Am J Physiol Gastrointest Liver Physiol 285: G1147–G1152, 2003.
July 17, 2003; 10.1152/ajpgi.00208.2003.

Determinants of transpyloric fluid transport: a study using combined real-time ultrasound, manometry, and impedance recording

Céline Savoye-Collet, Guillaume Savoye, and André Smout
Gastrointestinal Research Unit, University Medical Center, 3508 GA Utrecht, the Netherlands

Submitted 6 May 2003; accepted in final form 15 July 2003

Savoye-Collet, Céline, Guillaume Savoye, and André Smout. Determinants of transpyloric fluid transport: a study using combined real-time ultrasound, manometry, and impedance recording. *Am J Physiol Gastrointest Liver Physiol* 285: G1147–G1152, 2003. First published July 17, 2003; 10.1152/ajpgi.00208.2003.—Intraluminal impedance recording has made it possible to record fluid transport across the pylorus during the interdigestive state without filling the stomach. During antral phase II, fluid transport occurs with and without manometrically detectable antral contraction. Our aim was to investigate the relationships between ultrasonographic patterns of antral contraction, manometric pressure waves, and transpyloric fluid transport during antral phase II. Antral wall movements were recorded by real-time ultrasound (US) in eight healthy volunteers (mean age 24 ± 7 yr) during 17 ± 5 min of antral phase II. Concomitantly, a catheter positioned across the pylorus, monitored by transmucosal potential difference measurement, recorded five impedance signals (1 antral, 1 pyloric, and 3 duodenal) and six manometric signals (2 antral, 1 pyloric, and 3 duodenal). Antral contractions detected by US at the level of the two antral impedance electrodes were classified according to their association with a pyloric opening or a duodenal contraction. Transpyloric liquid transport events (impedance drop of >40% of the baseline with an antegrade or retrograde propagation) and manometric pressure waves (amplitude and duration) were identified during the whole study and especially during each period of US antral contraction. A total of 110 antral contractions was detected by US. Of these, 79 were also recorded by manometry. Fluid transport across the pylorus was observed in 70.9% of the US-detected antral contractions. Pyloric opening was observed in 98.6% of the contractions associated with fluid transport compared with 50% in the absence of fluid transport ($P < 0.05$). Antral contractions associated with fluid transport were significantly ($P < 0.05$) more often propagated to the duodenum (92%) than those without fluid transport (53%). Pressure waves associated with fluid transport were of higher amplitude (208 mmHg, range 22–493) and longer duration (7 s, range 2.5–13.5 s) than those not associated with fluid transport (102 mmHg, range 18–329 mmHg, and 4.1 s, range 2–8.5 s; $P < 0.05$). The propagation of the antral contractions in the duodenum in US was always associated with a pyloric opening, whereas only 8 of the 25 contractions without duodenal propagation were associated with a pyloric opening ($P < 0.05$). The presence of duodenal contractile activity before the onset of an antral contraction in US was always accompanied by pyloric opening and with fluid transport in 93.3%, compared with 56.8% in its absence ($P < 0.05$). In antral phase II, US is the most sensitive technique to detect antral contractions. Transpyloric fluid transport observed in relation to antral contractions occurs mainly in association with contractions of high amplitude and long duration and is associated with pyloric opening and/or duodenal propagation.

ultrasound; interdigestive phase II; pyloric opening; antral contractions

MEASUREMENT OF INTRALUMINAL impedance changes is now available to study transport of fluids in the gut (25, 26, 32, 33). This technique involves application of a low-voltage potential difference to closely spaced electrodes on a catheter in the gut lumen and measurement of the resulting current (32, 33). Passage of air or gas results in a temporary increase in intraluminal impedance, passage of hyperconductive fluid in a decrease in impedance (32, 33). In the last few years, the results of impedance studies have drastically changed views in the field of gastroesophageal reflux disease (5, 6, 24, 30, 31, 34, 35, 38).

Intraluminal impedance measurements provide the possibility to study interdigestive transpyloric fluid transport without the limitations imposed by stomach filling. A recent study in healthy subjects using impedance monitoring and concomitant manometry has shown that fluid transport is observed in all phases of the antral migrating motor complex and that transport events in phase II can occur without associated antral pressure event (29). The mechanisms involved in transport events without manometrically detected antral pressure event are uncertain. Similar to the transport events observed in phase I or after a low-caloric liquid meal, they may be driven by a tonic pressure pump (10), but the possibility of associated antral contractions that remained undetected by the manometric device cannot be excluded. It has previously been demonstrated that even with a manometric technique with high spatial resolution, only 86% of ultrasonographically detected antral contractions are associated with a manometric event (17). Real-time ultrasonography may not only be a sensitive technique to detect antral

Address for reprint requests and other correspondence: A. J. P. M. Smout, Gastrointestinal Motility Unit, Univ. Medical Center, Box 85500, 3508 GA Utrecht, The Netherlands (E-mail: a.smout@azu.nl).

contractions but may also provide information about the coordination among the antrum, the pylorus, and the duodenum during antral phase II by direct visualization of the gastric wall motion (14).

Our aim was to investigate the relationships among ultrasonographic patterns of antral contraction and pyloric opening, manometric pressure waves, and fluid transport across the pylorus assessed by impedance monitoring during antral phase II in healthy subjects.

MATERIALS AND METHODS

Subjects

Eight healthy volunteers (4 female, 4 male; mean age: 24.1 ± 7 yr; mean body mass index: 21.8 ± 4.1 kg/m^2) were studied after written informed consent. Subjects did not suffer from any gastrointestinal complaints, did not undergo major surgery in the past, and did not suffer from any chronic disease or used medication known to affect gastrointestinal motility. The study protocol was approved by the Human Research Committee of the Utrecht University Medical Center.

Methods

Combined impedance and pressure recording. The technology used in these studies involved combined monitoring of intraluminal impedance, intraluminal pressure, and transmucosal gastroduodenal potential difference. A perfused catheter was used that incorporates six side holes at 2-cm intervals (2 in the antrum, 1 in the pyloric area, and 3 in the duodenum) and six circular electrodes (2 in antrum, 4 in duodenum) positioned between the side holes, yielding five impedance signals (Fig. 1). During the study, the position of the catheter was monitored by measurement of the transmucosal potential difference (TMPD) between the distal antral side hole A2 and the most proximal duodenal side hole D1. The two TMPD channels were perfused with degassed saline from separate reservoirs at a rate of 0.2 ml/min. A disposable Ag/AgCl electrode, attached to the forearm, was used as the reference electrode. Pressures from the six perfused side holes and the five impedance signals were recorded using a dedicated stationary system (2-Lab TM MII system, Sandhill, Denver, CO). For measurement of the impedance signals, a 2-kHz current was used that was passively limited to <8 μA. All signals were sampled at a rate of 10 Hz and stored on the hard disk of a computer for subsequent analysis.

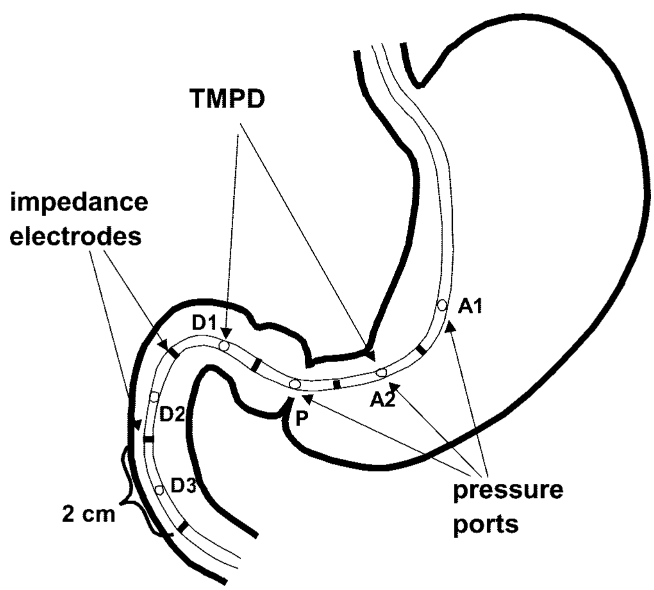

Fig. 1. Schematic representation of the catheter for combined pressure and impedance monitoring with 6 metallic rings at 2-cm intervals and 6 perfused side holes. TMPD, transmucosal potential difference; A1 and A2, antral side holes; D1–D3 duodenal side holes; P, pyloric area.

Real-time ultrasound technique. Real-time ultrasound (US) images were acquired using Scanner 350 equipment with a 2- to 4-MHz curved array transducer (Pie Medical, Maastricht, the Netherlands). The transducer was placed in the epigastrium allowing visualization of the antrum in the longitudinal section. It was positioned at the level of the transpyloric plane so that the antrum, the pylorus, the duodenal bulb, and, if possible, the proximal duodenum until the *genu superius* were visualized simultaneously. Normal respiratory movements constantly required fine adjustments of the position of the probe. The impedance metallic rings were used as echoic marks for exact positioning of the US probe. Scanning was carried out for a period of 5–20 min and recorded on videotape. To limit variability, all acquisitions were performed by the same physician who has ample experience with US studies of the gastrointestinal tract (C. Savoye-Collet).

Study protocol. After an overnight fasting period, the subjects were intubated transnasally with the combined manometric and impedance assembly, which was advanced slowly until it had reached its position in the antropylorodudoenal region. The position of the catheter was monitored continuously using TMPD measurement. An accommodation period of 30 min followed. Thereafter, the subjects were placed in a sitting position, slightly backwards, for the remainder of the study. During antral phase II, real-time US images were synchronously recorded during 5–20 min in one or two successive periods. The duration of the recording was decided according to the technical circumstances that were highly variable between individuals.

Data Evaluation

Ultrasonographic images. In the fasting state, the lumen of the antrum was nearly virtual and the antral wall was in close contact with the catheter. A contraction was defined as a transient loss of parallelism of the two gastric walls associated with an indentation of the gastric wall greater than one antral mucosal thickness. These signs were taken to be indicative of a contraction only when they were not due to respiration, to pulsation transmitted from the aorta or the heart, or to movements of adjacent intestine and when they propagated to some extent in space and time. It was not possible to distinguish lumen-occlusive from non-lumen-occlusive events, because in fasting condition, the gastric wall was usually too close to the catheter.

An aborally propagated contraction was defined as a gastric contraction seen to progress aborally along the entire length of the imaged antrum. The time of onset of the contraction was defined as the time at which the leading edge of the contraction reached the acoustic reflection of the proximal metal ring in the antrum. The contraction was considered to be present as long as it remained visible at the level of the distal metallic ring in the antrum. Opening of the pylorus was identified as a visibly patent lumen between the distal antrum and the duodenum bulb (Fig. 2). Contractions of the bulb and proximal duodenum were defined as an increased thickness of the duodenal wall with progressive

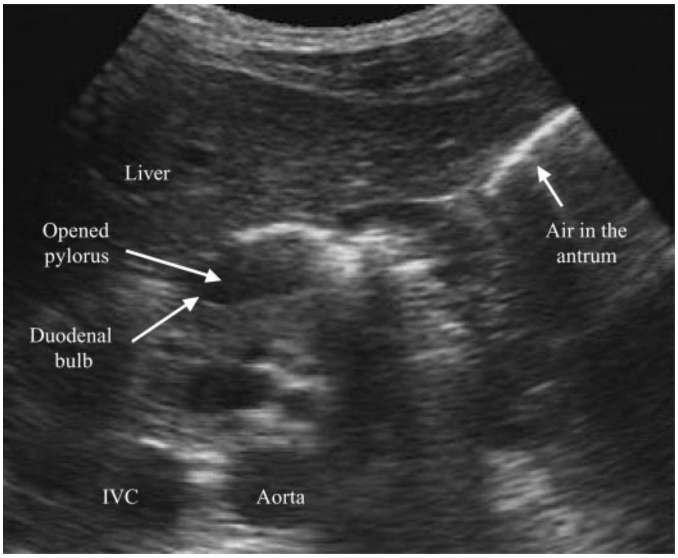

Fig. 2. Global view of ultrasound (US) screen showing an antral contraction in fasting condition with a concomitant opening of the pylorus. IVC, inferior vena cava.

ringlike narrowing. Each time when an antral contraction was clearly seen on the US screen, a marker was put in real time during the acquisition of the images on the manometric recording by the investigator who was unaware of the current manometric events. The video recordings were analyzed off-line by two of the investigators to confirm the identified contractions and to analyze the exact duration of each contraction, its propagation, and association with other events, such as pyloric opening or proximal duodenal contraction.

Manometric signals. Manometric recordings were analyzed only when TMPD recordings confirmed that the manometric assembly was correctly positioned across the pylorus. Correct position was defined as antral TMPD less than −20 mV and duodenal TMPD greater than −15 mV, with a difference between the two of at least 15 mV (7). Moreover, the transpyloric position of the probe was confirmed by US images during phase II showing the two proximal metallic rings positioned in the antrum.

Antral phase II was defined as pressure waves >1. 4 kPa occurring at a rate >2 per 10 min and less than the maximum frequency of the antrum (3 per min). The space-time organization of pressure event sequences was evaluated by following four of the five steps previously described by Sun et al. (36): *1*) any resolvable pressure event that was <20 s in duration was scored, provided it was not attributable to respiration, straining, or change in posture; *2*) time of onset of pressure events was measured in each individual recording channel; *3*) pressure events in individual channels were then examined for temporal association with events recorded in other channels. Two events were considered to be related if the event in the more distal channel occurred between 5 s before to 10 s after the event in the more proximal channel; *4*) and the space-time pattern of a pressure event sequence was then classified. If the difference in onset time between pressure events recorded in adjacent channels was ≤1 s, the spatial relationship was defined as synchronous; if this difference was >1 s, the relationship was defined as antegrade or retrograde according to the relative position of the recording points. If no other pressure event was present within the time window above, an event was defined as isolated.

Impedance signals. As previously described for the interdigestive state (29), the identification and characterization of bolus patterns using impedance changes included *1*) the nature of the bolus (air associated with a rapid increase in impedance, liquids associated with a progressing drop in impedance to <40% of the baseline value, the average impedance baseline was determined in the 5-s period immediately preceding the drop in impedance) and *2*) the direction of transport (antegrade or retrograde).

Temporal association among ultrasonographic, manometric, and impedance events. A purpose-designed time-coding system was used to synchronize the manometric and impedance signals with the videotaped US images. With the use of the time-coding information, each US-detected contraction was drawn as an area (Fig. 3) on the combined pressure and impedance recordings. An US contraction was categorized as having an associated pressure event when a pressure rise was recorded in the manometric reference channel within 10 s of the moment at which the US-detected contraction reached the proximal US antral marker. The presence of a fluid transport event in the impedance recording was also analyzed using a 10-s interval.

Statistical Analysis

Nonparametric statistics were calculated using the Mann-Whitney *U* test for unpaired data and the Wilcoxon's rank sum test for paired data. Categorical data were analyzed using a χ^2 test. All tests were two tailed. $P < 0.05$ was used as the criterion of statistical significance.

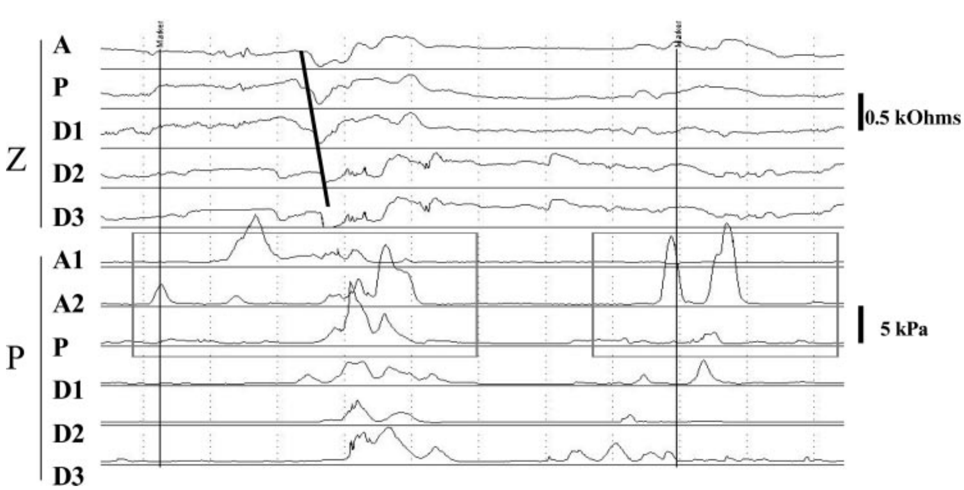

Fig. 3. Examples of antral contractions with (*left*) or without (*right*) fluid transport. The area occupied by the US-detected antral contraction is indicated by a frame in the manometric tracing. Z, impedance; P, pressure.

RESULTS

US-Detected Contractions and Their Relationship with Manometry-Detected Contractions

A longitudinal US image of the antropyloric area with clear visualization of the two metallic markers was achieved in all subjects. The catheter was seen lying approximately parallel to the antral wall with which it was in contact most closely. A satisfactory recording was obtained in all subjects on one or two separate occasions during phase II, with a total of 14 recordings and a mean duration of 17 ± 5 min per subject. A median of 15 contractions per subject (range 8–20) was recorded. All of the 110 antral contractions detected by US were propagated along the length of the imaged antrum, 107 of which were noticed during the real-time US examination. During the concomitant pressure recordings, 81 pressure event sequences or isolated pressure events were detected. Seventy-nine of these were associated with US-detected antral contraction, leading to a sensitivity of 75% for the manometric detection of antral contractions. The US-observed contractions had a duration of 12 ± 4 s.

A concomitant pyloric opening was observed during 93 antral contractions (84.5%). An associated contraction of the duodenal bulb and proximal duodenum was observed following 85 antral contractions (77.3%) or preceding 15 others (13.6%), whereas 10 antral contractions were not associated with duodenal motor activity.

Relationship Between Antral Contractions and Fluid Transport Events Assessed by Impedance Recording

Fluid transport across the pylorus was observed with 78 of the 110 US-detected contractions (Fig. 4). Seventy-five fluid transport events were antegrade, 72 of which were liquid and three of which were mixed liquid/gas. Sixty-seven percent of contractions without fluid transport were detected both by US and manometry, whereas 74% of contractions with fluid transport were detected by both techniques (NS). Pyloric opening was observed in 98.6% of the contractions associated with fluid transport compared with 50% in the absence of fluid transport ($P < 0.05$). Antral contractions associated with fluid transport were significantly ($P < 0.05$) more often propagated to the bulb and the proximal duodenum (92%) than those without fluid transport (53%). Pressure waves associated with fluid transport had a higher amplitude (median 208 mmHg, range 22–493 mmHg) and longer duration (median 7 s, range 2.5–13.5 s) than those not associated with fluid transport (median 102 mmHg, range 18–329 mmHg) and (median 4.1 s, range 2–8.5 s); $P < 0.05$.

The propagation of the antral contractions to the duodenal bulb observed with US ($n = 85$) was always associated with a pyloric opening, whereas only 8 of the 25 contractions without duodenal propagation were associated with a pyloric opening ($P < 0.05$). The presence of duodenal contractile activity before the onset of an antral contraction in US was always accompanied with pyloric opening and with fluid transport in 93.3% compared with 56.8% in its absence ($P < 0.05$). With all three retrograde transpyloric fluid transport events observed, there was duodenal contractile activity before the onset of the antral contraction (Fig. 4).

DISCUSSION

The most important observations made in the present study pertain to the mechanisms through which antral contractions in phase II of the interdigestive state move fluids toward the pylorus. These results were obtained by assessment of gastric wall motion with real-time US and by assessment of pressure changes and fluid transport with concurrent manometry and intraluminal impedance monitoring. Our study was limited in its goal mainly because of limitations in the assessment of gastric wall motion with US in the fasting state. Imaging of the stomach with real-time gastric US has been well described in the postprandial state, after intake of a liquid meal, and the technique can be used to measure gastric emptying of liquid (1, 2, 13, 16, 21, 22). Despite the fact that in the fasting state, the gastric walls are closely apposed, Hausken et al. (11) and Hveem et al. (15, 17) reported that, with

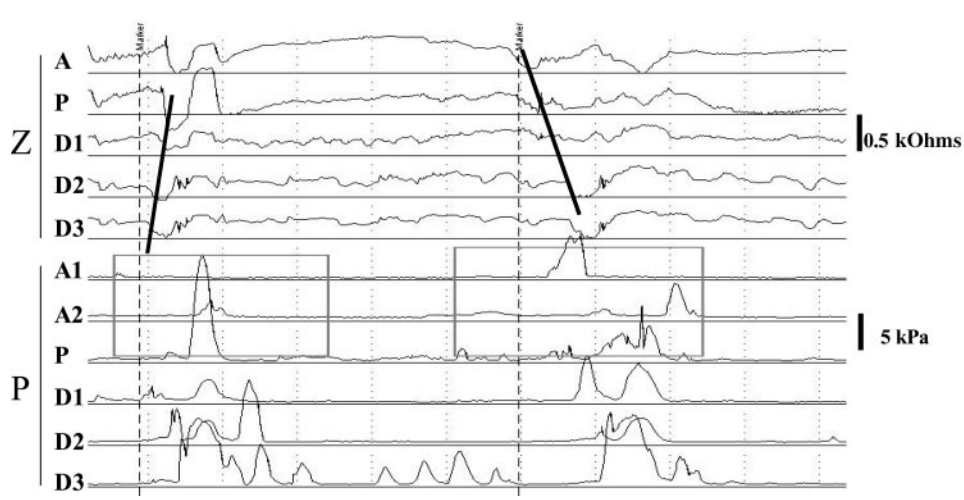

Fig. 4. Example of a retrograde (*left*) and antegrade (*right*) transpyloric fluid transport with concomitant antral and duodenal manometric activity.

real-time US, it is feasible to measure fasting liquid content in the human stomach to see antral contractions and to recognize the interdigestive phases. In the present study, we confirm the capacity of US to recognize antral contractions with a sensitivity that is higher than that of manometry. The magnitude of the difference in detection between US and manometry was comparable with the difference reported in a comparison of magnetic resonance imaging and manometry (4). The main limitation of the US examination in the interdigestive state is the necessity to continuously follow the slight movements of the subject that affect the position of the US probe. This technical point limited the duration of the examination to 5–10 min, after which the observer had to have a few minutes rest.

Understanding of how the stomach moves its contents into the small bowel in the interdigestive state requires information obtained by combined motility and transpyloric flow assessment. Application of such a combined approach in pig studies by Malbert and Mathis (23) led to a great improvement of our knowledge of the modulation of transpyloric flow. Their description of transpyloric fluid transport led Horowitz and Dent (14) to suggest a "conceptual frame" of the mechanics involved in transpyloric fluid transport in humans. It is now acknowledged that contractions and active lumen occlusions must be clearly distinguished, that transpyloric flow should be correlated precisely in time with motor events, that the motility of all motor components should be evaluated simultaneously, and that analysis of contraction and lumen occlusion should take into account both temporal and spatial organization.

A recent study (17) on the relationship between ultrasonically detected phasic antral contractions and antral pressure in the postprandial state (500 ml of soup) has shown that 86% of antral contractions have a corresponding pressure event and that lumen occlusion is more likely to occur with high-amplitude antral pressure events. High-resolution manometry (3, 17, 36), a combination of manometry and scintigraphy (19) or, more recently, dynamic magnetic resonance imaging (4) have allowed researchers to describe the space-time organization and pressure-geometry relationship in the antroduodenal region in humans. Although fluid transport in the human small intestine has been described years ago with fluoroscopy (20) and the major role of duodenum as an immediate brake to gastric outflow had been demonstrated (28), noninvasive techniques have long been lacking. Doppler US, in part, addressed this issue by allowing the precise description of transpyloric liquid transport events (8, 9, 11, 27) and their relationship with antral contractions or antroduodenal pressure gradients (10). However, all of these techniques required the stomach to be filled. Prolonged concomitant monitoring of impedance and pressure changes at the level of the antroduodenal area, which has recently been found to be possible in humans, has made it possible to correlate precisely in time transpyloric flow with motor events in the interdigestive state (29). Phase II of the MMC appeared to be responsible for most fluid transport events, and antral contractions provided the driving force of 80% of these transport events. On the other hand, antral contractions led to fluid transport in only 72% of the cases. A lack of sensitivity of manometry can explain, in part, our previous results: the present study shows that some fluid transport events without associated manometric event are in fact related to a contraction detected with US. Likewise the sensitivity of the impedance technique might be less than optimal, but no other method is available to detect transpyloric fluid transport without filling the stomach.

After a meal, gastric emptying can be interrupted by pyloric closure in relation to localized pyloric contractions that occur independently of antral or duodenal contractions (12, 37). In our study, it was not possible to incorporate a sleeve sensor in the combined manometry and impedance device to assess pyloric pressure changes. Instead, we evaluated pyloric opening in the US recordings. A majority of antral contractions was followed by pyloric opening, and, not surprisingly, opening was observed in 98.6% of the fluid transport events observed with impedancometry. Pyloric opening was more often observed when the antral activity was propagated to the duodenum. It was also observed that duodenal motor activity before the onset of antral contraction was always associated with a pyloric opening and nearly always with fluid transport, which could be retrograde. This suggests that in phase II, the peristaltic mechanisms are mainly involved in the transpyloric flow. On the other hand, the contribution of pressure-pump mechanisms controlled by pyloric opening during periods of relative quiescence in antral contractile wave activity appeared to be more important to explain the gastric emptying of a low (11)- or no-caloric meal (18).

Our results suggest that during interdigestive phase II, transpyloric flow is determined by active coordinated processes involving not only antral contraction but also duodenal motility and pyloric opening and closure.

DISCLOSURES

C. Savoye-Collet was supported by a grant from Guerbet-France, and G. Savoye was supported by grants from Glaxo-Wellcome France and from the National French Society of Gastroenterology.

REFERENCES

1. **Bateman DN and Whittingham TA.** Measurement of gastric emptying by real-time ultrasound. *Gut* 23: 524–527, 1982.
2. **Bolondi L, Bortolotti M, Santi V, Calletti T, Gaiani S, and Labo G.** Measurement of gastric emptying time by real time ultrasonography. *Gastroenterology* 89: 752–759, 1985.
3. **Ehrlein HJ, Schemann M, and Siegle ML.** Motor patterns of small intestine determined by closely spaced extraluminal transducers and videofluoroscopy. *Am J Physiol Gastrointest Liver Physiol* 253: G259–G267, 1987.
4. **Faas H, Hebbard GS, Feinle C, Kunz P, Brasseur JG, Indireshkumar K, Dent J, Boesiger P, Thumshirn M, Fried M, and Schwizer W.** Pressure-geometry relationship in the antroduodenal region in humans. *Am J Physiol Gastrointest Liver Physiol* 281: G1214–G1220, 2001.

5. **Fass J, Silny J, Braun J, Heindrichs U, Dreuw B, Schumpelick V, and Rau G.** Measuring esophageal motility with a new intraluminal impedance device. First clinical results in reflux patients. *Scand J Gastroenterol* 29: 693–702, 1994.
6. **Frieling T, Hermannn S, Kuhlbusch R, Enck P, Silny J, and Lübke HJ.** Comparison between intraluminal multiple electrical impedance measurement and manometry in the oesophagus. *Neurogastroenterol Motil* 8: 45–50, 1996.
7. **Geall MG, Philipps SF, and Summerskill WHJ.** Profile of gastric potential difference in man. *Gastroenterology* 8: 437–443, 1970.
8. **Hausken T, Gilja OH, Odegaard S, and Berstad A.** Flow across the human pylorus soon after ingestion of food, studied with duplex sonography. Effect of glyceryl trinitrate. *Scand J Gastroenterol* 33: 484–490, 1998.
9. **Hausken T, Gilja OH, Undeland KA, and Berstad A.** Timing of postprandial dyspeptic symptoms and transpyloric passage of gastric contents. *Scand J Gastroenterol* 33: 822–827, 1998.
10. **Hausken T, Mundt M, and Samsom M.** Low antroduodenal pressure gradients are responsible for gastric emptying of a low caloric liquid meal in humans. *Neurogastroenterol Motil* 14: 97–105, 2002.
11. **Hausken T, Odegaard S, Matre K, and Berstad A.** Antroduodenal motility and movements of luminal contents studied by duplex sonography. *Gastroenterology* 102: 1583–1590, 1992.
12. **Heddle R, Dent J, Toouli J, and Read NW.** Topography and measurement of pyloric pressure waves and tone in humans. *Am J Physiol Gastrointest Liver Physiol* 255: G490–G497, 1988.
13. **Holt S, McDicken WN, Anderson T, Stewart IC, and Heading RC.** Dynamic imaging of the stomach by real-time ultrasound, a method for the study of gastric motility. *Gut* 21: 597–601, 1980.
14. **Horowitz M and Dent J.** The study of gastric mechanics and flow: a mad hatter's tea party starting to make sense? *Gastroenterology* 107: 302–306, 1994.
15. **Hveem K, Hausken T, and Berstad A.** Ultrasonographic assessment of fasting liquid content in the human stomach. *Scand J Gastroenterol* 29: 786–789, 1994.
16. **Hveem K, Jones KL, Chatterton BE, and Horowitz M.** Scintigraphic measurment of gastric emptying and ultrasonographic assessment of antral area: relation to appetite. *Gut* 38: 816–821, 1996.
17. **Hveem K, Sun WM, Hebbard G, Horowitz M, Doran S, and Dent J.** Relationship between ultrasonically detected phasic antral contractions and antral pressure. *Am J Physiol Gastrointest Liver Physiol* 281: G95–G101, 2001.
18. **Indireshkumar K, Brasseur JG, Faas H, Hebbard GS, Kunz P, Dent J, Feinle C, Li M, Boesiger P, Fried M, and Schwizer W.** Relative contributions of pressure pump and peristaltic pump to gastric emptying. *Am J Physiol Gastrointest Liver Physiol* 278: G604–G616, 2000.
19. **Jones K, Edelbroek M, Horowitz M, Sun WM, Dent J, Roelofs J, Muecke T, and Akkermans L.** Evaluation of antral motility in humans using manometry and scintigraphy. *Gut* 37: 643–638, 1995.
20. **Kerlin P, Zinsmeister A, and Philipps S.** Relationship of motility to flow of contents in the human small intestine. *Gastroenterology* 82: 701–706, 1982.
21. **King PM, Adam RD, Pryde A, McDicken WN, and Heading RC.** Relationships of human antroduodenal motility and transpyloric fluid movement: non-invasine observations with real-time ultrasound. *Gut* 25: 1384–1391, 1984.
22. **King PM, Heading RC, and Pryde A.** Coordinated motor activity of the human gastroduodenal region. *Dig Dis Sci* 30: 219–224, 1985.
23. **Malbert CH and Mathis C.** Antropyloric modulation of transpyloric flow of liquids in pigs. *Gastroenterology* 107: 37–46, 1994.
24. **Nguyen HN, Silny J, Albers D, Roeb E, Gartung C, Rau G, and Matern S.** Dynamics of esophageal bolus transport in healthy subjects studied using multiple intraluminal impedancometry. *Am J Physiol Gastrointest Liver Physiol* 273: G958–G964, 1997.
25. **Nguyen HN, Silny J, Wüller S, Marshall HU, Rau G, and Matern S.** Chyme transport patterns in human duodenum determined by multiple intraluminal impedancemetry. *Am J Physiol Gastrointest Liver Physiol* 268: G700–G708, 1995.
26. **Nguyen HN, Silny J, Wüller S, Marshall HU, Rau G, and Matern S.** Abnormal postprandial duodenal chyme transport in patients with long standing insulin dependent diabetes mellitus. *Gut* 41: 624–631, 1997.
27. **Pallotta N, Cicala M, Frandina C, and Corazziari E.** Antropyloric contractile patterns and transpyloric flow after meal ingestion in humans. *Am J Gastroenterol* 93: 2513–2522, 1998.
28. **Rao ASC, Lu R, and Schulze-Delrieu K.** Duodenum as an immediate brake to gastric outflow: a videofluoroscopic and manometric assessment. *Gastroenterology* 110: 740–747.
29. **Savoye G, Savoye-Collet C, Oors J, and Smout A.** Interdigestive transpyloric fluid transport assessed by intraluminal impedance recording. *Am J Physiol Gastrointest Liver Physiol* 284: G663–G669, 2003.
30. **Sifrim D, Holloway R, Silny J, Xin Z, Lerut A, and Janssens J.** Acid, and gas reflux in patients with gastroesophageal reflux disease during ambulatory recordings. *Gastroenterology* 120: 1588–1598, 2001.
31. **Sifrim D, Silny J, Holloway RH, and Janssens JJ.** Patterns of gas and liquid reflex during transient lower oesophageal sphincter relaxation: a study using intraluminal electrical impedance. *Gut* 44: 47–54, 1999.
32. **Silny J.** Intraluminal multiple electric impedance procedure for measurement of gastrointestinal motility. *Neurogastroenterol Motil* 3: 151–162, 1991.
33. **Silny J, Knigge KP, Fass J, Rau G, Matern S, and Schumpelick V.** Verification of the intraluminal multiple electrical impedance measurement for the recording of gastrointestinal motility. *Neurogastroenterol Motil* 5: 107–122, 1993.
34. **Skopnik H, Silny J, Heiber O, Schulz J, Rau G, and Heimann G.** Gastroesophageal reflux in infants: evaluation of a new intraluminal impedance technique. *J Pediatr Gastroenterol Nutr* 23: 591–598, 1996.
35. **Srinivasan R, Vela MF, Katz PO, Tutuian R, Castell JA, and Castell DO.** Esophageal function testing using multichannel intraluminal impedance. *Am J Physiol Gastrointest Liver Physiol* 280: G456–G462, 2001.
36. **Sun WM, Hebbard GS, Malbert CH, Jones KL, Doran S, Horowitz M, and Dent J.** Spatial patterns of fasting and fed antropyloric pressure wave in humans. *J Physiol* 503: 455–462, 1997.
37. **Tougas G, Anvari M, Dent J, Somers S, Richards D, and Stevenson GW.** Relation of pyloric motility to pyloric opening and closure in healthy subjects. *Gut* 33: 466–471, 1992.
38. **Vela MF, Camacho-Lobato L, Srinivasan R, Tutuian R, Katz PO, and Castell DO.** Simultaneous intraesophageal impedance and pH measurement of acid and non-acid gastroesophageal reflux: effects of omeprazole. *Gastroenterology* 120: 1599–1606, 2001.