

Role of caloric content on gastric emptying in humans

J. A. L. Calbet* and D. A. MacLean

Copenhagen Muscle Research Center, Rigshospitalet, Copenhagen, Denmark and

**Departamento de Educación Física, Universidad de Las Palmas de Gran Canaria, Las Palmas de Gran Canaria, Spain*

1. This study examined the effects of caloric content (caloric density and the nature of calories) on the rate of gastric emptying using the double-sampling gastric aspiration technique. Four test meals of 600 ml (glucose, 0.1 kcal ml⁻¹; pea and whey peptide hydrolysates, both 0.2 kcal ml⁻¹; milk protein, 0.7 kcal ml⁻¹) were tested in six healthy subjects in random order on four separate occasions.
2. The glucose solution was emptied the fastest with a half-time of 9.4 ± 1.2 min ($P < 0.05$) and the milk protein the slowest with a half-time of 26.4 ± 10.0 min ($P < 0.05$); the pea peptide hydrolysate and whey peptide hydrolysate solutions had half-times of emptying of 16.3 ± 5.4 and 17.2 ± 6.1 min, respectively. The rates of gastric emptying for the peptide hydrolysate solutions derived from different protein sources were not different.
3. Despite the lower rate of gastric emptying for the milk protein solution, the rate of caloric delivery to the duodenum during the early phase of the gastric emptying process was higher than that for the other three solutions (46.3 ± 6 , 63.5 ± 22 , 62.5 ± 19 and 113.8 ± 25 cal min⁻¹ kg⁻¹ for the glucose, pea peptide hydrolysate, whey peptide hydrolysate and milk protein meals, respectively; $P < 0.05$). The caloric density of the test solutions was linearly related to the half-time of gastric emptying ($r = 0.96$, $P < 0.05$) as well as to the rate at which calories were delivered to the duodenum ($r = 0.99$, $P < 0.001$).
4. This study demonstrates that the rate of gastric emptying is a function of the caloric density of the ingested meal and that a linear relationship exists between these variables. Furthermore, the nature of the calories seems to play a minor role in determining the rate of gastric emptying in humans.

The regulation of gastric emptying is a complex process which depends on such factors as: (1) the systemic hormonal environment, (2) the activity of the enteric nerves, (3) the drive from the central nervous system, and, possibly the most important, (4) the properties of the ingested meal. Several studies have identified different properties of a meal which influence the rate of gastric emptying. It has been demonstrated that low pH and temperature, as well as high osmolality, viscosity, fibre content and caloric density (caloric content), delay gastric emptying (Costill & Saltin, 1974; Hunt & Stubbs, 1975; Holt, Heading, Carter, Prescott & Tothillet, 1979; McHugh & Moran, 1979; Brener, Hendrix & McHugh, 1983; Fisher, Rock & Malmud, 1987; Velchik, Reynolds & Alavi, 1989; Lin, Doty, Reedy & Meyer, 1990a,b; Lin, Elashoff, Gu & Meyer, 1993; Maerz, Sankaran, Scharpf & Deveney, 1994; Vist & Maughan, 1995). Moreover, ingestion of a large volume has been shown to increase the rate of gastric emptying (Hunt & McDonald, 1954; Hunt & Stubbs, 1975; Mitchell & Voss, 1991). The relative importance of these factors has not been established, but there is some evidence that caloric density may be the main factor in regulating the rate of gastric

emptying. Hunt & Stubbs (1975) showed by retrospective analysis of thirty-three different human studies that the rate of gastric emptying decreased as an exponential function of caloric density over the range of 0.14–2.3 kcal min⁻¹, regardless of the nature of the calories. Subsequently, a linear relationship was established between the rate of caloric delivery to the duodenum and the caloric density of the meal. However, this relationship has been questioned by others who found the rate of caloric delivery to the duodenum to be either constant (Costill & Saltin, 1974; McHugh & Moran, 1979; Brener *et al.* 1983; Maerz *et al.* 1994), or curvilinear (Velchik *et al.* 1989; Beckers, Leiper & Davidson, 1992; Vist & Maughan, 1994).

These discrepancies may be due to variations in meal properties, as well as differences in the methodologies used to measure the rate of gastric emptying. Several studies have used the single-sampling technique, whereby the gastric contents are determined at a single time point during the experiment. A drawback of this technique is the inability to examine the kinetic nature of gastric emptying over time, which is often exponential. Therefore, contradictory interpretations may have occurred when

trying to compare the results from different studies at different time points. However, by using the double-sampling technique, multiple determinations of gastric volume and secretion can be made during a single experiment (Beckers, Rehner, Brouns, Ten Hoor & Saris, 1988). Thus allowing the examination of the influence of various factors on the gastric emptying curve.

With regard to meal properties, Vist & Maughan (1995), using the double-sampling technique, demonstrated that both osmolality and carbohydrate content influenced the rate of gastric emptying, with caloric content being the strongest factor. However, no clues were given in that study to the role that the nature of calories (i.e. protein and fat) plays on the rate of gastric emptying. It has been reported that the rates of gastric emptying for isocaloric amounts of fat, protein and carbohydrates are similar (Hunt & Stubbs, 1975; McHugh & Moran, 1979; Maerz *et al.* 1994). In contrast, others have reported faster rates for fat than for protein calories (Fisher *et al.* 1987), or lower rates for fat than for carbohydrate calories (Sidery, MacDonald & Blackshaw, 1994). In addition, a recent study in rats by Maerz *et al.* (1994) showed that the rate of gastric emptying was constant, regardless of the nature of the calories (fat, protein, carbohydrate). However, none of these studies have controlled for the effect of osmolality on the rate of gastric emptying. Therefore, the purpose of present study was 2-fold: (1) to examine the effect of caloric density on the rate of gastric emptying in humans and (2) to investigate the role that the nature of calories plays on the rate of gastric emptying by using test meals differing in caloric density and composition but equalized for other meal properties such as osmolality, volume, pH and temperature.

METHODS

Subjects

Six healthy subjects (three males and three females) with no clinical history of gastrointestinal disease participated in this study. Their ages, weights and heights were (means \pm S.E.M.) 22.7 ± 0.9 years, 73.2 ± 3.2 kg and 177.3 ± 4.1 cm, respectively. The experimental protocol was approved by the ethical committee for Copenhagen and Frederiksberg communities and the subjects were informed of the purposes and risks of the study and written consent was obtained.

Test solutions

Four different test solutions of 600 ml were used in this study (Table 1). The glucose solution (control) was composed of glucose (0.025 g ml⁻¹) and NaCl (0.9%) and the three additional solutions were prepared so that they all contained the same quantity of glucose (0.025 g ml⁻¹) and protein (0.25 g (kg body mass)⁻¹, equivalent to one-third of the daily dietary allowance for protein). However, the protein compounds were derived from different sources. One of the solutions was prepared from a pea protein hydrolysate and the other was prepared from a whey protein hydrolysate (both from MD Foods, Denmark). The pea and whey peptide hydrolysate solutions contained different quantities of essential (35.5 and 45.1% , respectively) and non-essential amino

acids (64.5 and 54.9% , respectively). The last solution was prepared from milk protein (MD Foods) and represented an intact protein meal. Preliminary experiments showed that similar osmolalities between the three protein solutions could be achieved by adding 36.4 mg (kg body weight)⁻¹ of NaCl to both the pea and whey peptide hydrolysate solutions. Each test solution was delivered at 37°C after adjusting the pH to 7.0 – 7.1 with 1 N NaOH.

Experimental procedures

Subjects reported to the laboratory after an overnight fast and had a gastroduodenal catheter (Levine type, CH 12, 120 cm) placed in the stomach. Residual gastric contents were then aspirated and the pH measured. The stomach was then washed with 400 ml of deionized water administered with a 50 ml syringe through the nasogastric tube. The gastric washout was readily syphoned and the experiments were only carried out if the washout was clear and free of food residues. After resting for 30 min in a sitting position, one of the four different test solutions was administered through the nasogastric tube. Time zero was taken as the moment when all of the test solution had been administered. The volume remaining in the stomach was assessed using George's double-sampling technique as applied by Beckers *et al.* (1988). Briefly, this procedure is based on the addition of a known quantity of dye marker and gastric volume is calculated as a function of the dilution of this marker. To measure the gastric volume in the stomach, 9 mg of Phenol Red was added to each test solution as the marker. Immediately after the administration of the test solution the gastric contents were mixed using a 50 ml syringe to aspirate and re-inject a 20–30 ml volume 10 times; mixing took approximately 1 min. Immediately after mixing a gastric sample was taken and used to calculate the initial volume of the gastric residue. To assess the volume of the gastric contents at each time point, a 5 ml gastric sample was taken followed by the injection of 5 ml of marker (Phenol Red, 500 mg l⁻¹). The additional marker added was mixed with the gastric contents by pumping in and out with the syringe for 1 min followed by the aspiration of a 2.5 ml sample. Assuming that the amount of dye absorbed or secreted by the stomach during the sampling procedure is negligible, that no water is absorbed by the stomach and that gastric emptying does not occur during mixing or sampling, it is possible to calculate the gastric volume (Beckers *et al.* 1988). Thus, Phenol Red was measured twice at each sampling point, before and after the addition of a known quantity of marker. Gastric samples for the measurement of gastric volume, osmolality and pH were taken every 10 min during the first hour and every 20 min thereafter until the stomach was emptied. The pH was measured immediately during the experiment and the aspirated gastric samples were frozen at -80°C until analysed. The selection of test solution was randomized by Latin square design and each trial was separated by 1 week.

Analysis and calculations

The gastric samples for each subject were thawed and vortexed and the osmolality was immediately measured (by freezing-point depression using a 3W2 osmometer; Advanced Instruments, Norwood, MA, USA). The remainder of the gastric samples were centrifuged (10 000 r.p.m. for 10 min) and the supernatants filtered (Minisart NML, $0.2\ \mu\text{m}$ pore size; Sartorius, Switzerland). The concentration of Phenol Red in the filtrate was analysed spectrophotometrically after dilution (1:20) with NaOH/NaHCO₃.

Gastric emptying curves were constructed and tested for linearity using linear regression. Since the best fit was obtained when a logarithmic transformation of time was used, a linear function equation was derived, $y = a + bx$, where y is the volume remaining

Table 1. Composition of the administered solutions (600 ml)

| | Protein (g) | Nitrogen (g) | Glucose (g) | Lactose (g) | Fat (g) | Na (g) | Cl (g) | Ca (g) | Osmolality (mosmol kg ⁻¹) | pH | Caloric density (kcal ml ⁻¹) |
|-----|----------------|-----------------|----------------|----------------|------------|-----------|-----------|-----------|--|-----------|--|
| PPH | 17.9 ± 0.8 | 2.9 ± 0.1 | 15.0 ± 0.0 | — | — | 0.8 ± 0.0 | 0.5 ± 0.0 | — | 367 ± 9* | 7.0 ± 0.0 | 0.22 ± 0.00* |
| WPH | 18.3 ± 0.8 | 2.9 ± 0.1 | 15.0 ± 0.0 | 0.9 ± 0.0 | < 0.1 | 0.4 ± 0.0 | 0.5 ± 0.0 | 0.2 ± 0.0 | 381 ± 9* | 7.0 ± 0.0 | 0.23 ± 0.00* |
| MP | 18.3 ± 0.8 | 2.9 ± 0.1 | 15.0 ± 0.0 | 25.7 ± 1.1 | 17.6 ± 0.8 | 0.3 ± 0.0 | < 0.1 | 0.9 ± 0.1 | 348 ± 12* | 7.1 ± 0.0 | 0.66 ± 0.02*†‡ |
| Glu | — | — | 15.0 ± 0.0 | — | — | 2.0 ± 0.0 | 3.2 ± 0.0 | — | 418 ± 6 | 7.1 ± 0.1 | 0.10 ± 0.00 |

Values are means ± S.E.M.; $n = 6$ for all solutions tested. PPH, pea peptide hydrolysate; WPH, whey peptide hydrolysate; MP, milk protein; Glu, glucose. * $P < 0.05$, compared with glucose solution; † $P < 0.05$, compared with WPH solution; ‡ $P < 0.05$, compared with PPH solution (Student's t test; see Methods). The calculation of the composition of the protein solutions was based on information from the suppliers.

in the stomach and x is the logarithm of time. The time taken to empty one-half of the initial gastric volume ($t_{1/2}$) was derived by solving this equation.

Statistics

A two-way repeated measure analysis of variance was used to examine the effects of treatment and time. If significance was indicated, Student's paired t test was used to compare means among solutions and over time. The results were corrected for multiple comparisons using the Newman-Keuls *post hoc* test. The relationship between osmolality and gastric emptying was assessed using the Pearson's correlation test. Statistical significance was accepted at $P < 0.05$. Data are presented as means ± S.E.M.

RESULTS

Rate of gastric emptying

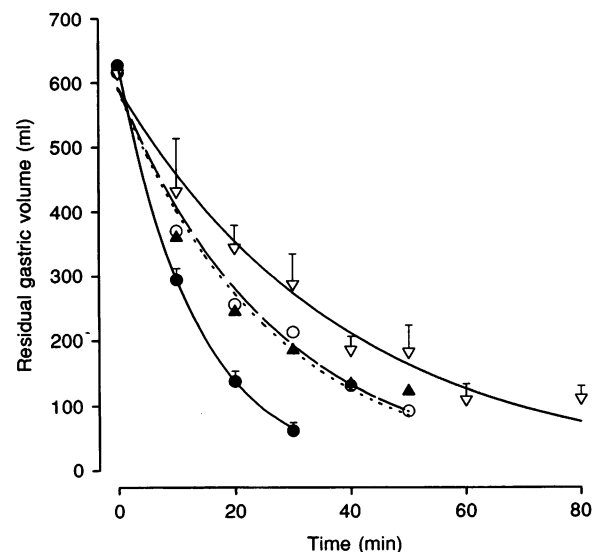
The rate of gastric emptying for all solutions was found to fit an exponential pattern (correlation coefficient $r = 0.86-0.99$; Fig. 1). Despite the higher osmolality (37–70 mosmol kg⁻¹; $P < 0.05$) for the glucose solution (control), it was emptied faster than the other three solutions, with a half-time of

9.4 ± 1.2 min ($P < 0.05$). In contrast, the milk protein solution, which had the highest caloric density, was emptied with a half-time of 26.4 ± 10.0 min ($P < 0.05$). The pea peptide hydrolysate and whey peptide hydrolysate solutions, which differed only in amino acid composition, were emptied at similar rates (16.3 ± 5.4 and 17.2 ± 6.1 min, respectively).

It should be noted that a small quantity of liquid was still present in the stomach (approximately 20 ml) at the time of administration of the test solutions. However, this gastric residue was similar in all trials. The volume remaining in the stomach at any given time represents not only the volume of the administered solution, but also the amount of gastric juice secreted and saliva swallowed. In the present study similar rates of gastric secretion (plus saliva swallowing) were elicited by the four test solutions during the first 30 min of gastric emptying (approximately 2 ml min⁻¹) and thus did not substantially influence the calculation of the rates of gastric emptying.

Figure 1. The rate of gastric emptying of the test solutions

The rate of gastric emptying for all solutions was exponential ($r = 0.86-0.99$). The glucose (●) solution was emptied the fastest (half-emptying time, 9.4 ± 1.2 min; $P < 0.05$) and the milk protein (▽) solution the slowest (26.4 ± 10.0 min; $P < 0.05$); the pea peptide hydrolysate (○) and whey peptide hydrolysate (▲) solutions had half-emptying times of 16.3 ± 5.4 and 17.2 ± 6.1 min, respectively. Symbols represent the mean value at each sampling time when $n = 6$, and vertical bars represent S.E.M.



Relationship between caloric density and gastric emptying

The caloric density of the milk protein solution was higher ($P < 0.05$) than that of the other three solutions, and the caloric density of the two peptide hydrolysate solutions was higher ($P < 0.05$) than that of the glucose solution (Table 1). The relationship between the caloric density of the test solutions and the half-time of gastric emptying is illustrated in Fig. 2. Caloric density was closely related to the half-time of gastric emptying ($r = 0.96$; $P < 0.05$). Although in this experimental setting caloric density played a major role in determining the half-time of gastric emptying (92% of the variance), some contribution of other factors cannot be excluded.

During the first half of the gastric emptying phase the rate of caloric delivery to the duodenum was higher for the milk protein solution than for the other three solutions. There were no significant differences in the rate at which calories were delivered to the duodenum between the glucose, pea and whey peptide hydrolysate solutions. As depicted in Fig. 2, a linear relationship was observed between the caloric density of the solutions and the rate at which calories were delivered to the duodenum ($r = 0.99$; $P < 0.001$). Despite the fact that the increased caloric density of the milk protein solution slowed gastric emptying, the actual rate of caloric delivery to the duodenum was increased compared with the other test solutions (46.3 ± 2.4 , 63.5 ± 9.0 , 62.5 ± 7.8 and 113.8 ± 10.2 cal min⁻¹ (kg body weight)⁻¹ for the glucose, pea and whey peptide hydrolysate meals, respectively; $P < 0.05$).

Changes in osmolality and pH of the gastric contents

All the test solutions had similar osmolalities except the glucose solution, which had a higher osmolality (9–17% higher). However, no relationship was found between the osmolality of any of the administered solutions and the rate

of gastric emptying (Fig. 3). During the first 30 min the glucose solution had consistently higher osmolalities, but this was only found to be significant at 10 min (400.7 ± 5.0 ; 344.5 ± 15.4 ; 333.2 ± 19.5 and 332.7 ± 20.1 mosmol kg⁻¹, for the glucose, pea peptide hydrolysate, whey peptide hydrolysate and milk protein solutions, respectively; $P < 0.05$). When the osmolality change of the gastric contents was represented in relative terms (percentage change from time 0; Fig. 3), no differences were observed between solutions during the first 30 min of gastric emptying. In contrast, at 50 min the percentage decrease in osmolality was greater for the pea peptide hydrolysate solution than for both the whey peptide hydrolysate and milk protein solutions ($P < 0.05$), and at 60 min the percentage decrease in osmolality was greater for the whey peptide hydrolysate than for the milk protein solution ($P < 0.05$).

The pH of all the solutions was adjusted to 7.0–7.1 prior to their administration. After delivering the solutions the pH of the glucose solution rapidly decreased ($P < 0.05$), and during the first 30 min the pH of the glucose solution was lower ($P < 0.05$) than the other three solutions (Fig. 4). Regardless of the solution, the pH of the gastric contents decreased as time progressed ($P < 0.05$) until it reached a value close to that observed prior to solution administration (pH before solution administration, 1.9 ± 0.1 ; final pH, 1.9 ± 0.1). No significant differences in pH were observed between the pea peptide hydrolysate, the whey peptide hydrolysate and the milk protein solutions.

DISCUSSION

Gastric emptying rates of the test solutions

The fastest rate of gastric emptying was observed for the glucose solution followed by the pea and whey peptide hydrolysate solutions, while the slowest rate of gastric

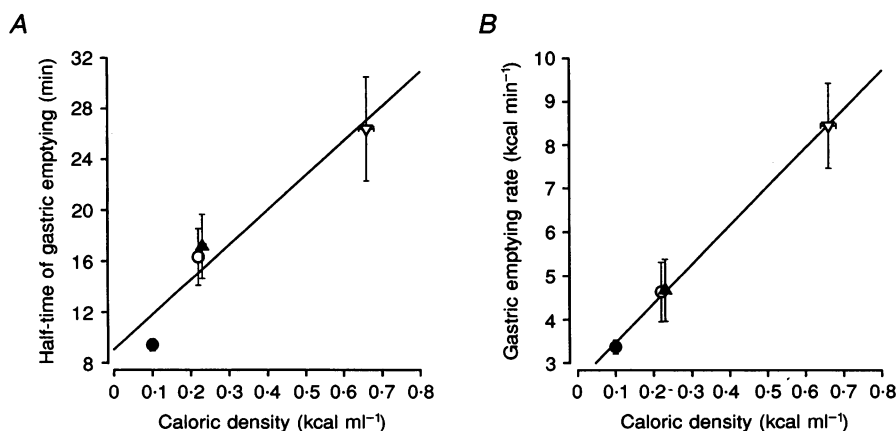


Figure 2. The relationship between caloric density and the rate of gastric emptying

A, the half-time of the gastric emptying process was closely related to the caloric density of the test solution ($r = 0.96$, $P < 0.05$). B, the rate of caloric delivery to the duodenum during the first half of the gastric emptying process was also closely related to the caloric density of the test solution ($r = 0.99$, $P < 0.001$). Symbols represent mean values ($n = 6$), and vertical as well as horizontal bars represent the s.e.m. values. Solutions: ●, glucose; ○, pea peptide hydrolysate; ▲, whey peptide hydrolysate; ▽, milk protein.

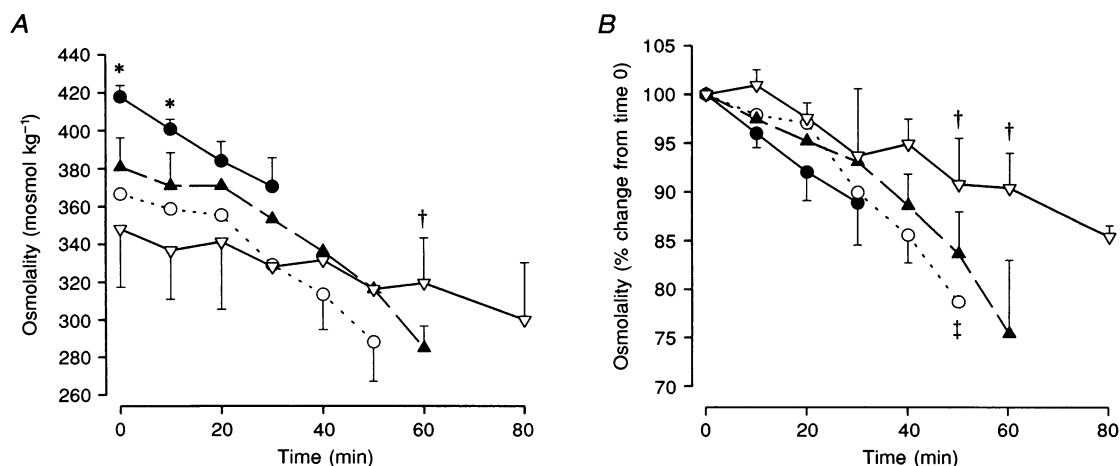


Figure 3. Osmolality of the gastric contents

A decrease in the osmolality of the gastric contents was observed when measured both in absolute units (A) and in standardized units (B). The line for each test solution ends at the last sampling point where $n = 6$. * $P < 0.05$, comparing glucose solution (●) with pea peptide hydrolysate (○), whey peptide hydrolysate (▲) and milk protein (▽) solutions. † $P < 0.05$, comparing milk protein with whey peptide hydrolysate. ‡ $P < 0.05$ when comparing milk protein with pea peptide hydrolysate. Symbols and vertical bars represent means \pm S.E.M. (error bars crossing each other are omitted).

emptying was observed for the milk protein solution. The half-emptying times observed for the glucose (9.4 min) and milk protein (26.4 min) solutions were similar to those previously reported for carbohydrate and protein solutions. For example, half-emptying times between 6 and 13 min have been reported for plain water (Hunt & McDonald, 1954; Rehner, Beckers, Brouns, Ten Hoor & Saris, 1989; Mahé, Huneau, Marteau, Thuiller & Tomé, 1992; Baglieri *et al.* 1994; Vist & Maughan 1994), a 2.5% glucose and water solution (Costill & Saltin, 1974; Vist & Maughan, 1994) physiological saline (0.9% NaCl; Brener *et al.* 1983) and an isotonic carbohydrate–electrolyte solution (Rehner *et al.* 1989). The half-emptying times observed for the milk protein solution (26 min) were close to that reported for skimmed milk (25 min; Mahé *et al.* 1992), but a little faster than those reported for soy-protein solutions (36–38 min)

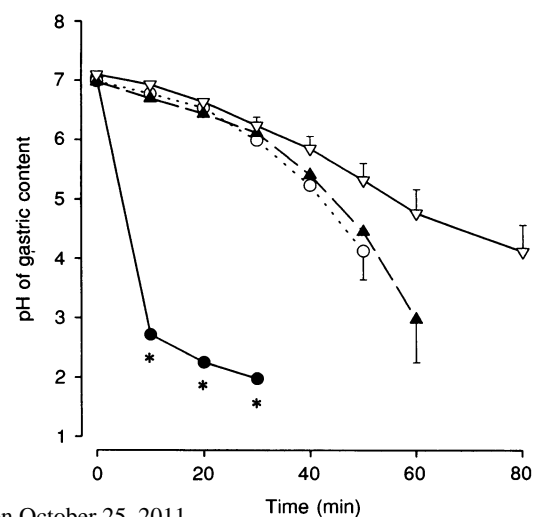
with a nitrogen content similar to that used in the present study (Baglieri *et al.* 1994). The pea and whey peptide hydrolysate solutions showed faster half-emptying times, which were closer to those reported for carbohydrate solutions of similar caloric density (Vist & Maughan, 1995).

Relationship between caloric density and gastric emptying

One interesting finding was the close linear relationship observed between the caloric density of the test solution and the rate of gastric emptying. Despite its higher osmolality the glucose solution was emptied at the fastest rate, confirming the notion that gastric emptying is controlled more by caloric content than by solute osmolality (Hunt, Smith & Jiang, 1985; Lin *et al.* 1993; Vist & Maughan, 1994, 1995). It has been suggested that the energy

Figure 4. The pH of the gastric contents

A faster decrease in pH was observed for the glucose (●) solution; * $P < 0.05$, comparing glucose with the other three test meals: pea peptide hydrolysate (○), whey peptide hydrolysate (▲) and milk protein (▽). Symbols and vertical bars represent means \pm S.E.M. ($n = 6$). In some instances, as for example for the glucose solution, error bars are smaller than the symbols.



properties of the meal are detected by duodenal receptors which regulate the rate of gastric emptying, as it has been shown that the direct instillation of 82 kcal of glucose into the duodenum inhibits the emptying of saline (Brenner *et al.* 1983). The delaying effect of caloric density on gastric emptying seems to be independent of the nature of the solutes, that is, being similar for isocaloric amounts of carbohydrate, protein and fat (Hunt & Stubs, 1975; McHugh & Moran, 1979; Maerz *et al.* 1994). Within the range of caloric densities tested in the present study (0.1–0.7 kcal ml⁻¹), the differences in test solution composition (i.e. protein and fat) did not markedly modify the rate of gastric emptying.

The caloric density of the milk protein solution was 6 times higher than the glucose solution and 3 times higher than both the peptide hydrolysate solutions. As a result, more calories per minute were delivered from the stomach to the duodenum when the milk protein solution was administered. These findings are in contrast to those of Brenner *et al.* (1983), who reported that the caloric delivery rate from the stomach to the duodenum was constant (2.1 kcal min⁻¹) for carbohydrate solutions over a wide range of glucose concentrations (50–1000 g l⁻¹). Similarly, Costill & Saltin (1974) reported a constant value of 2.5 kcal min⁻¹ for ingested solutions ranging in glucose concentration from 25 to 150 g l⁻¹. A constant rate of caloric delivery to the duodenum has also been reported in monkeys and rats (McHugh & Moran, 1979; Maerz *et al.* 1994), regardless of the nature of the solutes. In the present study the utilization of the double-marker dilution technique enabled us to calculate the $t_{1/2}$ for each solution with a precision similar to or higher than those reported using scintigraphic methods (Beckers *et al.* 1992). Thus, the rate of caloric delivery to the duodenum can be calculated by dividing one-half of the initial caloric content of the test solution by the half-time for gastric emptying. Using this approach, higher rates of caloric delivery to the duodenum were observed in the present study during the first half of the gastric emptying process (3.4 ± 0.4 kcal min⁻¹) than have normally been reported. However, these values are in close agreement with those reported by others who have also used the double-label sampling technique (Beckers *et al.* 1992; Vist & Maughan, 1994). Our higher rates of gastric emptying can also be related to the fact that a small amount of NaCl in the solutions can potentiate intestinal absorption of sugars and amino acids (Curran, Schultz, Chez & Fuisz, 1967).

Other factors influencing gastric emptying

In this study, caloric density seemed to be the main factor determining the rate of gastric emptying. However, when the solutions were adjusted for this variable, differences still existed. Therefore, other factors such as osmolality and nutrient composition have to be considered when explaining the regulation of gastric emptying. Differences in solution osmolality may play a crucial role in determining the rate of gastric emptying when a high osmolality delays gastric

emptying (Ferreira, Elliot, Watson, Brennan, Walker-Smith & Farthing, 1992; Hunt, Thillainayagam, Salim, Carnaby, Elliot & Farthing, 1992; Vist & Maughan, 1995). In this study, the glucose and milk protein solutions had the highest and lowest osmolalities, respectively, and thus one might expect that the rate of gastric emptying would be slowest for the glucose and fastest for the milk protein solution. However, completely the opposite was observed. Vist & Maughan (1995) demonstrated that for solutions of similar caloric densities, decreasing (5 times isotonic) the osmolality did not affect the rate of gastric emptying, while increasing (5 times isotonic) the osmolality delayed the rate of gastric emptying by 50%. The differences in osmolalities between solutions were quite small (348–418 mosmol kg⁻¹) in the present study, but increasing the caloric density 6-fold resulted in a 3-fold decrease in the rate of gastric emptying. Thus it would appear that the influence of osmolality on the rate of gastric emptying may be of physiological relevance only at high tonicity levels.

The nature of the calories incorporated in the meal has also been reported to influence the rate of gastric emptying. Fisher *et al.* (1987) assessed the rate of gastric emptying of four meals equalized for volume (315 ml) and caloric content (380 kcal). They observed that a pure fat meal (43 g) and a multicomponent meal (20 g fat, 17 g protein and 33 g carbohydrate) were emptied more rapidly than both a monocomponent protein meal (95 g of protein) and a monocomponent carbohydrate meal (95 g). However, the meals administered in the study of Fisher *et al.* (1987) differed markedly in osmolality (from 20 mosmol kg⁻¹ for the fat meal to 1720 mosmol kg⁻¹ for the pure carbohydrate meal), which, as discussed above, probably contributed to the delayed emptying of the carbohydrate meal. Conversely, a study by Sidery *et al.* (1994) reported lower gastric emptying rates for a high fat–low carbohydrate meal than for a high carbohydrate–low fat meal, both equalized for total calories. However, in that study the meals differed in total volume (i.e. caloric density) and the osmolality was not reported. Therefore, a number of other factors may have contributed to the lower rate of gastric emptying observed for the high fat meal. More recently, a study in rats showed that the rate of gastric emptying was constant, regardless of the nature of the calories (Maerz *et al.* 1994). In the present study similar rates of gastric emptying were found for peptide hydrolysate solutions derived from different sources (pea *vs.* whey) and differing in amino acid composition.

In summary, this study clearly shows that, in healthy humans, when solutions of similar volumes and osmolalities are administered at the same temperature and pH, the rate of gastric emptying is mainly a function of caloric density. In the range of caloric densities used in the present study, the pattern of gastric emptying from the stomach was observed to be exponential. Lastly, it was determined that a linear relationship exists between the caloric density of the test solution and the rate of gastric emptying.

- BAGLIERI, A., MAHE, S., ZIDI, S., HUNEAU, J. F., THUILLIER, F., MARTEUA, P. & TOME, D. (1994). Gastro-jejunal digestion of soya-bean-milk protein in humans. *British Journal of Nutrition* **72**, 519–532.
- BECKERS, E. J., LEIPER, J. B. & DAVIDSON, J. (1992). Comparison of aspiration and scintigraphic techniques for the measurement of gastric emptying rates of liquids in humans. *Gut* **33**, 115–117.
- BECKERS, E. J., REHRER, N. J., BROUNS, F., TEN HOOR, F. & SARIS, W. H. M. (1988). Determination of total gastric volume, gastric secretion and residual meal using the double sampling technique of George. *Gut* **29**, 1725–1729.
- BRENER, T., HENDRIX, T. R. & MCHUGH, P. R. (1983). Regulation of gastric emptying of glucose. *Gastroenterology* **85**, 76–82.
- COSTILL, D. L. & SALTIN, B. (1974). Factors limiting gastric emptying during rest and exercise. *Journal of Applied Physiology* **37**, 679–683.
- CURRAN, P. F., SCHULTZ, S. G., CHEZ, R. A. & FUISZ, R. E. (1967). Kinetic relations of the Na–amino acid interaction at the mucosal border of the intestine. *Journal of General Physiology* **50**, 1261–1286.
- FERREIRA, R. M., ELLIOT, E. J., WATSON, A. J. M., BRENNAN, E., WALKER-SMITH, J. A. & FARTHING, M. J. G. (1992). Dominant role of osmolality in the efficacy of glucose and glycine-containing oral rehydration solutions: studies in a rat model of secretory diarrhoea. *Acta Paediatrica* **81**, 46–50.
- FISHER, R. S., ROCK, E. & MALMUD, L. S. (1987). Effects of meal composition on gallbladder and gastric emptying in man. *Digestive Diseases and Sciences* **32**, 1337–1344.
- HOLT, S., HEADING, R. C., CARTER, D. C., PRESCOTT, L. F. & TOTHILL, P. (1979). Effect of gel fibre on gastric emptying and absorption of glucose and paracetamol. *Lancet* **125**, 636–639.
- HUNT, J. B., THILLAINAYAGAM, A. V., SALIM, A. F. M., CARNABY, S., ELLIOT, E. J. & FARTHING, M. J. G. (1992). Water and solute absorption from a new hypotonic oral rehydration solution: evaluation in human and animal perfusion models. *Gut* **33**, 1652–1659.
- HUNT, J. N. & McDONALD, I. (1954). The influence of volume on gastric emptying. *Journal of Physiology* **126**, 459–474.
- HUNT, J. N., SMITH, J. L. & JIANG, C. L. (1985). Effect of meal volume and energy density on the gastric emptying of carbohydrates. *Gastroenterology* **89**, 1326–1330.
- HUNT, J. N. & STUBBS, D. F. (1975). The volume and energy content of meals as determinants of gastric emptying. *Journal of Physiology* **245**, 209–225.
- LIN, H. C., DOTY, J. E., REEDY, T. J. & MEYER, J. H. (1990a). Inhibition of gastric emptying by acids depends on pH, titrable acidity, and length of intestine exposed to nutrient. *American Journal of Physiology* **259**, G1025–1030.
- LIN, H. C., DOTY, J. E., REEDY, T. J. & MEYER, J. H. (1990b). Inhibition of gastric emptying by sodium oleate depends on length of intestine exposed to nutrient. *American Journal of Physiology* **259**, G1031–1036.
- LIN, H. C., ELASHOFF, J. D., GU, Y. G. & MEYER, J. H. (1993). Nutrient feedback inhibition of gastric emptying plays a larger role than osmotically dependent duodenal resistance. *American Journal of Physiology* **265**, G672–676.
- MCHUGH, P. R. & MORAN, T. H. (1979). Calories and gastric emptying: a regulatory capacity with implications for feeding. *American Journal of Physiology* **242**, R491–497.
- MAERZ, L. L., SANKARAN, H., SCHARPF, S. J. & DEVENY, C. W. (1994). Effect of caloric content and composition of a liquid meal on gastric emptying in the rat. *American Journal of Physiology* **267**, R1163–1167.
- MAHÉ, S., HUNEAU, J. F., MARTEAU, P., THUILLER, F. & TOMÉ, D. (1992). Gastro-ileal and electrolyte movements after bovine milk ingestion in humans. *American Journal of Clinical Nutrition* **56**, 410–416.
- MITCHELL, J. B. & VOSS, K. W. (1991). The influence of volume on gastric emptying and fluid balance during prolonged exercise. *Medicine and Science in Sports and Exercise* **23**, 314–319.
- REHRER, N. J., BECKERS, E., BROUNS, F., TEN HOOR, F. & SARIS, W. H. M. (1989). Exercise and training effects on gastric emptying of carbohydrate beverages. *Medicine and Science in Sports and Exercise* **21**, 540–549.
- SIDERY, M. B., MACDONALD, I. A. & BLACKSHAW, P. E. (1994). Superior mesenteric artery blood flow and gastric emptying in humans and the differential effects of high fat and high carbohydrate meals. *Gut* **35**, 186–190.
- VELCHIK, M. G., REYNOLDS, J. C. & ALAVI, A. (1989). The effect of meal energy content on gastric emptying. *Journal of Nuclear Medicine* **30**, 1106–1110.
- VIST, G. E. & MAUGHAN, R. J. (1994). Gastric emptying of ingested solutions in man: effect of beverage glucose concentration. *Medicine and Science in Sports and Exercise* **26**, 1269–1273.
- VIST, G. E. & MAUGHAN, R. J. (1995). The effect of osmolality and carbohydrate content on the rate of gastric emptying of liquids in man. *Journal of Physiology* **486**, 523–531.

Acknowledgements

The authors wish to thank Charlotte Mortensen for her excellent technical assistance. The funding for this project, as well as the peptide hydrolysates, were generously provided by MD Foods, Denmark.

Received 16 April 1996; accepted 30 August 1996.