Effects of posture on gastric emptying and satiety ratings after a nutritive liquid and solid meal

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Spiegel, Theresa A., Harry Fried, Christine D. Hubert, Steven R. Peikin, Jeffry A. Siegel, and Louis S. Zeiger. Effects of posture on gastric emptying and satiety ratings after a nutritive liquid and solid meal. Am J Physiol Regulatory Integrative Comp Physiol 279: R684–R694, 2000.—To study the effects of posture and meal structure on gastric emptying and satiety, nine women ingested tomato soup and then immediately or 20 min later an egg sandwich, when seated and when supine. The lag time was not different, but the half-emptying time of the sandwich was 32% longer (P < 0.01) and the emptying rate after the lag phase was 39% slower (P < 0.01) when the subjects were supine than when they were seated. The half-emptying time of the soup was 50% longer (P < 0.01) when the subjects were supine and ingested the soup immediately before the sandwich than in the other three conditions. Postprandial hunger ratings recovered more slowly (P < 0.01) when the subjects ingested the soup 20 min before the sandwich than when they ingested the soup immediately before the sandwich. These results suggest that posture did not affect the intragastric distribution of the sandwich but affected propulsion of the meal into the intestine and that postprandial satiety was enhanced by the cumulative effect over time of a 20-min “head start” in stimulation of intestinal receptors by emptying of the soup.

THE RATE OF EMPTYING OF SALINE and water is slower when subjects are on the left side or supine than when they are on the right side or erect (1, 2, 28). The rate of emptying of glucose, on the other hand, when subjects are on the left side or supine is not different from that when they are on the right side or erect (2, 13, 19, 33). Hunt and colleagues (2, 19) argued that gravity hinders emptying when subjects are on the left side or supine because of the anterior position of the antrum and pylorus relative to the body of the stomach. When the meal contains nutrients that stimulate intestinal receptors, however, any hindrance to emptying due to gravity is offset by reduced stimulation of these receptors, which, in turn, reduces inhibition of motor mechanisms responsible for propulsion of the meal into the intestine.

The results of studies with more complex meals show, however, that the effects of posture on emptying depend not only on the nutritive content of the meal, but also on other factors that have yet to be identified and investigated. A low-nutrient soup ingested with olive oil, for example, empties more slowly when subjects are on the left side than when they are seated (3, 16). Posture does not affect emptying of a solid food ingested without a liquid (9, 23) but does affect emptying of a solid food ingested with a nutritive liquid (25). Emptying of the liquid was not measured in this latter study (25), and it is not known whether posture modifies the emptying of a nutritive liquid ingested with a solid.

Posture affects the emptying of a mixed aqueous and oil meal, at least in part, by altering the intragastric distribution of the components (3, 16). Posture has only a minimal effect on the intragastric distribution of a solid food ingested without a liquid (9). It is not known whether posture alters the intragastric distribution of a solid and/or nutritive liquid when they are ingested in the same meal. Nutritive liquids and solids ingested together do modify the emptying patterns of each other (6–8, 14, 17, 18, 30, 31, 35). Furthermore, this interaction depends on the timing of ingestion of the liquid and solid components (17, 30, 31). The possibility that posture modifies the interaction between liquids and solids as they empty has also not been examined.

A number of investigators have shown that postprandial hunger and fullness ratings are related to the rate of gastric emptying, but the extent to which gastric signals (e.g., distension) as opposed to postgastric signals (e.g., stimulation of intestinal receptors or hormones) contribute to intrameal satiation and postprandial satiety is not fully understood (3, 4, 11, 16, 21, 27). To the extent that posture and the timing of meal components affect gastric emptying, they will affect the pattern of signals arising from the gastrointestinal tract. Studying the effects of posture and meal struc-
ture could thus help elucidate the relative contributions of gastric and postgastric signals to intrameal satiation and postprandial satiety.

The purpose of the present study, therefore, was to examine further the effect of posture and meal structure on the emptying of a nutritive liquid and solid meal. Emptying of the liquid and solid components was measured so that the effects of posture on emptying of the liquid as well as the solid and on the interaction between the liquid and solid could be determined. Subjects also rated hunger and fullness before, during, and for several hours after the meal so that the effects of posture and meal structure on these measures of satiation and satiety could be evaluated.

METHODS

Subjects. The subjects were nine healthy normal-weight women. Their age was 29.6 ± 5.4 (SD) yr (range 20–38), and their body mass index (weight/height$^2$, kg/m$^2$) was 22.7 ± 1.9 (range 19.6–25.1). The subjects were not on a diet and had no history of weight problems. Their mean score on the cognitive restraint factor of the eating inventory (32), a scale that measures concern about dieting and body weight, was 5.2 ± 1.6 (2–8 of a possible score of 25). Women who smoked, were taking any medication including oral contraceptives, were pregnant or lactating, or did not like the foods to be used in the study were excluded. The protocol was approved by the Institutional Review Committee of Cooper Hospital/University Medical Center, and subjects gave written informed consent before participating in the study. Each subject was paid $50 for each gastric emptying study after she had completed all her studies.

Design. A repeated-measures 2 × 2 design was used, in which each subject was studied in a seated (Sit) and a supine (Sup) posture with two different intervals between the liquid and solid components of the meal. The subjects ingested an egg sandwich immediately (Sit-0 and Sup-0 conditions) and 20 min (Sit-20 and Sup-20 conditions) after they finished ingesting the soup. [5 subjects were also studied in a 5th condition, in which they were seated and ingested the sandwich without the tomato soup. The results of these studies are reported elsewhere (30).]

The order of the four conditions was counterbalanced across subjects. The four studies were conducted between days 3 and 12 of each subject’s menstrual cycle, since the rate of gastric emptying has been shown to vary with the phase of the menstrual cycle (12, 36). Studies were conducted on Monday through Friday, with at least 4 days between successive studies. The four studies with any given subject were completed over a 2- to 4-mo interval.

Foods. The tomato soup was reconstituted with water according to the manufacturer’s instructions (Campbell Soup, Camden, NJ); 300 g of soup contained 120 kcal (75.8% energy from carbohydrate, 20.0% from fat, and 4.4% from protein). The soup was labeled with 125 μCi of $^{111}$In-dithylenetriaminepentaacetic acid. The egg sandwich was made with two whole eggs (90 g) prepared as an omelet with 4.7 g of protein. The egg was labeled with 500 μCi of $^{99m}$Tc-sulfur colloid. The omelet was placed between two pieces of white bread. The sandwich weighed 134.7 g and contained 307 kcal (29% energy from carbohydrate, 47% from fat, and 24% from protein).

Procedure. On the day before each study, a negative serum pregnancy test report was obtained. The subjects were required to eat nothing after 8 PM on the evening before each study day and were asked to eat the same breakfast at 9:30 AM on each study day. After breakfast, the subjects were not allowed anything but water to drink until they came to the hospital for the gastric emptying study, which began between 4:30 and 5:30 PM.

At the time of each gastric emptying study, the soup and sandwich were prepared and labeled as described previously (31). The labeled soup was divided into 50-g portions in six small paper cups and was served at ~37°C. The labeled sandwich was cut into 12 equal-sized portions, which were each held together with toothpicks.

A single-head Siemens Orbiter gamma camera and computer system was used for the studies in the seated posture. A Siemens Multispect 2 gamma camera and computer system was used for the studies in the supine posture. The cameras were fitted with medium-energy collimators, and 20% energy windows were set centered at 140 keV for $^{99m}$Tc and 247 keV for $^{111}$In.

For the studies in the seated posture, the subject remained seated on a stool in front of the gamma camera for the duration of the study (~2.5 h). The subject ingested one portion of soup every 30 s, taking 3 min to ingest all the soup. In the Sit-0 condition, the subject then immediately began ingesting the first portion of the sandwich. In the Sit-20 condition, the subject began ingesting the first portion of the sandwich 20 min after she finished ingesting the soup. In both conditions, the subject ingested one portion of the sandwich every 50 s, taking 10 min to ingest the entire sandwich.

Imaging of the abdomen in the $^{111}$In window began immediately after the subject finished drinking the soup. Simultaneous imaging in the $^{111}$In and $^{99m}$Tc windows began immediately after the subject finished ingesting the sandwich. Sequential 1-min anterior images followed by 1-min posterior images were acquired every 5 min for the first 30 min after the subject finished drinking the soup. Imaging continued with anterior and posterior image pairs every 15 min until 120 min after the subject finished ingesting the sandwich. Markers were applied to the subject and to the camera to minimize the positioning variability between measurements.

For the studies in the supine posture, the subject lay on a table with a pillow under her head and another pillow under her knees if she desired. The table was positioned between the heads of the camera so that the stomach would be in the field of view. The imaging position was noted, and the table was repositioned so that the subject could sit up to drink the soup, as in the seated conditions. Immediately after the subject drank the last cup of soup, she lay down and the table was repositioned for imaging.

In the Sup-0 condition, simultaneous anterior and posterior images in the $^{111}$In window were acquired for 1 min. The table was then repositioned, and the subject sat up and consumed one portion of the sandwich every 45 s, taking 9 rather than 10 min to eat the entire sandwich (because of the time taken to image the soup before the subject began to ingest the sandwich). The subject then lay down, the table was repositioned, and simultaneous anterior and posterior images were acquired continuously in the $^{111}$In and $^{99m}$Tc windows for 120 min.

In the Sup-20 condition, continuous anterior and posterior images were acquired in the $^{111}$In window for 20 min after the subject ingested the soup before the table was repositioned so that the subject could sit up to eat the sandwich. The subject took 10 min to eat the sandwich, as in the seated conditions. The subject then lay supine, and simultaneous anterior and posterior images were acquired continuously in...
the $^{111}$In and $^{99m}$Tc windows for 120 min after ingestion of the sandwich.

Before and after the subject ingested the soup and sandwich every 30 min for 2 h after the meal, the experimenter verbally asked the subject two questions that the subject answered with a number between 0 and 100, according to the anchor “not at all” (0) and “extremely” (100). The questions were as follows: “How hungry do you feel right now?” and “How full do you feel right now?” Immediately after ingesting the soup and the sandwich, subjects were also asked, “How much did you like what you just ate?”

**Gastric emptying data analyses.** For the supine conditions, 1-min anterior and posterior image pairs that were collected at the same times as in the seated conditions were selected for analysis. Analyses of all the studies were conducted on the same computer system with use of software written by J. A. Siegel. For each anterior and posterior image pair in the $^{111}$In and $^{99m}$Tc windows, a region of interest (ROI) was drawn around the stomach by H. Fried, and the radioactivity counts were obtained and corrected for radioisotope decay. The geometric mean of the decay-corrected anterior and posterior counts at each time interval was computed to correct for tissue attenuation. Downscatter from $^{111}$In to $^{99m}$Tc, which could bias the results, was minimized by the differential doses of the two radioisotopes.

The geometric mean for each measurement interval was expressed as a fraction of the maximum count obtained after ingestion of the soup ($^{111}$In) or the sandwich ($^{99m}$Tc). The geometric means as a function of time were also fit with a modified power exponential function (10, 29, 34, 35) by use of a nonlinear least-squares regression computer program written by J. A. Siegel. The equation is as follows: $y(t) = 1 - (1 - e^{-eta t})^k$, where $y(t)$ is fractional meal retention at time $t$, $k$ is time (in min), $\beta$ is the extrapolated y-intercept from the terminal portion of the curve, and $k$ is gastric emptying rate (in %/min).

When $\beta > 1$, a curve that is characteristic of solid emptying is described. It has an initial shoulder, or lag phase with a constant emptying rate. When $\beta > 1$, $k$ is the gastric emptying rate (in %/min) for the terminal portion of the curve. When $\beta \leq 1$, the curve has an exponential form that is characteristic of liquid emptying. When $\beta = 1$, $k$ indicates the rate at which the early part of the emptying curve changes over time. (See Refs. 10, 29–31, 34, and 35 for more extensive discussions of the equation and interpretation of the parameters.)

The time it took 50% of the food to empty ($T_{1/2}$) was calculated using the values of $k$ and $\beta$ obtained from the fit of the equation to each emptying curve. For the sandwich, the lag time ($T_{lag}$) was determined by setting the second derivative $y''(t)$ equal to zero and solving for $t$. When $y''(t) = 0$, the rate of emptying has become constant, which corresponds to the time at which the first phase (the shoulder portion) of the curve ends and the terminal phase begins.

To compare the emptying rates of the soup and the sandwich combined in the four conditions, the cumulative percentage of the soup and sandwich emptied was converted to cumulative energy (in kcal) emptied. The values obtained for the soup and sandwich were added together for measurement intervals after the sandwich had been ingested. For each condition in each subject, the cumulative energy emptied as a function of time was analyzed using linear regression. The slopes of the regression lines were used as an estimate of the rate of delivery of energy to the intestine.

Because of the data acquisition and storage format, it was not possible to conceal the treatment condition from the person who drew the ROI for the gastric emptying analyses. However, once the ROI was drawn, the data were processed automatically. To check the reliability of the results, four studies in the seated conditions (2 each in the Sit-0 and Sit-20 conditions) and five studies in the supine conditions (2 in the Sup-20 and 3 in the Sup-0 condition) were chosen for redrawing the ROI and processing a second time by H. Fried. The differences between the two analyses were very small for all the parameters describing emptying of the soup and sandwich when the subjects were seated. For example, the mean difference between the two analyses was 3.81 (range 2.41–5.04) min for $T_{1/2}$ for the soup and 2.67 (range 2.01–3.39) min for $T_{1/2}$ for the sandwich. The mean difference between the two analyses for $T_{lag}$ for the sandwich was 5.65 (range 3.13–8.49) min. The differences between the two analyses were somewhat greater when the subjects were supine. The mean difference was 3.89 (range 0.42–9.11) min for $T_{1/2}$ for the soup and 7.81 (range 1.83–18.39) min for $T_{1/2}$ for the sandwich. The mean difference for $T_{lag}$ for the sandwich was 6.96 (range 2.61–11.54) min. The differences between the two analyses did not affect the study results.

**Statistical analyses.** Two-way repeated-measures ANOVA was used to evaluate the effects of posture and the soup-sandwich interval on the parameters of the gastric emptying curves, the slopes from the regression equations for cumulative energy emptied as a function of time, ratings of liking for the soup and sandwich, changes in hunger and fullness ratings from before to after ingestion of the soup and the sandwich, and hunger and fullness ratings at selected measurement intervals (e.g., before ingestion of any food). Pearson correlation coefficients were used to describe relationships between hunger and fullness ratings at the different measurement intervals.

Postprandial hunger and fullness ratings (at 5 rating times from immediately to 120 min after ingestion of the sandwich) were analyzed with a three-way mixed-model repeated-measures ANOVA to evaluate the effects of posture and the soup-sandwich interval on the slope of postprandial ratings as a function of time. (Proc MIXED in SAS was used. Posture and the soup-sandwich interval were treated as fixed factors, and time was treated as a continuous variable.) All statistical analyses were done using SAS (SAS Institute, Cary, NC) for the personal computer. Values are means ± SD unless indicated otherwise.

**RESULTS**

**Emptying of the sandwich.** The emptying curves in the four conditions (Fig. 1) show that emptying of the sandwich was slower when the subjects were supine than when they were seated. The mean percent retention was significantly greater when the subjects were supine than when they were seated beginning at 60 min and thereafter [$F(1,24) \geq 7.35, P < 0.025$ for the effect of posture in ANOVA of the percentage of counts remaining in the stomach at each measurement interval beginning at 60 min]. Although emptying of the sandwich was also slower when the subjects ingested the sandwich immediately after the soup than when they ingested the sandwich 20 min after the soup, the effect of the soup-sandwich interval was not significant at any measurement interval [all $F(1,24) \leq 2.82$, not significant (NS)]. The interaction between posture and the soup-sandwich interval was also not significant at any measurement interval [all $F(1,24) \leq 0.80$, NS].
The fit of the power exponential to the emptying data for the sandwich was excellent. Curves based on the actual data and on the derived parameters were virtually identical. All values for $\beta$ were $>1$, which is consistent with the initial shoulder, corresponding to the lag period, in the emptying curves. Neither posture [F(1,24) = 1.00, NS] nor the soup-sandwich interval [F(1,24) = 2.64, NS] had a significant effect on $\beta$, which was 2.30 ± 0.65, averaged across the four conditions, and the interaction was not significant [F(1,24) = 0.00, NS].

Values for $T_{lag}$, $T_{1/2}$, and $k$ (Table 1) were calculated from the equation obtained for each individual emptying curve. $T_{lag}$ for emptying of the sandwich was not different in the four conditions [F(1,24) = 0.03, NS, for the effect of posture; F(1,24) = 0.27, NS, for the effect of the soup-sandwich interval; and F(1,24) = 0.00, NS, for the interaction]. Emptying after the lag phase was slower, however, when the subjects were supine than when they were seated. $T_{1/2}$ was significantly longer [F(1,24) = 8.97, P < 0.01] and $k$ was significantly smaller [F(1,24) = 30.6, P < 0.01] when the subjects were supine than when they were seated (Table 1). The soup-sandwich interval did not have a significant effect on $T_{1/2}$ [F(1,24) = 1.67, NS] or $k$ [F(1,24) = 0.19, NS], and the interaction between posture and the soup-sandwich interval was not significant for $T_{1/2}$ or $k$ [F(1,24) = 0.22, NS, for both interactions].

Emptying of the soup. There were significant effects of posture [F(1,24) = 7.46, P < 0.05] and the soup-sandwich interval [F(1,24) = 5.23, P < 0.05] and a significant interaction between posture and the soup-sandwich interval [F(1,24) = 8.16, P < 0.01] for the $T_{1/2}$ of soup. The $T_{1/2}$ was significantly longer in the Sup-0 condition (44.3 ± 11.1 min) than in the other three conditions, which were not significantly different from each other (28.2 ± 10.8, 29.8 ± 12.0, and 29.5 ± 10.7 min in the Sit-0, Sit-20, and Sup-20 conditions, respectively).

To facilitate visual comparison of the emptying curves during the period of rapid emptying immediately after ingestion, the logarithm of the percentage of the soup remaining as a function of time is plotted in Fig. 2. Figure 2 shows that the soup emptied more slowly in both supine conditions than in the seated conditions for the first 20 min after ingestion of the soup. Emptying of the soup in the Sup-20 condition accelerated at 30 min, the first (supine) measurement after subjects sat up and ingested the sandwich. Ingestion of the sandwich did not affect the rate of emptying of the soup in either of the seated conditions.

The fit of the power exponential to the individual emptying curves for the soup was excellent. Graphs of the measured and predicted curves were virtually identical. $\beta < 1$ in all conditions, which is consistent with the exponential shape of the emptying curves. $\beta$ For the soup was significantly smaller when the sandwich was ingested immediately (0.63 ± 0.09) than when it was ingested 20 min after the soup (0.80 ± 0.15). Posture had a marginally significant effect on $\beta$ [F(1,24) = 3.50, P < 0.08], and the interaction was not significant [F(1,24) = 2.15, NS].

The values of $k$ (Table 2) show that the rate of change in the initial rate of emptying of the soup was significant.

### Table 1. $T_{lag}$, $T_{1/2}$, and $k$ for the sandwich

<table>
<thead>
<tr>
<th>Condition</th>
<th>Seated</th>
<th>Supine</th>
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<tbody>
<tr>
<td></td>
<td>Sit-0</td>
<td>Sit-20</td>
</tr>
<tr>
<td>$T_{lag}$, min</td>
<td>61.8 ± 22.6</td>
<td>54.2 ± 19.9</td>
</tr>
<tr>
<td>$T_{1/2}$, min</td>
<td>112 ± 63.0</td>
<td>93 ± 24.0</td>
</tr>
<tr>
<td>$k$,%/min</td>
<td>1.54 ± 0.52</td>
<td>1.45 ± 0.38</td>
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Values are means ± SD. $T_{lag}$, lag time; $T_{1/2}$, half-emptying time; $k$, linear emptying rate; Sit-0 and Sit-20, ingestion of sandwich immediately and 20 min after soup in seated position; Sup-0 and Sup-20, ingestion of sandwich immediately and 20 min after soup in supine position. *Significantly different, P < 0.01; †significantly different, P < 0.01.
cantly slower \( F(1,24) = 11.0, P < 0.01 \) when the subjects were supine than when they were seated and when the subjects ingested the sandwich immediately after the soup than when they ingested the sandwich 20 min after the soup \( F(1,24) = 16.2, P < 0.01 \). The interaction between posture and the soup-sandwich interval was not significant for the values of \( k \) \( F(1,24) = 0.96, \text{NS} \).

**Rate of delivery of energy to the small intestine.** The total energy (kcal of liquid + solid) emptying from the stomach as a function of time in each of the four conditions is shown in Fig. 3. A linear model fits these data very well: \( R^2 \approx 0.95 \) for all but one of the regression equations (for which \( R^2 = 0.88 \)). ANOVA of the slopes of the individual regression lines showed that the rate of emptying of energy into the small intestine was significantly lower when the subjects were supine than when they were seated \( F(1,24) = 18.09, P < 0.001 \). The average rate of emptying was 1.73 ± 0.38 kcal/min when the subjects were supine and 2.18 ± 0.39 kcal/min when they were seated. The soup-sandwich interval did not have a significant effect on the rate of total energy emptying from the stomach \( F(1,24) = 0.00, \text{NS} \), nor was the interaction significant \( F(1,24) = 0.92, \text{NS} \).

**Evaluation of possible measurement artifacts.** The measured rate of emptying may have been slower when the subjects were supine than when they were seated, because some of the small intestine was superimposed on the stomach when the subjects were supine, but not when they were seated. As food left the stomach, the radioactivity measured in the ROI would represent not only decreasing activity in the stomach but also increasing activity in the intestine, which would result in a slower measured than actual rate of emptying from the stomach. On the basis of visual inspection of the images, the author drawing the ROI judged that the intestine was not superimposed on the stomach in any of the seated studies but may have been superimposed on the stomach in 3 of the 18 supine studies. The intersecting area was excluded from the ROI, but in two of the three studies the \( ^{99m} \text{Tc} \) counts increased or remained constant 45–75 min after ingestion of the sandwich. The \( ^{111} \text{In} \) counts did not plateau or increase in any of the studies. Thus inclusion of the intestine in the ROI probably did not significantly affect the results.

**Ratings.** Subjects gave the soup and sandwich liking ratings in the neutral range (0–100). Mean liking ratings for the soup were 46.7 ± 18.4, 48.3 ± 24.0, 43.2 ± 23.1, and 57.2 ± 18.0 in the Sit-0, Sit-20, Sup-0, and Sup-20 conditions, respectively. There were no significant effects of posture or the soup-sandwich interval, nor was the interaction significant for ratings of liking of the sandwich (all \( F(1,24) < 1.50, \text{NS} \)).
There were a number of significant negative correlations between hunger and fullness ratings at the different measurement intervals within each condition, especially after the subjects ate the sandwich. Five of the 12 correlations between hunger and fullness ratings (in the 4 conditions) before the subjects drank the soup, after they drank the soup, and before they ate the sandwich were significant \( r = -0.75 (P < 0.025) \) to \( r = -0.98 (P < 0.001) \). Three of the correlations were marginally significant \( r = -0.61 \) to \( -0.65, P < 0.08 \). Fourteen of the 20 correlations between hunger and fullness ratings (in the 4 conditions) at measurement intervals after the subjects ingested the sandwich were significant \( r = -0.71 (P < 0.025) \) to \( r = -0.98 (P < 0.001) \).

Mean hunger ratings as a function of time for each of the conditions are shown in Fig. 4. To determine whether there were significant differences in hunger ratings before the subjects ingested any food, a two-way ANOVA of ratings just before the subjects ingested the soup was done. Posture had a significant effect \( [F(1,24) = 6.45, P < 0.025] \), the soup-sandwich interval was not significant \( [F(1,24) = 0.00, NS] \), and the interaction was not significant \( [F(1,24) = 1.41, NS] \). Hunger ratings immediately before the subjects ingested the soup were higher on the days of the two supine conditions (81.9 ± 15.0) than on the days of the two seated conditions (72.3 ± 23.9). The difference in hunger ratings between the supine and the seated conditions had disappeared by the time the subjects finished drinking the soup. Posture \( [F(1,24) = 0.94, NS] \), the soup-sandwich interval \( [F(1,24) = 0.18, NS] \), and the interaction \( [F(1,24) = 2.24, P < 0.09] \) were not significant in an ANOVA of hunger ratings just after the subjects drank the soup.

The effect of ingesting the soup on hunger ratings was similar in the four conditions. ANOVA of the difference in hunger ratings from before to after ingestion of the soup indicated that posture \( [F(1,24) = 1.46, NS] \), the soup-sandwich interval \( [F(1,24) = 0.30, NS] \), and the interaction \( [F(1,24) = 1.46, NS] \) were not significant. The mean decrease in hunger ratings from before to after ingestion of the soup, averaged across the four conditions, was 21.1 ± 10.6.

The effect of ingesting the soup and the sandwich on hunger ratings was also similar in the four conditions. ANOVA of the difference in hunger ratings from before ingestion of the soup to immediately after ingestion of the sandwich indicated that posture \( [F(1,24) = 2.58, NS] \) and the soup-sandwich interval \( [F(1,24) = 1.97, NS] \) were not significant. The interaction between posture and the soup-sandwich interval was marginally significant \( [F(1,24) = 3.98, P < 0.06] \). The mean decrease in hunger ratings from before ingestion of the soup to after ingestion of the sandwich, averaged across the four conditions, was 46.9 ± 12.4.

Ratings immediately after the sandwich were done 20 min earlier relative to ingestion of the soup in the 0-min compared with the 20-min interval conditions. Therefore, in the 0-min interval conditions, hunger and fullness ratings were also obtained 20 min after ingestion of the sandwich. (These data are not shown in Figs. 4 and 5.) To evaluate changes in ratings due to ingestion of the soup and sandwich over the same time interval, we compared the difference in hunger ratings from before ingestion of the soup to 20 min after ingestion of the sandwich in the 0-min interval conditions with the difference in hunger ratings from before ingestion of the soup to immediately after ingestion of the sandwich in the 20-min interval conditions. In other words, because it took 10 min to ingest the sandwich, the difference in ratings from before to 30 min after ingestion of the soup was compared across the four conditions.

The difference in hunger ratings from before to 30 min after ingestion of the soup was also not affected by posture \( [F(1,24) = 0.94, NS] \) or the soup-sandwich interval \( [F(1,24) = 0.45, NS] \), nor was the interaction \( [F(1,24) = 1.02, NS] \) significant. The mean decrease in ratings from before to 30 min after ingestion of the soup, averaged across the four conditions, was 41.8 ± 14.1. This decrease is smaller than the decrease from before ingestion of the soup to after ingestion of the sandwich (46.9 ± 12.4, see above), because, in the 0-min interval conditions, ratings of hunger increased from immediately to 20 min after ingestion of the sandwich. Hunger ratings increased from 33.3 ± 20.4 to 40.0 ± 23.4 in the Sit-0 condition and from 20.0 ± 20.0 to 33.8 ± 26.5 in the Sup-0 condition.

To evaluate the effects of posture and the soup-sandwich interval on recovery of postprandial hunger ratings, a three-way (posture × soup-sandwich interval × time) mixed-model ANOVA of ratings from immediately to 120 min after ingestion of the sandwich (5 rating times) was used. Time \( [F(1,164) = 28.5, P < 0.001] \), the posture × soup-sandwich interval interaction \( [F(1,164) = 14.2, P < 0.001] \), and the soup-sandwich interval × time interaction \( [F(1,164) = 7.96, P <
0.01] were significant. Posture \( F(1,164) = 0.58, \text{NS} \), the soup-sandwich interval \( F(1,164) = 2.08, \text{NS} \), the posture \( \times \) time interaction \( F(1,164) = 0.27, \text{NS} \), and the posture \( \times \) soup-sandwich interval \( \times \) time interaction \( F(1,164) = 1.55, \text{NS} \) were not significant.

The significant interaction between the soup-sandwich interval and time indicates that the soup-sandwich interval had a significant effect on the rate of change in postprandial hunger ratings. Postprandial hunger ratings recovered more slowly when subjects ingested the soup 20 min before the sandwich than when they ingested the soup immediately before the sandwich (Fig. 4). The slope was 0.019 ± 0.07 (SE) for the Sit-20 and Sup-20 conditions and 0.219 ± 0.07 (SE) for the Sit-0 and Sup-0 conditions. That is, ratings increased at a rate of 0.02%/min (on a scale of 0–100) or 0.6% every 30 min when the subjects ingested the soup 20 min before the sandwich and at a rate of 0.22%/min or 6.6% every 30 min when the subjects ingested the soup immediately before the sandwich.

To compare the rate of change in postprandial ratings obtained at similar time intervals relative to ingestion of the soup, the three-way mixed-model ANOVA was also applied to ratings synchronized by time since ingestion of the soup. That is, the (four) ratings obtained 0 (immediately), 30, 60, and 90 min after ingestion of the sandwich in the 20-min interval conditions and the (four) ratings obtained 30, 60, 90, and 120 min after ingestion of the sandwich in the 0-min interval conditions were used (Fig. 4). These times correspond to 30, 60, 90, and 120 min after ingestion of the soup in the 20-min interval conditions and 40, 70, 100, and 130 min after ingestion of the soup in the 0-min interval conditions. (As noted earlier, in the 0-min interval conditions, ratings were obtained 30 min after ingestion of the soup, but thereafter ratings were obtained every 30 min relative to ingestion of only the sandwich.)

The results of this analysis were similar to the results with the five postprandial ratings synchronized by time since ingestion of the sandwich, except the values for the slopes were lower. Time \( F(1,128) = 6.31, P < 0.025 \) and the posture \( \times \) soup-sandwich interval interaction \( F(1,128) = 4.97, P < 0.05 \) were significant. The soup-sandwich interval \( \times \) time interaction \( F(1,128) = 3.91, P = 0.0502 \) just missed significance. Posture \( F(1,128) = 0.90, \text{NS} \), the soup-sandwich interval \( F(1,128) = 0.10, \text{NS} \), the posture \( \times \) time interaction \( F(1,128) = 0.29, \text{NS} \), and the posture \( \times \) soup-sandwich interval \( \times \) time interaction \( F(1,128) = 0.23, \text{NS} \) were not significant. In other words, when ratings were synchronized relative to time since ingestion of the soup, hunger ratings recovered at a lower rate in the 20-min interval conditions (slope = −0.017 ± 0.098) than in the 0-min interval conditions (slope = 0.153 ± 0.098).

Mean fullness ratings as a function of time are shown for each condition in Fig. 5. Fullness ratings just before the subjects drank the soup were not significantly different in the four conditions \( F(1,24) = 0.28, \text{NS} \), for posture; \( F(1,24) = 1.43, \text{NS} \), for the soup-sandwich interval; and \( F(1,24) = 0.04, \text{NS} \), for the interaction. The effect of ingesting the soup on fullness ratings was similar in the four conditions. Although the increase in fullness ratings from before to after ingestion of the soup was smaller in the Sit-0 condition (9.4 ± 21.6) than in the other three conditions (26.1 ± 23.3 in Sit-20, 29.8 ± 26.4 in Sup-0, and 26.1 ± 22.3 in Sup-20), this apparent interaction was not significant. ANOVA of these difference scores indicated that posture \( F(1,24) = 2.74, \text{NS} \), the soup-sandwich interval \( F(1,24) = 1.12, \text{NS} \), and the interaction \( F(1,24) = 2.74, \text{NS} \) were not significant. The mean increase in fullness ratings from before to after ingestion of the soup, averaged across the four conditions, was 22.8 ± 17.2.

The effect of ingesting the soup and the sandwich on fullness ratings was different in the two soup-sandwich interval conditions. In an ANOVA of the difference in fullness ratings from before ingestion of the soup to after ingestion of the sandwich, the soup-sandwich interval \( F(1,24) = 5.25, P < 0.05 \) was significant. Posture \( F(1,24) = 1.08, \text{NS} \) and the interaction \( F(1,24) = 2.72, \text{NS} \) were not significant. The mean increase in fullness ratings from before ingestion of the soup to immediately after ingestion of the sandwich was greater when the soup was ingested immediately before the sandwich (57.0 ± 16.2) than when it was ingested 20 min (41.1 ± 22.4) before the sandwich.

To evaluate the effects of ingesting the soup and sandwich on the change in fullness ratings over the same time interval, the difference in ratings from before to 30 min after ingestion of the soup was compared across the four conditions, as for the hunger ratings. That is, the difference in ratings from before ingestion of the soup to 20 min after ingestion of the sandwich in the 0-min interval conditions was compared with the difference in ratings from before ingestion of the soup to immediately after ingestion of the sandwich in the 20-min interval conditions.
The soup-sandwich interval \([F(1,24) = 0.02, \text{NS}]\) did not affect the increase in fullness ratings from before to 30 min after ingestion of the soup, and posture \([F(1,24) = 0.73, \text{NS}]\) and the interaction \([F(1,24) = 2.05, \text{NS}]\) were not significant. Fullness ratings decreased from immediately to 20 min after ingestion of the sandwich in the 0-min interval conditions, from \(62.6 \pm 17.9\) to \(47.8 \pm 24.4\) in the Sit-0 condition and from \(77.0 \pm 16.6\) to \(61.7 \pm 20.5\) in the Sup-0 condition. Thus, in the 0-min interval conditions, the change in ratings from before to 30 min after ingestion of the soup was only \(42.1 \pm 21.7\) compared with \(57.0 \pm 16.2\) reported above for the change from before ingestion of the soup to immediately after ingestion of the sandwich. The mean increase in fullness ratings, averaged across the four conditions, was \(41.6 \pm 20.2\).

The three-way mixed-model ANOVA of postprandial ratings at five times beginning immediately after ingestion of the sandwich showed that fullness ratings changed significantly over time \([F(1,164) = 27.5, P < 0.001]\). The posture \(\times\) soup-sandwich interval interaction was also significant \([F(1,164) = 7.14, P < 0.001]\). The soup-sandwich interval \(\times\) time interaction was marginally significant \([F(1,164) = 3.43, P < 0.07]\). None of the other factors or interactions was significant: \(F(1,164) = 0.11, \text{NS for posture}; F(1,164) = 2.61, \text{NS, for the posture \(\times\) soup-sandwich interval interaction}; F(1,164) = 0.02, \text{NS, for the posture \(\times\) time interaction}; and F(1,164) = 0.31, \text{NS, for the soup-sandwich interval \(\times\) posture \(\times\) time interaction}. Similar to the hunger ratings, fullness ratings recovered more slowly when the subjects ingested the soup 20 min before the sandwich (slope = \(-0.084 \pm 0.091\)) than when they ingested the soup immediately before the sandwich (slope = \(-0.222 \pm 0.081\)), but this difference in the rate of recovery was only marginally significant for fullness ratings. The average slope of postprandial fullness ratings for the four conditions was \(-0.153 \pm 0.060\) (SE), an average decrease in fullness ratings of 4.6% every 30 min.

Postprandial fullness ratings synchronized relative to time since ingestion of the soup were also analyzed with a three-factor mixed-model ANOVA (see the description of this analysis for the hunger ratings). Only time was significant, indicating that the rate of change in postprandial fullness ratings over time was not affected by posture or the soup-sandwich interval. The average slope of postprandial fullness ratings in this analysis for the four conditions was \(-0.059 \pm 0.082\) (SE), an average decrease in fullness ratings of 1.8% every 30 min \([F(1,128) = 8.21, P < 0.01, \text{for time}; F(1,128) = 0.01, \text{NS, for the soup-sandwich interval}; F(1,128) = 0.02, \text{NS, for posture}; F(1,128) = 2.42, \text{NS, for the soup-sandwich interval \(\times\) posture interaction}; F(1,128) = 0.01, \text{NS, for the soup-sandwich interval \(\times\) time interaction}; \ F(1,128) = 0.05, \text{NS, for the posture \(\times\) time interaction}; and F(1,128) = 0.07, \text{NS, for the soup-sandwich interval \(\times\) posture \(\times\) time interaction]).

**DISCUSSION**

The results of the present study confirm and extend the findings of Moore et al. (25), who also showed that emptying of a solid ingested with a nutritive liquid was slower when subjects were supine than when they were seated. In the present study with normal-weight women and the study of Moore et al. with normal-weight men, \(T_{1/2}\) for the solid food was longer and the linear emptying rate was slower when subjects were supine than when they were seated. These results contrast with those for solid foods ingested without a liquid. In two studies, there was no difference between the rate of emptying of a solid food ingested without a liquid when subjects were supine (23) or on the left side (9) and when they were seated. In addition, we found that there was no difference in the present study in \(T_{lag}\) for emptying of a solid ingested with a nutritive liquid between the supine and the seated position and that the rate of emptying of a nutritive liquid ingested with a solid was slower when subjects were supine than when they were seated and ingested the liquid immediately before the solid.

Posture affects emptying of a soup and oil meal, at least in part, by changing the intragastric distribution of the meal components (3, 16). A change in the intragastric distribution of the soup and sandwich probably does not explain the slower emptying when subjects were supine than when they were seated in the present study. First, visual inspection of the images showed that the sandwich was retained in the proximal stomach and the soup filled the distal stomach during the early postprandial period in the seated and supine conditions. This distribution pattern is typical for mixed liquid and solid meals ingested by seated subjects (5, 7, 15, 18).

Second, \(T_{lag}\) for emptying of the sandwich was not altered by posture. \(T_{lag}\) is thought to correspond to the time during which the solid is distributed from the proximal to the distal stomach and trituration begins (15, 17, 18). The onset of the steady linear rate of emptying of a solid (the end of \(T_{lag}\) as we defined it) corresponds to the time of maximum radioactivity in the distal stomach (5, 34). If the solid were distributed more slowly to the distal stomach, \(T_{lag}\) of the sandwich should have been longer when the subjects were supine than when they were seated, and it was not. Thus it seems unlikely that there was a significant difference in intragastric distribution of the sandwich between the two postures.

On the other hand, slower emptying of the soup, slower emptying of the sandwich after the lag phase, and slower emptying of the soup and sandwich combined suggest that propulsion of the meal into the intestine was reduced when subjects were in the supine compared with the seated position. According to Hunt and colleagues (2, 19), when subjects are supine, any hindrance to emptying due to gravity is offset by reduced stimulation of intestinal receptors, which, in turn, reduces inhibition of motor mechanisms responsible for propulsion of the meal into the intestine. Such
an increase in propulsive motor activity apparently compensates for the effects of gravity in the case of single-item meals of nutritive liquids (2, 13, 19, 33) or solids (9, 23), because their emptying is not altered by posture. The results of the present study and the study of Moore et al. (25) show, however, that when the meal contains a nutritive liquid and a solid food, propulsive motor activity apparently does not increase sufficiently to overcome the effects of gravity. To determine how posture affects the different mechanisms responsible for emptying of liquids and solids ingested together, studies of mixed liquid and solid meals are needed in which the intragastric distribution of both components, emptying of both components, and motor activity are monitored simultaneously.

The timing of ingestion of the soup and sandwich did not significantly affect emptying of the sandwich in either posture or emptying of the soup in the seated posture, but it did affect emptying of the soup when the subjects were supine. The finding that the soup-sandwich interval did not affect emptying of the sandwich needs to be confirmed with a larger sample size. Emptying of the sandwich was slower in the supine and seated conditions when it was ingested immediately than when it was ingested 20 min after the soup. Given the variability of the data, the power for tests of the effects of the soup-sandwich interval on emptying parameters for the sandwich was low (< 50%).

The interpretation of the effects of posture and the soup-sandwich interval on emptying of the soup was confounded in the present study by the fact that the subjects sat up to ingest the sandwich in the supine conditions. Emptying of the soup accelerated in the Sup-20 condition relative to the Sup-0 condition at 30 min, the first measurement after the subjects sat up to ingest the sandwich (Fig. 2). Because ingestion of the sandwich in the seated conditions did not affect emptying of the soup, it is very likely that sitting up, rather than ingesting the sandwich, caused the acceleration in emptying of the soup in the Sup-20 condition. It is not clear, however, why sitting up 20 min after ingesting the soup accelerated emptying of the soup, but sitting up immediately after ingesting the soup (in the Sup-0 condition) did not accelerate emptying of the soup.

Our findings have several implications for clinical studies of gastric emptying. Many newer dual-head gamma cameras used for radionuclide scintigraphic measurement of emptying are designed for subjects to lay supine, whereas studies using the older single-head cameras were done with seated subjects. Clinical norms developed for nutritive liquid and solid meals with seated subjects will not apply to supine subjects and vice versa. Furthermore, in some gastric emptying studies (29) and possibly in many clinical settings, subjects are supine during brief measurement periods (e.g., 1 min) and are seated for longer periods between measurements (e.g., 15 min). If sitting up 20 min after ingesting a liquid accelerates emptying of the liquid, as we have suggested, the timing of postural changes needs to be controlled and standardized in studies of gastric emptying of mixed liquid and solid meals. Finally, it has been suggested that early satiety and other symptoms of patients with idiopathic dyspepsia may be related to delayed emptying (20, 26). Dyspeptic symptoms may be incorrectly attributed to delayed emptying if the emptying measurements are made when patients are supine and the symptom assessment is done when patients eat meals at home in the more typical seated posture.

With regard to the subjective ratings, in the present study there were no effects of posture or the soup-sandwich interval on the changes in hunger and fullness ratings from before to after ingestion of the soup. This finding is not surprising, since conditions for ingesting the soup were identical in the four conditions. Similarly, there were no significant effects of posture on the changes in hunger and fullness ratings from before ingestion of the soup to after ingestion of the sandwich. Because subjects sat up to ingest the sandwich in the two supine conditions, the difference between the supine and seated conditions in the time spent supine was small until some time after the subjects finished ingesting the sandwich. Thus it is not surprising that posture did not affect the changes in hunger and fullness ratings as a result of ingesting the soup and sandwich.

On the other hand, the soup-sandwich interval did affect the change in fullness ratings from before to after ingestion of the soup and sandwich. Fullness ratings increased more from before ingestion of the soup to immediately after ingestion of the sandwich when subjects ingested the soup immediately than when they ingested the soup 20 min before the sandwich. This effect of the soup-sandwich interval was short lived, however. When the postmeal ratings were matched relative to ingestion of the soup, rather than to ingestion of the sandwich, fullness ratings did not increase more from before to after ingestion of the soup and sandwich in the 0-min compared with the 20-min interval conditions.

These findings imply that in the interval shortly after the meal the subjects' perception of fullness, but not hunger, was very sensitive to the degree of gastric distension. More soup remained in the stomach immediately after ingestion of the sandwich when subjects ingested the soup immediately than when they ingested the soup 20 min before the sandwich. This effect of the soup-sandwich interval was short lived, however. When the postmeal ratings were matched relative to ingestion of the soup, rather than to ingestion of the sandwich, fullness ratings did not increase more from before to after ingestion of the soup and sandwich in the 0-min compared with the 20-min interval conditions.

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Posture did not affect the changes in postprandial hunger and fullness ratings from immediately to 120 min after the meal in the present study. Although emptying of the soup and sandwich was significantly slower in the supine than in the seated conditions, the difference was probably not sufficient to affect these measures of satiety. In two studies (3, 16) with soup
and oil meals, hunger ratings were lower when normal subjects ingested the meal in the left lateral decubitus posture than in the seated posture. Posture had a much greater effect on emptying of this meal than on emptying of the soup and sandwich meal of the present study, however. Furthermore, despite the marked effect of posture on emptying of the soup and oil meal in these two studies (3, 16), hunger ratings were not different between the two postures until 120 min after the meal.

On the other hand, in the present study the soup-sandwich interval affected postprandial satiety, measured by the change in hunger ratings. (The effects were similar but marginally significant in the case of the fullness ratings.) The slower recovery of postprandial hunger in the 20-min than in the 0-min interval conditions when ratings were synchronized relative to ingestion of the sandwich may be related to the cumulative effects of earlier stimulation of intestinal receptors by the soup. More soup had emptied before subjects began to ingest the sandwich in the 20-min than in the 0-min conditions. Because of this “head start” in emptying, a larger area of the intestine would have been stimulated by the soup at any given postprandial measurement interval.

In rats, the satiating effects of nutrients infused into the intestine increase with the area of intestine stimulated (24). The results of several studies suggest that a similar phenomenon occurs in human subjects. Slowing absorption of a glucose drink (22) or a high-fat soup (11) by addition of guar gum reduces postprandial hunger ratings and increases postprandial fullness ratings. The authors (11, 22) suggest that slowing absorption affects satiety by increasing the exposure time of intestinal receptors to nutrients.

The fact that the recovery of postprandial hunger ratings was still slower in the 20-min than in the 0-min interval conditions when ratings were synchronized by time since ingestion of the soup suggests that the area of intestine stimulated by emptying of the soup was not the only factor that enhanced postprandial satiety in the 20-min interval conditions. There was no evidence that the soup emptied more quickly in the 20-min than in the 0-min interval conditions. Thus, when ratings were synchronized relative to ingestion of the soup, the amount of soup that had emptied and, therefore, the area of intestine stimulated at each rating time were presumably similar across conditions. Apparently, the earlier stimulation of intestinal receptors by emptying of the soup relative to ingestion of the sandwich, not just the area of intestine stimulated, enhanced postprandial satiety in the 20-min compared with the 0-min interval conditions.

Our results suggest that the relative contributions of gastric distension, on the one hand, and intestinal stimulation by nutrients, on the other hand, to perceptions of hunger and fullness depend on time since the meal. The perception of fullness immediately after the meal was apparently driven more by gastric distension than by the 20-min head start in stimulation of intestinal receptors by emptying of the soup. On the other hand, the 20-min head start in emptying of the soup slowed the recovery of postprandial hunger ratings over the next 2 h. Hunger immediately after the meal was not different between the 20-min and 0-min interval conditions. Thus the advance stimulation of intestinal receptors by emptying of the soup had to be sustained for some length of time before it affected the subjects’ experience of hunger.

The generality of our findings needs to be explored using other meal components and intervals. The robustness of the effect of the soup-sandwich interval on postprandial satiety should be tested in future studies by measuring subjects’ intake in an ad libitum meal at the point of maximum difference in ratings between the two conditions (90 min after subjects ingested the sandwich in the present study). However, the present findings suggest that ingestion of a nutrient liquid course immediately rather than 20 min before ingestion of a solid food may enhance the perception of fullness immediately after the meal. Pausing between ingestion of a nutrient liquid course and ingestion of a solid food, on the other hand, may slow the postprandial recovery of hunger.

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REFERENCES