Postprandial duodenal function in man

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SUMMARY Duodenal function was studied in 11 healthy volunteers after intragastric instillation of a mixed semi-elemental meal. The duodenum accepted chyme of varying pH, osmolality, and nutrient concentration; and, as a result of biliary, pancreatic, and enteric secretion as well as absorption, it delivered chyme with nearly constant pH, osmolality, and nutrient concentration to the jejunum. The flow rate and nutrient load of jejunal chyme varied. The duodenum absorbed more carbohydrate than lipid and less protein, taking up each nutrient at a constant rate during most of the postprandial period. The percentage of nutrient load absorbed was greatest in the late postprandial period, when flow rate, nutrient load, and concentrations were low.

Duodenal chyme influences all major functions of the duodenum; yet postprandial chyme in normal man has not been fully characterised. Duodenal hormonal and neural regulation of gastric, pancreatic, and biliary secretion and of upper gastrointestinal motor activity is sensitive to chyme nutrient content (Windsor et al., 1969), osmolality (Meeroff et al., 1975), and pH (Johnston and Duthie, 1966). Pancreatic and biliary secretions that are important to digestion mix with chyme in this segment of bowel and are similarly sensitive to the characteristics of chyme. An example of this is seen in the Zollinger-Ellison syndrome, where duodenal delivery of an acidic chyme inactivates lipase and precipitates bile acids, thus producing steatorrhoea (Go et al., 1970). Also, duodenal absorption and secretion of fluid and electrolytes and absorption of nutrients are certainly dependent on the composition of duodenal chyme. This is apparent in considering the dumping syndrome (Abbott et al., 1960).

Little information has been obtained from normal man to characterise the postprandial gastric contents delivered into the duodenum, the modifications of this chyme that occur along the duodenum, and the chyme that is delivered into the jejunum. We have tried to develop more thorough knowledge of these substances and changes and of the nutrient absorption taking place at this level of the bowel after ingestion of a liquid, mixed, semi-elemental meal. Although this meal might not induce the same duodenal events as a more complex one, it was used to simplify analytical procedures.

Methods

SUBJECTS

Eleven healthy volunteers (two female and nine male, aged 21 to 62 years) participated in 16 studies after giving informed consent. All data reported as results are from the initial study performed in each of the 11 subjects. The five duplicate studies are used only to provide further independent assessment of the correlation between emptying of nutrient and of meal marker in a particular study.

MEAL

A 400-ml standard liquid meal containing about 300 calories distributed as 40% carbohydrate, 40% lipid, and 20% protein (similar to their distribution in the normal American diet) was used. The nutrients were semi-elemental, in forms normally appearing in the bowel lumen, which could be assimilated easily and which permitted simple analysis of intestinal chyme for nutrient composition. The meal was prepared by dissolving in water 30.7 g maltose (0.224 molar), 14 g oleic acid (0.124 molar), 16.4 g of a complete tryptic hydrolysate of casein, and 15 g of a nonabsorbable marker (polyethylene glycol 4000) and adjusting the pH to 7.0 with a small amount of NaOH. Sonication for 10 minutes produced an emulsion with osmolality 544 ± 5 mOsm/l which was stable for several hours, thus longer than the study period.

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Two peroral tubes were used (Fig. 1). For the duodenum, there was a sump tube that ran to a mercury-weighted tip beyond an occlusive balloon and had three small polyvinyl tubes cemented to it. This assembly (of total external diameter, except for the balloon, of approximately 6 mm) provided (1) the duodenal perfusion site; (2) an aspiration site with an air channel, to facilitate suction, located 20 cm distal to the perfusion site; (3) an inflatable balloon immediately distal to the aspiration site; and (4) an aspiration site immediately beyond the balloon. Gastric sampling was done via a separate 14-F sump tube.

**Procedure**

Each study was begun after an overnight fast. The volunteers were seated in an upright position throughout the study. Under fluoroscopic control, the duodenal tube was positioned with the balloon at the ligament of Treitz and the gastric tube was positioned with its tip in the most dependent area of the antrum. Duodenal perfusion with $^{14}$C-PEG (polyethylene glycol, specific activity $0.5 \mu$Ci/mg) dissolved in 0.15 M NaCl was maintained at 2 ml/min throughout the study period. The occlusive balloon was inflated with 30 to 45 ml of air until the subject sensed its presence, without having any discomfort. Total occlusion was confirmed by demonstrating that neither bile nor $^{14}$C-PEG was present distal to the balloon. More than 92% of marker was recovered proximal to the balloon in all studies. No study was included in which duodenal-gastric reflux of duodenal marker exceeded 15%.

Fasting gastric and duodenal collections were made by continuous suction ($-25$ mm Hg) during two 10-minute intervals.

Then the meal was injected via the gastric tube over eight minutes, and gastric and duodenal samples were collected for two hours after the meal. Every 10 minutes, 200 ml of gastric contents was aspirated, a 10-ml aliquot was taken from it, and the remainder was returned immediately to the stomach. The aliquots from each 30-minute interval were pooled.

Duodenal samples were aspirated by continuous suction ($-25$ mm Hg), collected over ice, and pooled at 30-minute intervals. No duodenal chyme was reinfused. To correct for transit time, duodenal collections were begun five minutes after corresponding gastric collections.

At the end of the study period, gastric contents were aspirated completely; then 200 ml of a normal saline gastric wash was aspirated over five minutes; and this was aspirated, to recover as much of the marker as possible.

Determinations of osmolality (Wescor 5100 Vapor Pressure Osmometer) and pH (Fisher 520 Digital pH/Ion Meter) were performed immediately on all gastric and duodenal samples. Marker concentrations also were measured in all samples (Brunner et al.,...
Postprandial duodenal function in man

1974), and bilirubin and trypsin concentrations were measured in all duodenal samples (Brunner et al., 1974). Bilirubin and trypsin outputs as well as the gastric volume emptied and meal emptied were calculated as previously reported (Brunner et al., 1974; Malagelada et al., 1976). The formulas were modified to include the actual volume collected at the ligament of Treitz rather than a flow rate previously calculated from the duodenal perfusate (Malagelada et al., 1976; Clain et al., 1977). Therefore, characterisation of gastric contents emptied into the duodenum was indirect (based on marker determinations), and that of chyme leaving the duodenum was measured directly.

Total protein was determined by the method of Lowry et al. (1951), fatty acid by the method of Cohen et al. (1969), carbohydrate by analysis of maltose (Bernaldf, 1955), and glucose by the hexokinase method (Bergmeyer et al., 1974). In the maltose assay, correction was made for free glucose present. Nutrient assays were performed on the meal, all duodenal samples, and the gastric contents aspirated at the end of the two-hour study period. Although we cannot be sure that we were measuring only exogenous nutrient, the contribution by endogenous secretions probably was very small.

Validation study

In an attempt to determine the maximal potential interference, a validation study was performed in which pancreatic and biliary secretions aspirated from five normal subjects at the time of maximal cholecystokinin stimulation were analysed for carbohydrate, lipid, and protein by the same techniques mentioned above. As proportions of the mean postprandial concentrations at the ligament of Treitz in the main study, the highest concentrations in the validation study were carbohydrate 3·5%, lipid 9·5%, and protein 15·1%. Adibi and Mercer (1973) also have shown that dietary protein makes up the major portion of intraluminal amino acids and peptides after a meal.

Statistical methods

Paired sets of data from individuals were analysed by the paired t test (Dixon and Massey, 1969).

Results

Ph and osmolality

After ingestion of the meal (pH 7·0), the pH of gastric contents—and therefore of chyme delivered into the proximal duodenum—decreased progressively (each point different from preceding point, p < 0·01). The pH at the distal end of the duodenum (aspirated at the ligament of Treitz) was quite stable, however, close to neutrality (Fig. 2). Osmolality of the chyme behaved similarly: after the meal (osmolality 544), gastric osmolality progressively decreased toward the osmolality of blood (each point different from preceding point, p < 0·01). This steady decline of the osmolality of gastric contents entering the duodenum was not reflected by chyme at the ligament of Treitz, where osmolality remained stable near isotonicity (Fig. 2).

![Figure 2 Simultaneously measured postprandial pH and osmolality of gastric contents entering duodenum (— — —) and chyme leaving duodenum at ligament of Treitz (— — —). Points plotted at zero time represent pH and osmolality of meal.](http://gut.bmj.com/)

Volume flow

Figure 3 demonstrates volume flows. The total volume of gastric contents emptied into the duodenum during each 30-minute interval was constant throughout the two-hour postprandial period (no point different from any other at p < 0·05 level). The actual meal volume emptied into the duodenum was greatest in the first 30 minutes, then progressively less in each interval thereafter as diluting gastric secretion became a greater proportion of the gastric volume emptied (each point different from preceding point, p < 0·01). Throughout the study period, the volume flow at the ligament of Treitz was greater than that entering the duodenum (p < 0·01). The net change of chyme volume along the duodenum is represented by...
protein, lipid, and carbohydrate were emptied from the stomach in the same proportions as administered—and in stable proportion to the meal marker. Figure 4 demonstrates the correlations among the meal marker, protein, lipid, and carbohydrate emptied over two hours, expressed as percentages of the marker or nutrient administered. (All values were calculated from actual measurements of residual gastric volume and of meal marker or nutrient concentrations.) These correlations validate our use of meal marker to calculate nutrient loads and concentrations entering the duodenum.

All nutrient loads and concentrations delivered into the duodenum were maximal in the early postprandial period and decreased progressively (Fig. 5; each point different from preceding point, \( P < 0.05 \)). The duodenum handled the three nutrients differently, however, absorbing more carbohydrate than lipid and less protein, and therefore delivering less carbohydrate than lipid and more protein to the jejunum. Consequently, separate lines are drawn to represent the different nutrient loads and concentrations at the level of the ligament of Treitz. The nutrient loads arriving at the ligament of Treitz were largest in the early postprandial period and diminished progressively (each point different from preceding point, except lipid and carbohydrate at 75 and 105 min, \( P < 0.05 \)). The nutrient concentrations, however, had stabilised; and there was no change of protein or lipid concentration in chyme between any 30-minute intervals in the study period (no point different from any other, at \( P < 0.05 \) level). The carbohydrate concentration in chyme at the ligament of Treitz, although much more stable than at the pylorus, gradually decreased (each point different from preceding point, \( P < 0.01 \)).
from preceding point, \( p < 0.05 \) because the duodenum absorbed a much greater proportion of this nutrient than of protein or lipid. Actual concentrations of each nutrient in chyme at the ligament of Treitz after this meal were: protein 9.71 ± 0.53 mg/ml, lipid 5.79 ± 0.56 mg/ml (20 mM), carbohydrate 7.22 ± 0.82 mg/ml (21 mM). During the two-hour study period, mean absorptions were 23 ± 6% of the protein load, 41 ± 9% of the lipid, and 62 ± 9% of the carbohydrate (differences significant, \( p < 0.01 \)).

**NUTRIENT ABSORPTION**

Duodenal nutrient handling is further demonstrated in Fig. 6. During the first 90 minutes postprandially, the amounts of each nutrient absorbed and, therefore, the rates of absorption (protein 0.68 ± 0.10, lipid 0.95 ± 0.09, carbohydrate 2.81 ± 0.24 g/30 min) were constant despite changes in nutrient loads, nutrient concentrations, and flow rates (no point different from any other at \( p < 0.05 \) level). The quantities of each nutrient absorbed decreased in the final 30 minutes as the nutrient load decreased (\( p < 0.05 \)). The percentage of the nutrient load absorbed each 30 minutes, a measure of absorptive efficiency, increased through the first three 30-minute postprandial intervals (each point different from preceding point, \( p < 0.05 \)).

**PANCREATIC AND BILIARY OUTPUTS**

Trypsin and bilirubin outputs are demonstrated in Fig. 7. Pancreatic enzyme output was maximal in the first 30 minutes postprandially and declined steadily thereafter. Bilirubin output, reflecting gallbladder contraction, also was maximal in the first 30 minutes; but thereafter it fell off faster than trypsin output.

**Discussion**

Isolation of the gastroduodenal field permitted study of the coordinated upper gastrointestinal events that occur in the postprandial period in normal man, making possible the determination of proximal and distal duodenal nutrient loads, amount of nutrient absorbed, and percentage of nutrient load absorbed from duodenal chyme in its normal postprandial form. Previous studies of duodenal absorption have utilised either isolated nutrient infusions (Abbott et al., 1940; DiMagno et al., 1971) or comparison of nutrient concentration with nonabsorbable marker concentration, a technique permitting calculation of
Percentage absorption but not nutrient load (Borgström et al., 1957). Although permitting these further observations, this study may not be directly comparable with studies in which chyme either was not diverted or was reintroduced, because of the recognized jejunal phase of gastric function (Clain et al., 1977).

Gastric contents entering the duodenum after a meal have progressively decreasing pH, osmolality, and nutrient concentration as the stomach dilutes the meal with acidic, near-isotonic gastric secretion and, at the same time, meal buffer is being emptied. Mechanisms to modify the chyme between its emptying from the stomach and its delivery to the jejunum include enteric, biliary, and pancreatic secretion as well as duodenal absorption. Consequently, the chyme delivered to the ligament of Treitz after this meal has constant pH near neutrality and constant osmolality near isotonicity. Fordtran and Locklear (1966) reported similar findings with a solid, complex meal. Individual nutrient concentrations also become fairly constant before reaching the ligament of Treitz.

In contrast, nutrient and volume loads at the ligament of Treitz change during the postprandial period. This reflects nutrient rather than volume delivery into the duodenum, since the rate of gastric volume emptying is constant throughout the study period.

Throughout the study period, the volume flow at the ligament of Treitz is greater than that entering the duodenum, with its greatest net increase occurring early postprandially. Pancreatic and biliary secretions contribute significantly to this increase of chyme volume. Pancreatic and biliary secretion is maximal early, when maximal nutrient loads and concentrations are being delivered into the duodenum, and decrease as the nutrient loads and concentrations...
Postprandial duodenal function in man

decrease. It is of interest that both trypsin and bili-
rubin outputs progressively decrease, while the
amount of each nutrient absorbed remains constant.
Although the early peaks of apparent output may
represent a washout phenomenon, the output curves
do not stabilise as would be expected if they were
controlled only by absorbed nutrient.

Another reason for the large early net increase in
duodenal volume is the limited amount of nutrient
absorption. The greatest percentage of the nutrient
load is absorbed in the third 30-minute postprandial
interval, when flow rates, loads, and concentrations
are less. Also, little duodenal fluid absorption can be
expected early in the postprandial period, when
chyme from the stomach is hypertonic and flows
through the duodenum rapidly.

Despite the changes of nutrient loads, nutrient
concentrations, and flow rates, the amount of each
nutrient absorbed by the duodenum per 30 minutes
is constant through two hours postprandially. More
carbohydrate than lipid is absorbed, and less protein.

Borgström et al. (1957) also have investigated
nutrient absorption from a mixed meal containing
skim milk, dextrose, corn oil, and albumin. Nutrient
absorption was found to be complete in the proximal
50 to 100 cm of jejunum, with lipid absorbed more
proximally than protein or carbohydrate. Amounts of
protein and lipid absorbed proximal to the ligament
of Treitz in that study were similar to the amounts
absorbed in ours, but carbohydrate absorption was
quite different.

The reason for this difference is uncertain. The
two studies used different forms of carbohydrate.
Maltose, used in our study, is well absorbed—at least
in the jejunum: 60% of a 72-mM/h infusion is
absorbed by a 30-cm segment of jejunum (Gray and
Santiago, 1966). Cook (1973) found greater absorp-
tion of carbohydrate from maltose than from glucose
perfused in the human jejunum. Dahlqvist and
Borgström (1961), however, found little absorption
or hydrolysis of maltose in the duodenum. In the
study of Borgström et al. (1957), 27% of the carbo-
hydrate was in the form of lactose, a disaccharide
requiring hydrolysis before absorption (Gray and
Santiago, 1966). But maltose can be absorbed intact,
even though its rate of hydrolysis is about twice that
of lactose (Gray and Santiago, 1966).

In our study, the rate of lipid absorption was
between the rates of carbohydrate and protein
absorption. Conditions should have been ideal for
absorption, since bile was permitted to mix with
duodenal chyme in a physiological manner to form
micelles. Pancreatic lipase was not necessary for
digestion, because the source of lipid used was a fatty
acid.

The nutrient absorbed most slowly was the pro-
tein, despite its presentation as small peptides, a form
that should maximise its absorption rate (Adibi,
1971; Crampton et al., 1971; Adibi et al., 1975).
Although actual analysis of amino acids and pep-
tides was not performed, characterisation of these in
similar tryptic hydrolysates demonstrates an average
peptide length of 2-2 amino acid units (Crampton et
al., 1971). This is similar to the form of protein
normally found in the intestinal lumen (Adibi and
Mercer, 1973). Normally, in fact, meal protein is
found as far distally as the mid-ileum (Adibi and

In summary, in the postprandial period after a
liquid semi-elemental meal, the normal human duo-
denum receives chyme of varying pH, osmolality, and
nutrient concentration; and as a result of biliary,
pancreatic, and enteric secretion as well as absorp-
tion, it delivers chyme with near constant pH,
osmolality, and nutrient concentration to the jeju-
um. Jejunal chyme varies in flow rate and nutrient
load. Duodenal conditions permit maximal absorp-
tion of each nutrient over the first 90 minutes post-
prandially, and more carbohydrate than lipid and
less protein is absorbed. The percentage of nutrient
load absorbed is greatest in the late postprandial
period when flow rates, nutrient load, and concen-
trations are low. How these results are modified by
meals of different size, composition, and physical
state will need to be evaluated in the future.

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