The effect of osmolality and carbohydrate content on the rate of gastric emptying of liquids in man

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1. The effect of osmolality and carbohydrate content on the rate of gastric emptying was assessed by using the double sampling gastric aspiration technique to measure the rate of gastric emptying of isoenergetic and isosmotic solutions of glucose and glucose polymer. Six healthy male subjects were each studied on four separate occasions using a test drink volume of 600 ml.

2. The half-emptying time ($t_{½}$, mean ± S.E.M.) for a dilute (40 g l^{-1}) solution of glucose (LG, 230 mosmol kg^{-1}) was 17 ± 1 min. This was greater than that (14 ± 1 min) for a glucose polymer solution with the same energy content (LP, 42 mosmol kg^{-1}). A concentrated (188 g l^{-1}) glucose polymer solution (HP, 237 mosmol kg^{-1}) emptied faster ($t_{½}$ = 64 ± 8 min) than the corresponding isoenergetic glucose solution (HG, 1300 mosmol kg^{-1}, $t_{½}$ = 130 ± 18 min).

3. The dilute (40 g l^{-1}) glucose solution emptied faster than the concentrated (188 g l^{-1}) glucose polymer solution with the same osmolality (LG, 230 mosmol kg^{-1}; HP, 237 mosmol kg^{-1}).

4. The two dilute solutions (40 g l^{-1}) delivered a similar amount of carbohydrate to the small intestine, whereas the concentrated (188 g l^{-1}) glucose polymer solution delivered a greater amount of carbohydrate at 20, 40 and 50 min than the isoenergetic glucose solution.

5. These results indicate that both osmolality and carbohydrate content influence gastric emptying of liquids in man, but the carbohydrate content appears to have greater influence than osmolality. The osmolality effect is more marked at high concentrations of carbohydrate.

The rate of gastric emptying in man has been shown to be slowed both by an increase in carbohydrate content and by an increase in osmolality (Hunt & Knox, 1968; Costill & Saltin, 1974; Barker, Cochrane, Corbett, Dufton, Hunt & Roberts, 1978; Foster, Costill & Fink, 1980), but the extent to which these two factors act independently on the emptying function of the stomach is at present unclear. For any given carbohydrate source, concentration and osmolality increase in parallel. Carbohydrate content and osmolality can be varied independently, however, by using mixtures of glucose, glucose polymers and starches. Mixtures of these sugars can therefore be employed to investigate the separate effects of osmolality and carbohydrate content on gastric emptying.

Based on the known effects of osmolality on gastric emptying, it might be proposed that, because a glucose polymer solution has a lower osmolality than an isoenergetic glucose solution, the glucose polymer solution will empty more quickly than the monomeric glucose solution. There is some experimental evidence to support this hypothesis, but the data in the published literature are inconclusive.

Hunt (1960) found that 20 min after ingesting isoenergetic solutions of starch and glucose, the starch solution had a smaller volume in the stomach than the glucose solution; at 30 min after ingestion, the volumes were similar. Foster *et al.* (1980) found a dilute (50 g l^{-1}) glucose polymer solution emptied faster after 30 min than an isoenergetic glucose solution, whereas more concentrated (100, 200 and 400 g l^{-1}) solutions of glucose polymer and glucose emptied at similar rates. In direct contrast to these results, however, Sole & Noakes (1989) found similar rates of gastric emptying for 50 g l^{-1} solutions of glucose polymer and glucose, whereas a 150 g l^{-1} glucose polymer solution was emptied faster than an isoenergetic glucose solution. Similar rates of gastric emptying for isoenergetic solutions of glucose polymer and glucose have also been reported for 30 g l^{-1} solutions (Naveri, Tikkanen, Kairento & Harkonen, 1989) and 100 g l^{-1} solutions (Owen, Kregel, Wall & Gisolfi, 1986).

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There are several possible explanations for these contradictory results. In all of the studies quoted above, a single time point gastric aspiration method was used to determine the rate of gastric emptying, and it has been common to report results as the volume remaining in the stomach after a predetermined time period. Because of the exponential nature of the rate of gastric emptying of most solutions (Hunt & Spurrell, 1951; Hunt & McDonald, 1954; Rehrer, Beckers, Brouns, ten Hoor & Saris, 1989), a single time point measurement may produce misleading results. Comparisons between results obtained from different laboratories are difficult because different investigators have used different times of sampling after ingestion. In an attempt to avoid this confusion, several investigators have reported the calculated rate of gastric emptying in millilitres per minute, but these results, apart from assuming a linear rate of emptying, are still strongly influenced by the time of sampling. The volume ingested and ingestion pattern have also varied, and volume itself influences the rate of gastric emptying. A further complicating factor in the studies referred to is the presence in some of the test solutions of a variety of other components, including electrolytes, vitamins and flavourings.

The rate of gastric emptying is strongly influenced by the osmolality of the contents of the upper small intestine (Hunt, 1960; Meeroff, Go & Phillips, 1975). If a polymer is rapidly and completely hydrolysed in the small intestine, the osmolality will be similar to that of an isoenergetic glucose solution and therefore the rates of gastric emptying should be similar. If the hydrolysis is slow or not complete, however, the glucose polymer is likely to give a lower osmolality in the small intestine and therefore be emptied at a faster rate than an isoenergetic glucose solution. An incomplete hydrolysis would be more likely when high concentrations of polymers are used, and perhaps also when larger volumes are given.

The aim of this study was to use a double sampling gastric aspiration method, which makes it possible to follow the time course of gastric emptying, to investigate the relative importance of osmolality and carbohydrate content by comparing the rate of gastric emptying of isoenergetic solutions of glucose and glucose polymer at high and low concentrations.

METHODS

The double sampling gastric aspiration method was approved for use in this study by the local ethics committee. Six healthy males volunteered to act as experimental subjects. Their physical characteristics were (median (range)): age, 24 years (21–44 years); height, 1·75 m (1·67–1·87 m); weight, 74·9 kg (65·7–84·2 kg). These subjects had all participated on previous occasions in similar studies, and were therefore entirely familiar with the experimental procedures. Subjects gave their informed, written consent before participation in this investigation.

Four solutions were studied: a dilute (40 g l^{-1}) monomeric glucose solution (LG), a dilute (40 g l^{-1}) glucose polymer solution (LP), an 188 g l^{-1} glucose solution (HG), and an 188 g l^{-1} glucose polymer solution (HP). The solutions were chosen such that LG and HP would have the same osmolality, and that LG and LP were isoenergetic, as were HG and HP. The measured osmolality (mosmol kg^{-1}) of the solutions was: LG, 230 ± 3; LP, 42 ± 1; HG, 1300 ± 4; and HP, 237 ± 3. Total glucosyl content was measured after acid hydrolysis and the mean values were (mmol l^{-1}): LG, 227; LP, 222; HG, 1038; and HP, 1048. The glucose polymer used (Maxijul; Scientific Hospital Supplies, Liverpool, UK) has an average chain length of approximately five glucosyl units. No electrolytes were added to any of the solutions.

Subjects were asked to refrain from strenuous exercise and alcohol for 24 h before the experiments, and reported to the laboratory in the morning after an overnight fast. A nasogastric tube (French Levine, 14 gauge; Vygon, Ecouen, France) was positioned by the recovery test method according to Hassan & Hobsley (1970). Tests were conducted 3–5 days apart and subjects were seated throughout the study. The 600 ml test drink contained 15 mg l^{-1} of Phenol Red, which is not absorbed to any appreciable extent in the stomach (Hollander & Glickstein, 1940), and solutions were given in a randomized order. Solutions were given at room temperature (18–20 °C) and were instilled into the stomach through the tube with the aid of gravity; this procedure was completed within 1 min. Although the test drink was instilled, this will be referred to as ingestion.

Gastric emptying was measured using a modification of the double sampling gastric aspiration technique of George (1968) as described by Beckers, Rehrer, Brouns, ten Hoor & Saris (1988). These procedures are described here only briefly. A sample (2·5 ml) of the test drink is removed before the test starts. Immediately after instillation of the remaining test drink, the contents of the stomach are mixed using a 50 ml syringe to aspirate and immediately re-inject 20–30 ml at least 10 times; mixing takes approximately 1 min. A second sample (2·5 ml) is then taken so that the volume and composition of gastric residue before instillation of the test drink can be calculated. Nine minutes after instillation of the test drink, the gastric contents are mixed and a sample (2·5 ml) aspirated. Ten minutes after instillation of the test drink, 5 ml of dye is added, and the contents mixed again before a second sample (2·5 ml) is aspirated at 11 min after instillation. The volumes calculated from these two samples are referred to as those of the 10 min sample point. From the concentration of dye in the samples, the total volume in the stomach and the volume of test drink remaining at these times are calculated (Beckers *et al.* 1988). The difference between the total gastric volume and the volume of test drink is the volume of secretion and swallowed saliva in the stomach.

Ingested carbohydrates influence the rate of gastric emptying by their action on receptors located in the upper part of the small intestine; the amount of carbohydrate emptied from the stomach into the small intestine is therefore reported. The amount of carbohydrate emptied (reported as moles of glucosyl units) is the difference between the amount ingested and the amount remaining in the stomach at each sample point. The quantity remaining is based on the measured concentration in the aspirated sample and the calculated volume in the stomach at each sample point.

Further measurements were made every 10 min for 1 h after ingestion. The concentration of Phenol Red in the 5 ml aliquot

added at each sampling point was increased progressively to improve the sensitivity of the method: 0·25 g l^{-1} at the 10 and 20 min sample points; 0·50 g l^{-1} at the 30 and 40 min sample points; 1·0 g l^{-1} at the 50 min sample point; and 2·0 g l^{-1} at the 60 min sample point. Phenol Red was analysed spectrophotometrically after dilution (1 : 20) with NaOH–$NaHCO_3$ buffer (250 : 500 mmol l^{-1}, pH 9·7). Free glucose and total glucosyl content after acid hydrolysis were measured enzymatically with a glucose test kit (GOD-Perid kit; Boehringer Mannheim). The pH of the gastric samples was measured within 2·5 h of sampling (pH meter 140; Corning Ltd, Halstead, Essex, UK), and the osmolality by freezing point depression (Osmomat 030; Gonotec, YSI, Farnborough, UK). Sodium and potassium concentration in the samples were measured using flame photometry (Corning Clinical Flame Photometer 410c and Corning 805 Diluter); chloride concentration was determined using a coulometric titrator (PCLM 3; Jenway, Dunmow, Essex, UK).

Statistical analysis was by a two-way repeated measure ANOVA followed by a least significant difference comparison of the means. The half-emptying time ($t_{½}$) was calculated for each solution for each subject, as described by Elashoff, Reedy & Meyer (1982); the values so obtained were compared by one-way analysis of variance followed by Student's t test for paired data. Significance level in all cases was taken to be $P < 0·05$ and results in the text and tables are reported as means ± S.E.M.

RESULTS

Total volume in the stomach

The total volume remaining in the stomach at each measurement point is shown in Fig. 1, and was greater after ingestion of the two concentrated solutions than after ingestion of the two dilute solutions. At the 10 min sample point, there was no difference between the two concentrated solutions (HG, 585 ± 32 ml; HP, 521 ± 20 ml), but at all subsequent sample points the total volume remaining in the stomach was greater after ingestion of the concentrated glucose monomer solution (HG) than after ingestion of the concentrated polymer solution (HP). At the 20 min sample point, the volume remaining in the stomach was greater with LG (277 ± 18 ml) than with LP (223 ± 16 ml), but no difference in the total volume remaining in the stomach between the two dilute solutions was found at any other time point.

Test drink volume remaining in the stomach

The total volume of fluid in the stomach at any time includes not only the ingested test meal, but also any residual fluid and gastric secretions. The test drink volume remaining in the stomach is calculated separately and is shown in Table 1. At the 10 min sample point, there was no difference in the volume of test drink in the stomach between the two dilute solutions (LG and LP) or between the two solutions of the same osmolality (LG and HP). However, the volume of test drink remaining in the stomach at this time was greater after ingestion of HG (535 ± 35 ml) than after ingestion of LG (394 ± 21 ml) or LP (349 ± 28 ml); there was also a significant difference at this time between the two polymer-containing solutions (LP, 349 ± 28 ml; HP, 470 ± 21 ml). At the 20 min sample point, and at all later sample points, the volume of test drink remaining in the stomach was greater after ingestion of HG than after ingestion of HP. The volume of test drink remaining in the stomach was greater after ingestion of either of the concentrated solutions than after ingestion of the dilute solutions.

Although the repeated measures test did not indicate a difference between the two dilute solutions, comparison of the $t_{½}$ data showed a significantly slower emptying rate for the dilute glucose solution (LG, 17 ± 1 min) than for the dilute polymer solution (LP, 14 ± 1 min); the corresponding values for HP and HG were 64 ± 8 and 130 ± 18 min, respectively.

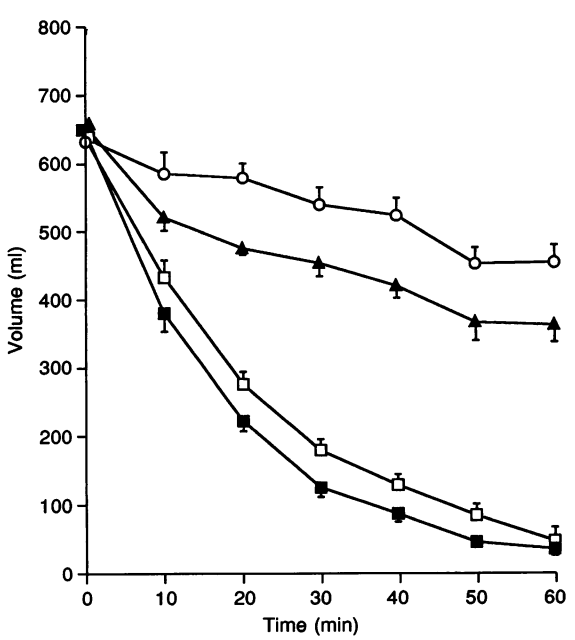

Figure 1. Fluid volume remaining in the stomach
Total volume remaining in the stomach after ingesting 600 ml of test drink containing 40 g l^{-1} glucose (LG, □), 40 g l^{-1} glucose polymer (LP, ■), 188 g l^{-1} glucose (HG, ○) or 188 g l^{-1} glucose polymer (HP, ▲).

Table 1. The volume of test drink remaining in the stomach after ingestion of 600 ml of test drink containing 40 g l^{-1} glucose (LG), 40 g l^{-1} glucose polymer (LP), 188 g l^{-1} glucose (HG) or 188 g l^{-1} glucose polymer (HP)

	Volume of test drink (ml)				
Time (min)	LG	LP	HG	HP	Differences
10	394 ± 21	349 ± 28	535 ± 35	470 ± 21	HG > LG, LP, HP > LP
20	240 ± 13	196 ± 16	506 ± 21	409 ± 13	HG > HP > LG, LP
30	145 ± 15	100 ± 12	455 ± 21	383 ± 21	HG > HP > LG, LP
40	92 ± 15	61 ± 10	426 ± 24	330 ± 31	HG > HP > LG, LP
50	52 ± 14	26 ± 5	350 ± 27	284 ± 36	HG > HP > LG, LP
60	25 ± 12	15 ± 3	334 ± 23	266 ± 35	HG > HP > LG, LP

Significant differences ($P < 0.05$) between pairs of conditions at any time are shown in the righthand column (Differences).

Volume of secretion in the stomach

The difference between the total volume in the stomach and the volume of test drink that remains in the stomach is a result of gastric secretions and swallowed saliva. These are referred to here as secretion volume and are shown in Fig. 2. Even though the stomach was washed and emptied, there is always some gastric residue in the stomach when the test solution is ingested. Differences between the tests in the volume of gastric residue present in the stomach when the solution was instilled were small, and do not reflect any properties of the ingested solutions. For this experiment, there was a greater volume of gastric residue present in the stomach when HP was ingested (55 ± 7 ml) than when HG (38 ± 4 ml) or LG (38 ± 10 ml) was ingested. The difference in gastric residue was small, about 20 ml, relative to the test drink volume instilled into the stomach (600 ml).

At the 10 min sample point and at all the following sample points, the volume of secretion in the stomach was greater after ingestion of the two concentrated solutions than after ingestion of the two dilute solutions. There was no significant difference in the volume of secretion in the stomach between the two concentrated solutions, nor was there any significant difference in the volume of secretion in the stomach between the two dilute solutions. The volume of secretion (ml) in the stomach at the 60 min sample point was: LG, 29 ± 11; LP, 22 ± 5; HG, 123 ± 18; and HP, 97 ± 20. These differences appear to be closely related to the total volume present in the stomach at any time.

Carbohydrate delivery to the small intestine

The amount of carbohydrate delivered to the small intestine from these solutions is shown in Fig. 3, and is

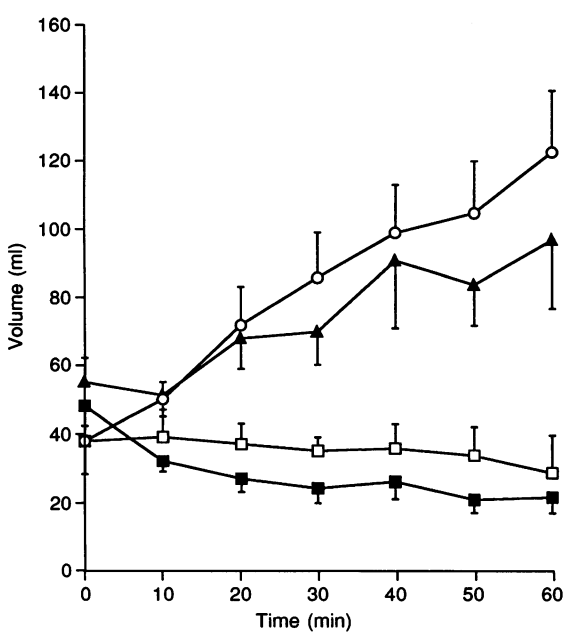

Figure 2. Volume of secretion and swallowed saliva in the stomach

Volume of secretion and swallowed saliva in the stomach after ingesting 600 ml of test drink containing 40 g l^{-1} glucose (LG, □), 40 g l^{-1} glucose polymer (LP, ■), 188 g l^{-1} glucose (HG, ○) or 188 g l^{-1} glucose polymer (HP, ▲).

Table 2. The pH of gastric aspirates after ingestion of 600 ml of test drink LG, LP, HG or HP

	pH of gastric aspirate				
Time (min)	LG	LP	HG	HP	Differences
0	5·4 ± 0·1	5·0 ± 0·1	5·0 ± 0·1	5·2 ± 0·1	—
10	2·3 ± 0·1	2·4 ± 0·1	2·4 ± 0·1	2·5 ± 0·1	—
20	2·0 ± 0·1	2·0 ± 0·1	2·2 ± 0·1	2·2 ± 0·1	HG, HP > LG, LP
30	1·9 ± 0·1	1·8 ± 0·1	2·2 ± 0·1	2·1 ± 0·1	HG, HP > LG, LP
40	1·7 ± 0·1	1·7 ± 0·1	2·2 ± 0·2	2·1 ± 0·1	HG, HP > LG, LP
50	1·6 ± 0·1	1·6 ± 0·1	2·2 ± 0·2	2·0 ± 0·1	HG, HP > LG, LP
60	1·5 ± 0·1	1·6 ± 0·1	2·3 ± 0·3	2·0 ± 0·1	HG > LG

obviously a function of the volume emptied and the carbohydrate concentration. There was no significant difference at the 10 min sample point between the four test solutions in the amount of carbohydrate that had been delivered to the small intestine. There was also no significant difference in the amount of carbohydrate delivered to the small intestine between the two dilute solutions (LG and LP) at any time. At the 20 min sample point, both of the glucose polymer solutions had delivered a greater amount of carbohydrate to the small intestine than HG. At the 30 min sample point, there was again no significant difference in the total amount of carbohydrate delivered to the small intestine from the four different solutions. The amount of carbohydrate (mmol glucosyl units) delivered to the small intestine during the first 30 min was: LG, 97 ± 4; LP, 109 ± 4; HG, 81 ± 22; and HP, 144 ± 30. At the 40 and 50 min sample points, HP had delivered a greater amount of carbohydrate to the small intestine than any of the other solutions, including the isoenergetic glucose solution. At the 60 min sample point, each of the concentrated solutions had delivered a greater amount of carbohydrate to the small intestine than either of the dilute solutions.

pH of the gastric contents

Before ingestion, the four solutions had similar pH values: LG, 5·4 ± 0·1; LP, 5·2 ± 0·03; HP, 5·0 ± 0·1; and HG, 5·0 ± 0·02. At the 10 min sample point, the pH of the gastric contents after ingestion of the four solutions had fallen in all cases, but the values for each of the solutions remained similar (Table 2). At the 20, 30, 40 and 50 min sample points, the pH of the gastric contents after ingesting the two concentrated solutions (HP and HG) was higher than after ingesting the two dilute solutions (LG and LP); this is probably a consequence of the fact that the volume remaining in the stomach was smaller after ingesting the dilute solutions. At the 30 min sample point, the pH of the gastric contents was: LG, 1·9 ± 0·1; LP, 1·8 ± 0·1; HP, 2·1 ± 0·1; and HG, 2·2 ± 0·1. At the 60 min sample point, the only significant difference in the

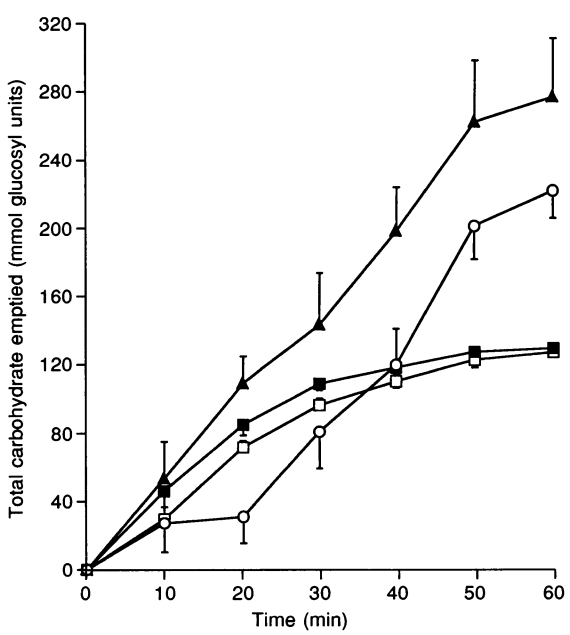

Figure 3. Gastric emptying of carbohydrate
The total amount of carbohydrate (mmol glucosyl units) delivered to the small intestine after ingesting 600 ml of test drink containing 40 g l^{-1} glucose (LG, □), 40 g l^{-1} glucose polymer (LP, ■), 188 g l^{-1} glucose (HG, ○) or 188 g l^{-1} glucose polymer (HP, ▲).

Table 3. Osmolality of gastric aspirates after ingestion of 600 ml of test drink LG, LP, HG or HP

	Osmolality of gastric aspirate (mosmol kg^{-1})				
Time (min)	LG	LP	HG	HP	Differences
0	230 ± 3	42 ± 1	1300 ± 4	237 ± 3	HG > HP, LG > LP
10	234 ± 1	58 ± 3	1172 ± 16	238 ± 2	HG > HP, LG > LP
20	237 ± 3	75 ± 5	1118 ± 17	238 ± 3	HG > HP, LG > LP
30	236 ± 5	95 ± 10	1060 ± 22	239 ± 3	HG > HP, LG > LP
40	238 ± 7	116 ± 16	1010 ± 24	237 ± 3	HG > HP, LG > LP
50	233 ± 9	136 ± 15	964 ± 24	236 ± 4	HG > HP, LG > LP
60	230 ± 12	144 ± 15	913 ± 26	234 ± 5	HG > HP, LG > LP

pH of the gastric contents was that HG (pH 2·3 ± 0·3) had a higher pH than LG (pH 1·5 ± 0·1).

Osmolality of the gastric contents

The measured osmolality of the gastric contents after ingestion of the four solutions is shown in Table 3. The osmolality of HG fell from 1300 ± 4 to 913 ± 26 mosmol kg^{-1} during the 1 h of measurement, but remained higher than that of the other solutions. The osmolality of the gastric content after ingestion of LP increased from 42 ± 1 to 144 ± 15 mosmol kg^{-1} during the hour, but remained lower than that of the other solutions. The osmolality of the gastric content after ingestion of the two solutions that were closest to the osmolality of body fluids remained essentially unchanged (LG, from 230 ± 3 to 230 ± 12 mosmol kg^{-1}; HP, from 237 ± 3 to 234 ± 5 mosmol kg^{-1}).

Electrolyte concentrations of the gastric contents

No electrolytes were added to any of the solutions before ingestion, so the electrolytes found in the gastric contents were there as a result of electrolytes in the gastric secretion and swallowed saliva. The electrolyte concentrations increased for all the solutions during the hour; the increase was greatest for the dilute solutions which had a smaller volume in the stomach. Even though the volume of secretion in the stomach was also less, the volume of secretion represented a greater proportion of the total volume than for the concentrated solutions.

The chloride concentration of the gastric contents at the 30, 40 and 50 min sample points was greater after ingestion of the dilute solutions than after ingestion of the concentrated solutions. At the 60 min sample point, the chloride concentration (mmol l^{-1}) of the gastric contents was: LG, 72 ± 13; LP, 63 ± 8; HP, 27 ± 5; and HG, 22 ± 4.

The sodium concentration in the gastric contents was generally greater after ingestion of the dilute solutions than after the concentrated solutions. At the 60 min sample point, the sodium concentration (mmol l^{-1}) of the gastric contents was: LG, 18 ± 3; LP, 23 ± 5; HP, 6 ± 1; and HG, 10 ± 1.

The potassium concentration of the gastric contents was similar for the four solutions at the 10 min sample point. At all following sample points, the potassium concentration was greater for LG and LP than for HP or HG. At the 60 min sample point, the potassium concentration (mmol l^{-1}) of the gastric contents was: LG, 8·2 ± 2·0; LP, 9·4 ± 0·8; HP, 2·6 ± 0·4; and HG, 2·7 ± 0·4.

DISCUSSION

The dilute solutions (40 g l^{-1}) of glucose and glucose polymer were both rapidly emptied from the stomach, and the emptying of these two solutions followed an exponential time course. The half-emptying time of the polymer solution (14 min) was faster than that of the free glucose solution (17 min). The carbohydrate concentration in these two solutions was the same, so a faster rate of carbohydrate emptying also occurred with the polymer solution, although the difference was rather small. The total volume of fluid in the stomach was greater at the 20 min time point after ingestion of the free glucose solution than after ingestion of the polymer, but no significant differences at other time points were observed.

These results clearly demonstrate the advantages of the double sampling aspiration technique. Many of the earlier gastric aspiration studies suffered from the twin handicaps of single time point sampling and an inability to distinguish between ingested fluid and endogenous secretion. In the study of Hunt (1960), who measured gastric emptying after administration of 750 ml of 33 or 41 g l^{-1} starch solutions and 36 or 45 g l^{-1} glucose solutions, the total fluid volume in the stomach was less after ingesting starch (372 ml) than after ingesting glucose (426 ml) in samples collected after 20 min, but when sampling was carried out after 30 min the volumes were similar. Although there was a trend in the present study for the total volume in the stomach to be smaller after ingestion of the dilute glucose polymer solution than after ingestion of the isoenergetic glucose solution, this was significant only at the 20 min sample point, giving a result similar to that of Hunt (1960). In the present study,

comparison of half-emptying times, which requires multiple samples over time, and distinction between the test meal ingested and endogenous secretion, allowed the difference in the emptying rate of the test meal to be identified.

Increasing the carbohydrate content of a solution generally decreases the rate of gastric emptying (Hunt & Knox, 1968; Barker *et al.* 1978; Foster *et al.* 1980; Brener, Hendrix & McHugh, 1980), and both of the concentrated (188 g l^{-1}) solutions studied in the present investigation had a slower rate of gastric emptying than that of the dilute (40 g l^{-1}) solutions. The two concentrated solutions (HP and HG) had the same carbohydrate content, but the concentrated glucose polymer solution was emptied faster than the isoenergetic glucose solution. The osmolality of these solutions was different (HP, 237 mosmol kg^{-1} and HG, 1300 mosmol kg^{-1}), and the much greater osmolality of the glucose solution may have contributed to its slower rate of gastric emptying. For these solutions, the pattern of emptying was approximately linear with respect to time, as opposed to the exponential pattern displayed by the more dilute solutions.

The dilute (40 g l^{-1}) solutions of glucose and glucose polymer were emptied at similar, albeit significantly different, rates, whereas there was a large difference in emptying rate between the two more concentrated solutions. The amount of carbohydrate delivered to the small intestine tended to be greater after ingesting HP than after ingesting HG, and was significantly greater at the 20, 40 and 50 min sample points. A faster emptying rate of HP therefore occurred in spite of the greater amount of carbohydrate delivered to the small intestine. This difference in carbohydrate delivery to the small intestine from isoenergetic solutions suggests that the rate of gastric emptying cannot be regulated so as to result in a constant rate of energy delivery to the small intestine, as was suggested by Brener *et al.* (1983). Others (Moore, Christian & Coleman, 1981; Hunt, Smith & Jiang, 1985; Mitchell, Costill, Houmard, Fink, Robergs & Davis, 1989; Mitchell & Voss, 1991) have also shown that the carbohydrate delivery to the small intestine is not constant: increasing either the ingested carbohydrate concentration or volume of the ingested solution increases the rate of carbohydrate delivery to the small intestine.

Increasing the carbohydrate content of a solution will generally increase the energy delivery to the small intestine (Hunt & Knox, 1968; Hunt & Stubbs, 1975; Foster *et al.* 1980; Hunt *et al.* 1985; Murray, 1987), but for the first 30 min after ingestion of the four solutions in this study, the carbohydrate delivery to the small intestine was approximately the same, irrespective of the carbohydrate content of the initial solution. At the end of this first 30 min period, however, almost all of LG and LP had emptied.

The results of the present study agree with Sole & Noakes (1989), who administered 400 ml and sampled after 15 min. They reported 50 g l^{-1} solutions of glucose and glucose polymer to empty at similar rates, whereas a 150 g l^{-1} solution of glucose polymer emptied faster than an isoenergetic glucose solution. In contrast, Foster *et al.* (1980), who administered 400 ml and sampled after 30 min, found that a 50 g l^{-1} glucose polymer solution emptied faster than an isoenergetic glucose solution; gastric residue was 249 ml after ingesting glucose and 146 ml after ingesting glucose polymer. The gastric residue at the time of ingestion was not measured and the glucose solution had a greater volume of secretion in the stomach at the time of sampling; subtracting the volume of secretion gives the volume of test drink remaining in the stomach of 123 ml after ingesting the glucose solution and 93 ml after ingesting the glucose polymer solution. Foster *et al.* (1980) found 100, 200 and 400 g l^{-1} solutions of glucose and glucose polymer to empty at similar rates; the difference in total gastric residue after ingesting these more concentrated solutions was between 16 and 27 ml. In both these earlier studies, however, measurements were made at only one time point, which reduces the validity of the findings.

The two solutions with the same initial osmolality, the dilute monomeric glucose solution and the concentrated glucose polymer solution, were not emptied at the same rate: $t_{½}$ for LG was 17 min, compared with 64 min for HP. However, the amount of carbohydrate delivered to the small intestine from these two solutions was similar for the first 30 min after ingestion. By this time, LG had delivered almost all of its original carbohydrate content, so during the last 30 min, the carbohydrate delivery to the small intestine was greater after ingestion of HP than after ingestion of LG.

The greater volume of secretion in the stomach following ingestion of the concentrated solutions compared with the dilute solutions is most likely to be a result of the fact that a rapidly emptying solution will empty the volume of secretion as well as the test drink, but a slowly emptying solution will accumulate the volume of secretion in the stomach together with the test drink.

The small changes in osmolality of the gastric contents after ingesting the glucose polymer solutions suggest that very little hydrolysis occurs in the stomach. As Hunt (1960) pointed out, this does not exclude the possible presence in the stomach of receptors sensitive to osmolality. However, Meeroff *et al.* (1975) showed the rate of gastric emptying to be independent of the osmolality of the gastric contents as long as the osmolality of the duodenal contents remained within the isotonic range. The same was not found in dogs (Lin, Doty, Reedy & Meyer, 1989), but further evidence is lacking.

If the rate of gastric emptying is regulated by receptors, responding either to free glucose or to luminal osmolality,

in the small intestine deep to the brush border, a similar rate of gastric emptying of glucose and glucose polymers is possible if the polymers are completely hydrolysed before they reach the receptors. At high rates of emptying and at high polymer concentrations, the rate of delivery of polymers to the small intestine may exceed the hydrolytic capacity of the upper small intestine. If that is the case, not all of the polymer will appear as free glucose, and the osmolality in the intestinal lumen will be lower than if a similar amount of free glucose had been ingested or if the polymer had been completely hydrolysed.

The difference in emptying rate between the two dilute solutions is small, and is consistent with the suggestion that the dilute polymer was rapidly and more or less completely hydrolysed, and therefore had a similar osmolality and free glucose content to that of the isoenergetic glucose solution before reaching the site of the receptor. It is also possible that these receptors are insensitive to relatively small differences in the composition of the luminal fluid.

The faster rate of gastric emptying of the concentrated glucose polymer solution than the isoenergetic glucose solution suggests that the glucose polymer was not completely hydrolysed when the receptors responded to the concentrated glucose polymer solution. The high concentration of glucose polymer presented to the small intestine after ingestion of 600 ml of this solution may have resulted in an amount of glucose polymer in the small intestine in excess of the hydrolytic capacity of the duodenum. This would also explain why there was a difference in the rate of gastric emptying between the concentrated solutions of glucose and glucose polymer but not between the dilute solutions. This also suggests that the site of the receptor is located past the site of hydrolysis, as was suggested by Hunt (1960) and by Elias, Gibson, Greenwood, Hunt & Tripp (1968).

Husband, Husband & Mallinson (1970) studied the rate of gastric emptying in infants of starch and glucose solutions. They found a 100 g l^{-1} starch solution to empty faster than an isoenergetic glucose solution; the increase in blood glucose in these infants was, however, faster and higher after ingesting glucose than after ingesting starch: this is most likely to be a result of a slow rate of hydrolysis owing to the low levels of pancreatic amylase in the newborn, and these results may not apply to adults. The lack of slowing of gastric emptying by the 100 g l^{-1} starch solution in infants would be expected only if the receptors respond to luminal osmolality (and/or free glucose concentration) and if the receptors are located beyond the site of hydrolysis. Hunt, Antonson, Paxon & Vanderhoof (1982) also studied the rate of gastric emptying in the newborn, but used mixed glucose–oligosaccharide solutions and found a similar volume in the stomach 30 min after ingestion to that of an isoenergetic glucose solution.

This study shows that both osmolality and carbohydrate content have an influence on the rate of gastric emptying. It appears that the carbohydrate content has a much greater influence on the rate of gastric emptying of liquids than osmolality within the range of concentrations and conditions of this study. Dilute (40 g l^{-1}) solutions of glucose and glucose polymer empty from the stomach at similar rates, whereas concentrated (188 g l^{-1}) solutions of glucose polymers empty faster from the stomach than isoenergetic monomeric glucose solutions.

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