Relationship between ultrasonically detected phasic antral contractions and antral pressure

K. HVEEM,1 W. M. SUN,2 G. HEBBARD,3 M. HOROWITZ,2 S. DORAN,2 AND J. DENT2
1Innherred Hospital, Levanger 7600, Norway; 2Departments of Gastrointestinal Medicine and Medicine, Royal Adelaide Hospital, and 3Division of Medicine, Repatriation General Hospital, Adelaide, South Australia 5000, Australia

Received 16 May 2000; accepted in final form 6 March 2001

Ultrasound has been used in several studies to evaluate patterns of gastric wall motion and intraluminal flow (5, 8, 9). These studies have revealed substantial variability in the patterning of wall motion and complex patterns of pulsatile flow episodes within and from the stomach.

Luminal manometry is the most widely used method for measuring gastric motility (6). We (11) have demonstrated that the patterns of intraluminal pressure are complex in both the fasting and fed states. Although information about the relationship between intraluminal pressure and gastric wall motion is very limited, it is clear that phasic and tonic contractions of the gastric wall provide the major forces favoring gastric emptying. The mechanisms by which gastric wall motion leads to changes in intraluminal pressure and the associations of movement of gastric contents with wall motion, however, are unclear. In this study, to investigate the relationship between wall motion and luminal pressures, we have combined antropyloric manometry with simultaneous ultrasound imaging of gastric wall motion in healthy human volunteers.

MATERIALS AND METHODS

Subjects

Nine healthy volunteers participated in the study. For technical reasons, ultrasound images and manometric data were considered to be of adequate quality for analysis in only five of the subjects (3 males and 2 females). None of the subjects had any history of clinically significant dyspeptic symptoms. The median age of the subjects was 21 yr (range 18–24 yr), and the median body mass index was 21 (range 17.7–22.7).

Protocol

Subjects fasted overnight before studies, which were conducted in the seated position. A multilumen sleeve/side hole manometric assembly (Fig. 1) was introduced through an anesthetized nostril and positioned across the pylorus, based on manometric and dual point transmucosal potential difference (TMPD) criteria as previously described (6). The positions of the manometric side holes 3 and 6 cm above the pyloric antrum occur despite a stereotyped pattern of contraction propagation seen on ultrasound. Lumen occlusion is more likely to be associated with higher peak antral pressure events.

Ultrasound

Fluoroscopic imaging has been used since the turn of the century for this purpose (2), but its application in humans is severely constrained by radiation exposure limits. Imaging with magnetic resonance and transabdominal ultrasound for 60 min after subjects drank 500 ml of clear soup. We found that 59% of antral contractions detected by ultrasound were propagated aborally, and 68% of contractions became lumen occlusive at the site of the ultrasound marker. Of the 203 contractions detected by ultrasound, 53% were associated with pressure events in the manometric reference channel, 86% of contractions had corresponding pressure events detectable somewhere in the antrum. Contractions that occluded the lumen were more likely to be associated with a pressure event in the manometric reference channel (P < 0.01) and to be of greater amplitude (P < 0.01) than non-lumen-occlusive contractions. We conclude that heterogeneous pressure event patterns in the antrum occur despite a stereotyped pattern of contraction propagation seen on ultrasound. Lumen occlusion is more likely to be associated with higher peak antral pressure events.
proximal sleeve margin were monitored by observation of the acoustic shadows of two metal markers (Fig. 1) and by continuous observation of TMPD (see Measurement of Antropyloric Pressures). Subjects drank 500 ml of clear meat soup (20 kcal, 1 g fat, TORO, Rieber & Søn, Bergen, Norway), and simultaneous recordings of antral wall motion and intraluminal pressure were made for 60 min.

Measurement of Antropyloric Pressures

The manometric technique used was similar to that described in previous studies (11). Pressures were measured with a 10-lumen perfused manometric assembly. This incorporated a 4.5-cm sleeve sensor in parallel with a chain of nine side holes spaced at 1.5-cm intervals that straddled the pyloric region (Fig. 1). Side holes positioned at each end of the sleeve were used to measure TMPD as well as pressure (6).

Manometric channels other than those used to record TMPD were perfused with degassed distilled water at 0.3 ml/min with a low compliance manometric infusion pump. TMPD channels were perfused with degassed normal saline from separate reservoirs. Signals from pressure transducers were amplified by a 16-channel Polygraf (Medtronic, Copenhagen, Denmark) and digitized at 10 Hz using an A-D card (NB-MI016, National Instruments Corporation, Austin, TX). Signals were then processed and stored in a personal computer (Apple Computer, Cupertino, CA) with purpose-designed software (MAD 16, Medtronic/Royal Adelaide Hospital/C. H. Malbert) based on LabVIEW (National Instruments).

Ultrasound imaging

A 5-MHz sector transducer was positioned on the abdomen to image the antrum and manometric assembly in longitudinal section. The orientation of the transducer was optimized to ensure clear images of the distal ultrasound marker, as this was where the manometric reference channel was located. Because of the orientation of the distal stomach, these images did not reliably include the most distal antrum, pylorus, or duodenum. The metal markers provided a hyperechoic signal that allowed them to be accurately located on the image (Fig. 1). The side hole closest to the distal marker was used as the manometric data reference channel for analysis.

In the first two subjects, a marker in the center lumen of the manometric assembly was situated 2 mm aboral to the reference channel (assembly A). In the last three subjects, a revised assembly design was used to obtain improved marker definition. In this assembly, the marker was external to the assembly and situated 2 mm oral to the reference side hole (assembly B).

Synchronization of Ultrasound Images with Manometric Data

A purpose-designed time-coding system was used. This recorded a time code both with the manometric data and on the videotaped ultrasound image. Correlation of the time code between the display of manometric data on the computer screen and the number recorded on the video image allowed accurate synchronization of data to within 100 ms. Manometric and image data were initially analyzed separately to avoid any possibility of observer bias (see Interobserver Agreement) before being correlated. Because of the minor differences between assemblies in the relative positions of recording side holes and markers, data used to examine the detailed temporal relationships between ultrasonographically visible contraction waves and manometric pressure events were drawn from the three studies in which assembly B was used (see Fig. 5). All other data were analyzed for both assemblies.

Data Analysis

Definitions and terminology relevant to motor events. A contraction was defined as an indentation of the gastric wall greater than one antral mucosal thickness, which was not due to respiration, pulsation transmitted from the aorta or the heart, or to movements of adjacent intestine, and was observed to propagate for some distance in space and time. Accordingly, for this study, contraction refers specifically to events observed by ultrasound imaging.

A lumen-occlusive contraction was defined as a contraction in which the ultrasound image showed the gastric walls to come into apposition at some point along the imaged antrum (Fig. 2). A propagated contraction was defined as a gastric contraction seen to progress aborally along the entire length of the imaged antrum. A phasic rise in pressure in a single manometric recording channel was referred to as a pressure event. When a group of pressure events recorded in different manometric channels was established as being related by specific spatiotemporal criteria (see Analysis of pressure event sequences), each of these grouped events was defined as a pressure event sequence. A contraction was defined as having an associated pressure event when a pressure event was recorded in the manometric reference channel within the heart, or to movements of adjacent intestine, and was observed to propagate for some distance in space and time. Accordingly, for this study, contraction refers specifically to events observed by ultrasound imaging.

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![Fig. 2](http://ajpgi.physiology.org/) Timing of contractions reaching the ultrasound marker. **Left:** the time of arrival of the leading edge of the contraction at the marker. **Right:** the timing of lumen occlusion at the marker.
10 s of the timing of the contraction first reaching the level of the ultrasound marker on imaging (see Analysis of pressure event sequences).

Analysis of pressure event sequences. Manometric recordings were analyzed only when the ultrasound images confirmed that the distal ultrasound marker was positioned in the distal antrum and TMPD recordings confirmed that the manometric assembly was correctly positioned across the pylorus (see Protocol). The position of the distal ultrasound marker (and manometric reference channel) was therefore maintained between 3 and 7.5 cm above the pylorus.

The space-time organization of pressure event sequences was evaluated by the following five steps, which were based on a technique previously described in detail (11). 1) Any resolvable pressure event that was <20 s in duration was scored, provided it was not attributable to respiration, strain, or change in posture. 2) The 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. An extra second was added to these values for each intervening channel. 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. An extra second was added to these values for each intervening channel. 4) 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 (s); if this difference was >1 s, the relationship was defined as antegrade (a) or retrograde (r), 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 (i). The space-time patterning of pressure event sequences was then summarized. For example, a sequence of events recorded over five side holes could be scored aaaa, aasa, assr, and so on, with each lower case letter denoting the relationship between events at a pair of side holes. 5) Pressure event sequence patterns were then grouped in two ways. First, they were grouped by the aboral evolution of propagation patterns within the sequence (i.e., aaaa became A, aasr became ASR, saar became SAR, and so on). Second, sequences were grouped by the propagation pattern of the most aboral pair of side holes of the pressure event sequence. Pressure event sequences terminating with a synchronous or retrograde component were grouped together and compared with those with a terminal antegrade pattern or with isolated pressure events.

Definitions and terminology relevant to ultrasound images. 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 distal metal ring (Fig. 2). In contractions classified as lumen occlusive, the time at which the occluding contraction wave merged with the acoustic shadow of the marker was taken as the time of lumen occlusion (Fig. 2). Interobserver Agreement

The timing of the onset of pressure events and of the characteristics of antral contractions was analyzed independently by two investigators (Hveem and Sun). Both scored the amplitude and time of appearance of pressure events in the manometric data as well as the timing and character (i.e., whether lumen occlusive and whether propagated) of wall motion on the ultrasound image. Events for which there was a discrepancy were reviewed, and a mutually agreed decision was arrived at before further analysis.

Statistical Analysis

Nonparametric statistics were calculated using the Wilcoxon rank sum test and the one-sample sign test. Categorical data were analyzed using a chi square test. All tests were two-tailed; P < 0.05 was used as the criterion of statistical significance.

RESULTS

Interobserver Agreement

Ultrasound data. There was a mean variability in the judgment of the two observers of the time of arrival of the contraction at the marker of 0.45 s (SE, 0.18 s) and a 90% concordance between the two observers for the first independent analysis of whether contractions were lumen occlusive.

Manometric data. The interobserver agreement for scoring of pressure events <5 mmHg, between 5 and 10 mmHg, and >10 mmHg was 85%, 97%, and 100%, respectively. Eighty-nine percent of the onset times of pressure events were in agreement within 1 s and 95% within 2 s.

Ultrasound Imaging of Distal Antrum

A longitudinal ultrasound image of ~10 cm of the antrum and clear definition of at least the distal metal marker was achieved in the five subjects in whom imaging was considered adequate for data evaluation. The manometric assembly was seen to lie approximately parallel to the gastric wall (Fig. 1). Satisfactory images were obtained for 72 min with a median duration of 11.5 min/subject (range 10.5 to 27 min, Fig. 3).

Of the 203 antral contractions detected by ultrasound, 99% (n = 201) were propagated along the length of the imaged antrum. At the level of the manometric assembly ultrasound marker, 68% (n = 138) of contractions were judged to be lumen occlusive.

Manometric Recordings

During the periods when ultrasound images were judged to be adequate (72 min), 174 pressure event sequences or isolated pressure events were detected. The frequencies of the different space-time patterns of these sequences are shown in Fig. 4. Antegrade pressure event sequences were the most numerous (40%,...
n = 59) followed by isolated pressure waves (25%, n = 37) and then initially antegrade pressure event sequences with a terminal synchronous component (20%, n = 30).

**Relationship Between Contractions and Pressure Events**

Sensitivity of pressure events for detection of antral contractions. Of the 203 antral contractions detected by ultrasound, 53% (n = 108) had a temporally associated pressure event in the manometric reference channel. In two-thirds (67%, n = 66) of the 47% (n = 95) of contractions for which no pressure event could be detected in the manometric reference channel, temporally associated pressure events were found in other antropyloric recording channels (i.e., within 10 s of the contraction reaching the metal marker). Therefore, in total, 86% of all contractions had a temporally related pressure event somewhere in the antrum.

Relative timing of pressure events and antral contractions. There was a nonsignificant trend for the time of arrival of the leading edge of the contraction wave at the marker to precede the onset of the pressure wave in the manometric reference channel (mean, 0.6 s; P = 0.07; Fig. 5). For lumen-occlusive pressure waves, the time of lumen occlusion at the marker (assessed with ultrasound) was not significantly different to the time of onset of the pressure event in the manometric reference channel (P > 0.5, Fig. 5).

Relationship between lumen occlusion and detection of pressure events. There was a significant association between contractions that were judged by ultrasound to have occluded the lumen at the level of the metal marker and the occurrence of a pressure event in the manometric reference channel; 69% (n = 95) of 138 lumen-occlusive contractions had an associated pressure event detected in the manometric reference channel. In contrast, of the 65 non-lumen-occlusive contractions, only 20% (n = 13) were associated with a pressure event (P < 0.01).

The median amplitude of the pressure events in the manometric reference channel was 16 mmHg (range 4–98) for lumen-occlusive and 7 mmHg (range 4–23) for non-lumen-occlusive contractions (P < 0.01). There

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**Fig. 4.** Relative frequencies of different patterns of pressure events for lumen-occlusive and non-lumen-occlusive contractions. See MATERIALS AND METHODS (Analysis of pressure event sequences) for coding of pressure event sequences.
was, however, a substantial overlap between the two categories of contraction, with 23% of lumen-occlusive contractions being associated with a pressure event $\leq 10$ mmHg and 25% of non-lumen-occlusive contractions being associated with a pressure event $>10$ mmHg (Fig. 6).

**Relationship between lumen occlusion and pressure event sequence.** There was no significant relationship between lumen occlusion and the spatial patterns of pressure event sequences ($P > 0.2$; Fig. 4). However, 54% of pressure event sequences temporally related to lumen-occlusive contractions had a terminal synchronous or retrograde component, compared with 22% of pressure event sequences temporally related to non-lumen-occlusive contractions ($P < 0.05$).

**DISCUSSION**

This study adds substantially to knowledge about antral mechanics by providing objective data on the relationships between time-space patterns of intraluminal pressure and antral wall motion and apposition in humans after ingestion of a low-nutrient liquid. Such data are remarkably scanty, especially in humans, but central to the understanding of how the antropyloric region varies the mechanical outcomes of individual contraction sequences. These outcomes vary from retropulsive mixing to pulsatile ejection of gastric content into the duodenum over a wide range of pulse volumes. Our major findings are as follows: 1) despite a very stereotyped and regular aboral progression of antral contraction to the pylorus, the simultaneously observed patterning of intraluminal pressure and antral wall apposition is variable; 2) in 86% of ultrasonically detected antral contractions, there is a temporally associated pressure wave somewhere in the

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**Fig. 5.** Time of onset of pressure events at the manometric reference side hole in relation to the arrival of contractions at the ultrasound marker and time of lumen occlusion. A positive value means that the pressure event occurred before the contractile event [arrival of the contraction at the marker or occlusion of the lumen at the marker (Fig. 2)].

**Fig. 6.** Amplitudes of pressure events associated with lumen-occlusive and non-lumen-occlusive contractions.
antropyloric region; and 3) there is a relationship between pressure wave amplitude, occurrence of lumen occlusion, and synchronous or retrograde onset times of terminal antral/pyloric pressure waves.

The scantiness of information about the relationships among antral contractions, contraction-induced antral luminal apposition, and intraluminal pressures reflects the technical challenge of studying these relationships, rather than indicating that they are not physiologically or clinically important. This importance is evident from the predominantly pulsatile pattern of emptying of gastric contents into the duodenum, which is timed with individual antropyloric contraction sequences. The mechanics of individual antropyloric contraction sequences are not stereotyped, as they produce widely differing outcomes with regard to flow, varying from relatively high-volume pulses to forcible retropulsion of the antral content with no forward transpyloric flow. In a previous study (11) in healthy subjects, we found a great diversity of spatial patterning of antral pressure wave onset times among individual contraction sequences, especially in the distal antrum. The observed diversity of antropyloric pressure patterns led us to propose that these spatial variations in antral pressures reflect the relatively subtle variations of antropyloric mechanics that account for the differing observed outcome of luminal flows associated with episodes of antropyloric contractions. Thus far, though, spatial-temporal patterns of pressure have not been well correlated with other changes of antropyloric geometry associated with individual antropyloric contractions or with simultaneous flow patterns. In the present study, we have followed through on our (11) previous observation that there is substantial spatiotemporal diversity of antral pressures, by making ultrasonic observations of antral wall motion concurrently with multipoint antropyloric manometry.

A major challenge in this study was to determine the position of the pressure recording point on the manometric assembly in the ultrasound image. Initially, a metal marker was placed within the center lumen of the manometric assembly, but the ultrasound signals from the markers could not be distinguished consistently from the acoustic shadow of the manometric assembly. However, when the metal markers were positioned around the manometric assembly, a sufficiently sharp and distinct acoustic shadow was seen. Because the distal marker was positioned close to the manometric reference side hole and manometric and image data were synchronized, the relationships between pressure events and gastric wall motion were able to be examined in both space and time.

In contrast to some previous studies (3, 4), we have found that the vast majority (86%) of antral contractions were associated with some form of pressure event, although in only about two-thirds of these was the pressure event identified in the manometric reference channel. This high detection rate of contractions by manometry may be due partly to the closeness of the manometric side holes and partly because we set a low threshold for detection of pressure events. Other factors such as the position of the manometric assembly within the antrum and the volume and composition of the meal probably also influence the relationship between the number of antral contractions and pressure events by changing the relative proportions of lumen-occlusive and non-lumen-occlusive contractions, especially under conditions of more substantial rates of nutrient delivery to the duodenum than was the case in the present setting. With regard to the differences between lumen-occlusive and non-lumen-occlusive contractions, we found that lumen-occlusive contractions were more likely to be associated with a pressure wave in the manometric reference channel, and these pressure waves were likely to be of higher amplitude than those associated with non-lumen-occlusive contractions. These observations, along with the observation that the onset of pressure events and arrival of the antral contraction waves at the ultrasound marker correlated closely in time, indicate that pressure events associated with contractions are usually relatively localized phenomena, with significant elevations in pressure extending perhaps only a few millimeters from the edge of the antral contraction. On the basis of physical principles, the spatial extent of the pressure waves would be expected to vary with the rate of propagation of the antral contraction, the degree of lumen occlusion, and the viscosity of the antral content. Contractions have also been noted (1) to result in a generalized rise in the luminal pressure of the stomach, the “common cavity” pressure. However, we did not identify this in the current study, probably because of the relatively modest volume within the stomach.

The characteristics of the antral contractions that we were able to observe using ultrasound (i.e., whether lumen occlusive and whether propagated) were not predictive of the overall pattern of the pressure event sequence as determined by manometry. This may reflect the limitations of the ultrasound image in terms of spatial resolution and the fact that only a single plane could be visualized. Three-dimensional ultrasound imaging of the antrum would provide better spatial information than the technique we employed, but at the cost of poorer temporal resolution.

These data indicate that complex patterns of pressure event sequences can be generated by contractions that have a stereotyped pattern of aboral propagation along the antrum. These patterns are likely to have significantly different mechanical outcomes, such as retropulsion within the stomach and/or transpyloric flow. However, currently there are no reliable data on the relationships between transpyloric flow, contraction patterns, and spatiotemporal patterning of pressure wave sequences in humans.

We observed that the presence and amplitude of pressure events in the manometric reference channel and the presence of a terminal synchronous or retrograde component of the pressure event sequence were all associated with lumen occlusion at the level of the metal marker. We believe that all of these factors probably reflect increased vigor of those contractions....
with a terminal retrograde component, or a synchronous component in some pressure wave sequences probably correlates with the “terminal antral contraction” observed fluoroscopically.

Our analysis of gastric wall motion and intraluminal pressures suggests that the maximum amplitude of pressure waves can only be used as an approximate predictor of the occurrence of lumen occlusion, with approximately one-quarter of lumen-occlusive contractions being associated with a pressure event sequence <10 mmHg, and a similar proportion of non-lumen-occlusive contractions being associated with a pressure event sequence >10 mmHg. Above a pressure of 25 mmHg, however, all pressure waves were associated with lumen-occlusive contractions, probably reflecting mucosal “contact pressure.”

One significant limitation of this and many other studies of gastric motor function is that the mechanical significance of the contractions and manometrically recorded pressures could not be determined. The patterns of intragastric pressure and wall motion associated with transpyloric flow have not been defined and await simultaneous measurement of these and other relevant parameters, such as pyloric resistance and the transpyloric pressure gradient (7).

REFERENCES