Digestive Diseases and Sciences, Vol. 43, No. 5 (May 1998), pp. 957–963

Characterization of Propagating Contractions in Proximal Colon of Ambulatory Mini Pigs

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The aim of this study was to characterize propagating contractions in the unprepared colon of freely ambulating mini pigs. A telemetric method was used to record colonic motility continuously for six consecutive days in a 40-cm segment of proximal colon. Propagating contractions occurred over a wide range of propagation rates (0.4–16.7 cm/sec), peak amplitudes (10–116 mm Hg) and pressure wave durations (5.3–40.0 sec). Propagating contractions were divided into two groups by duration and wave-form: short-duration symmetrical and long-duration asymmetrical. Short-duration (7.8 ± 0.9 sec) symmetrical wave-from propagating contractions exhibited a higher frequency (27.9 ± 2.6 events/day), more rapid propagation rate (3–16.7 cm/sec; mean ± SEM: 4.9 ± 1.7 cm/sec), and a lower peak amplitude (31.2 ± 0.9 mm Hg) compared to long-duration (19.2 ± 5.1 sec) asymmetrical propagating contractions, which were less frequent (6.1 ± 0.7 events/day), slower in propagation rate (0.4–2 cm/sec; mean ± SEM: 1.5 ± 0.7 cm/sec), and higher in peak amplitude (51.6 ± 2.4 mm Hg). The results show that propagating contractions occur over a wide spectrum, from short-duration, low-amplitude, rapidly propagating contractions to long-duration, high-amplitude, slowly propagating contractions.

KEY WORDS: propagating contractions; pig; large intestine; cecal fistula.

The mammalian large intestine is responsible for the mixing, dehydration, storage, transport, and evacuation of luminal contents exhibiting a wide range of viscosity, from solids to gas. Transit studies of intestinal gas in healthy individuals show whole gut transit times of 20–35 min (1) and jejunum to anus transit times of 15–20 min (2). This is in contrast to whole gut transit of solids, which is reported to average 33–56 hr in healthy individuals (3, 4). Additionally, flatulence episodes normally occur far more frequently (14/day) (5) than bowel movements, suggesting a separate or additional mechanism for transport of gas. The mechanism by which a low-viscosity substrate, such as gas, can be propelled at a higher transit rate beyond solids in the bowel lumen is unknown. The aim of this study was to use a high resolution telemetric recording system to characterize propagating contractions in the unprepared colon of freely ambulating mini pigs.

Manuscript received September 10, 1997; accepted January 26, 1998.

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This study was funded by The Procter & Gamble Company, Cincinnati, Ohio.

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MATERIALS AND METHODS

Surgery and Animal Care. Three female Yucatan miniature pigs (Charles River Co., Wilmington, Massachusetts) were studied. Each had undergone a surgical procedure (6) to establish a permanent cecal fistula three years prior to this study. The patency of the chronic fistula has been maintained without health problems for over four years by a silicon port with a removable cap

(Omni Technologies, Inc., Hebron, Kentucky), providing direct access to the cecum and unprepared colon. The mini pigs (all females, 80–95 kg) were housed in separate pens in an air (72°F, 75% humidity) and light (07:00–19:00 hr light, 19:00–07:00 hr dark) controlled room. Mini pigs had free access to water and were fed a maintenance diet of Purina Mini Porcine Chow [#5084, 500 g twice a day (07:30 and 14:00 hr)].

Study Protocol. The motility probe (Konigsberg Instruments, Inc., Pasadena, California) contained five pressure-sensing (−50 to +300 mm Hg) carriers mounted in a silastic probe spaced 10 cm apart, with the most distal carrier positioned 5 cm from the tip; overall probe length was 175 cm (6). The probe was inserted through the cecal fistula port, to the 125 cm mark, into the unprepared cecum/proximal colon (under isoflurane anesthesia). The mini pig cecum is approximately 20 cm in length, and the cecal fistula port enters at mid-cecum. The probe enters the large intestine approximately 10 cm proximal to the ileocecal junction. The aborad flow of luminal contents extended the catheter (125 cm) and maintained its position (verified by identical spacing of propagating contractions sequentially across five channels and by abdominal radiograph). The distinctive centripetal and centrifugal coils of the proximal colon, followed by two 90° fixed flexures at the proximal and distal ends of the transverse colon, provided landmarks for determination of probe position by abdominal radiograph. Continuous recordings (six days) of colonic motility were initiated approximately 24 hr after catheter insertion.

Data Acquisition/Storage/Analysis. The details of this method have been previously published (6). Briefly, real-time ambulatory manometric data were obtained with a Motility Telemetry System (Konigsberg Instruments). The system has three components: a custom-built motility probe (described above), an amplifier/telemetry transmitter, and a base station receiver/decoder. The ambulatory elements of the telemetry system were carried by the animals in a custom-made nylon/spandex jacket (Freedom Research Instruments, Torrington, Connecticut) within a dorsal pouch. A separate radio receiver was used to tune to each animal's transmitter. The computer recording and analysis program (6) (Data Integrated Scientific Systems, Pinckney, Missouri) has a dual monitor display that allows for uninterrupted acquisition with simultaneous graphic display and control of analysis parameters.

Recordings were continuous and uninterrupted for the duration of the monitoring period. The motility pressure signals were sampled and stored at 15 Hz in real time to a "write once read many" (WORM) optical drive. A sampling rate of 15 Hz yielded high-resolution analysis of colonic pressure events and manageable data files (20 Mbytes raw data/24 hr). The adjustable analysis parameters for event/wave-form recognition (and selected settings) include: minimum peak amplitude (5 mm Hg), minimum slope (0.1 mm Hg/sec), maximum slope (1000 mm Hg/sec), minimum return to baseline (66%), minimum duration (5 sec), and time-out (60 sec; maximum time for return to baseline). These settings optimized the differentiation of phasic colonic pressure events from tonic baseline changes (eg, pig position change). Simultaneous events (initiation of peaks within 0.01 sec), recognized as peaks in at least three

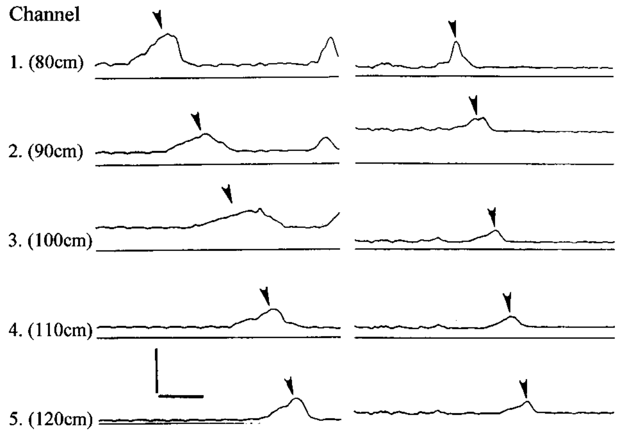

Fig 1. Intraluminal pressure tracing of long-duration propagating contractions (arrows). Recording sites are spaced 10 cm apart. Channels 1–5 are proximal to distal, 80–120 cm aborad to the cecal fistula, respectively. Note the slow-propagation rate, long-duration, and asymmetrical wave-form typical of LDPCs. Note also that the initiation point of each wave occurs before the peak pressure in the preceding channel. Vertical bar equals 100 mm Hg, horizontal bar equals 20 sec.

channels, were identified as movement artifact and removed from analysis.

From the digital recordings, colonic pressure events were identified by computer program, visually verified, and analyzed for: time of pressure event, peak amplitude, duration of pressure event, and time between channels for orad or aborad propagating events (6). Propagating contractions were identified visually as pressure events detected at equal time intervals in at least three sequential pressure ports (spaced 10 cm apart) within a defined period of time [range: 0.5–30 sec (20–0.3 cm/sec)].

RESULTS

During extended recording periods, activity level and appetite were unchanged. Bowel movement (BM) frequency was not specifically monitored, but stool was washed from each pen each study day, showing a frequency of at least 1 BM/day. Twenty-seven 24-hr recordings were analyzed. Nonpropagating or segmental contractions represented 94% of all recorded colonic motor events, with propagating contractions comprising the remaining 6%. Contractions propagated in an aborad direction only and exhibited a wide range of propagation velocity (0.4–16.7 cm/sec) and pressure wave duration (5.3–40.0 sec). Two types of wave-form were observed. The first type exhibited a long-duration (mean ± SE; 19.2 ± 5.1 sec), asymmetrical wave-form (gradual up-slope; Figure 1), and they were typically high amplitude (up to 118 mm Hg), slowly propagating (0.4–2 cm/sec) contractions (long-duration propagating contractions: LDPCs). The second type exhibited a shorter dura-

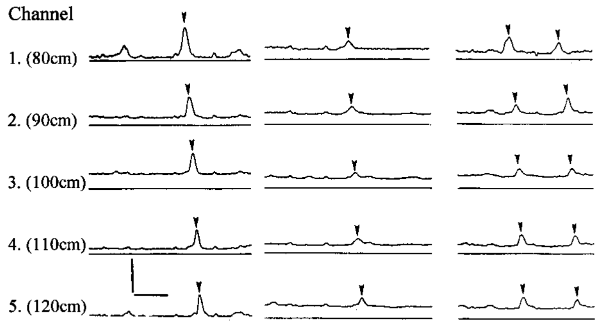

Fig 2. Intraluminal pressure tracings of short-duration propagating contractions (SDPCs; arrows). Recording sites are spaced 10 cm apart. Channels 1–5 are proximal to distal, 80–120 cm aborad to the cecal fistula, respectively. Note the rapid propagation rate, symmetrical wave form, and short duration. Vertical bar equals 100 mm Hg, horizontal bar equals 20 sec.

tion (7.8 ± 0.9 sec), symmetrical wave form (Figure 2), and they were typically low amplitude, rapidly propagating (3–16.7 cm/sec) contractions (short-duration propagating contractions: SDPCs). A summary of the two wave-form types (twenty-seven 24-hr recordings) is presented in Table 1.

TABLE 1. COMPARISON OF LONG- AND SHORT-DURATION PROPAGATED CONTRACTIONS

	Events/24-hr (mean ± SE)	*Amplitude (mm Hg, mean ± SE)*	*Duration (sec, mean ± SE)*	*Velocity (cm/sec, mean ± SE)*
LDPCs	6.1 ± 0.7	51.6 ± 2.4	19.2 ± 5.1	1.5 ± 0.7
SDPCs	27.9 ± 2.6	31.2 ± 0.9	7.8 ± 0.9	4.9 ± 1.7

The transition between symmetrical and asymmetrical wave-forms occurred at 11 sec duration, providing a reasonable delineation between the two groups for analysis (Figure 3). The observed transition in wave-form proved to have functional significance. LDPCs were observed in all five channels, suggesting that their initiation point was orad to the proximal colon recording sites. In contrast, SDPCs were observed to initiate in channels 1, 2, and 3, showing that SDPCs initiated both proximal to the recording sites and in mid-probe. By definition, propagating contractions required observation in at least three channels, disqualifying propagating contractions beginning in channels 4 or 5. For both groups, propagating contractions continued to channel 5 and were detected in the aborad direction only.

Both types of propagating contractions were observed in temporal proximity (Figure 4). Note the progressive divergence between the two propagating waves. The relationships of propagation rate versus peak amplitude and peak amplitude versus duration are shown in Figures 5 and 6, respectively. Slower propagating contractions trend toward higher peak amplitudes compared to more rapidly propagated contractions (Figure 5). The correlation of peak amplitude and wave-form duration is more diffuse, but lower peak amplitudes trend toward shorter wave-form durations (Figure 6).

Figure 7 shows the 24-hr distribution of propagating contractions. For SDPCs, there is a diurnal pattern, with 64.7% occurring during light hours (07:00–

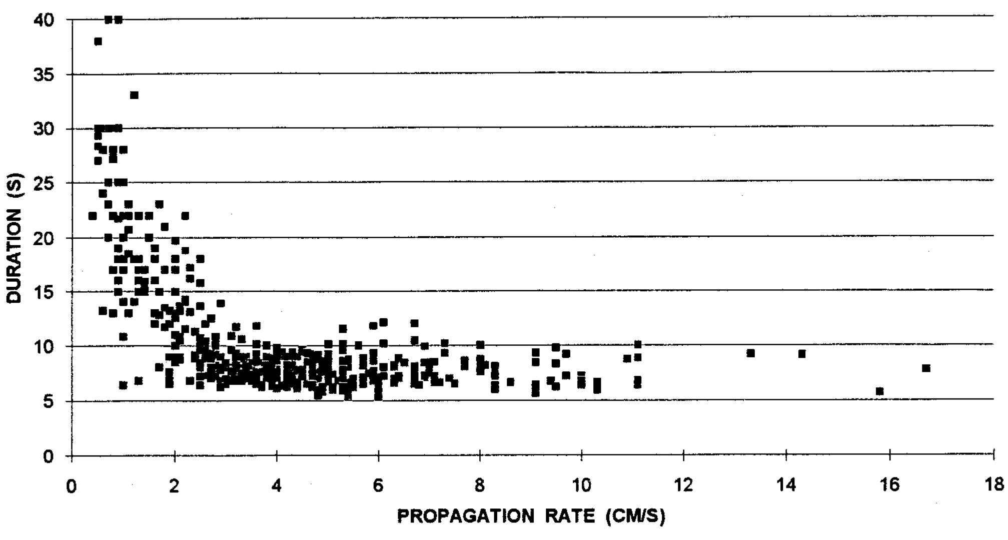

Fig 3. Graph of relationship of wave-form duration versus propagation rate in twenty-seven 24-hr recordings (504 propagating contractions shown). Note that the duration of the pressure events remains relatively constant for propagation rates ≥3 cm/sec, but increase in duration for propagation rates ≤2 cm/sec.

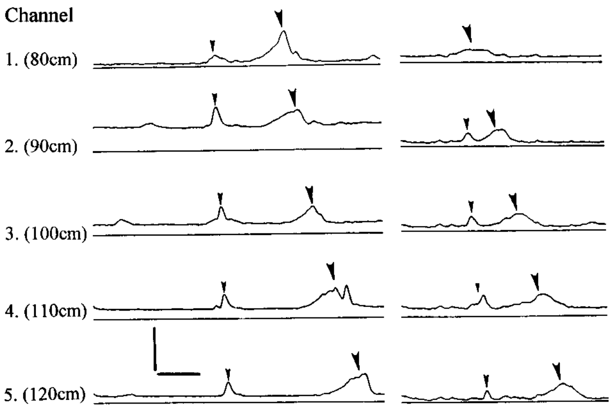

Fig 4. Intraluminal pressure tracing of SDPCs (small arrows) and LDPCs (large arrows). Recording sites are spaced 10 cm apart. Channels 1–5 are proximal to distal, 80–120 cm aborad to the cecal fistula, respectively. Note the progressive divergence between wave-forms of the rapidly propagating SDPCs and the slowly propagating LDPCs. Vertical bar equals 100 mm Hg, horizontal bar equals 20 sec.

19:00 hr) and 35.3% occurring during darkness (19:00–07:00 hr). For LDPCs, there is also a diurnal pattern, with 58.9% occurring during light hours (07:00–19:00 hr) and 41.1% occurring during darkness (19:00–07:00 hr).

DISCUSSION

The observations in this study have established physiological patterns of propagating contractions in the proximal colon of Yucatan mini pigs. Our analysis of propagating contractions in the ambulatory mini pig demonstrate that propagating contractions comprise 6% of colonic motor events and occur over a wide spectrum of propagation rates, peak amplitudes, and wave-form durations. There is a trend for slower propagating contractions to be higher in amplitude and longer in duration, and for more rapidly propagating contractions to be lower in amplitude and shorter in duration.

Based on our observations, propagating contractions were analyzed as two groups differentiated by wave-form. The first group exhibited an asymmetrical wave-from morphology (gradual up-slope) and were observed in all five recording channels, suggesting that their initiation point was orad to the proximal colon recording sites. Moreover, our findings illustrate that the first group is similar in frequency, propagation velocity, and wave-form duration to the high-amplitude propagating contractions (HAPCs) (7–9) reported in man and giant migrating contractions (GMCs) reported in dog (10, 11) and man (3). These HAPCs and GMCs have been associated with the propulsion of luminal contents and the urge to defecate (3, 7, 8, 10, 11).

In our study, the second group of propagating contractions exhibited a symmetrical wave-form of short duration, low peak amplitude, high propagation velocity, and high frequency. These short-duration propagating contractions (SDPCs) initiated both proximal to the recording sites and in mid-probe, suggesting that SDPCs may begin spontaneously throughout the proximal colon. SDPCs occur over a wide range of propagating velocities. Interestingly, we observed propagation rates ≥10 cm/sec, but such rapidly propagating contractions have not been previously reported using manometric techniques. In hu-

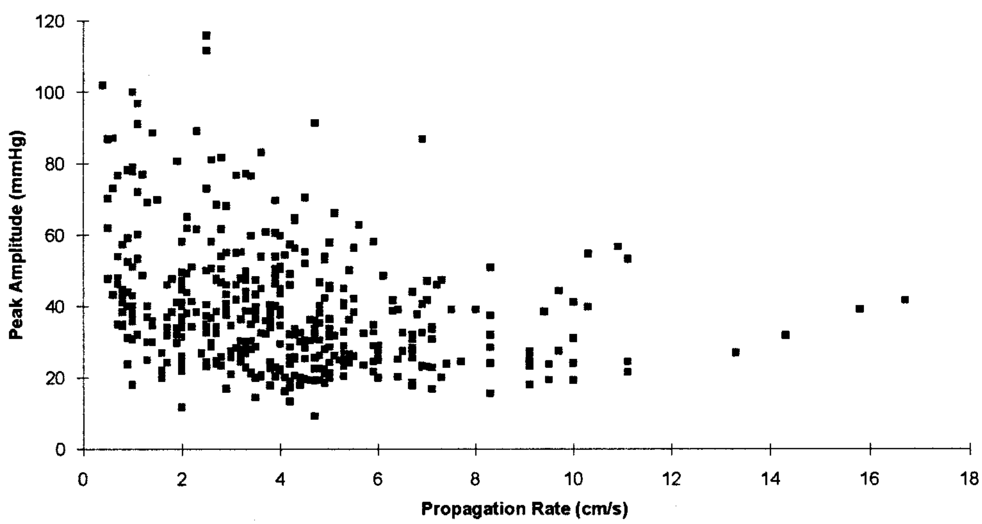

Fig 5. Graph of relationship of peak amplitude versus propagation rate in twenty-seven 24-hr recordings.

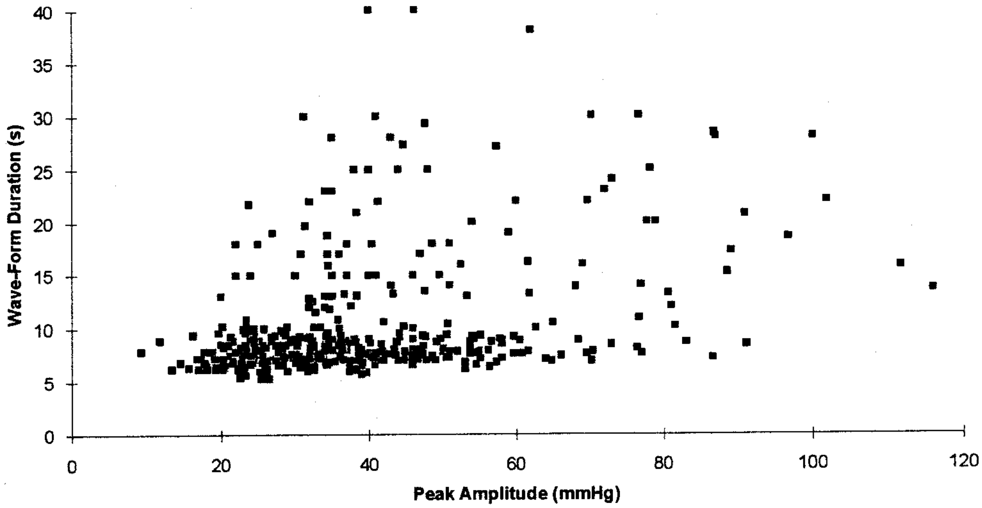

Fig 6. Graph of relationship of wave-form duration versus peak amplitude in twenty-seven 24-hr recordings.

man radiographic studies, however, gas and radiopaque liquids were observed transiting the large bowel at rates up to 10 cm/sec (4, 12, 13). While the mechanism for this rapid transit was unknown at the time, the rate of propulsion is very similar to the propagation rates noted for SDPCs in our study. Myoelectric spike bursts have also been observed propagating aborad at 10.5 cm/sec (±2.6 cm/sec) in healthy volunteers (14).

Gas can transit the entire gastrointestinal tract in 20–35 minutes, and flatulence episodes normally occur far more frequently (14/day) (5) than bowel movements, suggesting a separate or additional mechanism for transport of gas. A recent study in man has shown that spontaneous flatus is associated with colorectal and anal low-amplitude propagating contractions (15). The higher frequency of SDPCs (28/day) compared to LDPCs (6/day) supports the concept that the high-frequency, rapidly propagating SDPCs may be the mechanism driving rapid gas propulsion in the bowel. While the propulsion of solids may require a lumen-occluding event, the propulsion of gas may only require occlusion of the lumen available to the gas bubbles. Figure 8A depicts a lumen-occluding LDPC propelling all luminal contents, gas and solids, aborad (arrow). Figure 8B depicts an SDPC propelling only the low-viscosity gas aborad (arrow) by occluding the luminal space available to the gas around the solid digesta. High-frequency, low-amplitude, rapidly propagating contractions could propel gas in the lumen by maintaining contact with the surface of more viscous luminal contents, thereby occluding the lumen to the gas pocket and selectively propelling gas at a much faster rate past the solids. This hypothesis also describes the possible mechanism for transport of liquids past solids in ascending colon (14) and for passage of liquid stool beyond a bowel obstruction or fecal impaction. SDPCs may be the first colonic motor activity to recover following abdominal surgery, since flatulence is one of the first signs of recovering postoperative bowel function.

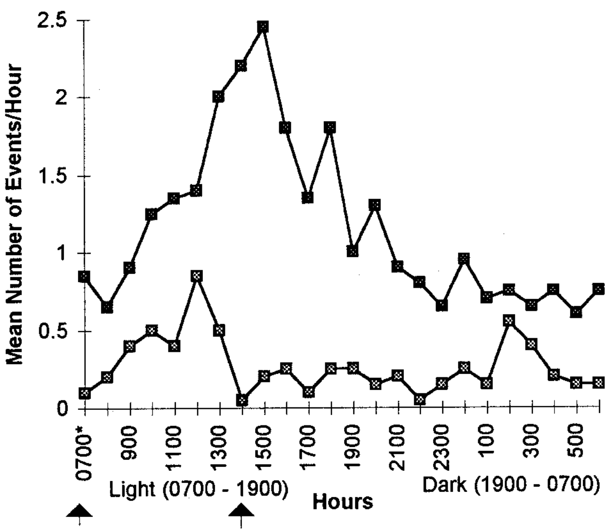

Fig 7. Graph of mean 24-hr distribution of LDPCs (hatched boxes) and SDPCs (solid boxes) from twenty-seven 24-hr recordings in three animals. Arrows indicate meal times.

In man, propagating contractions are eliminated by slow-wave sleep, but rapid eye movement (REM) sleep, arousal, and awakening have immediate stimulatory effects on colonic motility (16). In this study,

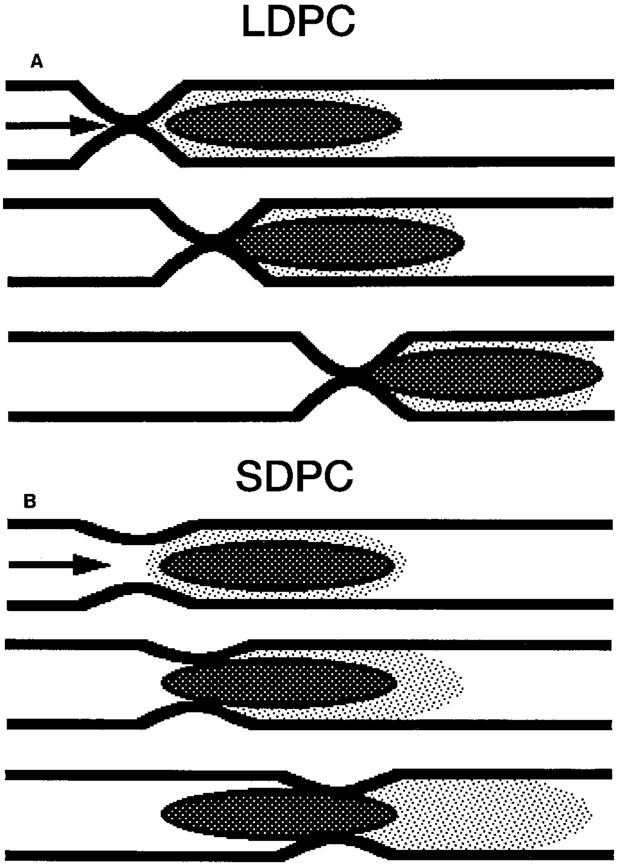

Fig 8. (A) Drawing of a lumen-occluding LDPC propelling all luminal contents, gas and solids, aborad (arrow). (B) Drawing of a SDPC propelling only the low viscosity gas aborad (arrow) by occluding the luminal space available to the gas around the solid digesta.

propagating contractions were less frequent during the 12 hr of darkness, but were not eliminated. The sleep patterns of the mini pigs were not consistently monitored, but general observations of their erratic sleep habits may explain the continued occurrence of propagating contractions during the night hours. The mini pigs often nap intermittently during the day, and it is not unusual to observe one or more of the pigs awake during the day or night while the others appear to be sleeping.

In the ambulatory mini pig, propagating contractions traveled in an aborad direction only and continued to the distal recording site, suggesting that propagating contractions continued beyond the recording probe into more distal colonic regions. The apparent lack of orad propagating contractions is in agreement with a human study of large intestine motility (17), in which the authors suggest that the apparent retrograde movement of luminal contents is due not to propagating contractions, but to regional intraluminal pressure differences generated by non-propagated motility.

In summary, our study has demonstrated that propagating contractions occur over a wide range of propagation rates, amplitude, and wave-form duration in the large bowel. We propose that the wide spectrum of propagating contractions may explain the differential propulsion of solids, liquids, and gas in the bowel and represents a focus of our future studies. Similar analyses of normal human colonic contractile activity will be required to generalize these findings to our understanding of human colonic physiology.

ACKNOWLEDGMENTS

Portions of the data have been previously reported in abstract form (18). The authors would like to acknowledge Susan Pepple for her technical support of this study.

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