be expected to be found in a commercial sourdough bread) had no influence on gastric emptying, as judged from the lack of effect on blood paracetamol concentrations in comparison with the reference bread. Similarly, no effect was noted in rats tube-fed a comparable amount of lactic acid. In fact, the glucose solution with added lactic acid had a tendency to leave the stomachs of rats even more rapidly than the

### TABLE 3

<table>
<thead>
<tr>
<th>Fasting serum insulin</th>
<th>Area under curve</th>
<th>( \Delta^2 )</th>
<th>0-120 min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-45 min</td>
<td>0-95 min</td>
<td></td>
</tr>
<tr>
<td>Whole-meal bread</td>
<td>( \text{nmol/L} )</td>
<td>( \text{nmol \cdot min/L} )</td>
<td>( \text{nmol \cdot min/L} )</td>
</tr>
<tr>
<td>+ Lactic acid</td>
<td>0.07 ( \pm 0.01 )</td>
<td>10.8 ( \pm 1.8^a )</td>
<td>21.3 ( \pm 3.7^a )</td>
</tr>
<tr>
<td>+ Sodium propionate</td>
<td>0.06 ( \pm 0.01 )</td>
<td>9.0 ( \pm 1.3^b )</td>
<td>16.1 ( \pm 2.4^b )</td>
</tr>
<tr>
<td></td>
<td>0.06 ( \pm 0.01 )</td>
<td>4.6 ( \pm 0.8^c )</td>
<td>12.7 ( \pm 1.8^c )</td>
</tr>
</tbody>
</table>

\( ^a \) SEM; \( n = 12 \). Values with different superscript letters are significantly different, \( P < 0.05 \).  
\( ^b \) Reduction in postprandial serum insulin area (0-95 min) as a percentage of the reference product value.
FIGURE 3. Incremental serum paracetamol responses in healthy subjects after ingestion of breakfast meals with whole-meal bread (WMB), WMB with added lactic acid (WMB-la), and WMB with added sodium propionate (WMB-p). Values are means; n = 12. Values with different letters are significantly different, P < 0.05.

FIGURE 4. Satiety scores in healthy subjects after ingestion of breakfast meals with whole-meal bread (WMB), WMB with added lactic acid (WMB-la), and WMB with added sodium propionate (WMB-p). Values are means; n = 12. Values with different letters are significantly different, P < 0.05.

glucose reference. However, a high acid load of lactic acid did reduce the gastric emptying rate in rats. Approximately 55% of tube-fed glucose remained compared with 18% in the case of the glucose control. This agrees with the findings of Ebihara et al (31), who registered a similar result in a comparable rat study. Moreover, a correlation between increased acid load of organic acid and a concomitant slowing of gastric emptying has been reported in both human (32) and animal (33) experiments. Previously, we reported that lactic acid reduced the rate of starch digestion (18). In fact, the reduced in vitro rate of starch digestion could essentially explain the lowered area under the glucose curve with bread containing lactic acid in healthy subjects. In contrast, it has been suggested that the blunting effect observed with fermented vegetables is caused by an increase in the viscosity of the dietary fiber components (19). However, when lactic acid was added to white bread, thus excluding any effect of viscosity, we still registered a reduced rate of release of starch degradation products during enzyme incubation in dialysis tubing (unpublished observations). Consequently, it is suggested that lactic acid at concentrations reached in sourdough bread interferes with the digestive phase, because no influence on gastric emptying could be observed in...
the present study unless it was provided in excessive and unphysiologic amounts.

A high load of sodium propionate in bread reduced the rate of gastric emptying in healthy subjects. The 95-min incremental paracetamol area was lowered by ~30%. This effect of propionate (pH 5.7) could not be registered in tube-fed rats. However, an equimolar amount of propionic acid (pH 3.3) reduced the rate of gastric emptying, suggesting a role of pH rather than acid load. A similar slowing of gastric emptying in the presence of propionic acid was shown previously in humans (32) and animals (33).

The influence of sodium propionate on the rate of gastric emptying in humans and rats was not consistent. A plausible explanation might be that the propionate was administered differently. Thus, whereas propionate was ingested in the bread in the human study, an aqueous solution of the salt was tube-fed to the rats. It is well known that liquids leave the stomach more rapidly than do solids (34). Possibly, the propionate included in the bread was converted to propionic acid in the acidic conditions prevailing in the stomach. According to Hunt and Knox (35) and Hunt and Pathak (36), organic salts (the sodium salts of citrate, chloride, and sulfate) have only minor effects on gastric emptying. However, this conclusion was based on results in humans tube-fed with salt solutions. To our knowledge, there are no data available in which propionate was included in food and subsequently studied with respect to gastric emptying rate. Consequently, it is likely that the organic acid is the active component in slowing gastric emptying, whereas the corresponding salt has no such ability.

It has been suggested that the inhibition of gastric emptying, seen with most acids, might be explained by both low pH values and acid load (37). However, results from the present study show that solutions with hydrochloric and lactic acid acted differently, despite identical pH values (2.4). Thus, whereas lactic acid delayed gastric emptying in rats, no effect was noted with hydrochloric acid. This could be due to the higher acid load of lactic acid (133 mmol/L) than hydrochloric acid (8 mmol/L) in the tube-feeding solutions, or to a specific receptor responding to organic acids. The pH hypothesis has been rejected by different investigators (33, 38), and instead, a receptor mechanism has been proposed. According to Lin et al (37), a nonspecific acid or pH receptor is responsible for inhibition of gastric emptying. A receptor that recognizes intragastric volume has been suggested. According to Mayer (39), it is likely that the volume receptors are located in the stomach as well as in the small intestine. However, the chemoreceptors are probably limited to the proximal part of the duodenum (37).

Taken together with the rat experiments, it could be concluded that the acid load as well as the pH can be detected by the gastrointestinal tract to generate inhibitory feedback on gastric emptying. However, the lack of effect of sodium propionate on the rate of gastric emptying in rats was in contrast with that shown in humans. Thus, despite a near neutral pH (6.1) of the sodium propionate bread, this product did delay gastric emptying in humans. The purpose of the present study was to study whether a reduced gastric emptying rate could explain the lowered postmeal glucose and insulin responses seen with bread products containing lactic acid or sodium propionate. Although it was clearly shown that this was the case with the sodium propionate bread, the mechanism for the delay of gastric emptying remains to be elucidated.

In addition to the evaluation of metabolic responses and the rate of gastric emptying, the satiating effect was studied 3 h after the test meals. Prolonged satiety was noted with the propionate bread, whereas the satiety score with the lactic acid bread did not deviate from that with the control bread. The satiety score registered with the propionate bread agrees with previous observations (18), and is in accordance with this organic salt having a delaying effect on gastric emptying rate. It was proposed previously that certain foods that contribute to stomach distension are linked to the feeling of fullness (22). The recent finding that sodium propionate had no effect on the in vitro rate of starch hydrolysis in bread (18) further strengthens the likelihood that the mechanism is related to gastric emptying. In contrast, Todesco et al (21) found a reduced rate of amyolysis of starch in a similar propionate-enriched bread. However, when using the same in vitro method we failed to show any inhibition of a-amylase by sodium propionate (18).

Results from the present study showed that bread products with added lactic acid or sodium propionate displayed lowered postprandial glucose and insulin responses in healthy subjects. Because low-GI flour–based bread products are scarce on the market, sourdough fermentation should be used more frequently as a baking process.

We conclude that sourdough baking, and other fermentation processes, should be explored to reduce glycemia and insulin demand after ingestion of cereal products. Also, the addition of organic acids and/or their corresponding salts could be used. Such low-GI cereals could offer health benefits and facilitate the management of diabetes (40) and might even reduce incidence of certain metabolic diseases (15).

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GASTRIC EMPTYING RATE IN RELATION TO GLYCEMIA