Preventing Gastric Sieving by Blending a Solid/Water Meal Enhances Satiation in Healthy Humans1–3

Luca Marciani,4 Nicholas Hall,4 Susan E. Pritchard,5 Eleanor F. Cox,5 John J. Totman,5 Mita Lad,6 Caroline L. Hoad,5 Tim J. Foster,6 Penny A. Gowland,5 and Robin C. Spiller4*

1Nottingham Digestive Diseases Centre and NIHR Biomedical Research Unit, Nottingham University Hospitals, and 2Sir Peter Mansfield Magnetic Resonance Centre, School of Physics and Astronomy, University of Nottingham, Nottingham, UK; and 3Division of Food Sciences, School of Biosciences, University of Nottingham, Sutton Bonington Campus, Loughborough, UK

Abstract

Separation of solids and liquids within the stomach allows faster gastric emptying of liquids compared with solids, a phenomenon known as sieving. We tested the hypothesis that blending a solid and water meal would abolish sieving, preventing the early rapid decrease in gastric volume and thereby enhancing satiety. We carried out 2 separate studies. Study 1 was a 2-way, crossover, satiety study of 22 healthy volunteers who consumed roasted chicken and vegetables with a glass of water (1008 kJ) or the same blended to a soup. They completed satiety visual analogue scales at intervals for 3 h. Study 2 was a 2-way, crossover, mechanistic study of 18 volunteers who consumed the same meals and underwent an MRI to assess gastric emptying, gallbladder contraction, and small bowel water content (SBWC) at intervals for 3 h. In Study 1, the soup meal was associated with reduced hunger \((P = 0.02)\). In Study 2, the volume of the gastric contents after the soup meal decreased more slowly than after the solid/liquid meal \((P = 0.0003)\). The soup meal caused greater gallbladder contraction \((P < 0.04)\). SBWC showed a biphasic response with an initial “gastric” phase during which SBWC was greater when the solid/liquid meal was consumed \((P < 0.001)\) and a later “small bowel” phase when SBWC was greater when the soup meal was consumed \((P < 0.01)\). Blending the solid/liquid meal to a soup delayed gastric emptying and increased the hormonal response to feeding, which may contribute to enhanced postprandial satiety. J. Nutr. 142: 1253–1258, 2012.

Introduction

The ability to sieve solids and liquids is an important feature of i.e. processing of food \((1–3)\). The liquid phase of mixed solid/liquid meals empties rapidly, while larger solid particles are retained for longer and are subject to a grinding process to reduce their size before they can be emptied after a lag phase \((2,4–7)\). A blended soup that has only one phase can be expected to empty more homogeneously. A mixed solid/liquid meal will first undergo oral comminution and bolus formation \((8)\). Such meals can be thought of as large pieces (in the millimeter to centimeter size range) of food material surrounded by a bulk, low-viscosity water phase. However, the particle size of the food material can be considerably decreased if the food and water are blended together to form a soup. The subsequent physical properties of the resulting mixture will be dominated by particle–particle interactions due to a significant increase in interfacial area for the smaller particles, and the colloidal system can be seen as homogeneous. Previous studies have shown that when homogenized, a mixed solid/liquid, fat- and vegetable-rich, 2573-kJ meal delayed gastric emptying and increased satiety compared with the unhomogenized meal \((9)\). Another study established that incorporating water into a meal as a soup decreased energy intake in lean women \((10)\), though again the mechanisms and impact on gastric emptying were not defined.

Assessing the gastrointestinal (GI) fate of complex solid/liquid meals traditionally has been difficult due to limitations of techniques. MRI, however, is a noninvasive technique not involving ionizing radiation, that can provide high resolution, dynamic images of foods in the gastric lumen \((3,11–15)\) and GI function \((16)\).

We hypothesized that differences in satiety and physiological effects between solid/liquid and soup meals are due to changes in

---

1 Supported in part by an educational grant from the British Broadcasting Corporation, UK for the television series “The Truth About Food.”
2 Author disclosures: L. Marciani, N. Hall, S. E. Pritchard, E. F. Cox, J. J. Totman, M. Lad, C. L. Hoad, T. J. Foster, P. A. Gowland, and R. C. Spiller, no conflicts of interest.
3 Supplemental Figures 1–4 and Supplemental Material are available from the “Online Supporting Material” link in the online posting of the article and from the same link in the online table of contents at http://jn.nutrition.org.
4 To whom correspondence should be addressed. E-mail: Robin.Spiller@nottingham.ac.uk.
5 Abbreviations used: GI, gastrointestinal; SBWC, small bowel water content; VAS, visual analogue scale.
food microstructure (17–19). By incorporating the water phase into the meal by blending the solid and liquid mixed phases to a soup, we aimed to reduce gastric sieving. This would prevent the selective emptying of the low-nutrient water phase of the solid/liquid meal, ensuring that duodenal receptors were stimulated by nutrient-rich soup during the early phase of gastric emptying. We report here an initial feeding study designed to assess the effect this would have on satiety and a subsequent mechanistic GI imaging study to examine the effect this would have on gastric emptying, gallbladder contraction, and small bowel water content (SBWC).

Participants and Methods

Test meals
The 2 meals used were isonenergetic and isovolumetric and differed only in their physical state. The base meal consisted of 75 g char-grilled chicken (Tesco "finest" Chicken Chausseur, Tesco) (364 kJ), 62.5 g roasted vegetables (Tesco "finest" Mediterranean Style Vegetables, Tesco) (276 kJ), 62.5 g breaded mushrooms (Tesco "value" breaded mushrooms, Tesco) (368 kJ), and 250 mL of still bottled water (0 kJ). The total energy was 1008 kJ. The meals were bought from the chilled foods section of a main supermarket and heated using a microwave oven, as recommended on the packaging. For the soup meal, the water was heated as well so that blending the mix would not cool the soup. Based on the packaging label, the meals contained chicken breast, pepper, courgette, red onion, cherry tomato, mushroom, vegetable oil, extra virgin olive oil, and traces of pectin, potato starch, and corn flour, giving 15 g protein, 11 g carbohydrates, 12 g fat, 5 g fiber, and 0.3 g sodium. The meal was then served to the participants at a temperature of ~60°C either as a solid/liquid meal (eaten with fork and knife and using the glass of water as a drink) or with all components blended finely to a soup using a hand-held kitchen blender (Breville 3-in-1 hand blender) at the high speed setting for 5 min (the soup meal, eaten with a spoon) (Supplemental Fig. 1). The soup meal was characterized using in vitro physiological measurements such as viscometry, optical microscopy, and laser diffraction particle size analysis (techniques and results described in Supplemental Fig. 2).

Participants and study design

Satiety study (Study 1). Twenty-two healthy volunteers participated in this 2-way, randomized, crossover study. Thirteen male and 9 female participants (age 25.0 ± 0.9 y) with normal BMI (22.1 ± 0.8 kg/m²) attended 2 experimental morning studies 1 wk apart. They were asked to fast from 2000 h the previous evening and to avoid alcohol, caffeine, strenuous exercise, and any medication that could affect GI function for 18 h prior to the experiment. In quiet controlled conditions, they consumed either the solid/liquid or the soup meal at 0900 h. Five participants were studied at the same time on each study morning, but they could not see or talk to each other during the study. Participants were given 15 min to consume their meal. They were instructed to drink the water while eating the solid meal, with no standardization of timing or size of swallows. The participants were asked to complete visual analog scale (VAS) (20,21) at baseline and while fasting at intervals for 3 h postprandially. The VAS contained questions asking participants to rate on numerical scales with numbers from 1 to 10 their sense of fullness (1 = "I feel not full," 10 = "I feel extremely full"), hunger (1 = "I do not feel hungry," 10 = "I feel extremely hungry"), and desire to eat (1 = "I would eat nothing," 10 = "I would eat an enormous meal") (22,23). No further questions (e.g., about the sensory quality of the meal) were asked.

Mechanistic study (Study 2). Eighteen volunteers participated in this 2-way, randomized, crossover study. Nine healthy male and 9 healthy female participants (age 20.3 ± 0.2 y) with normal BMI (22.2 ± 0.5 kg/m²) attended in the morning. The same restrictions and exclusion and inclusion criteria as described above applied. Additionally, the participants were to have no contraindications to MRI scanning.

A fasting scan, defined as time t = −45 min, was performed before each volunteer consumed the test meal (soup or solid/liquid allocated in random order) at 0900 h. Participants were given 15 min to consume their meal as described above, except they were able to communicate with each other. After this, 5 more scans were performed at 0, 30, 75, 120, and 165 min.

This protocol was approved by the University of Nottingham Medical School Research Ethics Committee and all participants gave informed written consent prior to experiments.

MRI

The MRI scanning was carried out on a research-dedicated 1.5T Philips Achieva MRI scanner. The participants were positioned supine in the scanner with a 4-element parallel imaging coil wrapped around the abdomen. Gastric emptying and gallbladder contraction were assessed using a balanced gradient echo (balanced turbo field echo) sequence acquiring 20 contiguous axial slices with a reconstructed in-plane resolution of 1.56 mm × 1.56 mm and slice thickness of 10 mm. The sequence parameters were: echo time = 1.2 ms, repetition time = 2.4 ms, flip angle = 45°, and reconstructed matrix = 256 × 256. The data were collected during an expiration breath hold of 9 s. This imaging sequence yields a good contrast between the stomach and gallbladder contents against other abdominal organs. The SBWC was assessed as previously described (24,25) using a coronal, single-shot, fast-spin echo (similar to that used for magnetic resonance cholangiopancreatography) sequence acquiring 24 contiguous coronal slices with a reconstructed in-plane resolution of 0.78 mm × 0.78 mm and slice thickness of 7 mm. The sequence parameters were: echo time = 320 ms, repetition time = 8000 ms, refocusing flip angle = 150°, fat saturation using the spectral presaturation with inversion recovery pulse, and reconstructed matrix = 512 × 512. The data were collected during an expiration breath hold of 24 s. This sequence yields high-intensity signals from areas with liquid fluid and dark signals from other body tissues. At each time point, the positioning of the participant on the scanner bed, set up, scanning, and data collection took ~5 min, after which the volunteers were removed from the scanner and kept sitting upright in a quiet room next to the scanner.

Data analysis

The individual VAS time courses were corrected by subtracting individual baseline values from each test value. Therefore, the time courses are changes from baseline (Fig. 1). The VAS AUC were calculated using the trapezoidal method. Measurements of the volume of the gastric contents were performed. Gastric emptying and gallbladder contraction were assessed using magnetic resonance imaging (magnetic resonance imaging), using a coronal, single-shot, fast-spin echo (similar to that used for magnetic resonance cholangiopancreatography) sequence acquiring 24 contiguous coronal slices with an in-plane resolution of 0.78 mm × 0.78 mm and slice thickness of 7 mm. The sequence parameters were: echo time = 320 ms, repetition time = 8000 ms, refocusing flip angle = 150°, fat saturation using the spectral presaturation with inversion recovery pulse, and reconstructed matrix = 512 × 512. The data were collected during an expiration breath hold of 24 s. This sequence yields high-intensity signals from areas with fluid and dark signals from other body tissues. At each time point, the positioning of the participant on the scanner bed, set up, scanning, and data collection took ~5 min, after which the volunteers were removed from the scanner and kept sitting upright in a quiet room next to the scanner.

Power and statistical methods

For the satiety study, our primary endpoint was satiety score. Based on our previous data on fat emulsion meals (23), the power calculation showed that we could detect a 15% change in hunger scores, which we judged to be clinically significant, with α = 0.05 and a power of 90% using 22 participants in a cross-over design. For the mechanistic study, data from the same previous study showed that we could detect a 20% change in the mean gastric volume primary endpoint with α = 0.05 and a power of 90% using 18 participants in a cross-over design.

1254 Marciani et al.
The data are expressed as mean ± SEM. All statistical analysis was carried out using Prism 4 (GraphPad Software). Tests for normality of the data were carried out using the Shapiro-Wilk’s test. Repeated-measures ANOVA was used to assess the significance of differences. The SBWC data were mostly not normally distributed; hence, a log-transformation was applied to these data to normalize them before performing the ANOVA. Post hoc test assessments using the Bonferroni method in Prism 4 were carried out to compare the 2 meals at each time point. Paired comparisons for AUC and half gastric emptying times were performed using 2-tailed Student’s \( t \) test. Differences were considered significant at \( P < 0.05 \).

**Results**

**Satiety study (Study 1)**

All 22 participants tolerated the study procedures well and completed all the meals and all the satiety VAS (Table 1; Fig. 1). The sense of hunger was lower when the soup meal was consumed than when the solid/liquid meal was consumed (\( P = 0.02 \)). Linearly extrapolating the last 3 data points indicated that the soup meal delayed the return of the sense of hunger to the baseline by 28 min.

**Mechanistic study (Study 2)**

All 18 participants tolerated the study procedures well and completed all the meals and all the MRI scans. The soup meal maintained a homogeneous appearance throughout the period of the experiment with no phase separation or sedimentation (Fig. 2A–C). Conversely, for the solid/liquid meal, pieces of solid food were seen surrounded by water in the stomach (Fig. 2D). The liquid phase appeared to empty faster, leaving behind solid pieces of food in the stomach (Fig. 2E,F), which is consistent with gastric sieving of the meal.

Postprandially, the volume of the gastric contents after the soup meal decreased linearly (\( r^2 = 0.99 \)) and more slowly (\( P = 0.0003 \)) than after the solid/liquid meal, which had a faster initial exponential emptying rate (\( r^2 = 0.98 \)) (Table 2). The soup meal tended to delay the time to one-half gastric emptying (92 ± 7 min) compared with the solid/liquid meal (77 ± 6 min) (\( P = 0.06 \)). The volume of the gastric contents was significantly higher when the soup meal was consumed than when the solid/liquid meal was consumed at 30 and 75 min (Fig. 3). Accordingly, the AUC for the gastric emptying integrated over the whole experiment was significantly higher when the soup meal was consumed than when the solid/liquid meal was consumed (Table 2). By the end of the study period, the mean volumes of the gastric contents did not differ.

Postprandially, the soup meal induced a greater gallbladder contraction than the solid/liquid meal (Supplemental Fig. 3) (ANOVA \( P < 0.04 \)). The gallbladder contracted rapidly, reaching a maximum contraction at 75 min, with the percentage of gallbladder volume at that time point being smaller when the soup meal was consumed than when the solid/liquid meal was consumed (\( P < 0.01 \)).

Subdividing the postprandial phase into a gastric and a small bowel postprandial phase as was done previously (25) showed that during the initial gastric phase, the water content of the small bowel rose with the solid/liquid meal, whereas it remained unchanged with the soup meal (Supplemental Fig. 4). In this gastric phase, in keeping with the faster gastric emptying, the SBWC was significantly higher for the solid/liquid meal (Table 2). However, during a later small bowel phase, the SBWC rose markedly when the soup meal was consumed (Table 2).

**FIGURE 1** Satiety VAS scores for fullness (A), hunger (B), and desire to eat (C) of healthy men and women after they consumed the solid/liquid and soup meals (Study 1). Values are baseline-corrected mean ± SEM, \( n = 22 \). The arrow indicates the meal time. VAS, visual analogue scale.

**TABLE 1** Satiety ratings by healthy men and women after they consumed the solid/liquid and soup meals (Study 1) \(^1\)

<table>
<thead>
<tr>
<th>Meal</th>
<th>Solid/liquid</th>
<th>Soup</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUC (VAS scores · min)</td>
<td>1086 ± 58</td>
<td>1144 ± 69</td>
</tr>
<tr>
<td>Fullness</td>
<td>1166 ± 76</td>
<td>1106 ± 65*</td>
</tr>
<tr>
<td>Hunger</td>
<td>1289 ± 76</td>
<td>1230 ± 77</td>
</tr>
</tbody>
</table>

\(^1\) Values are mean ± SEM, \( n = 22 \). * Different from solid/liquid, \( P < 0.02 \). VAS, visual analogue scale.
AUC SBWC for small bowel phase, AUC SBWC for gastric phase, 1256 Marciani et al.

By making use of noninvasive MRI methods of studying GI function (16), we were able to simultaneously examine the behavior of the stomach, small intestine, and gallbladder. The main difference in gastric emptying between the 2 test meals was seen in the first 75 min after feeding (Fig. 3). For the solid/liquid meal, there was an initial rapid emptying of the nutrient-poor water phase of the meal from 0 to 75 min postprandially. Because water does not excite nutrient-sensitive enteroendocrine cells or nerves to initiate the duodenal (27), jejunal (28), and ileal (29) braking mechanisms, the fluid is rapidly transported through or absorbed in the small bowel. Thereafter, the emptying of gastric contents slowed, presumably because of the need for antral grinding of the solid phase before it could pass the pylorus. In contrast, the soup meal emptied in a linear, homogeneous fashion, resulting in larger gastric volumes from 0 to 75 min, something our previous studies suggest would increase the sense of fullness and induce satiation (13). This was initially associated with lower SBWC, but at later times, the SBWC increased steadily so that after 90 min, the SBWC was consistent with gastric sieving of the water phase.

Discussion

Previous studies showed that incorporating water into a solid food by blending it to a soup made the meal more satiating than serving the solid food with a drink of water (10,26), but the underlying GI mechanisms remained unclear. Our results support the hypothesis that blending a mixed solid/liquid meal to a soup delays gastric emptying while enhancing the biliary and intestinal response to the meal, and this combination of effects results in prolonged satiety.

Oral processing of a solid meal is a complex process that creates a range of particle sizes and prepares a bolus for optimal swallowing (8). Large particles resulting from such oral processing of the solid/liquid meal were clearly seen here in the images of the stomach. The unblended, heterogeneous meal was sieved by the stomach, expelling the nutrient-thin water phase first, while large particles were retained to undergo antral grinding. In contrast, the more homogeneous blended meal was clearly visible against the surrounding abdominal organs. The bTFE sequence has the signal intensity characteristics of a steady-state, free precession sequence, so that liquids appeared bright and solids were dark in the images. The soup meal (A–C) appears homogeneous with no sedimentation throughout the experiment. Immediately after consumption, the solid/liquid meal is seen as pieces of solid food (looking very dark) surrounded by water (D). With time postprandially (E,F), the water appeared to be emptying faster, leaving visible solid pieces of food in the stomach, which is consistent with gastric sieving of the water phase.

TABLE 2 GI MRI parameters for healthy men and women after they consumed the solid/liquid and soup meals (Study 2)1

<table>
<thead>
<tr>
<th>Meal</th>
<th>Solid/liquid</th>
<th>Soup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of gastric contents at 30 min, mL</td>
<td>265 ± 8</td>
<td>360 ± 15***</td>
</tr>
<tr>
<td>Volume of gastric contents at 75 min, mL</td>
<td>198 ± 10</td>
<td>256 ± 22**</td>
</tr>
<tr>
<td>Time to half empty the stomach, T1/2, min</td>
<td>77 ± 6</td>
<td>92 ± 7</td>
</tr>
<tr>
<td>AUC gastric emptying, L · min</td>
<td>43 ± 2</td>
<td>49 ± 3*</td>
</tr>
<tr>
<td>Percentage gallbladder contraction at 75 min, %</td>
<td>44 ± 2</td>
<td>32 ± 2*</td>
</tr>
<tr>
<td>AUC gallbladder contraction, % · h</td>
<td>220 ± 7</td>
<td>206 ± 8*</td>
</tr>
<tr>
<td>AUC SBWC for gastric phase, L · min</td>
<td>8.8 ± 0.9</td>
<td>5.7 ± 0.7**</td>
</tr>
<tr>
<td>AUC SBWC for small bowel phase, L · min</td>
<td>8 ± 1</td>
<td>12 ± 1**</td>
</tr>
</tbody>
</table>

1 Values are mean ± SEM, n = 18. * Different from solid/liquid, P < 0.05. **Different from solid/liquid, P < 0.01. *** Different from solid/liquid, P < 0.001. SBWC, small bowel water content.
greater after the soup meal than after the solid/liquid meal was consumed (Supplemental Fig. 4).

During the early phase, the soup meal delivered fine particles of nutrients to the small bowel, whereas the solid/liquid meal delivered only the low-nutrient liquid phase of the meal to the small bowel. This is likely to explain why the soup meal was more efficient in stimulating gallbladder contraction at 0–90 min (Supplemental Fig. 3), suggesting more cholecystokinin was released by this meal. This would also be expected to enhance pancreatic secretion, which might account for the later increase in SBWC. Because the rate-limiting steps in digestion occur at the solid/liquid interface, the finer particles would be predicted to enhance digestion and hence stimulation of the many other gut peptides found in enteroendocrine cells, including glucagon-like peptide-1 and peptide YY, which both delay transit and enhance satiety.

However, it is not only the delivery of nutrients to the small bowel that is altered between the soup and solid/liquid meal. Blending the mixed solid/liquid meal to a soup yielded a homogeneous dispersion of small, irregular particles that was 400 times more viscous than water (Supplemental Material) and it is known that increased viscosity slows gastric emptying (13).

Here, we observed that even when diluted by 20%, the soup meal still had a viscosity which was 150 times higher than water. Such a dilution is similar to that expected to be produced by salivary and gastric secretions 1 h after ingestion (13), indicating that the soup meal will remain viscous within the stomach, which will slow emptying.

This study had some limitations. One limitation was the use of 2 separate studies with 2 groups of participants, which precluded direct correlations between MRI and satiety data. However, scanning does introduce a number of distracting variables, including the noise of the scanner and the supine posture, which encouraged us to perform Study 1 without scanning to ensure the results would extrapolate to everyday eating behavior. In normal eating conditions, one would consume a soup with an additional glass of water, which would increase further soup dilution and reduce viscosity. Study 2 involved scanning in the supine position, which may have a small effect on gastric emptying (30). However, we minimized this effect in the MRI study by keeping participants mostly upright in a sitting position, assuming a supine position in the scanner only for a few minutes at a time. Another limitation was the different orosensory stimulation by the soup and the solid/liquid meal, which may have an effect on anticipatory reflexes (31), appetite, and GI responses (32). The visual appearance of the 2 meals used here was clearly different and this might alter the cephalic response, which is important for both gastric and pancreatic secretions. We decided not to collect blood from the participants in Study 2, because venous cannulation does introduce a stressor in some participants that can delay gastric emptying.

In summary, changing the food microstructure of a mixed solid/liquid meal by blending it to a soup reduced gastric sieving of the water phase of the meal and induced decreased hunger, slower gastric emptying, and greater gallbladder contraction. A better understanding of the relationship between the GI response and changes in food microstructure and satiety will be helpful in the design of foods with desired and health-promoting structure-function characteristics (18).

**Acknowledgments**


**Literature Cited**