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Faster gastric emptying for glucose-polymer and fructose solutions than for glucose in humans

C. C. Sole and T. D. Noakes

MRC/UCT Bioenergetics of Exercise Research Unit, Department of Physiology, University of Cape Town Medical School, Observatory, 7925, South Africa

Summary. This study examined the rates of gastric emptying for water and 13 different carbohydrate-containing solutions in seven subjects, using conventional gastric intubation techniques. The rates of gastric emptying for water and a 10% glucose-polymer solution were also measured during 90 min of treadmill running at 75% of each subject's maximum oxygen consumption ($\dot{V}_{O_{2max}}$). At rest, 15% glucose-polymer (P) and fructose (F) solutions emptied more rapidly from the stomach and provided a faster rate of carbohydrate delivery than did a 15% glucose (G) solution ($p < 0.05$). The G solutions showed a constant energy delivery rate of 3.3 kcal·min^{-1}; energy delivery from P and F solutions rose with increasing solution concentrations. The osmolality of the gastric aspirate predicted the rate of gastric emptying for all solutions ($p < 0.05$) but overestimated rates of emptying for 10% and 15% P solutions and underestimated emptying rates for 10% and 15% F solutions. Exercise at 75% $\dot{V}_{O_{2max}}$ decreased the rate of gastric emptying of water but not of 10% P solutions. Thus the different rates of gastric emptying for different carbohydrate-containing solutions were not entirely explained by differences in osmolality. Furthermore, exercise may have different effects on the gastric emptying rates of water and carbohydrate solutions.

Key words: Osmolality — Constant energy delivery — Carbohydrate solutions — Exercise — Gastric secretion — Gastric emptying

Introduction

Numerous studies have shown that gastric emptying is delayed in proportion to the osmolality of the ingested carbohydrate solution (Barker et al. 1974, 1978; Brener et al. 1983; Costill and Saltin 1974; Coyle et al. 1978; Fordtran and Ingelfinger 1968; Foster et al. 1980; Hunt 1961; McHugh and Moran 1979; Moran and McHugh 1981). Osmolality is thought to activate osmoreceptors which alter the muscle tone of the gastric antrum via nervous or hormonal stimuli (Barker et al. 1974, 1978; Elias et al. 1968; Hunt and Pathak 1960; Hunt 1960, 1961, 1963; Hunt and Knox 1968). The current theory suggests that the osmoreceptor is located in the lateral intercellular space and responds to alterations in its shape produced by water fluxes (Barker et al. 1978; Hunt and McHugh 1982; Hunt 1983).

If osmolality is an important determinant of the rate of gastric emptying, then starch, glucose-polymer (P) and disaccharide solutions should, because of their lower osmolality, empty more rapidly from the stomach than isocaloric glucose (G) solutions (Elias et al. 1968; Hunt 1960). However, Hunt (1960) showed that starch solutions emptied from the stomach at the same rate as did isocaloric G solutions and therefore proposed that the osmoreceptors were located distal to the gastric antrum. Consistent with this interpretation are the findings that disaccharide solutions empty at the same rate as their constituent monosaccharides (Elias et al. 1968) and that in persons with pancreatic amylase deficiency, starch and water solutions empty from the stomach at faster rates than do isocaloric G solutions (Mallinson 1968).

In contrast, Foster et al. (1980) showed that a 5% P solution emptied more rapidly from the stomach than did a 5% G solution. However P solutions of 10%, 20% and 40% emptied at the same rates as did the corresponding G solutions, despite large differences in osmolalities of both the test solutions and the gastric aspirates. Similarly, osmolality alone does not explain the finding that

Offprint requests to: T. D. Noakes

the rate of gastric emptying of fructose (F) solutions of high osmolality is greater than that of isoosmotic G solutions (Elias et al. 1968; McHugh and Moran 1979; Moran and McHugh 1981).

An alternate postulate is that gastric emptying is controlled by the rate at which energy is delivered to the duodenum (Brener et al. 1983; Costill and Saltin 1974; McHugh and Moran 1979; Moran and McHugh 1981).

However, other studies suggest that energy delivery increases linearly with increasing osmolality of the ingested solution (Coyle et al. 1978; Foster et al. 1980; Hunt and Stubbs 1975; Seiple et al. 1983) and conclude that the inverse relationship between nutritive density and gastric emptying rate does not prevent an increase in the rate of energy delivery from solutions of increasing osmolality.

One result of the lack of concensus from these studies is that the most appropriate carbohydrate solution for ingestion during prolonged exercise has yet to be established. Accordingly, the aim of this study was to compare the gastric emptying characteristics of P, G and F solutions of different concentrations, to determine whether the findings would differentiate between osmolality or a constant rate of energy delivery, or both, as the important factor(s) controlling the rate of gastric emptying. We wished to use this information to determine which carbohydrate solution would be optimum for ingestion during exercise.

These data were supplemented with studies of gastric emptying rates of a range of commercially available electrolyte- and carbohydrate-containing drinks which are frequently ingested by sportspersons. We also studied the effects of exercise on gastric emptying. Gastric emptying rates were optimised by excluding electrolytes from the carbohydrate drinks and by studying solutions at optimal temperature (Costill and Saltin 1974). In addition, the subjects were habituated to the testing procedure, thereby reducing their anxiety at the time of testing, as anxiety is known to influence the rate of gastric emptying (Cammack et al. 1982).

Methods

The techniques used were based on those previously described (Costill and Saltin 1974; Coyle et al. 1978; Foster et al. 1980; Hunt 1960; Ivey and Schedl 1970; Schedl et al. 1966). Seven-endurance-trained athletes habituated to laboratory experimentation were studied. Their mean (range) age, height, weight and maximum oxygen consumption ($\dot{V}_{O_{2max}}$) was 26 years (21-30), 181 cm (178-185), 76 kg (52-71) and 66 $ml \cdot kg^{-1} \cdot min^{-1}$ (49-85) respectively. Trained athletes were chosen in order that they would be able to complete the exercise protocol and because of their proven tolerance for discomfort. All tests were conducted after a 9- to 12-h fast.

Gastric emptying at rest. A no. 14 French Levine nasogastric tube was passed through the nasal passage into the stomach. As soon as the nasogastric tube was considered to be in the stomach, the subjects ingested 400 ml distilled water. The gastric contents were aspirated immediately thereafter using a 50-ml syringe. This test was used to ensure correct placement of the tube and to remove any gastric residue. The tube was repositioned until more than 95% of the original volume had been aspirated. After 6 min a second 400 ml water was ingested and the procedure repeated. Subjects were discouraged from swallowing saliva in order to minimise the presence of salivary amylase in the stomach. After a further 6-min break, the first test solution for that day was ingested.

The temperature of all solutions was 5° C and subjects were instructed to ingest the 400-ml solutions in less than 2 min. Gastric contents were aspirated 15 min later, aspiration taking from 2 to 4 min. During aspiration the tube was moved to prevent its occlusion against the stomach wall. Four to six tests were performed each week depending on the subject's well-being.

In order to improve further the reliability of this technique, each subject was first habituated to the procedure by ingesting up to 15 test solutions until reproducible results were achieved for each subject. Once this pre-trial phase was completed, subjects ingested the 14 test solutions in random order. No more than three test solutions were administered on any single day. The test solutions were water; 5%, 10% and 15% solutions ($g \cdot 100\ ml^{-1}$) of P (P5, P10, P15) (FRN Carboboost, G. W. Leppin, Johannesburg), G (G5, G10, G15) (G. W. Leppin, Johannesburg) and F (F5, F10, F15) (G. W. Leppin, Johannesburg); Coca Cola (C); Pepsi Cola (P); Tropika (T; Clover, Johannesburg) and Isostar (I; Wander, Bern, Switzerland). An amount of 25 $mg \cdot l^{-1}$ of the non-absorbable marker phenol red (PR) was added to each solution. The P chain lengths were determined by gel filtration with Bio-Gel using a 55 × 2.5 cm column (Churms and Stephen 1971). In all cases the eluent used was 1 M NaCl set at a flow rate of 50 $ml \cdot h^{-1}$.

Gastric emptying during exercise. Only water and P10 solutions were used in the study of gastric emptying during exercise. Subjects ran on a treadmill at speeds of 15-19 $km \cdot h^{-1}$, corresponding to 75% of their $\dot{V}_{O_{2max}}$, which had been determined earlier using a progressive treadmill test as described previously from this laboratory (Scrimgeour et al. 1986). The gastric emptying rate of the test solution was first determined at rest before the start of exercise. The subject then began running and the treadmill speed was gradually increased until each subject's target speed was reached. The speed was decreased during the last 45 s before a drink was taken or before the stomach was aspirated. Each solution was ingested in 2-3 min while the subject was seated. Immediately after he had drunk the solution, the subject resumed running, stopping after another 15 min for gastric aspiration.

In the first test a water solution was drunk after 30 min of running and aspirated 15 min later. During the second test, which was conducted and another day, P10 was ingested at 30, 60 and 90 min with aspiration occurring at 45, 75 and 105 min, giving a total running time of 1 h 45 min.

Analysis of gastric aspirate. The volume of aspirate was recorded and PR concentrations were determined using conventional methods (Foster et al. 1980; Ivey and Schedl 1970; Schedl et al. 1966). The gastric aspirates taken while running were centrifuged prior to analysis because of the presence of a precipitate (Schedl et al. 1966). The pH (using a glass electrode) and osmolality (using the freezing point depression method; Osmette A, Precision Systems, Inc., Newton, Mass., USA) were measured for each solution.

Calculations and expression of results. The volume of the test solution recovered was calculated using the formula: $(PR_{aspirate})/(PR_{solution}) \times$ volume of aspirate. Gastric secretion was calculated by subtracting the volume of the recovered test solution from the volume of the aspirate. Volume emptied was the difference between the 400-ml test solution and the recovered test solution.

Carbohydrate delivery was calculated by multiplying the initial carbohydrate concentration with the volume delivered. This was then converted to $g \cdot h^{-1}$: $kcal \cdot min^{-1}$ was calculated using the approximate conversion 1 g = 4 kcal. Results for the seven subjects are expressed as means, medians and ranges. Non-parametric one-way analysis of variance, ANOVA, was used to determine statistically significant differences between the solutions with regard to gastric emptying, osmolality, pH and gastric secretion. The Kruskal-Wallis test was used to determine significant differences between pairs of solutions. The significance level was set at $p < 0.05$. A sample correlation coefficient was used to determine the correlation between gastric emptying and osmolality, pH and gastric secretion. A linear regression equation was determined for osmolality of aspirate and gastric emptying rate.

Results

Characteristics of the test solutions

The osmolalities of the different solutions are listed in Table 1. Water and the P solutions had osmolalities varying between 2 and 117 mosmol $\cdot l^{-1}$, which were considerably lower than those of the other test solutions. The average P chain length was 6 G units as shown by dividing the osmolality of a G solution with the corresponding osmolality of P. Forty-three percent of P had a chain length of 8 G units as determined by gel filtration.

Characteristics of the gastric aspirate in studies at rest

The osmolalities of the gastric aspirate of the P solutions were slightly higher than those of the ingested solution but remained significantly different from the G and F solutions (Table 1). The osmolality of water increased from 2 to 76 mosmol $\cdot l^{-1}$, while G10 and G15 solutions decreased by 54–84 mosmol $\cdot l^{-1}$. There was a similar decrease in osmolality in the F10 and F15 solutions (Table 1). The pH of the gastric aspirate was the

Table 1. Osmolality and pH of test solutions and gastric aspirate, calculated volume of gastric secretion and carbohydrate concentration of test solutions

		Water	P5	P10	P15	G5	G10	G15	F5	F10	F15	C	P	T	I
OS TS		2	39	77	117	251	499	739	273	539	819	440	719	514	348
	Mean	76	99*	127*	156*	244*	426*	600*	258*	434*	622*	455	556	423	396
	Median	74	107	120	156	243	429	612	260	435	644	463	563	443	414
	Range	126–41	117–72	149–106	183–137	275–207	452–391	668–501	276–238	485–391	656–518	495–386	585–500	473–353	463–319
pH TS		6.4	4.2	4.5	4.8	3.8	5.5	5.2	5.3	5.4	5.9	2.6	2.6	2.4	3.2
	Mean	2.1	1.8	2.0	2.0	1.9	1.8	1.9	1.9	1.9	1.9	1.8	1.8	2.4***	2.2***
	Median	2.0	1.7	1.9	1.8	1.8	1.8	1.9	1.9	1.9	1.8	1.9	1.8	2.4	2.2
	Range	3.2–1.6	2.3–1.7	2.5–1.7	3.0–1.7	2.3–1.7	2.0–1.7	2.3–1.8	2.2–1.7	2.2–1.7	2.3–1.8	2.1–1.6	2.1–1.6	2.7–2.2	2.6–2.1
GS	Mean	40**	49	83	80	57	54	67	71	65	84	86	84	96	73
	Median	38	33	80	84	46	60	60	70	63	84	87	82	93	64
	Range	49–15	96–22	118–50	120–54	94–43	98–9	101–24	96–54	86–46	106–52	139–47	123–45	127–35	109–34
CHO TS		0	5	10	15	5	10	15	5	10	15	4.6	8		8

P = glucose-polymer; G = glucose; F = fructose; C = Coca-cola; P = Pepsi-cola; T = Tropika; I = Isostar. The concentrations of the solutions are as defined in Fig. 1. TS = test solution; GA = gastric aspirate; OS = osmolality (mosmol $\cdot l^{-1}$); GS = gastric secretion (ml); CHO = carbohydrate concentration

* $p < 0.05$; P5, P10, P15 vs G5, G10, G15 and F5, F10, F15

** $p < 0.05$; water vs all other solutions

*** $p < 0.05$; T and I vs all other solutions

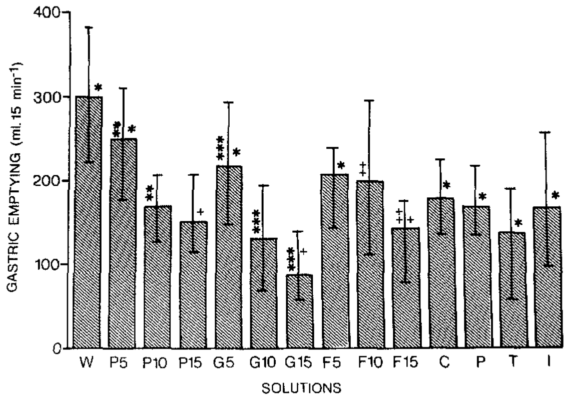

Fig. 1. Gastric emptying rate (ml · 15 min^{-1}) of 14 solutions at rest. Values are means plus ranges for seven subjects. *W*, Water; *P*5–15, glucose-polymer solutions, 5%–15%; *G*5–15, glucose solutions, 5%–15%; *F*5–15, fructose solutions, 5%–15%; *C*, Coca-cola; *P*, Pepsi-cola; *T*, Tropika; *I*, Isostar. * $p<0.05$ Water vs all solutions; ** $p<0.05$ P5 vs P10; *** $p<0.05$ G5 vs G10 vs G15; + $p<0.05$ P15, F15 vs G15; + + $p<0.05$ F10 vs F15

same for all solutions except for T and I. There were no statistically significant differences in the volume of gastric secretion (Table 1), although there were large inter-individual variations.

Gastric emptying at rest

Figure 1 shows the mean values (plus range) of gastric emptying rates for the 14 solutions. The mean volume of water emptied (300 ml · 15 min^{-1}) was significantly greater than that of the other solutions. Increasing the carbohydrate concentration resulted in a decline in the emptying rate. However, P15 and F15 solutions emptied significantly faster (150 ml · 15 min^{-1} and 142 ml · 15 min^{-1} respectively) than did the G15 solution (86 ml · 15 min^{-1}). The F10 solution (197 ml · 15 min^{-1}) emptied at a rate similar to that of F5 (207 ml · 15 min^{-1}) although there was a greater range in the subject values for the F10 solution. C, P, T and I emptied at the same rate as did the 10% solutions, although their carbohydrate contents were lower.

Characteristics of the gastric aspirate during exercise

Table 2 lists the changes in osmolality, pH and gastric secretion of the two solutions ingested during exercise. During exercise, osmolality and the volume of gastric secretion fell for the water trial, whereas pH rose. Osmolality and pH of the P10 solution rose, whereas gastric secretion fell. The pH increased to approach the solution pH of 4.55. Osmolality increased from 127 mosmol · l^{-1} at rest to values that were similar to the G5 solutions, suggesting hydrolysis to a mean chain length of approximately 2 units.

Gastric emptying during exercise

The volume of water emptied from the stomach after 30 min of intense exercise was reduced to 187 ml · 15 min^{-1}, which was not different from that of the P10 solution (Fig. 2). In contrast the emptying rate of the P10 solution did not change even during 105 min of exercise.

Calculated carbohydrate delivery

The P solutions produced an almost linear increase in the rate of both carbohydrate (Fig. 3)

Table 2. Osmolality and pH of gastric aspirate and calculated volume of gastric secretion for test solutions at rest and after varying times of running

Test solution		Water		P1O			
	Time	0 min	30 min	0 min	30 min	60 min	90 min
Osmolality	Mean	76*	49*	127**	292**	289**	287**
(mosmol · l^{-1})	Median	74	46	120	284	261	302
	Range	126–41	93–22	149–106	619–117	570–122	414–143
(pH)	Mean	2.1*	5.5*	2.0**	3.2**	3.7**	4.4**
	Median	2.0	5.5	1.9	3.0	3.7	3.7
	Range	3.2–1.6	7.6–2.4	2.5–1.7	5.0–2.5	4.8–2.9	7.0–3.4
Gastric	Mean	40	30	83**	44**	20**	28**
Secretion	Median	38	24	80	49	19	14
(ml)	Range	49–15	56–5	118–50	67–20	37–11	58–3

* $p<0.05$; water at rest vs running after 30 min
** $p<0.05$; P10 at rest vs running after 30, 60 and 90 min
P10 = 10% glucose-polymer solution

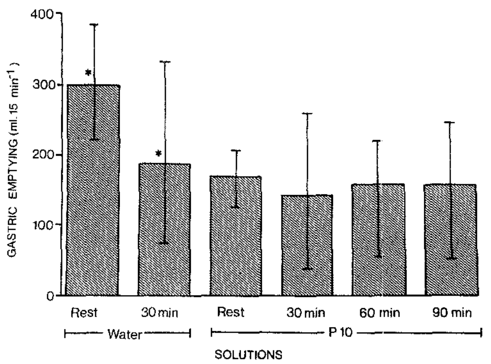

Fig. 2. Gastric emptying rate (ml · 15 min^{-1}) of water and glucose-polymer 10% solution (P10) during treadmill running at 75% $\dot{V}_{O_{2max}}$. Values are means plus range for seven subjects. * $p<0.05$ Water at rest vs water after 30 min running

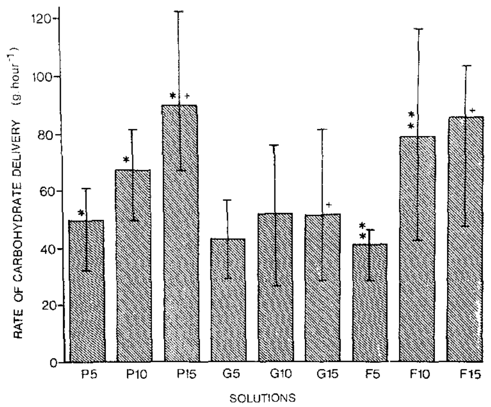

Fig. 3. Calculated mean rate of carbohydrate delivery (g · h^{-1}) of glucose-polymer (*P*), glucose (*G*) and fructose (*F*) solutions. The range is also indicated. The concentrations of the solutions are as defined in Fig. 1. * $p<0.05$ P5 vs P10 vs P15; ** $p<0.05$ F5 vs F10; + $p<0.05$ P15, F15 vs G15

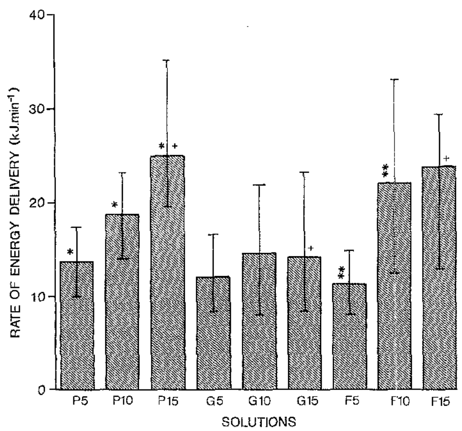

Fig. 4. Calculated mean rate of energy delivery (kJ · min^{-1}) of glucose-polymer (*P*), glucose (*G*) and fructose (*F*) solutions. The range is also indicated the concentrations of the solutions are as defined in Fig. 1. * $p<0.05$ P5 vs P10 vs P15; ** $p<0.05$ F5 vs F10; + $p<0.05$ P15, F15 vs G15

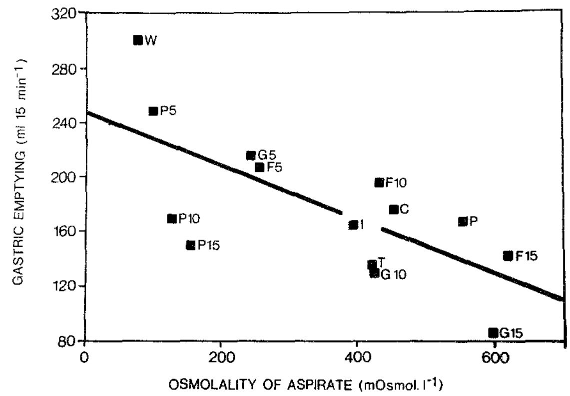

Fig. 5. Linear regression for osmolality (mosmol · l^{-1}) of the gastric aspirate vs the rate of gastric emptying (ml · 15 min^{-1}) of the 14 solutions. Means for seven subjects ($r=-0.7$, $y=247.7-0.2x$). *W*, water; *P*, glucose-polymer, *F*, fructose; *G*, glucose; *C*, Coca-cola; *P*, Pepsi-cola; *T*, Tropika; *I*, Isostar. The concentrations of the solutions are as defined in Fig. 1

and therefore energy delivery with an increasing P concentration of the ingested solution. No such effect was found for solutions of increasing glucose concentration. P5, G5, G10, G15 and F5 solutions each delivered a mean of 13.3 kJ · min^{-1} into the duodenum (Fig. 4).

Osmolality vs gastric emptying rate at rest

There was a significant correlation between the osmolality of the gastric aspirate and the rate of gastric emptying at rest ($r=-0.7, p<0.05$) (Fig. 5) and between the osmolality of the ingested solution and the rate of gastric emptying at rest ($r=-0.75$, $p<0.05$). No significant correlations existed between the gastric emptying rate and the volume of gastric secretion or between the emptying rate and pH. There was a correlation between gastric secretion and the osmolality of the gastric aspirate ($r=0.5$, $p<0.05$).

Discussion

Rates of gastric emptying for G, P and F solutions

The most important finding of this study was to show that P15 and F15 solutions emptied more rapidly from the stomach than did isocaloric G solutions. Furthermore, whereas there was a constant rate of energy delivery from G solutions of increasing energy content, the rate of energy delivery from P solutions increased with increasing energy content up to the highest concentration studied (Fig. 3), whereas that of F reached a maximum at a 10% solution. Thus, whereas the theory of constant energy delivery (Brener et al. 1983; McHugh and Moran 1979; Moran and McHugh 1981) could explain the gastric emptying characteristics of G solutions of increasing osmolality, this theory could not explain the control of gastric emptying for all the P solutions or for the F5 and F10 solutions.

There was a significant correlation between the rate of gastric emptying and the osmolality of the gastric aspirate (Fig. 5) but the correlation was relatively poor ($r = -0.7$) so that variations in osmolality of the gastric aspirate could explain only 50% of the variation in the rates of gastric emptying for the different solutions.

Thus, the rates of gastric emptying of all the P solutions were less, and those of F solutions more than would have been predicted from the osmolalities of their respective gastric aspirates (Fig. 5). Possibly rapid but incomplete hydrolysis of the P10 and P15 solutions to an osmolality of 400 $\mathrm{mosmol \cdot l^{-1}}$ (equivalent to an average chain length of 2 units) by the time these solutions reached the duodenal osmoreceptor would explain the slower emptying rates of P solutions than would have been predicted from their osmolalities when in the stomach.

Similarly the finding that F10 and F15 solutions emptied more rapidly from the stomach than did G10 and G15 solutions despite their similar gastric aspirate osmolalities (Fig. 5) might be explained if the osmolality of the fructose solutions decreased rapidly in the duodenum. The activity of a separate facilitated diffusion mechanism for fructose uptake across the duodenal villae, which increases linearly with increasing fructose concentration in the ingested solution, might explain this effect (Crane 1968; Fordtran and Ingelfinger 1968).

The finding that P solutions did not empty as rapidly from the stomach as would be predicted on the basis of their gastric aspirate osmolalities indicates that it cannot be concluded as in some studies (Foster et al. 1980; Seiple et al. 1983) that the lower osmolalities of P compared to G solutions will necessarily ensure that they empty more rapidly from the stomach than do isocaloric G solutions. Possibly the rate and degree of hydrolysis of the P solutions prior to arrival at the duodenal osmoreceptors and their different effects on gastric secretion determines their rates of gastric emptying.

The findings of the study of Foster et al. (1980) are in line with this interpretation. The P used by those workers had a mean chain length of only 3 units. The identical blood glucose and insulin responses to ingested G and some P solutions (Fordtran and Ingelfinger 1968) indicates that hydrolysis of short-chain P occurs very rapidly in the duodenum. Rapid and complete hydrolysis of that short-chain P solution prior to arrival at the intestinal osmoreceptors would explain why that study failed to show a difference in the rates of gastric emptying for P and G solutions.

It should also be noted that the calculations of Foster et al. (1980) showing increasing energy delivery with increasing concentration of especially G, but also P solutions, a finding that is in conflict with both the osmotic and constant energy delivery theories of the control of gastric emptying, appear to be erroneous. Their data were calculated as the rate of gastric emptying for each solution multiplied by the measured carbohydrate content of the gastric aspirate. Calculations based on these analyses suggest that for some solutions as much as 44 g carbohydrate was absorbed directly from the stomach within 15 min. Such a rapid rate of carbohydrate absorption would have produced a very rapid and profound hyperglycaemia and hyperinsulinaemia, which does not occur (Fordtran and Ingelfinger 1968). Recalculation of their data for the rate of carbohydrate delivery using the rate of gastric emptying multiplied by the carbohydrate content of the different solutions shows that the rate of carbohydrate delivery did not increase with increasing carbohydrate content of either the G or P solutions. A significant under-analysis of the true carbohydrate content of the gastric aspirates for the different solutions would explain their unusual results.

In summary, our data for gastric emptying rates of G, P and F solutions indicate that neither the osmolality nor the constant energy delivery (Brener et al. 1983; McHugh and Moran 1979; Moran and McHugh 1981) theories of gastric emptying adequately explain all our findings. That an increasing rate of energy delivery to the duodenum occurred with increasing carbohydrate content of P and F but not G solutions shows that the constant energy delivery theory does not apply for all carbohydrate solutions. That P solutions emptied slower, and F solutions faster than was predicted on the basis of the osmolalities of their respective gastric aspirates might be explained if substantial changes in the osmolalities of these solutions occurred prior to their reaching the duodenal osmoreceptors.

The effect of exercise

Gastric secretion decreased significantly during prolonged exercise, with a concomitant rise in the pH of the gastric aspirate. This finding is in agreement with many previous studies (Cammack et al. 1982; Campbell et al. 1928; Crandall 1928; Hellenbrandt and Hoopes 1934; Konturek et al. 1973; Ramsbottom and Hunt 1974). Prolonged exercise at a high intensity did not affect the rate of gastric emptying of the P10 solution, despite an increase in the osmolality of the gastric aspirate, but caused a large decrease in the rate at which water emptied from the stomach. This finding contrasts with that of Neufer et al. (1986), who found that exercise at 50%–70% of $\dot{V}_{O_{2\,max}}$ increases the rates of gastric emptying of both water and carbohydrate-containing solutions. It should be noted, however, that their data for the gastric emptying rates of water and P5 at rest were between 16% and 25% lower than ours.

Other studies have indicated that the rate of gastric emptying is reduced at high exercise intensities (>70% $\dot{V}_{O_{2\,max}}$) (Cammack et al. 1982; Campbell et al. 1928; Costill and Saltin 1974; Ramsbottom and Hunt 1974); most of these studies have been either of solid meals or of 2.5%–5% glucose-electrolyte solutions. Our finding that the rate of gastric emptying for water but not P solutions is reduced during exercise is in line with the findings of Fordtran and Saltin (1967) and Owen et al. (1986) and suggests that an additional mechanism controlling gastric emptying may be activated during exercise.

The finding that the rate of gastric emptying of water and P10 solutions was equivalent during prolonged, high intensity exercise also indicates that no practical advantage is gained by drinking pure water during prolonged exercise as is usually recommended (Neufer et al. 1986).

Practical conclusions

The first important practical finding of this study was that, at rest, the rate of gastric emptying and of carbohydrate delivery of P15 and F15 solutions was significantly greater than that of G15 solutions. Thus at the highest concentrations tested, P and F solutions were superior to G.

The second relevant finding was that, during exercise, the rate of gastric emptying of P10 and water was the same, confirming the findings of Owen et al. (1986). This suggests that, during exercise, additional or alternate mechanisms controlling gastric emptying may be activated. Thus, conclusions regarding the appropriate solution for use during exercise can be extrapolated only with extreme caution from data collected in resting subjects.

Others have also reported that solutions with widely differing carbohydrate and electrolyte contents and different osmolalities appear to empty from the stomach at relatively similar rates during exercise (Owen et al. 1986). These findings indicate the need for further research to determine the optimum carbohydrate solution for use during exercise.

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