Nutrient modulation of intestinal gas dynamics in healthy humans: dependence on caloric content and meal consistency

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Gonlachanvit, Sutep, Radoslav Coleski, Chung Owyang, and William L. Hasler. Nutrient modulation of intestinal gas dynamics in healthy humans: dependence on caloric content and meal consistency. Am J Physiol Gastrointest Liver Physiol 291: G389–G395, 2006; doi:10.1152/ajpgi.00526.2005.—The actions of nutrients on gut transit of liquids and solids have been extensively studied, but the effects of meal ingestion on intestinal gas flow are unexplored. We hypothesized that meals of varying caloric content and consistency modulate gas transit to different degrees. Nine healthy volunteers underwent jejunal perfusion of physiological gas mixtures at 12 ml·min⁻¹·h⁻¹, with ingestion of nothing (control), water (240 ml), 240-kcal liquid meals, and 240-kcal solid meals at the end of the second hour in separate studies. Gas was quantified from an intrarectal catheter. After an initial lag phase, gas evacuation approached steady state by the end of the fasting period. Solid and liquid caloric meals increased total gas volumes evacuated from 5–40 min after ingestion vs. control studies (P < 0.05). These increases resulted from increased numbers of bolus gas evacuations (P < 0.05), whereas bolus volumes, pressures, and flow rates were similar for all test conditions. Solid and liquid caloric meals elicited similar effects on bolus gas dynamic parameters, whereas water did not affect these measures vs. control (NS, not significant). Both caloric meals and the noncaloric liquid meal increased continuous gas flow, which represented <2% of total gas expulsion. In conclusion, caloric meals promote bolus gas transit in healthy humans, whereas noncaloric liquids have no effect. Solids stimulate early postprandial gas dynamics to the same extent as liquid meals of similar caloric content. Thus modulatory effects of meals on intestinal gas transit depend on their caloric content but not their consistency.

MATERIALS AND METHODS

Test Subjects

Nine healthy volunteers (6 men and 3 women, age 19–46 yr) with no history of gastrointestinal symptoms, no prior gastrointestinal surgery, and on no medications known to alter gut motor function or transit were recruited through campus-wide advertisement. Each subject gave written informed consent before entering the study. Women of child-bearing potential underwent serum pregnancy testing before enrollment. All studies were approved by the University of Michigan Medical Center Institutional Review Board.

Study Design

All subjects underwent four intestinal gas dynamic studies to study the effects of four different test meal conditions in random order. Volunteers fasted overnight and reported at 7:30 AM on each study day. Subjects underwent initial rectal evacuation with a 500-ml water enema. A silicone rubber catheter with an outside diameter of 4.2 mm and a 1.9 × 2.4-mm central lumen open at its tip (Dentsleeve, Mississauga, ON, Canada) was passed using fluoroscopy, with positioning of the tip 5 cm distal to the ligament of Treitz for gas perfusion. A 24-Fr Foley catheter was inserted into the rectum for gas evacuation.

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collection. The subject was placed in a quiet room and lay supine at a 30° incline for a 30-min equilibration period before initiation of gas perfusion.

A gas mixture containing 88% nitrogen, 6.5% carbon dioxide, and 5.5% oxygen was perfused into the jejunum at a rate of 12 ml/min as described and validated previously (12, 32). This mixture of gases approximates the concentrations in venous blood and thus has been termed physiological. Furthermore, using this perfusion protocol with inclusion of a marker gas, there is no significant gas reflux into the stomach, and 95% of perfused gas is recovered in the rectum, indicating that unobserved gas losses are minimal. Gas perfusion was controlled by a digital smart mass flow controller (model 5850S; Brooks Instrument, Hatfield, PA), and flow entering the jejunum was monitored by a digital mass flow meter (model 5860E; Brooks Instruments). The mass flow controller and the mass flow meter were interfaced with a personal computer (Dimension 8200; Dell, Round Rock, TX) via a digital converter (USB data acquisition function module, Data Translation, Marlboro, MA). Rates of gas perfusion were set and monitored using Data Acquisition software version 1.0 (Data Translation). Perfusion was performed for 2 h under fasting conditions to achieve a steady state of gas transit. We previously observed that the mean lag time for the first rectal gas expulsion after initiation of gas perfusion is ~30–40 min, with some individuals not evacuating gas until after completion of the first hour of perfusion (12). Thus steady-state gas transit is not reliably approached until the second perfusion hour. Subjects then ingested one of the test meals, and gas perfusion under postprandial conditions continued for another hour. In control studies, fasting recording continued for a third hour without ingestion of any meal.

Evacuated gas collected from the rectal catheter was connected to a low-resistance, low-compliance tubing and was measured by a barostat (Isobar III; G&J Electronics, Hamilton, ON, Canada) that was controlled by Protocol Plus software (G&J Electronics). Before the study, the barostat was emptied and the pressure was set at 0 mmHg with a sensitivity of 0.3 mmHg and a maximum flow rate of 35 ml/s. Any gas flow generating a pressure >0.3 mmHg was collected into the barostat. Volumes and pressures of gas collected in the barostat were recorded over the 2-h fasting and 1-h postprandial period for subsequent analysis.

Test Meal Composition

Four different test meal conditions were tested on separate days at least 7 days apart in random order. These included 1) control studies in which no meal was ingested, 2) a noncaloric liquid meal (240 ml water), 3) a calorically liquid meal (Ensure, vanilla flavor, 240 ml containing 41 g carbohydrate, 4 g fat, and 10 g protein; 240 kcal), and 4) a calorically solid meal (scrambled eggs and toast with 60 ml water containing total weight of 240 g containing 40 g carbohydrate, 6.7 g fat, and 5 g protein; 240 kcal). All meals were consumed within 5 min.

Intestinal Gas Dynamic Parameters

After an initial lag period, gas was evacuated from the rectum either as bolus movements or as continuous flow during jejunal gas perfusion. The lag period was defined as the time from initiation of gas perfusion to the first passage of gas from the rectum. Bolus movements were defined as passages >10 ml in volume at a rate >2 ml/s with an interval between movements >10 s, regardless of the pressure of the gas movement, as previously described (12). The volume, duration, and peak pressure for each bolus movement were determined as shown in Fig. 1. The flow rate for each bolus movement was calculated by dividing the bolus volume by its duration. Continuous flow was defined as a gas movement that generated an output <10 ml or at a rate <2 ml/s. The total gas volume evacuated during the fasting and postprandial period was calculated as the sum of bolus and continuous gas flow volumes. The beginning of the postprandial period was defined as the time the subjects began ingesting each test meal.

Perceptual Assessment

Abdominal symptoms were quantified before initiation of jejunal gas perfusion, every 15 min during gas perfusion under fasting conditions, and after consumption of each of the test meals. Symptom scores for bloating, fullness, discomfort, and nausea were assessed using 10-cm-long visual analog scales where 0 = no symptoms and 10 = maximal symptoms.

Statistical Analysis

Values are means ± SE. Repeated-measures ANOVA was performed on total gas evacuation volumes; total gas evacuation volumes in the form of boluses, bolus numbers, and mean volumes of individual boluses; and continuous flow volumes to compare responses to the test meals and to test whether there were significant interactions between the different test meals and time after eating. Repeated-measures ANOVA was performed separately between test meals to estimate magnitudes of the distinct nutrient effects. When the main effect of a given test meal was significant within an analysis, the Newman-Keuls multiple-range test was employed to identify differences between test meals. Two-tailed Student’s paired t-testing was performed as appropriate to determine significant differences among
other gas dynamic parameters, including net gas retention at the end of the study, bolus pressure, bolus flow rate, and symptoms. A $P$ value $<0.05$ defined statistical significance.

**RESULTS**

All volunteers completed four separate gas dynamic studies under each of the different test meal conditions. Representative 30-min gas evacuation profiles beginning at the start of the third hour of jejunal gas perfusion are shown in Fig. 2 for one volunteer under control conditions and after consumption of the liquid caloric meal. In the control study without meal ingestion, gas evacuation is characterized by infrequent elimination of discrete gas boluses that proceed at a rate similar to the rate of jejunal gas perfusion. Ingestion of the liquid caloric meal elicits more rapid gas evacuation and results in greater total volume expelled at the end of the recording period.

**Fasting Gas Evacuation Profiles**

All volunteers exhibited fasting gas evacuation profiles, which were similar on each of the different study days. After gas perfusion was begun, an initial lag period was observed, which was comparable for each test meal condition (Table 1). Thereafter, gas expulsion proceeded in predominantly pulsatile fashion until a steady state was approached. By the end of the 2-h fasting period, gas evacuation volumes approached the values perfused with small volumes of gas retained under each of the test conditions (NS) (Fig. 3). Ingestion of the liquid caloric meal elicits more rapid gas evacuation and results in greater total volume expelled at the end of the recording period.

**Test Meal Effects on Gas Evacuation Profiles**

Test meal effects on gas evacuation volumes. Total volumes of gas expelled from the rectum were compared for each of the test meal conditions as a function of time. Postprandial recordings exhibited time-dependent increases in total gas expelled for all test conditions ($P < 0.05$). Analysis of differences between the different test meals revealed that consumption of both the liquid caloric and solid caloric meals produced greater increases in gas expulsion compared with the control studies, which were evident in the initial 5 min after eating and which persisted for 40 min ($P < 0.05$) (Fig. 3). Evacuation profiles for the liquid and solid caloric meals overlapped throughout the early postprandial period from 5–40 min and showed no differences between meals of different consistency (NS) (Fig. 3). Ingestion of the liquid noncaloric meal (water) produced a gas expulsion pattern that was not different from control studies (NS) (Fig. 3). By the end of the postprandial recording, gas evacuation profiles for the caloric test meal conditions showed some convergence with the control studies at 60 min. There were no significant increases in net gas retention at the end of the 60-min postprandial period with the liquid noncaloric (21 ± 74 ml) or liquid caloric (−132 ± 77 ml) meals compared with control (−97 ± 71 ml) (NS), although there was a trend toward decreased net retention with the solid caloric meal (−275 ± 77 ml) ($P = 0.08$) (Table 2).

**Table 1. Fasting gas dynamic parameters on the different study days**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control</th>
<th>Noncaloric Liquid</th>
<th>Caloric Liquid</th>
<th>Caloric Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lag time, s</td>
<td>1.76±0.56</td>
<td>1.59±0.47</td>
<td>2.14±0.67</td>
<td>2.05±0.54</td>
</tr>
<tr>
<td>Volume expelled, ml</td>
<td>1.31±0.09</td>
<td>1.33±0.79</td>
<td>1.32±0.98</td>
<td>1.30±0.81</td>
</tr>
<tr>
<td>Volume retained, ml</td>
<td>1.27±0.90</td>
<td>1.07±0.79</td>
<td>1.11±0.98</td>
<td>1.38±0.81</td>
</tr>
</tbody>
</table>

Values are means ± SE. All $P$ values were not significant.

**Table 2. Effects of different test meals on gas dynamic properties**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control</th>
<th>Noncaloric Liquid</th>
<th>Caloric Liquid</th>
<th>Caloric Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolus volume, ml</td>
<td>66.2±5.8</td>
<td>58.4±4.3</td>
<td>64.5±5.8</td>
<td>67.8±5.3</td>
</tr>
<tr>
<td>Bolus pressure, mmHg</td>
<td>13.1±3.3</td>
<td>11.3±2.3</td>
<td>14.3±3.9</td>
<td>14.6±4.4</td>
</tr>
<tr>
<td>Bolus duration, s</td>
<td>5.1±0.3</td>
<td>4.6±0.3</td>
<td>5.3±0.4</td>
<td>6.0±0.5</td>
</tr>
<tr>
<td>Bolus flow rate, ml/s</td>
<td>14.0±0.8</td>
<td>13.5±0.8</td>
<td>14.4±1.0</td>
<td>13.9±1.0</td>
</tr>
<tr>
<td>Continuous flow at 30 min, ml</td>
<td>4.1±1.7</td>
<td>10.8±3.0*</td>
<td>9.6±2.3*</td>
<td>9.2±3.0*</td>
</tr>
</tbody>
</table>

Values are means ± SE. *$P < 0.05$ vs. control.
Test meal effects on specific gas dynamic parameters. Expulsion of gas in the postprandial period was largely the consequence of evacuation of discrete boluses (>98% of gas expelled) but also included a small contribution from gas passed in continuous fashion. As with total volumes of gas expelled, total volumes expelled in the form of bolus evacuations showed time-dependent increases that were greater for the liquid and solid caloric meals compared with the liquid noncaloric meal and control studies (P < 0.05) (data not shown). Total volumes of gas expelled in the form of boluses represent the product of bolus number and individual bolus volume. Postprandial recordings exhibited a time-dependent increase in numbers of bolus gas expulsions for all test conditions (P < 0.05). Analysis of differences between the different test meals revealed that ingestion of both the liquid caloric and solid caloric meals produced greater increases in numbers of bolus gas evacuations compared with the control studies, which were evident in the initial 10 min after eating and which persisted for 30 min (P < 0.05) (Fig. 4). As with the quantification of total gas volume expulsion, numbers of bolus evacuations were not different for the liquid and solid caloric meals in the early postprandial period from 5 to 40 min (NS) (Fig. 4). Numbers of boluses expelled also were similar after ingestion of water vs. the control studies (NS) (Fig. 4). Bolus number determinations for the caloric meals showed some convergence with the control studies by the end of the 1-h postprandial recording (NS). There were no significant increases in bolus numbers at the end of the 60-min postprandial period with the liquid noncaloric (11.7 ± 1.7) or liquid caloric (13.0 ± 2.2) meals compared with control (12.2 ± 1.6) (NS), although there was a trend toward increased bolus numbers with the solid caloric meal (14.4 ± 2.0) (P = 0.08).

Consumption of the different test meals did not affect other parameters of bolus gas evacuation. There was no time-dependent increase or decrease in mean volumes of individual boluses for any of the test meal conditions (NS) (data not shown). Analysis of differences between the different test meals revealed no differences in mean bolus volumes for the caloric meals, water, or control conditions (NS) (Table 2). Likewise, in the postprandial period, mean bolus pressures, mean bolus durations, and mean bolus flow rates were similar for each of the different test meal conditions (Table 2).

Gas expelled in the form of continuous flow represented a small fraction of total gas evacuation. Postprandial recordings exhibited a time-dependent increase in continuous gas expulsion for all test conditions, which represented 1.6 ± 0.3% of all gas evacuated at the end of the 1-h postprandial period (P < 0.05) (Table 2). In contrast to the results observed with bolus gas evacuation parameters, analysis of differences between the different test meals revealed that ingestion of both caloric test meals as well as the noncaloric meal (water) produced greater increases in continuous gas expulsions compared with the control studies, which were evident in the initial 5 min after eating and which persisted for 30 min (P < 0.05) (Table 2). However, evacuation profiles for the liquid and solid caloric meals and the liquid noncaloric meals overlapped throughout the postprandial period and showed no significant differences between meals of different properties (NS) (Table 2).

Perceptual Assessment

Under basal conditions before initiation of gas perfusion, symptom scores for bloating (0.03 ± 0.01), fullness (0.03 ± 0.01), discomfort (0.02 ± 0.01), and nausea (0.03 ± 0.01) were very low (maximal possible score for each symptom = 10). Jejunal gas perfusion produced minor increases in symptom scores during fasting that were recorded as very mild (mean scores during 2-h fasting periods: bloating = 0.21 ± 0.05, fullness = 0.15 ± 0.05, discomfort = 0.21 ± 0.05, and nausea = 0.02 ± 0.01). After ingestion of each of the test meals, symptom scores were compared with control conditions in which no meal was consumed. Symptom scores for bloating for the liquid caloric (0.17 ± 0.15), solid caloric (0.29 ± 0.11), and liquid noncaloric (0.50 ± 0.25) meals 30 min after meal ingestion were not different from control conditions (0.36 ± 0.15) (NS). Symptom scores for fullness for the liquid caloric (0.17 ± 0.10), solid caloric (0.22 ± 0.11), and liquid noncaloric (0.26 ± 0.16) meals were not different from control (0.38 ± 0.17) (P = NS). Symptom scores for discomfort for the liquid caloric (0.46 ± 0.23), solid caloric (0.30 ± 0.15), and liquid noncaloric (0.26 ± 0.23) meals were not different from control (0.37 ± 0.23) (NS). Finally, symptom scores for nausea for the liquid caloric (0.11 ± 0.10), solid caloric (0 ± 0), and liquid noncaloric (0 ± 0) meals were not different from control (0 ± 0) (NS). There were no significant differences between the different test meals for any of the individual symptoms.

DISCUSSION

Meals of varied characteristics modulate transit in different gut regions. Gastric emptying of solids is slower than that of liquids (34). Emptying of caloric liquids is retarded vs. water (23). The small intestine propels solids and water similarly (22). In the colon, meals induce a propulsive reflex, the gastrocolonic response, which relates to caloric content (36–
Control of gas transit is less well-characterized than for solids or liquids. Understanding gas flow is important because of the prevalence of gaseous symptoms in the general population and in the functional bowel disorders (4, 13, 21, 29). In irritable bowel syndrome (IBS), bloating is at least as prominent as pain (13, 21). Postprandial bloating also is prevalent in functional dyspepsia (28). The mechanisms for gaseous symptoms are poorly understood. Some studies show increased gas retention in IBS, whereas others suggest that altered gas transit plays a lesser role (8, 20, 31). To understand the pathogenesis of gaseous symptoms, regulation of gas flow in healthy subjects must be characterized. To date, studies have focused on modulating transit of gases perfused into the jejunum during fasting or under test conditions such as gastric distention, intestinal nutrient perfusion (including mixed nutrients, lipids, amino acids, and glucose), marked hyperglycemia, body posture, physical exertion, and anal contraction (5, 6, 10, 14–16, 30, 33). No studies have focused on gas flow responses to oral ingestion of meals of varying properties.

Using a validated gas perfusion method, we characterized gas transit responses to meals of different caloric content and physical consistency (32). Ingesting noncaloric liquids (water) did not influence volumes evacuated, numbers of boluses expelled, or individual bolus characteristics. In contrast, 240-kcal liquid meals of similar volumes increased total volumes expelled due to increased bolus numbers with no change in bolus volumes, flow rates, or pressures, confirming that caloric content influences bolus gas transit. Solid meals of similar caloric content produced comparable expulsion profiles as the liquid caloríc meal, suggesting that consistency does not influence early postprandial gas flow. There was a trend toward increased gas expulsion for the solid caloríc meals at the end of the 1-h postprandial period vs. the liquid caloríc meals, which was not observed in the initial 40 min, raising the possibility of subtle differences in responses to meals of different consistency in the late postprandial period. Future studies beyond 1 h in larger numbers of subjects may clarify this issue.

The source of the increased expelled gas with nutrient ingestion cannot be determined from this study. Because increased evacuation was observed within 5 min of caloric consumption, the released gas most likely was colonic in origin. It is less likely that expelled gas originated proximally, because we observed lag times of 30–40 min from initiating jejunal gas perfusion to first gas evacuation. Thus swallowed air is almost certainly not responsible for meal-stimulated gas release. It also is unlikely that more air would be swallowed with the caloríc liquid meal vs. the noncaloric meal. Other groups have employed inert gaseous markers such as sulfur hexafluoride to verify gas recovery (30–33). However, this method would be unable to distinguish the source of the expelled gas, as any gas being evacuated from the colon would have the same steady-state level of inert marker as the gas being perfused in the jejunum.

Mechanisms underlying nutrient modulation of gas dynamics are uncertain. The predominant bolus character of gas expulsion suggests that the different test meals may be differentially modifying phasic motor patterns in the distal gut. In healthy subjects, spontaneous gas passages and those evoked by air insufflation were associated with propagating colonic contractions followed by rectal pressure increases and anal relaxations (1). Likewise in preliminary studies, we showed that gas expulsion correlates with small bowel motor activity (9). It is unlikely that the bolus evacuations relate to venting around obstructing feces as the bolus pattern persists after colonic lavage with polyethylene glycol (11).

The effects of eating on gut motor activity are well characterized. In the small intestine, caloríc meals induce fed motor patterns, whereas water has no effect (19, 24, 40). Liquid meals modulate the number of small bowel contractions, suggesting a possible mechanism for the increased boluses after the caloríc meals in this study (19, 40, 41). In the colon, caloríc meals increase tone and numbers of phasic contractions that relate to caloríc content (2, 7, 25, 35, 43, 42). Temporal profiles of stimulated gas transit by caloríc meals in this study mirror the gastrocolonic response (30–60 min) (35, 36). Alternatively, the brief time course of meal-evoked gas flow may reflect complete evacuation of residual gas in the colon such that no further gas can be expelled. This hypothesis can be tested in healthy subjects pharmacologically treated to retain gas or IBS patients with gas retention (31, 33). The gastrocolonic response consists of gastric mechanomediated and intestinal chemoreceptor-mediated components (3, 42). Antral distention evokes gas expulsion, supporting a mechanoreceptor-activated pathway of gas transit (10). However, in this study, water had no effect on gas flow, perhaps due to inadequate antral distention or brisk emptying of the water into the duodenum. Responses to caloríc meals are not completely explained by this phenomenon either, as similar high fat meals preferentially distribute to the fundus (17). Duodenal mechanisms are unlikely explanations for our findings, because the highest duodenal delivery would have occurred after water, which did not affect gas flow (23, 34). Duodenal chemoreceptor activation by fat is improbable as duodenal lipids delay rather than accelerate gas transit (30). Participation by other factors including meal osmolarity or a cephalic response from meal palatability cannot be excluded (26, 27). Some studies (18, 39) have observed a cephalic component of the gastrocolonic response, whereas others have not.

All meals increased continuous gas passage, which comprised <2% of gas evacuated, suggesting it is of lesser physiological relevance than bolus passages. Visual examination of gas expulsion profiles shows discrete periods in which evacuation proceeds in linear rather than pulsatile fashion, whereas inspection of other parts of the same tracings show no gas elimination, indicating continuous flow does not result from collection system leaks. Continuous evacuations may reflect altered luminal tone or generation of a common cavity with prolonged jejunal perfusion. The ability of water to increase continuous flow but not bolus evacuation suggests different mechanisms for the two forms of gas expulsion. However, given the small continuous volumes passed, it is difficult to reliably quantify differences between the distinct meals. The protocol used in this study produced minimal bloating or other symptoms, and meals did not elicit any change in gaseous symptoms in these subjects. The purpose of this study was to characterize physiological gas transit responses to meal ingestion to form the foundation for investigating the pathophysiology of postprandial gaseous symptoms in patients with pathological gas retention. In fasting studies, such individuals report increased symptoms associated with decreased gas evacuation compared with normal subjects (31). If impairments in meal-evoked gas evacuation are shown to directly relate to
in increases in bloating, then this would provide evidence of an etiological role for postprandial gas transit abnormalities in these patients.

In conclusion, caloric meals promote bolus gas evacuation in healthy humans, whereas noncaloric liquids have no effect. Solid nutrients stimulate gas dynamics similar to liquid meals of identical caloric content. Differences in gas evacuation after the distinct test meals result from modification of gas bolus numbers but not volumes, pressures, durations, or flow rates. Continuous evacuation represents a small component of total gas expulsion but was increased by both caloric meals and water. Thus modulatory effects of meals on early postprandial gas transit depend on caloric content but not meal consistency. These findings provide the foundation for exploring postprandial gas flow abnormalities in patients with gaseous complaints.

GRANTS
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DISCLOSURES
W. L. Hasler serves on the Speaker’s Bureau of Novartis Pharmaceuticals, GlaxoSmithKline, and Solvay Pharmaceuticals.

REFERENCES

