Relationships of human antroduodenal motility and transpyloric fluid movement: non-invasive observations with real-time ultrasound

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SUMMARY To study the relationships between gastric antral and proximal duodenal motor activity, and the movement of liquid across the pylorus, 10 healthy volunteers were given a test meal of dilute orange juice and bran, and events at the gastric outlet monitored by real-time ultrasound. A total of 116 complete gastric peristaltic cycles were observed and in 86% of these, associated proximal duodenal contractions were seen. Transpyloric fluid movement, as reflected by the movement of the bran particles, occurred as brief episodes during the time when the pylorus was open. Distal flow, in episodes lasting 2-4 seconds, was seen to occur in 81% of the 116 complete cycles and 75% of these episodes occurred just after the relaxation of the terminal antrum, pylorus, and proximal duodenum. The remainder occurred shortly before the terminal antral contraction. Retrograde flow, in episodes of up to 5 seconds, occurred in 78% of observed cycles with the majority occurring immediately before contraction of the terminal antrum. Our findings indicate that transpyloric fluid movement occurs in brief episodes lasting a few seconds only and that retrograde flow across the pylorus occurs in normal subjects. This pattern of fluid movement can bear no direct relationship to a steadily advancing antral peristaltic contraction, nor be wholly attributable to constant intragastric pressure.

Currently available methods for the study of gastric emptying in man do not provide information about the movements of gastric contents in relation to individual gastric peristaltic contractions. Manometric methods permit observation of the timing and magnitude of pressure changes within the gastric lumen¹⁻⁴ and some electrical recordings from the human stomach and duodenum have been obtained^{2,5,6} but although both of these give information about muscle contraction, they do not identify the movement of intragastric contents. Simultaneous studies of antral contractions and gastric emptying in man have been undertaken using intubation methods,^{5,7} and also with a scintigraphic procedure,^{8,9} but much of the current knowledge about the relationships between flow of luminal contents and contractions of the human stomach, pylorus, and duodenum has been obtained from radiological investigations using contrast media.^{3,10}

These are, however, far more difficult than they initially appear.^{3,7} Double contrast techniques may irritate the gastric mucosa¹¹ and will cause gastric distension, inducing motility abnormalities,¹² whereas with single contrast procedures, it is often impossible to determine direction of movements of the gastric contents in response to an antral contraction.^{13,14} Furthermore, the duration of radiographic studies in man is limited by considerations of radiation dosage.^{12,13,15,16}

We have previously described the application of real time ultrasonic imaging to the study of gastric motility in man¹⁷ and now report our use of the technique to examine the relationships between peristaltic contractions and the movement of gastric contents through the pylorus.

Methods

SUBJECTS

Studies have been attempted on 17 healthy normal subjects. There were nine men and eight women

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with an age range of 21–62 years. After fasting overnight, the subject was given a test meal of 500 ml water flavoured with orange juice and warmed to 37°C, to which 0.5 g of chopped and sieved bran was added. The test meal had an osmolality of 285 mOsm/l and a pH of 2.8; the wet particle size of the bran was 1.5 mm. Ultrasound scanning of the upper abdomen was then performed using a rotating transducer real-time ultrasound scanner with a 5 MHz probe (Fischer Ultrasound Limited). Scanning was carried out for a period of up to 30 minutes after consumption of the test meal and recorded on video tape. Because previous experience had shown that satisfactory scans were not obtained from recumbent or supine patients, the present investigation was undertaken with the subject seated upright.

The immediate objective was to obtain and maintain an image of the distal antrum, pylorus, and proximal duodenum. The optimum position for the scanner head on each subject's abdomen was found by initially placing the scanner on the abdomen in the midline at the level of the transpyloric plane and subsequently moving it to the right. The probe was initially held to scan horizontally to identify the antrum and then rotated to an angle of up to 60° to bring the distal antrum, pylorus, and proximal duodenum into line. Small deviations from the above position were necessary according to variation in the subject's anatomy, and normal respiratory movements required that the probe was hand-held so that fine adjustments could constantly be made to compensate for them.

The video recordings were then reviewed to identify the periods when a clear image of the distal antrum, pyloric channel and proximal duodenum was maintained, and there was a sufficient concentration of bran particles suspended in the luminal contents to identify movement through the pylorus, throughout a period of several consecutive antral contractions which lasted a minimum of 2 minutes and up to 4 minutes. Figure 1 shows two photographs from a satisfactory record to illustrate the criteria. The lumen of the stomach and proximal duodenum contains a density of bran particles sufficient to establish their direction of movement through the pylorus and the pyloric channel is visualised. In Figure 1a a peristaltic wave is appearing in the mid antrum whereas 10 seconds later, the wave is approaching the pylorus (Figure 1b).

A satisfactory recording was arbitrarily defined as one in which these criteria were met and sustained for at least 2.5 minutes. The segments to be analysed were often more readily and quickly selected by viewing a fast replay of the recording, allowing rapid exclusion of unsatisfactory data. The timescale

compression also markedly enhanced subjective appreciation of regular patterns of events. These sections of the record were then analysed at normal speed with the aid of a simple event marking system on a 4-channel chart recorder. The terminal antrum contractions (contractions of the immediate prepyloric area) and proximal duodenum contractions were both timed from the point where the opposing gastric or duodenal walls began to occlude their lumina until they subsequently relaxed and the lumina became widely patent. A first observer noted this, while a second observer recorded the direction of particle movement through the pylorus. Forward flow was defined as movement of particles through the pylorus from the stomach to the proximal duodenum, and retrograde flow as movement through the pylorus from the proximal duodenum to the stomach. The observations on the direction of particle movement do not reflect their rate of movement and so do not differentiate slow drift from rapid flow. The video tapes were reviewed on several occasions, so that each variable was studied by two observers and at least on six occasions in all. The individual observations on each event were then averaged to provide a 'best estimate' of the timing and duration of each variable studied. The data were subsequently transferred to a specially designed programme on an Apple II computer to allow data storage, subsequent retrieval, and statistical analysis.

An example of repeated analysis of the video record with the event marking system is illustrated in Figure 2. An event was judged to have occurred if two or more closely grouped observations by two observers were marked on the trace. Overall, this criterion resulted in rejection of 15% of the individual observations. Some observer variation is apparent in Figure 2, particularly in respect of retrograde flow.

Results

Satisfactory recordings were obtained in 10 of the 17 subjects. Three of these subjects had satisfactory recordings carried out on two separate occasions and a further subject had three separate recordings. These 15 recordings form the basis of this study; each satisfactory period of recording lasted a minimum of 2.5 minutes and a maximum of 4 minutes. On some occasions it would have been possible to continue the analysis for up to 10 minutes but in the context of the present study a 4 minute limit seemed sufficient. In the remaining seven subjects, one or more of the previously mentioned criteria of a satisfactory recording could not be fulfilled. A similar set of observations was obtained

Fig. 1 (a) Transverse B-scan, using a 5 mHz probe, of the abdomen at level of transpyloric plane. Stomach and proximal duodenum are distended and bran particles can be seen as small white specks suspended in gastric contents. Concentric antral contraction, which is throwing an acoustic shadow, is travelling along the mid portion of the antrum towards the pylorus. (b) Peristaltic wave has progressed along the antrum and is now approaching the pylorus.

Fig. 2 4-channel chart recording of repeated analysis of the timed events from subject 3. Individual observations, represented by single line, on each event are subsequently compared and averaged to provide 'best estimate' of timing and duration of terminal antral and duodenal contraction and particle movement through pylorus.

from each of the 15 satisfactory recordings making a total of 53.5 minutes of observations.

The timing and duration of the terminal antral contractions, proximal duodenal contractions, and periods of forward and retrograde flow through the pylorus from each individual set of observations were then compared in an effort to establish the relationships between them. Figure 3 illustrates the pattern of events in four different subjects. The midpoint of each terminal antral contraction was taken as the point from which the duration of each gastric peristaltic cycle was determined and a mean cycle time was calculated for each subject. The mean cycle times for subjects 3, 4 and 10 are all similar but that of subject 7 is somewhat shorter. Duodenal contractions can be seen to occur just after the midpoint of the majority of terminal antral contractions. Episodes of forward flow occur mainly as the terminal antrum and proximal duodenum relax although in subject 4, two episodes occur just before the start of the terminal antral contraction. Only one episode of forward flow was observed in

Fig. 3 Comparison of timed events in four separate subjects. 'Best estimates' of timing and duration of terminal antral contractions (TAC), proximal duodenal contraction (DC), and episodes of forward flow (FF) and retrograde flow (RF) through the pylorus from four different subjects have been plotted to illustrate pattern of events and to allow comparisons to be made.

this sequence of cycles from subject 7 despite an opening and closing pylorus and steadily advancing antral contractions. Although the duration of forward flow in subject 4 is shorter than subject 3, it could be seen from the video tapes that the rate of particle movement in the former was considerably greater than the latter. The volume of fluid passing through the pylorus cannot be inferred from the duration of the period of flow. Retrograde flow is seen in most cycles.

The 15 sets of satisfactory recordings contained a total of 116 complete peristaltic cycles; the number of events observed and their mean duration are shown in Table 1. The mean gastric peristaltic cycle time observed in each subject is shown in column 4 of Table 1 and the range is from 18.7 to 29.6 seconds. Detailed analysis of the cycle times from each of the 15 sets of satisfactory observations has shown a significant difference in the mean times between sets of data when compared with the intervals within each set ($F=7.38$; $p<0.01$). The standard deviation between the mean cycle times of the 15 sets of observations was considerably greater than within each individual set (9.25 compared with 3.41). More interestingly, however, there was no significant difference in cycle times between the sets

of data from the individuals who have been satisfactorily recorded on different occasions (Table 2). Each subject, using this particular test meal, would appear to have cycle times which remain relatively constant but may differ from the next individual.

The duration of the terminal antral contraction was about 4 seconds (mean 3.93 seconds $SD \pm 0.8$) with little individual variation. Pyloric closure invariably occurred as the gastric peristaltic wave reached the pylorus at the midpoint of the terminal antral contraction. Contractions of the first part of the duodenum were associated with 86% of the terminal antral contractions. Ninety two per cent of these duodenal contractions occurred immediately after the terminal antral contraction, 5.5% simultaneously and only 2.5% (3) were ectopic. There was some variation in the duration of the contraction of the first part of the duodenum which lasted about 5 seconds (mean 4.93 seconds $SD \pm 1.75$).

Transpyloric fluid movement, as reflected by the movement of the bran particles, occurred as brief episodes during the time when the pylorus was open. Forward flow was seen to occur in 81% of the 116 complete cycles and lasted about 2-4 seconds (overall mean 3.0 seconds $SD \pm 1.2$). Seventy five per cent of these episodes occurred after relaxation

Table 1 Number and mean duration of events in subjects 1 to 10

Subject	Observation	Forward flow through pylorus					Retrograde flow through pylorus					Total duration forward, minus retrograde flow			
		Cycles (no)	Mean cycle time* (sec)	±SD	DCs† (no)	DC/TAC ratio‡	Episodes (no)	Cycles with episodes (no)	Mean duration	±SD (sec)	Episodes (no)		Cycles with episodes (no)	Mean duration	±SD (sec)
1	1	4	29.6	0.6	5	1.0	5	4	5.4	2.9	4	4	3.8	0.9	+11.8
	2	9	29.4	4.1	10	1.0	11	9	5.6	1.7	9	8	9.6	3.3	-24.8
	3	8	26.8	3.7	9	1.0	8	7	2.9	1.1	14	7	2.0	0.6	-4.8
2	4	9	24.0	2.9	9	0.9	13	8	2.7	1.6	10	8	1.8	0.6	+17.1
	5	6	24.4	6.5	7	1.0	11	6	3.7	1.1	8	4	1.9	0.6	+25.5
	6	6	24.5	5.1	7	1.0	9	6	5.2	2.4	5	5	1.8	0.7	+37.8
3	7	7	22.8	0.7	7	0.87	9	6	2.4	1.4	8	5	1.6	0.7	+8.8
	8	8	24.6	3.5	8	0.89	9	7	2.8	0.9	8	7	2.3	1.0	+6.8
	9	9	25.2	3.2	7	0.78	13	7	2.8	1.3	7	6	1.8	0.7	+23.8
5	10	9	23.2	2.0	7	0.7	13	8	2.9	1.1	8	4	1.5	0.5	+25.7
	11	9	18.9	2.8	8	0.8	15	8	2.3	1.2	12	8	2.0	0.8	+10.5
	12	12	18.7	1.7	9	0.69	3	3	2.0	0.6	8	8	1.8	0.5	-8.4
8	13	6	21.3	3.3	4	0.57	4	4	2.5	0.6	5	5	1.6	0.8	+2.0
	14	6	19.5	3.7	6	0.86	6	4	2.8	1.9	8	5	1.7	0.5	+3.2
	15	8	24.9	3.8	8	0.89	9	7	3.7	1.7	8	7	2.3	1.1	+14.9

* Cycle time measured from midpoint of each terminal antral contraction. † Contraction of first part of duodenum.

‡ Number of duodenal contractions occurring after contraction of the terminal antrum expressed as a ratio.

Table 2 Comparison of individual mean gastric peristaltic cycle times

Subject	Observation	Mean cycle time	t*	p
1	1	29.6	0.115	0.1 < p < 0.5
	2	29.4		
2	3	26.8	1.72	0.1 < p < 0.2
	4	24.0		
2	4	24.0	0.16	0.1 < p < 0.9
	5	24.4		
3	6	24.5	0.87	0.4 < p < 0.5
	7	22.8		
4	8	24.6	0.37	0.7 < p < 0.8
	9	25.2		

* Unpaired t test.

of the terminal antrum, pylorus and duodenum with the remaining 25% occurring just before the terminal antral contraction. Retrograde flow, in episodes lasting up to about 5 seconds (mean 2.5 seconds SD ± 2), occurred in 78% of observed gastric cycles. Sixty one per cent of these episodes occurred just before the terminal antral contraction with 39% following it. Although the impression given by a large number of observations is that many of the episodes of retrograde flow occurred just after a distinct episode of forward flow, there was no consistent or measurable pattern between or within individuals.

It is clear that the direction of particle movement and its duration do not reflect the flow rate through the pylorus. An impression of the flow rate, however, could be gained from the number of particles which were seen to flow through the pylorus and the rate at which they moved. There appeared to be much variation in the rate of both forward and retrograde movement of particles.

The same general pattern of distal stomach and duodenal contraction and luminal movement was also observed in the partial recordings made from the seven other subjects from whom satisfactory recordings could not be obtained. No observations made on these subjects were inconsistent with the findings from the 15 satisfactory recordings.

Discussion

This investigation has shown that real-time ultrasonic imaging can be applied to observation of motor activity at the human gastric outlet. The observations made are most readily compared with previous radiograph fluoroscopic studies in man and experimental animals, with the advantage that more information is gained about the passage of gastric contents through the pylorus. Studies based on

gastric or duodenal intubation methods in man, or using strain gauges and duodenal cannulae in animals will identify motor activity and 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.^{12 18} Quite obviously, radiographic studies do allow excellent temporal resolution of events at the gastric outlet, and are able to identify when a contraction occurs, but there can be difficulties in determining the direction of movement of antral and duodenal contents.^{13 14}

We presume our findings with the ultrasonic technique relate to the behaviour of liquids as they empty from the stomach. Although the bran particles producing the ultrasound echos were strictly solids suspended in the liquid gastric contents, the particles were so small that their behaviour may reasonably be taken to represent movements of the liquid phase of the gastric contents, rather than the behaviour of intragastric solids. Currently available evidence suggests that food particles less than 2 mm in diameter empty from the human stomach indistinguishably from liquids.¹² Bran with a wet particle size of 1.5 mm was chosen as an ultrasonically identifiable marker of fluid movement because it was simple to prepare and did not aggregate.

The most unexpected observation made during the present investigation was the timing and episodic pattern of movement of gastric contents through the pylorus. Our findings indicate that emptying of the gastric contents through the pylorus occurs in discrete episodes of 2–5 seconds only, and that the majority of these occur as the terminal antrum, pylorus and duodenum relax at the end/start of each gastric peristaltic cycle. This brief period of forward flow often terminated abruptly and was sometimes immediately followed by a period of retrograde flow. This pattern appears to be in conflict with the traditional view that gastric emptying of liquids occurs either as gushes in response to the pumping action of the antral peristaltic contractions,^{9 19 20–22} or as a steady flow, induced by a pressure gradient maintained and regulated by the tone of the proximal stomach^{7 22–26} and interrupted only by the intermittent closure of the pylorus.²³ Clearly the intermittent pattern of transpyloric flow we have observed can bear no direct relationship to a steadily advancing antral peristaltic contraction, nor can it be attributed to constant intragastric pressure.

Because fluid movement can occur only as a response to a pressure gradient across the pylorus,^{11 18 26} It would seem that rapid fluctuations in this pressure gradient must occur. Whether there

are rapid changes in contractile tone of the proximal stomach, or rapid fluctuations in intraduodenal pressure remains to be determined. These findings, however, clearly invite further consideration of the idea that the discharge of fluid from the stomach is regulated as much by a process of 'duodenal receiving' as by 'gastric emptying'.

In 78% of all gastric cycles, episodes of retrograde flow through the pylorus were observed. Sixty one per cent of these episodes occurred while the antral wave was approaching the pylorus and still remained non-occlusive, but then these episodes ended abruptly as the channel was obliterated by the terminal antral contraction. The remaining 39% occurred after relaxation of the terminal antrum and pylorus when their lumina were once again patent. Most episodes of retrograde flow through the pylorus were not associated with demonstrable contraction of the proximal duodenum and the impression given by the video image was that duodenal contents from the second part passed through the relaxed first part of the duodenum and pylorus into the stomach. Occasional contractions of the second part of the duodenum were observed to occur in mid cycle when the pylorus was still open and these were associated with retrograde flow into the stomach. None of the observed episodes of retrograde flow, however, were associated with recognisable true retroperistaltic waves originating in the second part of the duodenum, which have been described in humans in the presence of peptic ulceration.²⁷ In addition, on several occasions when the second part of the duodenum was well visualised, contraction of this part were seen to occur when the pylorus was closed and retrograde flow into the stomach did not then occur. While this is consistent with other evidence which suggests that duodenogastric reflux occurs in healthy individuals,^{16 28-31} it should be noted that many of the observed episodes of retrograde flow through the pylorus followed immediately after an episode of flow from the stomach to duodenum. It is therefore possible that the refluxed fluid had not become mixed with intraduodenal bile or pancreatic secretions and thus it did not necessarily represent duodenogastric reflux in the usual sense of the term, which carries an implication that duodenal fluid containing bile has entered the stomach. Nevertheless, the present observations have shown clearly that a period of retrograde flow at the pylorus occurs during most gastric peristaltic cycles in normal man.

The range of mean gastric peristaltic cycle times from 18.8 to 29.6 seconds is entirely consistent with the reported frequency of gastric slow wave activity at 2.1 to 3.7 cycles per minute.²⁰ In addition, the

consistently similar mean cycle times of individuals confirms the statement that individuals are consistent to within 10%.²⁰ Ninety seven per cent of observed contractions of the proximal duodenum (bulb) occurred immediately after or simultaneously with the terminal antral contraction. Although the frequency of the duodenal pacemaker is around 11 cycles/minute it is recognised that the motility of the bulb differs from the rest of the duodenum³ and that the terminal antrum, pylorus, and proximal duodenum function as the gastroduodenal unit.³² Migration of antral slow wave activity across the pylorus is thought to modify the response of the muscle of the proximal duodenum to the firing of the duodenal pacemaker²² and produces a progressive wave of contraction in antrum, pylorus and proximal duodenum.

Intragastric volume, particle size, pH, calorie content and osmolarity are all factors which are thought to influence gastric emptying. We arbitrarily chose a test meal of orange juice and bran because we had previously shown that 500 ml of liquid was sufficient to distend the stomach producing the fluid solid interface required for ultrasonic imaging and also this volume would allow around 30 minutes of possible observation time before the stomach emptied. The addition of orange juice to the water and bran mixture gave the meal an osmolarity of 285 mOsm/l and a pH of 2.8. Thus although we cannot be entirely certain about the effect of the various components of our test meal on gastroduodenal motor activity and emptying we have established a definable baseline for future comparisons.

There are obvious attractions in a non-invasive technique which allows prolonged study of events at the gastric outlet.^{19 33} We must emphasise, however, that in our experience the use of real-time ultrasonic imaging for this purpose is not easy and so far has been successful only for relatively brief periods in about half of the subjects studied. The two main problems are firstly, individual anatomical variation which sometimes renders it impossible to display the proximal duodenum, pyloric channel, and distal antrum in a single plane, and secondly, the clarity of imaging is much impaired by subcutaneous fat. No useful recording has been obtained from an overweight individual using the 5 mHz probe. Despite these difficulties the present study has shown ultrasonic imaging can be used to study events at the gastric outlet and at present there is no other technique which can generate the same information. The intermittent and episodic pattern of movement of gastric contents through the pylorus clearly requires further study given that the present observations were made with a single test meal which was isotonic, of low nutrient value, and of low

pH. Nevertheless it would seem that influences which modify the intermittent pattern of emptying seen with this meal must be fundamental to the physiology of gastric emptying.

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