

Relationships between pressure and flow across the gastroduodenal junction in dogs

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MALBERT, CHARLES H., AND YVES RUCKEBUSCH. *Relationships between pressure and flow across the gastroduodenal junction in dogs*. *Am. J. Physiol.* 260 (Gastrointest. Liver Physiol. 23): G653–G657, 1991.—Antroduodenal pressure events were measured simultaneously with transpyloric flow, in conscious dogs, to evaluate the role of mechanical factors modulating this flow. The relationships between pressure and flow across the gastroduodenal junction were never linear. During the interdigestive state, terminal antral contraction occurred 0.9 ± 0.29 s after the onset of the gush of gastric contents. Hence, the highest flow rate occurred during the period of lowest resistance. After a meal, terminal antral contraction began 3.3 ± 0.87 s before the flow of chyme, and resistance rose simultaneously with flow rate. The antroduodenal resistance was 10 times higher than during the interdigestive state (8.33 ± 1.56 vs. 0.73 ± 0.34 mmHg·ml⁻¹·s). The pyloroduodenal resistance was always lower than the antropyloric one. It is concluded that, because of the temporal relationship between motor events and flow, pure resistive behavior of the junction occurred only after a meal.

flow rate of digesta; intrapyloric pressure; pyloric resistance

AMONG THE FACTORS modifying the outflow of gastric chyme other than those originating from gastroduodenal pressure waves, the flow-resistive properties of the antroduodenal region have been suggested in cats and rabbits (17). Nevertheless, the efficacy of the antroduodenal resistance in controlling gastric emptying is still a matter of controversy because of the difficulties encountered in the evaluation of this resistance under physiological conditions. However, resistance of the gastroduodenal junction might be important to control gastric outflow. Indeed, its value depends on the timing between pyloric and antral contraction and the degree of opening of the pyloric sphincter, two parameters that have been shown to be involved in the regulation of gastric emptying (3, 7). During the interdigestive period in conscious dogs, pyloric resistance has been extrapolated under constant pressure gradient (13). However, the length of the cylinder did not allow the measurement of individual antropyloric and pyloroduodenal resistance. In addition, changes in resistance induced by the ingestion of food has never been assessed. Indeed, this evaluation could not be achieved by the use of a resistometer, which partly blocks the gastric outlet and therefore might alter gastric emptying.

The aim of this study was twofold: first, to evaluate

the relationship between the passage of gastric contents and the pressure waves occurring at the antroduodenal level on a gush-to-gush basis; second, to measure the flow-resistive properties of the antropyloroduodenal segment during individual passage of gastric contents, before and after a meal.

METHODS

Experimental surgery. Under general anesthesia (halothane vapor 1.2% vol/vol) and aseptic conditions five male mongrel dogs weighing 25–30 kg were fitted with a multilumen manometric assembly (5 mm OD). The manometric probe was inserted through a small hole inside the lumen of the proximal antrum and positioned so that the side holes were located at the terminal antral (–5 cm from the pylorus), pyloric, and duodenal bulb level, respectively. To ensure the correct position of the pyloric side hole, the distal (duodenal) end of the manometric assembly was sutured to the duodenal wall by means of a small piece of reinforced silicone-Dacron sheet (Sigma Medical) that was glued around the tip of the assembly.

During the same surgical procedure, a flowmeter probe built as formerly described (11, 12) was fixed with its proximal edge placed as close as possible (<2 mm) to the duodenal side of the pylorus. A 10-mm longitudinal incision in the wall of the duodenal bulb enabled the probe to be inserted. To maintain the flowmeter probe at this location, four threads were passed through the duodenal wall and through a reinforced silicone-Dacron sheet that was glued at the outer surface of the flowmeter probe. The wires of the flowmeter probe and the multilumen assembly were exteriorized through a subcutaneous channel between the shoulders, and the anesthesia was finished.

Recordings. The manometric catheters were perfused with degassed distilled water using a low-compliance pneumohydraulic system (IP 8000, Gould) at a reservoir pressure of 380 mmHg, giving a constant flow rate of 0.3 ml/min. Pressures, recorded with Statham P23 Db (Gould) pressure transducers, were plotted on a multi-channel recorder (Beckman Dynograph 641). The flowmeter probe was connected to an electromagnetic flowmeter (8, 12). The flowmeter output was fed into a microcomputer, which suppressed artifacts caused by air bubbles and attachment of particles and calculated the volume of each individual gush. A baseline was recreated by the computer from the input data minus the occurrence of duodenal gushes. All the values were reactualized

†Deceased.

with the level of this "true zero" (10). Retrograde flow was detected as deflection of flow trace under the baseline and was noted as negative flow rate values. The area under the baseline was subtracted from that above the baseline to obtain the volume of liquid flowing from the stomach to the duodenum. The sensitivity of the whole recording apparatus was 0.2 ml regardless of the measurement time (10). The time response of the flow-recording system was 50 μ s, and this value was taken into account when simultaneous pressure-flow measurements were achieved.

The flow rate was plotted on one channel of the multichannel recorder, and both flow rate and pressure events were recorded on a digital tape recorder for further analysis.

Experimental protocol. The dogs were allowed to recover for 1 wk before the recordings were started. Each recording session started at 0900 h and ended at 1800 h. The experiment was completed within 40 days, and the schedule was 1 day recording/1 day rest. During this period, a standard meal (400 ml) was given every other day. A whole meal (1,000 ml) was given during the non-recording day. Experiments were carried out after an overnight fast of at least 12 h, during which dogs had free access to water.

All test meals consisted of 200 g of canned food (9% crude protein, 5.5% fat, 2% minerals, and 0.5% bran) added to water to make a total meal volume of 400 ml. The meal was homogenized with a blender; its viscosity was equal to 1,630 mPa·s. The consistency of food obtained was that of a thin cream.

Data analysis. Because of the pulsatile nature of the passage of liquid through the gastroduodenal area, three parameters were used to characterize each gush: mean flow rate, peak flow rate, and volume of fluid propelled. Peak flow rate corresponded to the maximal flow rate recorded, i.e., the point connecting the rise and decay curve. Mean flow rate was obtained by calculation of the mean of all data pairs comprised between the onset and the end of a gush. The area under the flow-rate curve during one gush was equal to the volume propelled, thereafter called stroke volume. Resistance is defined as the partial derivative of the pressure difference with respect to the flow. Antropyloric and pyloroduodenal resistances were calculated from the relationship between the pressure gradient within the antrum and the pylorus on the one hand and the pylorus and the duodenum on the other hand and flow rate. To compute the resistance, pressure and flow trace were off-line digitized by use of a flat-bed scanner (Apple) and transformed as coordinate pairs by means of curve analysis software (DataScan, Brainpower). The pressure gradient at each side of the pylorus was calculated each 0.05 s by difference between pressure. Mean resistance was estimated as the slope of the line that crossed the points of maximal and minimal flow rate for a single passage of digesta. Pressure-flow curves were obtained through the time-independent representation of the flow against pressure difference during a single passage of digesta (9).

The values are presented as means \pm SE. Statistical significance was tested by one-way analysis of variance.

RESULTS

Patterns of flow at the pylorus. During phase II of the interdigestive period, the passage of gastric contents occurred in a pulsatile manner with a total net flow of 60 ml/h. The volume of the reflux amounted to \sim 25% of the transpyloric fluid movement, i.e., 20 ml/h. The mean flow rate during individual gushes was 1.0 ± 0.08 ml/s. However, peak flow rate values temporarily reached 10 ml/s. The stroke volume ranged from 0.1 to 1.6 ml (mean, 0.5 ± 0.31 ml).

After a meal, the volume of chyme flowing through the probe was increased because of numerous gushes of small volume. Hence, the total net flow recorded 1 h after a meal amounted to 420 ± 20 ml/h instead of 60 ml/h in the interdigestive period. The peak flow rate during the gushes was reduced to 8 ml/s, but the mean flow rate was not significantly different from that recorded during fasting (1.1 ± 0.12 ml/s). The stroke volume was 2.5 ± 0.25 ml. The higher volume corresponded not to a higher flow rate but to a longer duration of period of flow rate >1 ml/s for each individual gush (1.02 ± 0.3 s after a meal vs. 0.65 ± 0.3 s before a meal).

Contractile events associated with passage of chyme. During phase II of the interdigestive period, terminal antral, pyloric, and duodenal pressure waves occurred after the passage of gastric contents. However, \sim 10% of the gushes were not accompanied with detectable terminal antral, pyloric, or duodenal pressure waves. The transpyloric passage of gastric contents occurred 0.9 ± 0.29 s before the terminal antral contraction (Fig. 1). The volume of the gush remained unchanged despite the absence of a terminal antral pressure wave (8% of the gushes) (Table 1). Fifty-two percent of the pyloric pressure waves were associated with transpyloric passage of gastric contents. Most of these waves were propagated toward the duodenum. Indeed, isolated pyloric contractions were associated with only 5% of the gushes (Table 1). However, when pyloric contractions were included within a propagated antroduodenal pressure wave, the gush occurred 2.8 ± 0.73 s before it. Duodenal pressure waves appeared 4.6 ± 0.99 s after the onset of the passage

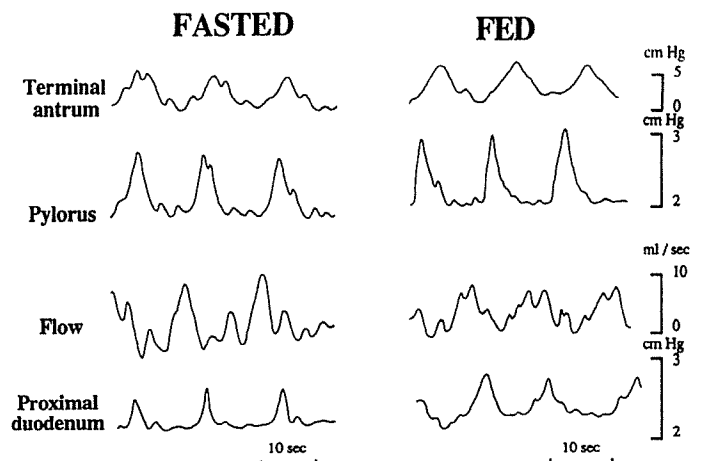


FIG. 1. Pressure waves and passage of gastric contents at the gastroduodenal junction during the interdigestive (left) and digestive (right) states. During fasting, antral contraction followed flow; after the meal, it preceded passage of chyme.

TABLE 1. Propagation characteristics of antroduodenal pressure waves associated with transpyloric passage of gastric fluid, in conscious dogs, during interdigestive and digestive states

	Sequence			
	a	b	c	d
T. antrum	● ↓	● ↓	● ↓	● ↓
Pylorus	● ↓	● ↓	● ↓	● ↓
Duodenum	● ↓	● ↓	● ↓	● ↓
Fasting	801	15	23	81
Fed	93	604	140	140

Number of the various contractile sequences observed out of a total of 1,000 passages of gastric contents of >0.8 ml in the fasted state or 1 h after food intake (200 contractile sequences analyzed on 5 dogs). Contraction and passage of gastric contents were all considered from their onset. Thus in the 1st column, passage of gastric contents occurred before onset of terminal antral contraction. Isolated pyloric (48 during interdigestive and 10 during digestive state) or duodenal (32 during interdigestive and 13 during digestive state) contractions associated with passage of gastric contents were not represented. ●, Onset of contraction; ↓, onset of passage of gastric contents.

TABLE 2. Interval between onset of pressure rise at antroduodenal area and onset of flow measured at pyloric level during interdigestive and digestive states

	Interdigestive State	Digestive State
T. antrum, s	0.9±0.29	-3.3±0.87*
Pylorus, s	2.8±0.73	-3.0±0.51*
Duodenum, s	4.6±0.99	4.0±1.06

Values are means ± SE of 10 experiments (100 gushes analyzed per experiment) in each dog. Negative values indicate that onset of pressure rise was recorded before the gush. * Significantly different at $P < 0.01$.

of gastric contents.

During the digestive period, the antral pressure waves occurred 3.3 ± 0.87 s before the delivery of chyme (Table 2), and the associated pyloric contractions occurred also before the onset of the passage of digesta. The duodenal contraction was observed 4.0 ± 1.06 s after the flow, which was similar to the situation observed during the interdigestive state.

In 60.4% of the cases, the passage of chyme was preceded by an antral and a pyloric contraction and followed by a duodenal contraction (Table 1). Retrograde contractions, originating from the duodenum, preceded 14% of the gushes observed after a meal. These gushes were characterized by large backflow amounting to >50% of the forward flow. The number of isolated pyloric or duodenal contractions associated with flow was lower compared with the fasted state (2% vs. 8%). In the absence of a detectable antral pressure wave, the volume of the gush was reduced by $64 \pm 8\%$.

Resistance at antroduodenal junction. During phase II of the interdigestive period, the pressure-flow relationship at the antroduodenal junction was not linear and could be represented by two ellipsoids with shared portions at the origin of the pressure-flow axis (Fig. 2A). At the onset of the passage of gastric contents, the flow increased with a limited pressure difference across the

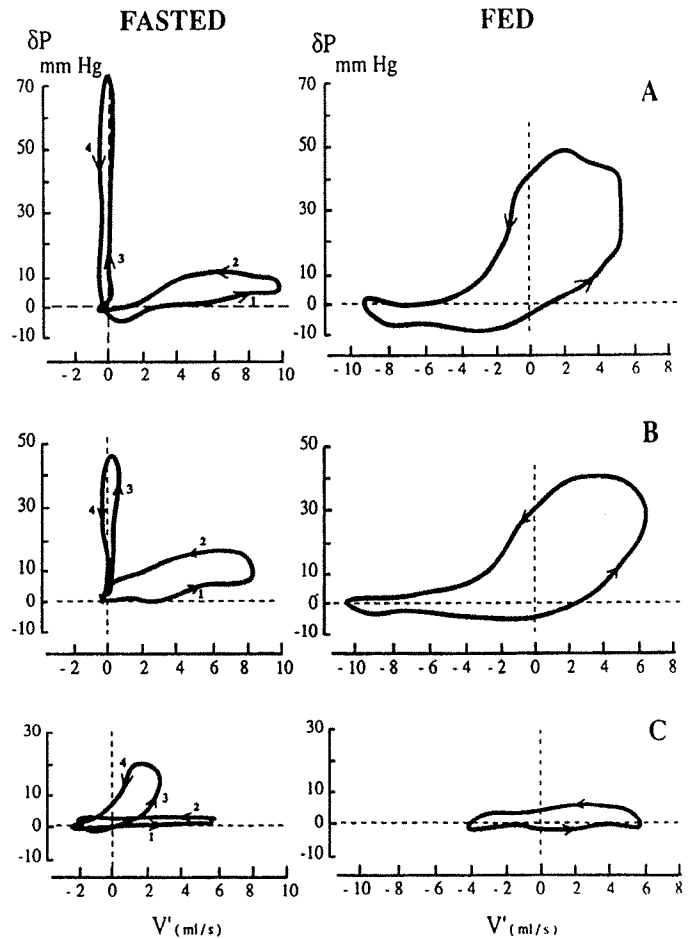


FIG. 2. Pressure-flow relationship at the antroduodenal (A), antropyloric (B), and pyloroduodenal (C) segment during the interdigestive and digestive states. Horizontal axis: flow rate; vertical axis: pressure difference between antrum and pylorus (A), pylorus and duodenum (B), and antrum and duodenum (C). During interdigestive state, pressure-flow relationship was represented as 2 ellipsoids; after the meal only one was present. Curves are an example of the values obtained for a single passage of gastric contents.

junction. After the peak flow rate had been reached, the flow and pressure difference decreased simultaneously. When the flow and pressure difference reached zero, a second change in the pressure-flow relationship was observed. The pressure difference rose without significant increase in the flow. The antropyloric (Fig. 2B) and the pyloroduodenal (Fig. 2C) pressure-flow curves exhibited a similar shape. Calculation of the resistance over the whole passage of liquid was not possible. However, one could compute the resistance for each single loop of the curve. Therefore, a very low and a very high resistance value were obtained. The highest resistance value (>50 mmHg·ml⁻¹·s, vertical part) was observed during an almost absence of flow. The lower value, representing the presence of simultaneous flow and contraction, was chosen as the true fasted resistance. The antropyloric resistance was five times higher than the pyloroduodenal resistance (Table 3). The antroduodenal resistance was always lower than the sum of the individual resistance.

During the digestive period, the antroduodenal, antropyloric, and pyloroduodenal resistances to flow were represented as a single loop (Fig. 2). The flow rate increased simultaneously with the pressure difference.

TABLE 3. Individual and overall resistance of antroduodenal area measured, in conscious dogs, during interdigestive and digestive (1 h after meal) states

	Interdigestive State	Digestive State
Antropyloric resistance, mmHg·ml ⁻¹ ·s	0.94±0.26	6.9±0.84*
Pyloroduodenal resistance, mmHg·ml ⁻¹ ·s	0.19±0.10	0.26±0.09
Antroduodenal resistance, mmHg·ml ⁻¹ ·s	0.73±0.34	8.33±1.56*

Values are means ± SE of 10 experiments (10 gushes analyzed per experiment) in each dog. * Significantly different at $P < 0.01$.

Afterward, flow and pressure difference decreased together. The resistance of the antropyloric segment was ~20 times higher than that of the pyloroduodenal segment (Fig. 2, B and C; Table 3). The antroduodenal resistance was always lower than the arithmetic sum of the two individual resistances (Table 3). The resistance of the pyloroduodenal segment was almost unchanged before (0.19 ± 0.10 mmHg·ml⁻¹·s) and after (0.26 ± 0.09 mmHg·ml⁻¹·s) the meal.

During the first minutes after the ingestion of food, the antropyloric resistance was reduced to about one-tenth that of the pyloroduodenal resistance. The post-prandial antropyloric resistance value was reached ~30 min after the meal, i.e., for a volume of individual gushes >1.5 ml. Conversely, the pyloroduodenal resistance increased about fourfold during the first 10 min after the meal.

DISCUSSION

Simultaneous pressure and flow measurements at the gastroduodenal junction allowed the individual evaluation of antropyloric and pyloroduodenal resistance. In contrast to the resistometer method (13), resistance can be obtained without inserting an inflatable device that partly blocks the pyloric outlet. Hence, our model permitted the measurement of resistance before and after a meal without changes in gastric outflow. However, because of the pulsatile nature of the transpyloric flow, permanent assessment of resistance was impossible.

Currently available methods for studying gastric emptying in conscious animals do not provide quantitative information about the movement of gastric contents in relation to individual gastric, pyloric, and duodenal contractions. Studies based on dye dilution at the gastric and duodenal level will measure overall rates of gastric emptying and duodenogastric reflux, but these methods do not have the temporal resolution to distinguish flow through the pylorus at one moment from the flow a few seconds later. As a consequence, gastric emptying was considered as a steady, nonpulsatile process (15) despite its intermittent appearance on imaging study (3). In contrast, radiographic (3) or echotomographic (6) studies do allow excellent temporal resolution of the events at the gastroduodenal area and are able to identify them when a contraction occurs. Unfortunately, imaging studies have not provided any quantitative data on stroke volume and flow. Stroke volumes and flow have been

measured only in vitro or on anesthetized animals and were within the range of those obtained by the electromagnetic flowmeter method (16, 17).

During the interdigestive period, terminal antral contraction always occurred after the passage of chyme. Because there is a certain amount of time elapsed between the passage of digesta through the pylorus and the terminal antral contraction, it cannot have a propulsive role. This phenomenon was in accordance with the radiological observations of Carlson et al. (3) and Keinke et al. (7). Indeed, gastric emptying is caused by antral peristaltic waves and gastric evacuation is already started when the peristaltic waves move over the midantrum (3, 5, 6). The contraction of the terminal antrum causes mainly retropulsion even though the pyloric sphincter does not contract simultaneously with the terminal antrum.

After a meal, the passage of nutrients through the pylorus was preceded by a terminal antral contraction. This finding was reminiscent of that obtained by Miller et al. (14) who found that the antrum can propel liquid chyme under barostatically controlled gastric pressure. However, the contractile sequence observed was slightly different from the one described by other authors (3, 5, 6). In our study, the flow takes place at the end of the terminal antral contraction, whereas X-ray imaging shows that flow appears before and during the terminal antral contraction. Investigators using ultrasound imaging techniques have demonstrated that flow occurs after the terminal antral contraction. One reason for this discrepancy could relate to the density of the test meal used: high density for X-ray imaging and lower density for ultrasound or electromagnetic flowmeter techniques. Our study showed, in agreement with earlier investigations (3, 5, 6, 19), that the main flow of gastric chyme into the duodenum occurs during the phase of pyloric opening.

The antropyloric resistance to flow was always higher than that of the pyloroduodenal segment. In vitro, the pyloric segment also generates a greater resistance to flow per unit length than the duodenum (16). The resistive behavior of the pyloroduodenal area, despite its low value, might explain the accelerated gastric emptying observed after an extramucosal section of the circular muscle coat of the duodenum (2). In addition, this resistance might act as the postfundic resistance, which remains present after pyloroplasty or antrectomy (20).

The assessment of pressure difference across the junction was necessary to measure its resistance. True luminal pressure measurement could not be made by presently available techniques. Therefore, the pressure used to compute resistance might partly yield pressure, i.e., pressure produced by apposition of the wall onto the sensor. Despite their diameter, the sensors did not alter gastric emptying rate or gastroduodenal motility (12), and the values of resistance obtained during fasting were similar to those measured by Mearin et al. (13). In their study, when the pressure gradient was set to 2 mmHg, the air flow rate was 238 ml/min, hence a resistance equal to 0.5 mmHg·ml⁻¹·s. This value is not different from the one measured in the present study. On the other hand, these values are 10 times lower than those meas-

ured by Schulze-Delrieu and Wall (17), in vitro, for the cat stomach.

One of the most striking features of this study was the difference between the pressure-flow relationships observed before and after the meal. In the interdigestive state, during and immediately after the passage of gastric contents, resistances at the gastroduodenal junction were very low and then very high. The related two pressure-flow loops located at 90° from each other suggest that during the interdigestive state, the pressure gradient across the gastroduodenal area is not at the origin of the flow. Gastric emptying is caused by antral peristaltic waves, and gastric evacuation starts when peristaltic waves move across the midantrum. Therefore, flow occurs with a low antropyloric pressure difference, and the antropyloric and the pyloroduodenal resistance are intermittent phenomena. The loop with an almost horizontal axis represents the passage of gastric contents in the absence of terminal antral contraction. The loop with its large axis parallel to the vertical axis corresponds to contraction of the terminal antrum that is not associated with a gush. On the other hand, after a meal, only one loop was obtained on the pressure-flow graph because flow and pressure occurred almost simultaneously. Therefore, the antropyloroduodenal segment behaved as a resistive system. This is in accordance with the hypothesis of Strunz and Grossman (18), who found that factors other than fundic pressure, probably the resistance of the antroduodenal segment, are responsible for the rate of gastric emptying of a liquid meal.

The overall increase in the antroduodenal resistance after the meal was a major finding of this study. The resistance appeared to increase as the flow rate was enhanced and therefore acted as an inconstant barrier controlling the flow. This phenomenon might explain the poor relationship between gastric emptying and motility (15). However, the increased resistance after a meal seems consistent with previous findings of a decrease in pyloric diameter after a nutrient meal (6). In addition, in the absence of any real measurement of resistance, a direct relationship between pyloric diameter and gastroduodenal resistance cannot be established. The resistance might increase as a consequence of a higher pyloric tone without any changes in pyloric diameter. Also the measurement of resistance involved determination of the pressure gradient, a parameter that itself depends on the amplitude and the time relationship of the antral and pyloric contraction. We have demonstrated that this last parameter is altered by the meal. Therefore, the value of resistance might be more dependent on the pattern than on the amplitude of the contractions.

The prediction of the flow rate from the pressures generated by the gut wall is difficult, except after a meal. The concomitant use of the real-time flow and pressure measurements represents a physical approach to the study of the determinants of flow across the junction.

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