Nutrient Requirements and Interactions

Absorption of Nutrients Is Only Slightly Reduced by Supplementing Enteral Formulas with Viscous Fiber in Miniature Pigs[1,2]

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ABSTRACT   Viscous polysaccharides reduce intestinal absorption of glucose and diminish postprandial hyperglycemia. However, it is unknown whether viscous fiber also inhibits absorption of nutrients under conditions of enteric feeding. Therefore, we measured the absorption rates of nutrients in miniature pigs by perfusing a 150-cm length of jejunum with 8.37 kJ/min of the three following enteral diets: an isoosmotic oligomeric diet (1670 kJ/L), a hyperosmotic oligomeric diet and an isoosmotic polymeric diet (both 3350 kJ/L). The diets were supplemented with guar gum from 0 to 4.4 g/L. With the three guar-free diets, the mean absorption rate of energy was 5.2 ± 0.32 kJ/min, corresponding to 62% of the energy infused. Absorption rates of carbohydrate, protein, fat and energy linearly declined as concentrations of guar or the logarithm of chyme viscosity increased. Due to modulations in viscosity, the inhibitory effects of guar were significantly different among the three diets. With the isoosmotic and hyperosmotic oligomeric and the polymeric diets, the addition of 1 g guar/L diminished the absorption of energy by 9.7, 6.6 and 3.7%, respectively. The strong inhibitory effect on nutrient absorption with the isoosmotic oligomeric diet was caused by an increase in chyme viscosity due to water absorption. With the hyperosmotic oligomeric and the polymeric diets, the chyme viscosity and thus inhibitory effects on absorption were diminished by water secretion and the concomitant infusion of pancreatic enzymes. Results indicate that the addition of small amounts of guar gum to enteral diets of high energy density exerts only small effects on absorption of nutrients.   J. Nutr. 128: 2446–2455, 1998.

KEY WORDS: • *enteral nutrition* • *fiber* • *absorption* • *viscosity* • *miniature pigs*

Dietary fiber exerts several effects on gastrointestinal functions. There are also physiologic reasons for including dietary fiber in enteral diets (Compher et al. 1997). Because fiber-supplemented diets are available commercially, they are in widespread clinical use. Liquid formula diets are most commonly supplemented with soy polysaccharides, which are rich in insoluble fiber and contain only small amounts of soluble viscous fiber. However, in addition to soy fiber, some of the enteral diets are additionally supplemented with pectin, xanthan gum or guar gum, either as solution stabilizer or because these kinds of fiber have special effects on gastrointestinal functions (Compher et al. 1997). Viscous fiber, in particular pectin, is highly fermentable in the large intestine and promotes production of short-chain fatty acids (SCFA).[4] The SCFA absorption increases sodium and water absorption, thereby decreasing diarrhea (Roth et al. 1995, Zimmaro et al. 1989). Additionally, pectin-supplemented enteral diets enhance small bowel and colonic mucosal proliferation (Koruda et al. 1986, Roth et al. 1995). This might be important in preserving gut barrier function. Another well-known function of viscous fiber when added to carbohydrate meals is the reduction of postprandial blood glucose concentration in humans (Jenkins et al. 1978, Taylor et al. 1980, Vahouny 1987). This effect suggests an impairment of carbohydrate absorption. Enteral infusion of glucose solutions supplemented with viscous fiber revealed a reduced disappearance of glucose from the intestinal lumen in both humans (Blackburn et al. 1984, Flourie et al. 1984, Fuse et al. 1989) and animals (Blackburn and Johnson 1981, Elsenhans et al. 1984, Johnson and Gee 1981, Rainbird et al. 1984). The reduced glucose absorption, and thus the enhanced glucose tolerance after ingestion of fiber-supplemented meals, is of benefit in diabetic patients. In contrast, in critically ill patients, an inhibition of nutrient absorption may diminish the tolerance of enteric feeding and may induce intestinal sequelae. A recent study showed that fiber-supplemented commercial formula slowed down the transit along the proximal small intestine (Lin et al. 1997). The effect was interpreted as the result of diminished absorption of nutrients and consequently intensifying inhibitory feedback mechanisms from the distal gut. However, the effects of viscous fiber on reduction of postprandial hyperglycemia were significant only when relatively large amounts of fiber were added to the meal. Additionally, in previous studies on the inhibitory effects of viscous fiber on intestinal absorption, isoosmotic electrolyte-glucose solutions of low energy density and relatively large concentration of the viscous fiber were

used (Blackburn and Johnson 1981, Flourie et al. 1984, Fuse et al. 1989, Rainbird et al. 1984). In contrast, in enteral nutrition solutions, the concentration of viscous fiber is limited because the diets have to pass through small gastric or enteric tubes. Furthermore, the diets for enteral feeding require a high energy density to meet the daily energy supply without a surplus of water. Therefore, it is likely that enteral diets induce secretion of water due to their osmolality and consequently dilute the chyme. There is evidence to suggest that viscous polysaccharides reduce glucose absorption due to their viscosity (Eastwood and Morris 1992). The viscosity increases exponentially as the concentration of viscous fiber increases; thus the viscosity of the intestinal contents depends on the concentration of fiber and is highly sensitive to secretion or absorption of liquids along the gastrointestinal tract (Eastwood and Morris 1992). Consequently, results of studies on reduction of blood glucose levels cannot be applied to the conditions of enteric feeding. Therefore, it remains to be determined whether and to what extent supplementing enteral diets with viscous fiber modulates the absorption of nutrients.

This study was designed to clarify possible effects of viscous fiber on absorption of nutrients under the conditions of enteral feeding. Because the effects of fiber on absorption might depend on the type of enteral diet, in this study, we used iso- and hyperosmotic oligomeric diets and an isoosmotic polymeric diet supplemented with soy fiber and different amounts of guar gum. Absorption of nutrients was measured by perfusing a 150-cm jejunal segment in unanesthetized miniature pigs.

MATERIAL AND METHODS

Four female Troll miniature pigs (Medical Service München, Germany) weighing 43–45 kg were used. The animals were fed a special diet containing 50% of energy as carbohydrate (cornstarch), 20% as protein (casein) and 30% as fat (soy oil). The daily energy supply was 7 MJ/d (400 kJ/kg$^{0.75}$).

Surgical procedures. The procedures used in this study were approved by the local Animal Care Committee. Anesthesia was introduced intravenously with 1.2 mg/kg Tilest (Parke-Davis, Berlin, Germany) and maintained with 0.6–1.5% halothane on O_2-N_2O. Two silicone cannulas were implanted into the proximal jejunum 150 and 365 cm distal to the ligament of Treitz. The cannulas were exteriorized through the right abdominal wall. To facilitate outflow of chyme through the opened cannulas, the bases of the cannulas were positioned in a ventrodorsal direction (**Fig. 1**).

Measurement of nutrient absorption. The jejunal segment located between both cannulas was perfused with different enteral diets. Absorption of nutrients was measured by the differences between infused and recovered nutrients according to the equation described by Modigliani et al. (1973):
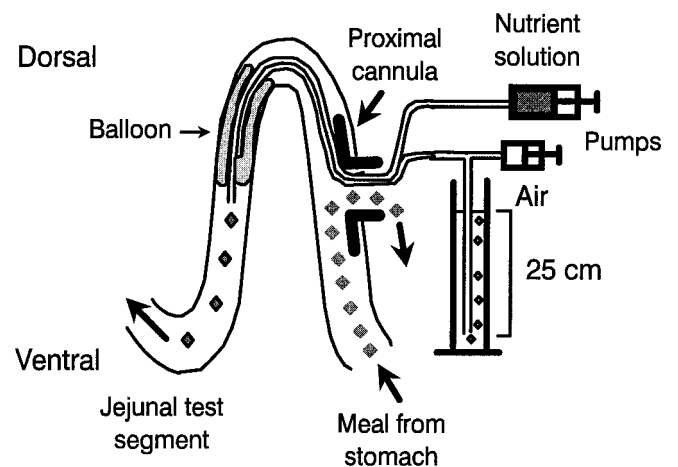

FIGURE 1 Positioning of the cannulas in the proximal jejunum of miniature pigs infused with different diets. A balloon catheter prepared from a condom was inserted through the proximal cannula. The balloon was continuously inflated at constant pressure. Diets were infused via the catheter. Backflow at the infusion site was minimal because the intestinal loop ran ventrally. Outflow of chyme from the cannulas was facilitated by the ventrodorsal position of the bases of the cannulas.

$$\text{Absorption}_{\text{nutrient}} = \text{Nutrient}_{\text{infused}} - \text{Nutrient}_{\text{recovered}} \cdot \frac{\text{marker}_{\text{infused}}}{\text{marker}_{\text{recovered}}}$$

Enteral diets. Three different types of enteral diets were used, an oligomeric diet of low energy density (OL), an oligomeric diet of high energy density (OH) and a polymeric diet of high energy density (PH). All diets were supplemented with 15 g/L of a commercial soy fiber (NutriVital, Braun, Melsungen, Germany). The soy fiber is a largely insoluble fiber. Additionally, guar gum (Meyprogat type 150, Meyhall Chemical, Kreuzlingen, Switzerland) was added with increasing amounts resulting in guar concentrations of 0 (G0), 1.1 (G1), 2.2 (G2), 3.3 (G3) and 4.4 (G4) g/L. Due to the different concentrations of guar gum, five diets were prepared with each of the three types of diets. The oligomeric diet of low energy density, the oligomeric diet of high energy density and the polymeric diet of high energy density contained 1670, 3350 and 4190 kJ/L, respectively. Because bile and pancreatic juice were lacking in the jejunal test segment, the polymeric diet was supplemented with bile and a solution of pancreatic enzymes, thus reducing the energy density to 3350 kJ/L.

The compositions of the enteral diets are summarized in **Table 1**. With all diets, the ratio of carbohydrate/protein/fat was 50:20:30% of energy, respectively. The polymeric diet (P) was composed of soluble

TABLE 1

Composition of enteral diets, amounts of nutrients, electrolytes and osmolality[1]

Diet	Composition of nutrients			Energy density	Osmolality	Concentration of electrolytes					
	Carbohydrate	Protein	Fat			Na$^+$	K$^+$	Ca^{2+}	Mg^{2+}	Cl$^-$	PO$_4^{3-}$
	g/L			MJ/L	mosmol/kg	mmol/L					
OL/G0-G4	51.8	16.8	15.0	1.67	280	35	45	37	3	63	27
OH/G0-G4	103.6	33.6	29.9	3.35	590	76	89	73	6	125	54
PH/G0-G4	128.7	36.9	37.4	4.19[2]	285	76	16	15	3	9	4

[1] Abbreviations used: OL, oligomeric diet of low energy density; OH, oligomeric diet of high energy density; PH, polymeric diet of high energy density; G0-G4, addition of guar gum, 0–4.4 g/L.

[2] 3.35 MJ/L after dilution with pancreatic enzymes.

starch (C-Pur 1905, Cerestar, Krefeld), lactalbumin and emulsified triglycerides (Lipovenös 10%, Fresenius, Bad Homburg, Germany). The oligomeric diets consisted of hydrolyzed substrates that could be digested by the brush border enzymes and absorbed without further hydrolysis by pancreatic enzymes. Maltodextrin (C-Pur 1934, Cerestar) was used as carbohydrate. It was composed of 1.5% glucose, 35% maltose, 21% maltotriose and 42.5% oligosaccharides. The protein consisted of hydrolyzed whey protein (Hyprol 8080, Quest International, Zwijndrecht, The Netherlands). It was composed of 15% amino acids, 50% di- and tripeptides, 30% oligopeptides and 5% polypeptides. A commercial emulsion of triglycerides (Lipovenös 10%, Fresenius) was used as the fat component. The fat emulsion was hydrolyzed in vitro by pancreatic enzymes. For this purpose, 66.7 g of Lipovenös was mixed with 6.7 mg cholesterol (C-3292, Sigma Chemical, St. Louis, MO), 623 mg bile salts (B-8756, Sigma), 667 mg Pancreatin (P-1750, Sigma) and small amounts of distilled water. During the hydrolysis at 37°C, the pH was kept at 7.0 by pH-stat titration with 0.3 mol/L NaOH (Titrator D3, Metrohm, Herisau, Switzerland). After the addition of 6 mmol NaOH, the hydrolysis was stopped by cooling, and distilled water was added to produce a final weight of 100 g. The hydrolyzed fat solution represented a micellar suspension. Analysis by gas chromatography showed that the hydrolyzed fat was composed of 48.7% free fatty acids, 24.7% monoglycerides, 13.1% diglycerides and 13.5% triglycerides. The carbohydrate/protein solution and the hydrolyzed fat were infused by separate pumps because of an instability of the solution of all three components. The oligomeric diets were administered without pancreatic enzymes. All diets were supplemented with the nonabsorbable marker cobalt-EDTA (100 mg/L).

The diets contained electrolytes (Table 1). The sodium content of the diets was 76 mmol/L. The quantity of other electrolytes was small compared with that in commercial enteral diets. However, the concentrations of electrolytes had no effects on the absorption rates of nutrients (unpublished data).

The polymeric diet was supplemented with bile. The bile was produced by dissolving 15 g bile extract (B-8631, Sigma) in 100 mL distilled water; 1.82 g of the bile solution was added to 100 mL of the polymeric diet. The solution of pancreatic enzymes was prepared by dissolving 3.33 g Pancreatin (P-1750, Sigma) in 100 mL distilled water. The pancreatic solution and the polymeric diet were infused into the jejunum with separate pumps (KP 2000, Desaga, Heidelberg, Germany) so that hydrolysis of nutrients commenced in the small intestine. Pancreatic solution (0.5 mL) was added to 2.0 mL of the polymeric diet resulting in a Pancreatin concentration of 4.4 g/L for the combined solution.

Experimental procedure. Experiments were started ~2 wk after surgery. At this time, the pigs had been fed normally for at least 1 wk. Before each experiment, food was withheld for 12 h. The cannulas were opened and a balloon catheter was inserted into the proximal cannula. The balloon catheter was continuously inflated with air by a pump at a constant pressure of 25 cm of water (Fig. 1). The volume of the balloon varied between 5 and 10 mL. One of the enteral diets was infused into the jejunal segment via the balloon catheter over a period of 90 min. The residues of the diets that were unabsorbed were drained from the distal cannula. Approximately 10 min after onset of infusion, the diet reached the distal cannula, and after 20 to 30 min steady-state conditions of flow occurred. Therefore, the initial 30 min served as an equilibration period. During the subsequent 60-min test period, absorption rates of nutrients and energy were measured. At the onset of the test period, a test meal was administered to induce postprandial conditions. The energy of the meal (3485 kJ) met one half of the daily requirement. The meal was drained by the proximal cannula as it emptied from the stomach. Consequently, bile and pancreatic juice did not enter the jejunal test segment during the experiment. Pancreatic enzymes were concomitantly infused with the polymeric diets. The infusion rate of all diets including infusion of pancreatic enzymes was 2.5 mL/min with the exception of the oligomeric diets of low energy density (OL/G0-G4) that were infused at 5 mL/min. Infusion was performed with piston pumps (KP 2000, Desaga, Heidelberg, Germany) with an accuracy of 0.5%. With all diets, the energy load of the jejunal segment was 8.37 kJ/min (2 kcal/min). The sequence of the diets was selected in random order. At the end

of the 60-min test period, infusion of the diet was stopped. A saline solution was perfused for a further 30 min for marker recovery. The mean recovery of the cobalt marker during the 60-min test period and the complete experiment was 99.2 ± 6.0 and 96.7 ± 3.5%, respectively. At the middle of the test period, the transit time was measured by injection of a 1-mL bolus of chromium-EDTA into the jejunal segment. During the subsequent period, the effluent of the distal cannula was collected in short intervals for recovery of the transit marker.

Analysis of nutrients, energy and marker. The concentrations of nutrients (carbohydrate, protein and fat) and of markers, and the energy content were determined in the diets and the effluents of the distal cannula. The methods of analysis have been previously described in detail (Weber and Ehrlein 1998).

The concentration of carbohydrate was determined by a commercial kit (starch-test, Boehringer, Mannheim, Germany). The content of protein was determined by an automatic nitrogen analyzer (Macro-N, Heraeus, Hanau, Germany). The fat was extracted with petroleum ether after hydrolysis with 8 mol/L hydrochloric acid. Fat extraction was performed with a semi-automatic device (Soxtherm, Gerhardt, Bonn, Germany). The fat content was determined by weighing the extracted fat. The energy content of the diets and of the chyme was determined by two methods: first, by an adiabatic electronic calorimeter (C7000-T, IKA Labortechnik, Staufen, Germany) after freeze-drying of the material, and second, as the sum of the energy of each nutrient. The energy values used to convert amounts of carbohydrate, protein and fat from g to kJ were 16.154, 19.921 and 39.925, respectively, for the oligmeric diets, and 16.263, 22.683 and 39.925, respectively, for the polymeric diet. Results of both methods were similar for the enteral diets but differed for the intestinal effluent. The energy content of the effluent determined by calorimetry was larger because intestinal secretions such as mucous or the detritus of epithelial cells enhanced the energy of the chyme. Therefore, in this study, the energy content was determined as the sum of the energy of the three nutrients. The concentrations of cobalt and chromium were measured by atomic absorption spectrometry (Perkin Elmer, Überlingen, Germany).

Analysis of water content and water flux. The content of water was determined by the differences in weight of the liquid and freeze-dried samples. The absorption or secretion of water was evaluated by the same equation as that used for nutrient absorption.

Transit time and flow rate. The mean transit time of the marker bolus was determined as the time interval between injection of cobalt-EDTA and recovery of 50% of the marker in the jejunal effluent. The flow rate was defined as the volume of fluid passing the jejunal segment per minute. It was determined from the equation:

$$\text{Flow rate (mL/min)} = \text{volume}_{\text{effluent}} \cdot \frac{\text{marker}_{\text{infused}}}{\text{marker}_{\text{recovered}}}$$

where volume$_{\text{effluent}}$ is the volume recovered at the distal cannula, and marker$_{\text{infused}}$ and marker$_{\text{recovered}}$ are the amounts of marker that were infused and recovered during the 60-min test period.

Measurement of viscosity. The viscosity of the enteral diets and of the jejunal effluent was measured with a rotation viscometer (CV0 50, Bohlin Instruments, Mühlacker, Germany). For the diets, a cone-plate device (CP 2/60) with a gap of 70 μm was used as measuring tool. For the jejunal effluent, a plate-plate device (PU 60) with a gap of 1000 μm was used because sometimes the intestinal samples contained small particles. The viscometer measured the viscosity by evaluating the rate of shear as dependent on shear stress according to the equation of Newton:

$$\text{Viscosity } (\eta)[\text{Pa} \cdot \text{s}] = \frac{\text{shear stress } (\tau)[\text{Pa}]}{\text{rate of shear } (\gamma)[\text{s}^{-1}]}$$

During an increasing shear stress between 0.01 and 1, 10 or 50 pascal (Pa), 15 viscosity values [Pa · s] were determined at 37°C. Because the enteral diets were pseudoplastic non-Newtonian solutions, the viscosity decreased as the rate of shear increased (**Fig. 2**). Therefore, the viscosity cannot be determined as an absolute value. The viscosity depending on the shear rate is called "apparent viscos-
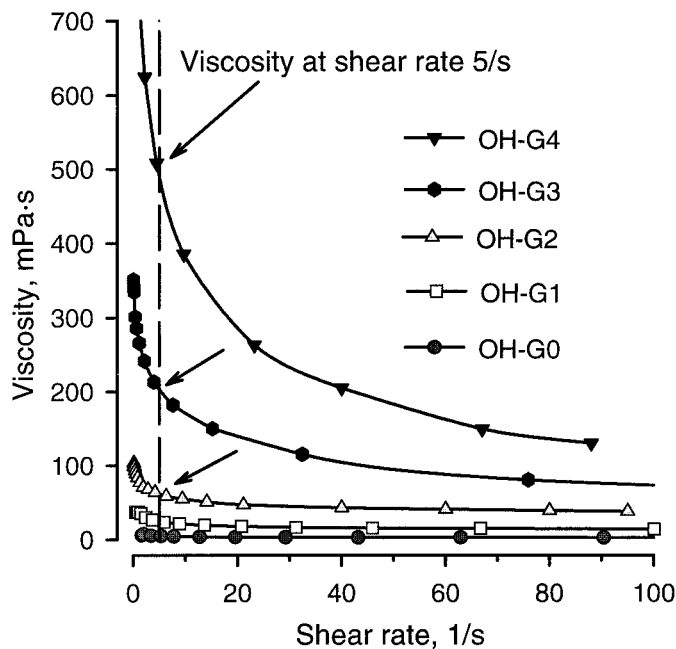
FIGURE 2 Relationship between shear rate and viscosity of the five diets infused into miniature pigs. Values and curves are results of single measurements by the viscometer. With all diets, viscosity decreased with increasing shear rate because the diets were non-Newtonian solutions. For comparison of viscosity among diets, apparent viscosity was determined at the shear rate 5/s. OH, oligomeric diet of high energy density; G0-G4, addition of guar gum 0–4.4g/L.

ity." The function of the apparent viscosity can be described by the equation of Ostwald and De Waele (Tscheuschner 1993):

$$\text{Apparent viscosity } \eta_a = C \cdot \gamma^{F-1}$$

where C is the coefficient of flow and F is the flow index. The

functions of the apparent viscosities of the diets measured in this study are summarized in **Table 2**.

Because the viscosity of the enteral diets depended on the rate of shear, it was necessary to choose a definite shear rate that would allow comparison of the viscosity among the enteral diets. This shear rate should correspond to that occurring in the small intestine during the luminal transport of chyme. Because this shear rate is not known, it was estimated by using common rheologic functions. According to the law of flow of Ostwald and De-Waele (Heritage 1995), the shear rate at the border of a pipe depends on the flow rate (Q), the radius (R), and the flow index (F) as follows:

$$\text{Shear rate}_{\text{border}} = \frac{4 \cdot Q}{\pi \cdot R^3} \cdot \frac{4}{(3 + 1/F)}$$

The shear rate produced by a moving plate depends on the velocity (v) and the distance (d) between the plates as follows:

$$\text{Rate of shear } (\gamma)[s^{-1}] = \frac{v}{d}$$

In this study, the mean intestinal flow rate was 4 mL/min, the mean velocity of jejunal peristaltic waves in miniature pigs was 5.6 cm/min (unpublished data), and the diameter of an intestinal bolus might vary between 0.5 and 1 cm. When these figures are used, the estimated intestinal shear rate varies between 0.7 and 5.8/s according to the law of flow, and between 5.6 and 11/s according to the model of plates. Therefore, in the small intestine, the mean shear rate might be ~5/s. In this study, this shear rate was used to determine the apparent viscosity of the enteral diets.

In vitro hydrolysis of polymeric diet. The polymeric diet was hydrolyzed in vitro to estimate the increase in osmolality due to the degradation of carbohydrate and protein. For this purpose, 12.5 mL of a 3.33% Pancreatin solution was added to 50 mL of the diet. Samples were taken in 1-min intervals and the osmolality was immediately measured by an osmometer (OM 801, Vogel, Giessen, Germany).

Statistics. Two experiments were performed with each diet and each miniature pig. From the data of the two experiments, a mean value was calculated. Data are presented as grand means ± SD of the four miniature pigs. Linear regressions were found between concentration of guar gum and absorption of nutrients and energy. The

TABLE 2

Parameters of viscosity curves of original undiluted enteral diets[1]

Diets	Parameters of viscosity curves			Viscosity of diets[2]	
	F	C	r	without Pancreatin	with Pancreatin
		mPa s^{-n}			mPa · s
OL/G0	0.82	9.02	0.983[3]	6.8	—
OL/G1	0.79	23.91	0.996[3]	17.1	—
OL/G2	0.81	61.91	0.996[3]	45.6	—
OL/G3	0.85	210.12	0.974[3]	165.1	—
OL/G4	0.83	648.10	0.980[3]	493.0	—
OH/G0	0.84	9.27	0.985[3]	7.2	—
OH/G1	0.80	34.31	0.980[3]	24.9	—
OH/G2	0.85	79.15	0.994[3]	62.2	—
OH/G3	0.87	257.30	0.977[3]	208.7	—
OH/G4	0.84	719.55	0.974[3]	556.2	—
PH/G0	0.83	6.30	0.956[3]	10.2	4.8
PH/G1	0.74	17.17	0.967[3]	20.4	11.3
PH/G2	0.88	36.42	0.950[3]	57.5	30.0
PH/G3	0.88	91.03	0.961[3]	203.9	75.0
PH/G4	0.81	260.44	0.987[3]	554.3	191.8

[1] Abbreviations used: F, flow-index; C, coefficient of flow; r, correlation coefficient; OL, oligomeric diet of low energy density; OH, oligomeric diet of high energy density; PH, polymeric diet of high energy density; G0-G4, addition of guar gum, 0–4.4 g/L.
[2] Apparent viscosity at shear rate of 5/s.
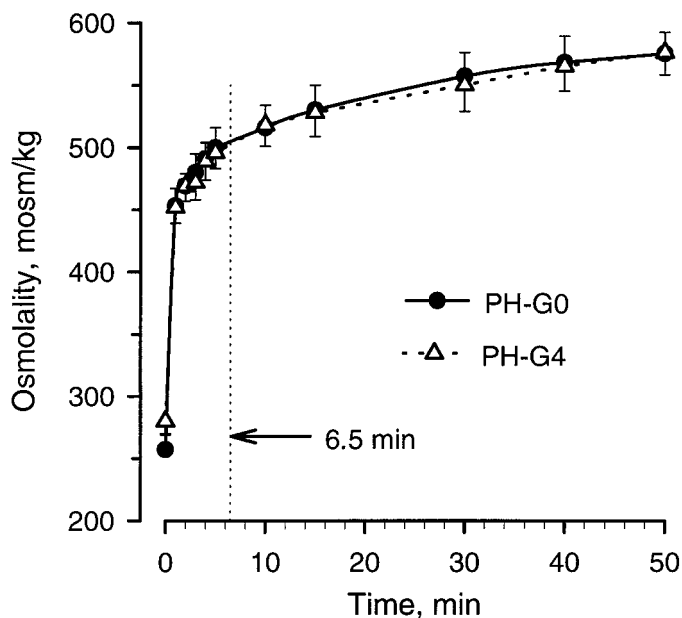[3] Significance of curve fit (t statistic), P < 0.05.

FIGURE 3 The pattern of increase in osmolality with the addition of guar gum to the diets infused into miniature pigs. During in vitro hydrolysis of the polymeric diets by pancreatic enzymes, osmolality increased within a few minutes. There was no difference in hydrolysis between the polymeric diets with and without guar gum. Because the mean transit was 6.5 min in the perfusion experiments, the osmolality was determined after this time of hydrolysis. Values are means ± SD of 5 measurments.

equations, correlation coefficients and the levels of significance are presented. Differences in regressions coefficients (slope) among the diets were tested by a one-way ANOVA using SigmaStat (Version 1.0, Jandel, Erkrath, Germany). To validate how exactly functions describe the data of apparent viscosity and shear rate, the coefficients of correlation (r) were estimated according to Fisher (Sachs 1984) using the t statistic. Differences in water flux, transit time and flow rate among diets with different guar concentrations and among the different types of diets were tested by ANOVA; $P < 0.05$ differences were considered significant.

RESULTS

Effects of guar gum on osmolality, flux of water, flow rate and transit time. The in vitro hydrolysis of the polymeric diet by pancreatic enzymes displayed saturation kinetics. Osmolality increased rapidly within a few minutes and approached plateau values (**Fig. 3**). The addition of guar gum to the polymeric diet did not alter the pattern of osmolality, i.e., guar gum did not influence the hydrolysis of nutrients (Fig. 3). Because the mean transit time along the jejunal segment was 6.5 min, the osmolality evaluated in vitro after this time might correspond to that of the chyme in the jejunal segment. The osmolality of the polymeric diets (PH/G0–G4) increased by the hydrolysis of nutrients from 298 ± 4 to 511 ± 13 mosmol/kg. This value was similar to the osmolality (590 mosmol/kg) of the oligomeric diet of high energy density. The osmolality of the chyme at the distal end of the jejunal segment was always isoosmotic.

The perfusion of the oligomeric diets with low energy density (OL/G0–G4) was associated with net absorption of water (**Table 3**). In contrast, the oligomeric diet of high energy density (OH) and the polymeric diet (PH) were associated with net secretion of water (Table 3). The addition of guar gum had no significant effect on water fluxes. Secretion of

water was not significantly different between the hyperosmotic oligomeric diet (OH) and the polymeric diet (PH) due to the rapid increase in osmolality by the degradation of carbohydrate and protein along the jejunal segment.

The flow rate of chyme at the distal end of the jejunal segment depended on the infusion rate and the net flux of water. With the oligomeric diets of low energy density (OL/G0–G4), absorption of water resulted in a decrease of the flow rate (Table 3) compared with the infusion rate (5 mL/min). In contrast, with the oligomeric diets (OH) and the polymeric diets, the flow rates at the end of the jejunal segment exceeded that of the infusion rate (2.5 mL/min) due to the secretion of water (Table 3). However, the flow rate remained slower than that of the isoosmotic oligomeric diet. Supplementing the enteral diets with guar gum had no effects on flow rates. The transit time did not differ significantly among the three diets and was not influenced by the addition of guar gum. The mean transit time of the three diets was 6.5 ± 0.5 min (Table 3).

Effects of guar gum on absorption of energy and nutrients. During perfusion of the three diets without guar gum, the mean absorption rate of total energy along the 150-cm length of jejunum was 5.2 ± 0.32 kJ/min, corresponding to 62% of the energy that was infused (8.37 kJ/min). The small variations in energy absorption among the three diets were not significantly different (**Fig. 4**). With increasing concentration of guar gum, the absorption rates of energy decreased linearly with all three diets (Fig. 4 and **Table 4**). These declining absorption rates of energy were due to a linear reduction in the absorption rates of each of the three nutrients (**Fig. 5**). The parameters of linear regressions between concentrations of guar gum and absorption rates of the three nutrients and of energy are summarized in **Table 5**. The reduction in the absorption rate of total energy differed significantly among the three diets (Table 5), i.e., the strongest inhibitory effect occurred with the oligomeric diet of low energy density (OL/G0–G4), and the smallest effect with the polymeric diet (Fig. 4). Increasing the concentration of guar gum by 1 g/L with the oligomeric diets of low energy density (OL), the high energy density (OH) and the polymeric diet (PH) diminished the absorption rates of energy by 0.52, 0.35 and 0.18 kJ/min, respectively (Table 5). In comparison with the diets without guar gum, the addition of 1 g/L guar gum diminished the absorption rates of energy by 9.7, 6.6 and 3.7%, respectively.

TABLE 3

Fluxes of water, flow rate, and transit time during perfusion into miniature pigs of the three diets supplemented with different amounts of guar gum[1]

Diet	Flux of water[2]	Flow rate[3]	Transit time[4]
	g/min	*mL/min*	*min*
OL/G0-G4	0.7 ± 0.29	4.2 ± 0.29	6.0 ± 1.90
OH/G0-G4	−1.3 ± 0.47	3.6 ± 0.47	6.9 ± 1.26
PH/G0-G4	−1.0 ± 0.66	3.3 ± 0.62	6.7 ± 0.60
		Mean of all solutions:	6.5 ± 0.47

[1] Values are means ± SD, n = 4 miniature pigs. Abbreviations used: OL, oligomeric diet of low energy density; OH, oligomeric diet of high energy density; PH, polymeric diet of high energy density; G0-G4, addition of guar gum, 0–4.4g/L.

[2] Positive number means absorption, negative numbers secretion of water.

[2,3,4] Differences in flux of water, flow rate and transit time among diets were not significant (ANOVA).
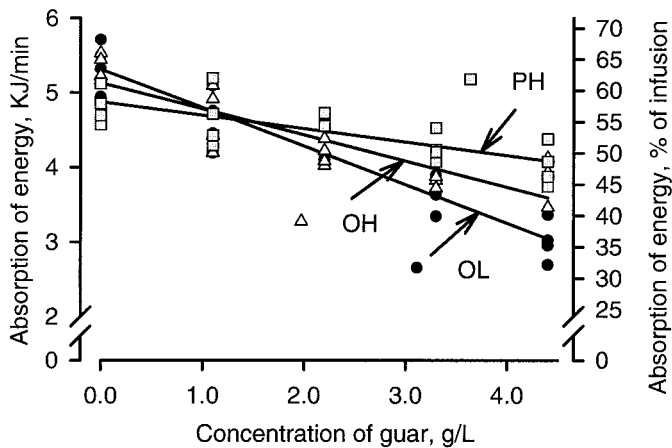
FIGURE 4 Absorption rate of total energy with increasing concentrations of guar gum added to the diets infused into miniature pigs. With all three diets, linear correlation existed between concentration of guar gum and absorption of total energy. The inhibition of absorption was strongest with the oligomeric diet of low energy density (OL) and less pronounced with the oligomeric diet of high energy density (OH) and the polymeric diet (PH). Points represent values of each miniature pig.
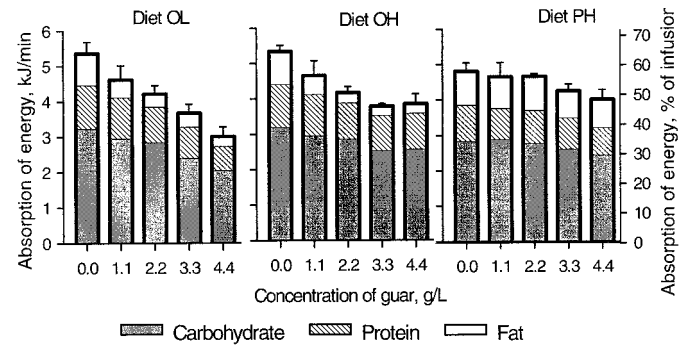

FIGURE 5 Absorption rate of nutrients and energy with increasing concentrations of guar gum in the low energy and two high energy diets infused into miniature pigs. With increasing concentrations of guar gum, absorption rates of carbohydrate, protein, and fat were diminished. Absorption of fat was markedly reduced with both oligomeric diets. Stacked columns represent mean values of carbohydrate, protein, and fat absorption of the four miniature pigs; the full columns, indicated by black lines and error bars, show mean energy absorption ± SD of four miniatur pigs. Abbreviations used: OL, oligomeric diet of low energy density; OH, oligomeric diet of high energy density; PH, polymeric diet.

Additionally, the reduction in the absorption rates of the three nutrients also differed among the three diets (Table 5). The inhibitory effects of guar gum on the absorption rates of all three nutrients were significantly greater with the oligomeric diet of low energy density (OL/G0–G4) than with the polymeric diet (PH/G0–G4). In particular, the reduction in the absorption rate of fat was most pronounced with both oligomeric diets and significantly less with the polymeric diet (Table 5 and Fig. 5).

Relationships among guar gum, viscosity and absorption. Increasing the concentration of guar gum enhanced the viscosity of the three diets exponentially (**Fig. 6**). An optimal curve fit between concentration of guar gum and the apparent viscosity was obtained by the following function: ln $\eta s = a + b \cdot x$, where s is the apparent viscosity and x represents the amount of guar gum in grams. With the oligomeric diets (OL and OH), the increase in viscosity was larger than with the

polymeric diet because the latter was diluted by the concomitant infusion of pancreatic enzymes (Fig. 6). In the small intestine, the viscosity was modulated by the fluxes of water. Consequently, with the isoosmotic oligomeric diets (OL), the viscosity of the chyme increased due to the absorption of water, whereas with the hyperosmotic oligomeric diets (OH) and the polymeric diets, viscosity decreased due to the secretion of water (**Fig. 7**). The viscosity of the chyme was deter-

TABLE 4

Mean absorption rates of energy in miniature pigs infused with the oligomeric diets of low and high energy density and the polymeric diets supplemented with 0–4.4g/L guar gum[1]

Diet	Absorption rates of energy		
	OL	OH	PH
	kJ/min		
G0[2]	5.37 ± 0.33	5.34 ± 0.18	4.81 ± 0.24
G1	4.62 ± 0.39	4.65 ± 0.42	4.65 ± 0.40
G2	4.21 ± 0.24	4.18 ± 0.16	4.66 ± 0.08
G3	3.67 ± 0.25	3.78 ± 0.07	4.26 ± 0.19
G4	3.01 ± 0.28	3.85 ± 0.28	4.01 ± 0.27

[1] Values are means ± SD, $n = 4$ miniature pigs. Abbreviations used: OL, oligomeric diet of low energy density; OH, oligomeric diet of high energy density; PH, polymeric diet of high energy density; G0–G4, addition of guar gum, 0–4.4 g/L.
[2] Absorption rates among diets without guar gum (G0) were not significantly different (ANOVA).

TABLE 5

Parameters of regression between concentration of guar and absorption and differences in the absorption rates of energy, carbohydrate, protein and fat among the three diets[2]

Energy	a	b	r
Energy			
OL/G0–G4	5.31	−0.516 ⎤[3]	0.9478[4]
OH/G0–G4	5.13	−0.350 ⎦	0.8809[4]
PH/G0–G4	4.88	−0.181 ⎦	0.7571[4]
Carbohydrate			
OL/G0–G4	3.29	−0.268 ⎤	0.8871[4]
OH/G0–G4	3.16	−0.152 ⎦	0.7377[4]
PH/G0–G4	2.93	−0.097 ⎦	0.5758[4]
Protein			
OL/G0–G4	1.26	−0.123 ⎤	0.9253[4]
OH/G0–G4	1.20	−0.054 ⎦	0.6315[4]
PH/G0–G4	0.99	−0.043 ⎦	0.5606[4]
Fat			
OL/G0–G4	0.76	−0.124 ⎤	0.7943[4]
OH/G0–G4	0.77	−0.143 ⎦	0.7790[4]
PH/G0–G4	0.95	−0.040 ⎦	0.6154[4]

[1] Function of regression, $y = a + bx$; y, absorption; a, intersection with y-axis; b, slope; x, concentration of guar; r, coefficient of correlation.
[2] Abbreviations used: OL, oligomeric diet of low energy density; OH, oligomeric diet of high energy density; PH, polymeric diet of high energy density; G0–G4, addition of guar gum, 0–4.4g/L.
[3] Brackets indicate significant differences of regression coefficient (slope) among diets (ANOVA), $P < 0.05$.
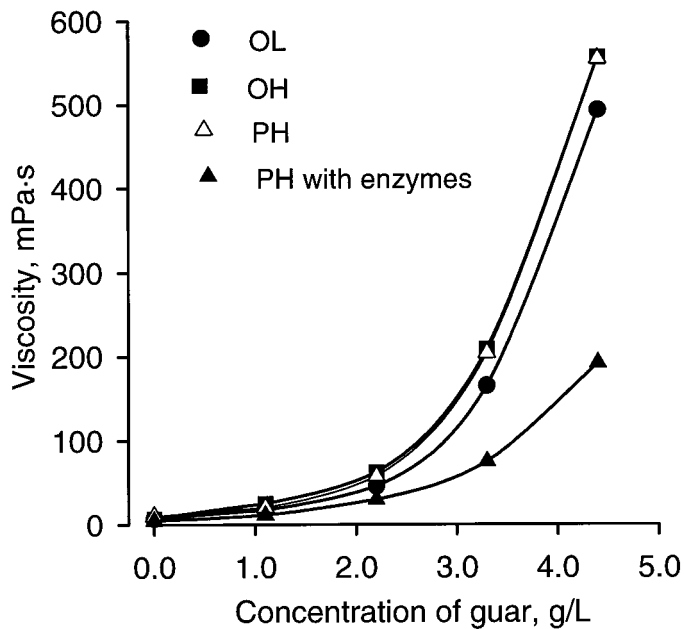[4] Significance of linear regression, $P < 0.05$.

FIGURE 6 Change in viscosity of the three diets infused into miniature pigs with increasing concentrations of guar gum. Viscosity of the diets increased exponentially as the concentration of guar gum increased. Dilution of the polymeric diet with pancreatic enzyme solution diminished viscosity markedly. Values are results of viscosity measurements of each diet and each concentration of guar gum. Viscosity represents "apparent viscosity" at shear rate of 5/s. Abbreviations used: OL, oligomeric diet of low energy density; OH, oligomeric diet of high energy density; PH, polymeric diet with and without supplementation of pancreatic enzymes.

mined as the mean value between the viscosity of the diet and the viscosity of effluent at the distal end of the jejunal segment. With all diets, absorption of total energy declined exponentially as viscosity of the chyme increased (**Fig. 8**). Figure 8 additionally illustrates that the viscosity of the chyme differed among the three diets as follows: the range of viscosity of chyme was large with the isoosmotic oligomeric diet OL, smaller with the hyperosmotic oligomeric diet OH due to secretion of water and smallest with the polymeric diet due to both secretion of water and dilution by pancreatic enzymes. Consequently, increasing concentrations of guar gum had a strong effect on absorption rates of nutrients and energy with the isoosmotic oligomeric diet OL, a smaller effect on absorption rates with the hyperosmotic oligomeric diet OH and the smallest effect on absorption rates with the polymeric diet (Figs. 4 and 5).

DISCUSSION

This study revealed several major findings: *1*) Absorption rates of the three nutrients and of total energy declined linearly with increasing concentrations of guar gum. *2*) Relationships between concentration of guar gum and viscosity showed an exponential pattern. Consequently, absorption of nutrients declined exponentially as viscosity of the chyme increased. *3*) The viscosity was altered by fluxes of water and dilution of the chyme by pancreatic juice. Due to such differences in viscosity, the inhibitory effects of guar gum on absorption were significantly different among the three diets. With the isoosmotic oligomeric diet of low energy density, guar gum exerted a strong inhibitory effect on absorption, whereas with the polymeric diet, the inhibitory effect was small. *4*) The flow rate of

the luminal content and the transit time along the jejunal segment were not influenced by guar gum. *5*) Guar gum had no effect on the hydrolysis of nutrients.

Previous studies have shown that gel-forming polysaccharide gums retard intestinal glucose absorption (Blackburn and Johnson 1981, Blackburn et al. 1984, Elsenhans et al. 1984, Flourie et al. 1984, Fuse et al. 1989, Johnson and Gee 1981, Rainbird et al. 1984). These studies were per-
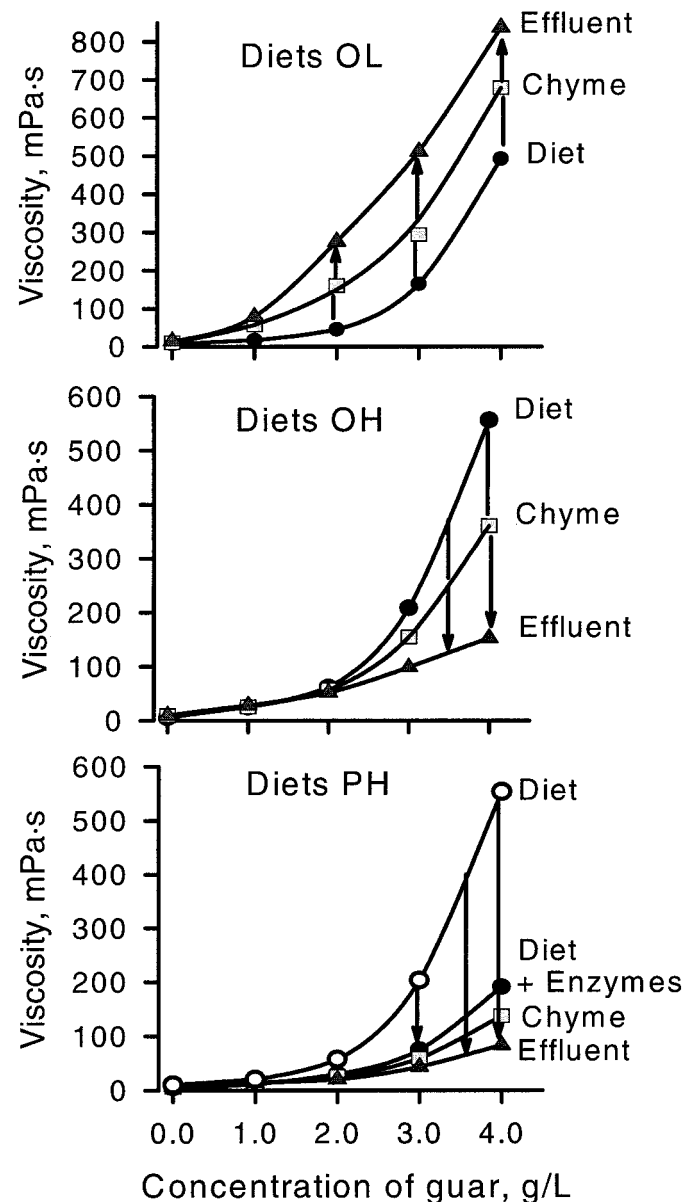

FIGURE 7 Viscosity of the chyme in relation to the oligomeric and polymeric diets infused into miniature pigs. The viscosity of the chyme was different compared with that of the diets. With the isoosmotic oligomeric diet (OL), viscosity of chyme was raised due to water absorption. With the hyperosmotic oligomeric diet (OH) and the polymeric diet (PH), viscosity of chyme was reduced due to secretion of water. With the polymeric diet, the concomitant infusion of pancreatic enzyme solution additionally diminished the viscosity of the chyme. Viscosity represents "apparent viscosity" at a shear rate of 5/s. Values of diet are results of single viscosity measurements with each diet and each concentration of guar gum. Viscosity of effluent represents mean values of the four pigs. Viscosity of chyme was defined as mean value between viscosity of diets and effluent.
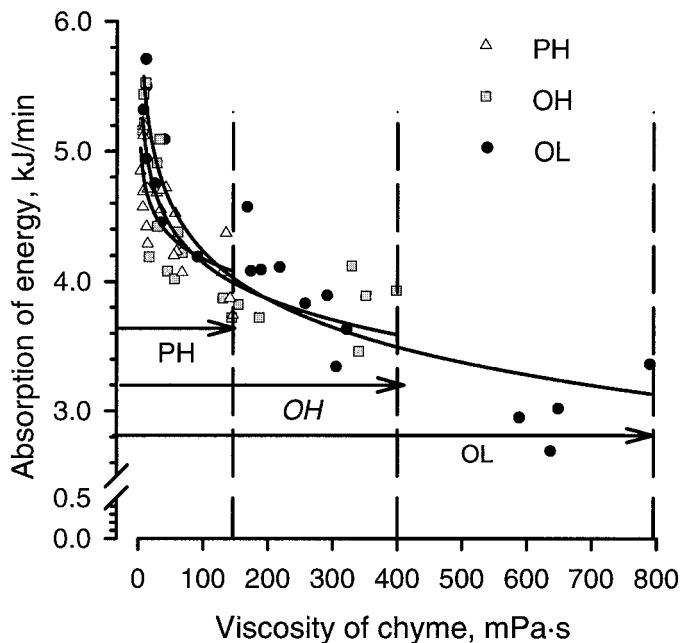
FIGURE 8 Relationships between viscosity of chyme and absorption rates of energy in miniature pigs infused with different diets. These relationships were characterized by exponential functions. The figure further illustrates the differences in viscosity of the chyme among the three diets. Points represent values of each miniature pig. Abbreviations used: OL, oligomeric diet of low energy density; OH, oligomeric diet of high energy density; PH, polymeric diet.

formed primarily to clarify the mechanism by which the addition of viscous fiber to carbohydrate meals reduces postprandial hyperglycemia. Results showed that the major effect of polysaccharides is probably to raise the viscosity of the chyme, thereby decreasing convection within the intestinal lumen, increasing the thickness of the unstirred water layer and thus slowing diffusion and luminal transport of the nutrients (Edwards 1990, Flourie et al. 1984, Johnson and Gee 1981). Although the results of our study were similar to those of the previous studies, the experimental conditions differed in the following ways: *1*) several investigations were performed in anesthetized animals; *2*) in absorption studies in humans, short intestinal segments and high perfusion rates were used; *3*) in all previous studies, only isoosmotic electrolyte-glucose solutions of low energy density were used; and *4*) the concentration of viscous fiber was relatively high. Perfusion studies in anesthetized animals are nonphysiologic because intestinal motility is inhibited, luminal flow becomes laminar and convection within the intestinal lumen is eliminated (Anderson et al. 1989, Edwards 1990, Schwartz and Levine 1980). Additionally, infusion of viscous solutions increased intraluminal pressure and volume, resulting in an enlargement of the absorptive surface area (Elsenhans et al. 1984). These effects caused the paradoxical result that increasing concentrations of guar did not reduce, but rather enhanced glucose absorption (Elsenhans et al. 1984). Absorption studies in humans (Blackburn et al. 1984, Flourie et al. 1984, Fuse et al. 1989), using short intestinal segments and large perfusion rates, might also be nonphysiologic because luminal flow might depend more on the perfusion rate than on intestinal contractions. This might influence the release of nutrients from the gut and

slow absorption, in particular with viscous chyme. In this study, we used physiologic perfusion rates and measured nutrient absorption within a 150-cm length of jejunum. Therefore, aboral transport was produced primarily by intestinal contractions.

The concentration of viscous fiber used in most previous studies was adapted to that observed in the intestinal content after ingestion of fiber-supplemented meals (Blackburn and Johnson 1981, Rainbird et al. 1984). Because the effects of viscous fiber on reduction of postprandial hyperglycemia were significant only when relative large amounts of viscous polysaccharides (~60 g/L) were supplemented, the concentration of fiber used in previous perfusion studies was also relatively high. Concentrations of guar varied from 0.5 to 0.67% (Blackburn and Johnson 1981, Rainbird et al. 1984), and pectin from 0.5 to 1.5% (Flourie et al. 1984, Fuse et al. 1989). In enteral nutrition solutions, high concentrations of viscous fiber are not useful because the solutions have to pass through small gastric or enteric tubes. In this study, we added guar gum in concentrations from 1.1 to 4.4 g/L. However, the amounts of viscous fiber are difficult to compare with those used in previous studies because different types of viscous polysaccharides, and even various kinds of guar gum, exert different degrees of viscosity. The guar gum (Meyprogat type 150) used in this study is characterized by a high viscosity. In this connection, a further problem is the measurement of viscosity. Because enteral diets are non-Newtonian solutions, viscosity changes as the shear rate increases. Therefore, only the "apparent" viscosity but not a definite viscosity can be determined. The shear rate occurring in the small intestine is not known. In previous studies on viscosities of fiber-supplemented nutrient solutions and meals, shear rates were chosen arbitrarily, resulting in large variations from <1/s (Cameron-Smith et al. 1994, Cherbut et al. 1990) to>1000/s (Anderson et al. 1989, Blackburn and Johnson 1981). Consequently, viscosity values cannot be compared. A further problem in rheologic studies is the low viscosity of nutrient solutions. The measurement of the apparent viscosity with small samples and at low shear rates requires a high quality and thus a very expensive viscometer. This may be a reason why the apparent viscosity was often measured at high shear rates. Additionally, simple viscometers often do not measure the shear rate but only the frequency of rotation. We tried to solve these problems by measuring the viscosity in the laboratory of a company using high quality equipment. Furthermore, we determined the function between shear rate and viscosity because the viscosity-shear profile characterizes the apparent viscosity most powerfully. For comparison of viscosity among the enteral diets, it was necessary to estimate the shear rate. We tried for the first time to calculate the shear rate that might occur in the small intestine using common rheologic functions. If further investigations would show that the shear rate calculated in our study was not quite correct, the apparent viscosity can be easily corrected by the parameters of the viscosity-shear profile.

Commercial enteral diets are usually supplemented with soy polysaccharides. This fiber is largely insoluble and contains only small amounts of viscous fiber (Shinnick et al. 1989). However, supplementing enteral diets with viscous polysaccharides other than insoluble fiber might have some advantages. Viscous polysaccharides stabilize the nutrient solution. They have further beneficial effects on gastrointestinal functions (Compher et al. 1997). Viscous polysaccharides are highly fermentable in the large intestine. The absorption of SCFA stimulates water absorption. Therefore,

supplementing enteral diets with viscous fiber might reduce diarrhea (Roth et al. 1995, Zimmaro et al. 1989). Viscous polysaccharides further cause mucosal proliferation of the small and large intestine (Koruda et al. 1986, Roth et al. 1995). This effect might preserve gut barrier function and avoid bacterial translocation. However, in enteral nutrition, it is important that nutrient absorption not be impaired by the addition of fiber. In a parallel study, we demonstrated that soy polysaccharides did not influence intestinal absorption of nutrients (Ehrlein and Stockmann 1998). In contrast, results of this study showed that viscous polysaccharides inhibit absorption of nutrients and energy. The inhibitory effect linearly increased as the concentration of guar gum increased. However, there were marked differences in the degree of inhibition among various enteral diets. With an isoosmotic oligomeric diet of low energy density, guar gum exerted a strong inhibitory effect on absorption of nutrients because the absorption of water raised the viscosity of the chyme. This result is consistent with that of previous studies in which isoosmotic electrolyte solutions supplemented with glucose (Blackburn and Johnson 1981, Flourie et al. 1984, Fuse et al. 1989), amino acids (Elsenhans et al. 1984) or fatty acids (Fuse et al. 1989) were used. This study also showed that viscous fiber diminished absorption not only of individual nutrients but also of complex enteral diets. With the hyperosmotic oligomeric and the polymeric diets, the viscosity of the chyme was diminished by secretion of water; consequently, the inhibitory effect of guar gum was markedly reduced. With the polymeric diet, viscosity was further reduced by the concomitant infusion of pancreatic enzymes that was required for degradation of the nutrients. Consequently, with the polymeric diet, the inhibitory effects of guar gum were small. These results, in agreement with previous findings (Edwards 1990, Flourie et al. 1984, Johnson and Gee 1981), clearly show that the effects of guar gum on nutrient absorption depended on the viscosity and that the viscosity of the chyme was highly sensitive to water fluxes and dilution by secretions. In enteric feeding, either oligomeric or polymeric diets of high energy density are required. Both diets cause secretion of water. The nutrients also stimulate pancreatic and biliary secretion. Therefore, the chyme is diluted so much that viscous polysaccharides have only a small effect on intestinal absorption. Additionally, the small intestine provides reserve capacities for absorption and reserves in length (Weber and Ehrlein 1998) so that a slightly delayed absorption rate might be compensated even in enteric feeding of patients.

With enteric feeding, a specific modulation of intestinal motility might play a major role in the effects of viscous fiber. Intestinal infusion of nutrient solutions (Schmid et al. 1992) and hyperosmotic solutions in particular (Schmid and Ehrlein 1993) stimulates clustered contractions that are characterized by an intensive mixing and a slow aboral movement of luminal content. This might also support convection of luminal content and the transport of nutrients from the bulk to the mucosa and thus reduce the inhibitory effects of the viscosity.

Viscous polysaccharides usually delay intestinal transit (Brown et al. 1988, Bueno et al. 1981, Jenkins et al. 1978, Leeds 1982). In this study, the presence of guar gum had no effect on the transit time or flow rate. This discrepancy might be due to the experimental conditions. As already discussed, the water secretion induced by the high osmolality of enteral diets markedly reduced the viscosity of the guar gum, and the characteristic motor pattern induced by concentrated nutrient solutions might produce a constant aboral propulsion of the chyme.

ACKNOWLEDGMENTS

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