Temporal relationships between wall motion, intraluminal pressure, and flow in the isolated rabbit small intestine

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1St. George Clinical School, University of New South Wales; 2Material Science and Engineering, Commonwealth Scientific and Industrial Research Organization, New South Wales; 3Department of Human Physiology, School of Medicine, Flinders University, South Australia, Australia; and 4Department of Cell Physiology, University of Nevada, Reno, Nevada

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Dinning PG, Arkwright JW, Costa M, Wiklendt L, Hennig G, Brookes SJ, Spencer NJ. Temporal relationships between wall motion, intraluminal pressure, and flow in the isolated rabbit small intestine. Am J Physiol Gastrointest Liver Physiol 300: G577–G585, 2011. First published December 30, 2010; doi:10.1152/ajpgi.00532.2010.—Intraluminal manometry is a tool commonly used to record motility in the human digestive tract. The recorded signal results from a combination of factors, including the hydrodynamic pressure transmitted through the intestinal contents due to contraction of the gut wall and the force of the gut wall acting on the sensors in regions of a luminal occlusion. However, the actual relationships between small bowel wall contraction, the measured intraluminal pressure, and the resultant flow have not been directly addressed. Video recording and high-resolution fiber-optic manometry were used to create spatiotemporal video maps of diameter and intraluminal pressure from isolated segments of rabbit small intestine. In the unstimulated gut, longitudinal muscle contractions were the only detectable motor pattern; circular muscle contractions were elicited by distension or erythromycin (1 μM). Longitudinal muscle contractions were not lumen-occlusive, although they caused measurable low-amplitude changes in pressure. Localized nonpropagating circular muscle contractions caused small localized, nonpropagating peaks of intraluminal pressure. Propagating contractions of circular muscle evoked larger, propagating pressure changes that were associated with outflow. Propagating circular muscle contractions often caused dilation of aboral receiving segments, corresponding to “common cavities”; these were propulsive, despite their low intraluminal pressure. The highest-amplitude pressure events were caused by lumen-occlusive circular muscle contractions that squeezed directly against the catheter. These data allow us to define the complex relationships between wall motion, intraluminal pressure, and flow. A strong correlation between circular and longitudinal muscle contraction and intraluminal pressure was demonstrated. Common-cavity pressure events, caused by propulsion of content by circular muscle contractions into a receptive segment, were often of low amplitude but were highly propulsive. Studies of wall motion in isolated preparations, combined with manometry, can assist in interpretation of pressure recordings in vivo.

high-resolution manometry; spatiotemporal maps; small intestine; motility

SINCE THE INTRODUCTION of intraluminal pressure recording by Legros and Onimus in 1869 (21), intraluminal manometry has been recognized as a useful experimental technique to record gastrointestinal motility. The development of high-resolution manometry, coupled with improved interpolation and graphical representation, has enabled construction of accurate pressure profiles along regions of the human gut (33). These profiles have been restricted to <36-cm-long segments and are generally confined to accessible regions of the gut, such as the esophagus (25).

We previously established techniques to create spatiotemporal maps of colonic pressure patterns from manometric data (13, 15); recently, we extended these techniques to high-resolution recordings from fiber-optic-based catheters. The resultant pressure profiles illustrate the complexity of muscular activity in the colon (2). Intuitively, it is clear that there must be a close relationship between movements of the gut wall and intraluminal pressure profiles, but the experimental data to support such understanding is very sparse.

Intraluminal pressures result from hydrodynamic pressure transmitted via the column of liquid content interacting with force generated by the gut wall, mostly by contractions of the circular muscle. As the gut cannot be readily visualized in vivo, measurement of the relationship between wall movement and the intraluminal pressure is challenging. In the pharynx and esophagus, manometry and video fluoroscopy have been combined to monitor the real-time movement of a labeled bolus after swallowing (11, 17). Similar techniques have been applied in animals to demonstrate a close temporal relationship between the flow of digesta and colonic propagating pressure waves (19). However, these techniques have not related changes in gut diameter along an extended length to intraluminal pressure profiles from the same length. Furthermore, below the stomach, safety concerns greatly limit real-time prolonged fluoroscopic recording in humans. Only relatively crude temporal associations have been made between pressure and flow of isotopically labeled content (12, 14).

The ability to record and display changes in gut diameter over time was significantly improved by the development of spatiotemporal video diameter mapping (5, 7, 18). This method involves processing video-recorded images of gut tissue in vitro into a map in which gray-scale pixels represent gut diameter at each point along an extended segment. In the present study, this technique was readily combined with high-resolution manometry in isolated rabbit small intestine in vitro. The aim of the study was to correlate and quantify the movements of the gut wall of the small intestine with intraluminal pressure and the flow of luminal contents.

METHODS

Tissue preparation. Four New Zealand albino male rabbits (2–4 kg body wt) were euthanized humanely by intravenous injection of pentobarbital sodium (0.5 ml/kg) according to a protocol approved by the Animal Welfare Committee of Flinders University. A ventral
Midline incision was made to expose the peritoneal cavity, and a 15- to 20-cm-long segment of small intestine was removed and placed immediately into an organ bath containing warm (36°C) oxygenated Krebs solution (in mM: 118 NaCl, 4.7 KCl, 1.0 NaHPO4, 25 NaHCO3, 1.2 MgCl2, 11 d-glucose, and 2.5 CaCl2) bubbled with 95% O2–5% CO2.

The rabbit small intestine was chosen because, in the empty isolated segments, the circular muscle slow waves do not reach threshold for contraction; there are, however, pendular movements due to longitudinal muscle contractions (9, 20). Circular muscle contractions can be readily activated by distension or pharmacological agents (see Experimental setup). Because longitudinal muscle contractions can be separated from circular muscle contractions in the rabbit small intestine, it is the ideal preparation to clearly assess the ability of recording techniques to detect a variety of motility patterns.

Experimental setup. After a period of equilibration (30–60 min), the oral end of the small intestine was cannulated via a Y-shaped plastic connector (Fig. 1) to an infusion pump for warm (35°C) Krebs solution. The anal end was cannulated and fitted to a T junction, via a one-way valve to prevent backflow of Krebs solution, and to an outflow cannula. The level of the outflow was set 2–4 cm above the isolated intestinal segment to provide constant backpressure (corresponding to 1.5–2.9 mmHg) during emptying. A pressure level of 1.5 mmHg was needed to open the nonreturn valve. Thus outflow of fluid occurred only if the intraluminal pressure reached 3.0–4.4 mmHg. The outflow of intraluminal fluid was recorded as the weight of fluid expelled into a beaker connected to an isometric force transducer (model FT03C, Grass Instruments, Quincy, MA). Intraluminal pressure at the aboral end of the isolated segment was recorded by a pressure transducer (model P23ID, Gould). Both signals were acquired in Chart 5.05 software via a PowerLab 8S recording system (ADInstruments). The oral and aboral ends were fixed to the organ bath to prevent shortening of the preparation (Fig. 1).

Motor activity in segments of small intestine was recorded under resting conditions or when the gut was stimulated by slow distension (2–4 ml/min) by Krebs solution via the oral cannula or by erythromycin (10–6 M) introduced into the bath. Erythromycin is a motilide (H11002; G578 RELATING WALL MOTION TO PRESSURE AND FLOW). Because longitudinal muscle contractions can be readily activated by distension or pharmacological agents (see Experimental setup). Because longitudinal muscle contractions can be separated from circular muscle contractions in the rabbit small intestine, it is the ideal preparation to clearly assess the ability of recording techniques to detect a variety of motility patterns.

Recording motor activity. The fiber-optic catheter was inserted through the other branch of the oral Y-shaped connector and positioned with its tip located in the anal cannula (Fig. 1). The location of the sensors within the gut was noted and marked on the edge of the tissue bath, so that they were recorded on video.

Full description of the catheter design and validation can be found elsewhere (1, 2). Briefly, the fiber-optic catheter was fabricated from a series of fiber Bragg grating elements written into a continuous length of single-mode fiber (10). Each fiber Bragg grating element was designed to respond to a different wavelength and was fixed to a rigid metallic substrate with a flexible diaphragm. The catheter (3 mm OD) consisted of 32 fiber Bragg grating sensors spaced at 1-cm intervals. Changes in intraluminal pressure caused the diaphragms to flex sideways against the fiber Bragg grating elements, which modified the reflected Bragg wavelength of that element. The catheter was attached to a spectral interrogator unit (BlueBox, IPHT, Jena, Germany), and calibrated pressures were recorded in real time on a custom-written LabVIEW program (National Instruments).

Video recording. A digital video camera (model DCR-TRV80E, Sony), positioned above the small intestine (Fig. 1), was used to record 10-min clips of intestinal wall motion using iMovie (Apple, Cupertino, CA) with a Macintosh G4 computer. A small light-emitting diode, placed next to the intestine, was used to synchronize fiber-optic pressure recordings, the pressure transducer, and video frames. Voltage pulses to the light-emitting diode were recorded below pressure recordings, and associated light flashes were recorded on the video.

Construction of spatiotemporal maps. Spatiotemporal maps of changes in intraluminal pressure (P intr) and of changes in gut diameter (D maps) were constructed in parallel from each preparation. P intr and D maps were created using software written in Matlab (MathWorks) and Java (Sun Microsystems) developed at St. George Hospital Clinical School. Video recordings of the gut were downsampled to 4 frames/s and imported into a custom-written software program (Volumetry G7mv, Grant Hennig, University of Nevada, Reno, NV). The diameter at each point along the entire length of the ileal segment was automatically calculated for each frame and converted to a gray scale to create a spatiotemporal map of diameter changes (18). D maps were made of each 10-min video clip. In resting conditions, longitudinal muscle pendular movements were readily distinguished by movement of striations (caused by irregularities in the profile of the gut wall) in the longitudinal axis of the D maps. Longitudinal muscle contractions appeared in the D maps as low-amplitude increases in diameter caused by passive bulging of the gut wall during local shortening of the

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**Fig. 1.** A: segment of rabbit small intestine positioned in the tissue bath. LED, light-emitting diode; B: Y junction at the oral end, with the fiber-optic catheter and infusion inflow visible. C: T junction at the anal end, leading to pressure transducer and outflow to a non-return valve.
longitudinal muscle. All such “longitudinal muscle events” were classified as nonpropagating, retrogradely propagating, or anterogradely propagating. Contractions of the circular muscle (“circular muscle events”) were readily identified as prominent pale streaks or patches in \( D_{\text{maps}} \) and, again, classified as nonpropagating or anterogradely or retrograde (18). During contraction of the circular muscle, longitudinal movements were not assessed. Thus muscle movements were classified as longitudinal or circular muscle events.

**Pressure maps.** Pressure changes were classified as “nonpropagating,” “retrogradely propagating,” or “anterogradely propagating” pressure events. Utilizing criteria from human in vivo recordings (3), we defined “propagating pressure events” [called “propagating sequences” in human in vivo recordings (3)] as three or more pressure waves, of any amplitude, recorded in adjacent recording sites in which the conduction velocity between wave onset within that event lays between 0.2 and 1 s. Nonpropagating pressure events were confined to a single channel or appeared synchronously in several channels simultaneously (onsets between adjacent channels <0.2 s).

**Correlating \( D_{\text{maps}} \) with \( P_{\text{maps}} \).** To investigate the relationship between “events” in \( D_{\text{maps}} \) and \( P_{\text{maps}} \), corresponding maps were aligned in space and time in Microsoft Powerpoint. A grid divided into 20-s intervals was then overlaid onto the maps, and each longitudinal muscle event, circular muscle event, or pressure event was identified, classified, and numbered. With use of the transparency function in Powerpoint, the \( D_{\text{map}} \) was slowly faded out to reveal the \( P_{\text{map}} \) beneath. All possible combinations of “muscle events” and “pressure events” are listed in Table 1, along with their occurrence during the study.

**Correlation between pressure and flow.** The outflow trace (recorded in Chart 5.05) was also aligned with the corresponding \( D_{\text{map}} \) and \( P_{\text{map}} \), and each 20-s grid was examined for episodes of outflow.

**Nomenclature.** The field of gastrointestinal motility uses a plethora of terms to describe motor events. Terms such as “waves,” “contractions,” “constrictions,” “dilations,” “peaks,” “sequences,” and “complexes” (among others) carry particular implications from prior usage in the literature. In this study, we identified changes in wall diameter or intraluminal pressure from aligned spatiotemporal maps of diameter and pressure (\( D_{\text{maps}} \) and \( P_{\text{maps}} \), respectively). To avoid loaded terminology, we have used what we hope is a neutral term that describes what was observed. “Event” is used to describe any discrete region on a spatiotemporal map that was visibly different from background. Muscle events were identified in \( D_{\text{maps}} \), and pressure events were localized in \( P_{\text{maps}} \). If events were elongated with a slope in relation to the time or space axes, the event was described as a “propagating event.” Anterogradely propagating events spread aborally; retrogradely propagating events advanced toward the oral end. Some “propagating muscle events” and their corresponding “propagating pressure events” caused outflow, measured as fluid ejected from the aboral outlet. These events were classified as “propulsive.” In some cases, a length of small intestine was distended by propagating contractions in proximal regions, giving rise to a synchronous small increase in pressure spread over several centimeters of the preparation. These are referred to as a “common-cavity” phenomenon. Alternatively, the distal regions of the preparation could simultaneously contract in response to proximal propagating contractions. When these nonpropagating events were temporally associated with proximal propagating contractions, they were referred to as “common-occluded” contractions.

**Statistical analysis.** All comparisons between the amplitude and extent of propagation were performed with a standard two-tailed unpaired \( t \)-test. Data are presented as means \( \pm \) SD.

**RESULTS**

Approximately 85 min of combined \( D_{\text{maps}} \) and \( P_{\text{maps}} \) were analyzed from four animals. In total, 813 longitudinal muscle events, 288 circular muscle events, and 1,049 pressure events were identified. The breakdown of the events and their temporal association with one another is shown in Table 1. From Table 1, it is clear that both recording techniques are highly reliable, in terms of correlating temporal relationships between pressure events and muscle events. Of the total 1,121 events detected (as pressure events or muscle events), the fiber-optic manometric catheter detected 1,049 (93.6%). Of all events, the video \( D_{\text{maps}} \) detected a slightly higher proportion (1,101 of 1,121 (98.2%)).

**Association between longitudinal muscle events and pressure events.** A total of 813 longitudinal muscle events were recorded when circular muscle events were absent; all were recorded in the absence of distension or pharmacological stimulation. Just over half (53.7%) propagated anterogradely, 20% propagated retrogradely, and the remainder were nonpropagating. Of the anterogradely propagating longitudinal muscle events, most (62.8%) evoked small, anterogradely propagating pressure events (Figs. 2 and 3). As would be expected, none gave rise to retrogradely propagating pressure events, but 35.0% caused pressure events where directionality could not be determined (i.e., nonpropagating pressure events). Just 1.4% were not detected by the manometric catheter. Retrogradely propagating longitudinal muscle events had similar effects on pressure; the majority caused detectable small retrogradely propagating pressure events. Nonpropagating longitudinal muscle events usually (in >85% of cases) caused nonpropagating pressure events.

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<th>Table 1. Temporal association between all propagating and nonpropagating muscle and pressure events</th>
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Number of times each particular event was detected is displayed at the end of each column for pressure event (pressure map) and at the end of each row for muscle events (diameter map). Number in each grid represents the number of times 2 corresponding events were deemed to be associated with one another.
spread for considerable distances along the gut sometimes faded out in the aboral half of the preparation. These were always associated with anterogradely propagating pressure events, which started orally and also propagated to the midpoint. However, at the midpoint (or wherever the propagating circular muscle event faded out), propulsion of content from the contracted segment led to dilation distally. Throughout the length of the dilated segment, intraluminal pressure increased simultaneously, including at the anal pressure transducer. This common-cavity phenomenon is shown in Fig. 4.

Two circular muscle propagating muscle events did not fit this description. Both started at the oral end, rapidly traversed the entire segment, and gave rise to lumen-occluding non-propagating events. These common-occluded contractions were associated with nonpropagating pressure events, similar to common-cavity events but of much larger amplitude (12.3 ± 2.3 vs. 4.2 ± 1.2 mmHg; Fig. 5).

Association between contractile activity and propulsion of fluid. None of the propagating longitudinal muscle events recorded in unstimulated preparations was associated with propulsion of content (measured as outflow), suggesting that longitudinal muscle contractions alone are nonpropulsive (n = 4). Flow episodes were recorded for a total of 45 min in three of the four experiments. During this time, 11 individual episodes of outflow of fluid, ranging from 8 to 195 s in duration, occurred. All flow episodes were associated with anterogradely propagating pressure events or nonpropagating pressure events and with corresponding circular muscle events (Figs. 2 and 4). Single anterogradely propagating circular muscle events correlated well with short periods of outflow (Fig. 4), while repetitive sequences of anterogradely propagating circular muscle events were associated with longer periods of outflow.

**Fig. 2.** Strong correlation between “antergrade circular muscle propagating events” identified in the diameter maps (Dmap; arrow) and “antergrade propagating pressure events” identified in the pressure maps (Pmap; arrow). A series of anterogradely propagating pressure events at ~8-s intervals were visible in the distal end of the preparation. Each propagating event detected on the Dmap was recorded by the manometric catheter. Each “propagated pressure and associated muscle event” caused fluid outflow from the aboral end (trace at bottom).

**Fig. 3.** Association of longitudinal muscle activity (pendular contractions) with intraluminal pressure. Top: “propagating longitudinal muscle activity” is clearly visible on the Dmap (caused by bulge of locally contracted muscle). It is initiated simultaneously at the proximal and distal ends of the preparation and propagates toward the middle. Bottom: motor patterns caused “pressure events” detected by the intraluminal catheter. “Anterogradely propagating longitudinal muscle events” in the proximal region gave rise to “nonpropagating pressure events,” while “retrogradely propagating longitudinal muscle contractions” starting at the aboral end correlated with low-amplitude “retrogradely propagating pressure events.”
For the first time, video imaging of the diameter of the intestinal wall (18) has been combined with simultaneous intraluminal fiber-optic high-resolution manometry (2). This work represents the first direct correlation between movements of the intestinal wall, intraluminal pressure, and intraluminal flow, comparing kinematic and kinetic motor events. Intraluminal manometry is commonly used by researchers and clinicians to investigate motor patterns within the digestive tract. In the esophagus and anorectum, the pressure profiles of motor activity are used to help diagnose abnormalities and guide treatment (6, 25). To understand how pressure patterns relate to flow, it is necessary to combine several techniques. For example, in the esophagus, manometry has been combined with video fluoroscopy (11, 17) and/or intraluminal impedance (28, 30, 31). These studies have enabled flow to be temporally associated with intraluminal pressures. Once objective measures have been established, one can infer normal or abnormal flow on the basis of a manometric study (24). However, the esophagus is short, is easily accessible, and has relatively predictable motility (i.e., a subject can be told when to swallow). The motor responses of interest are immediate and short-lived (<20 s), and high-resolution manometry has made it possible to construct detailed pressure profiles (25). Other regions, such as the small bowel or colon, are much longer, are relatively inaccessible, and show infrequent and very diverse spontaneous motor activity. In contrast to the esophagus, quantitative data on the small and large intestine are sparse, and interventional studies based on manometric investigation are scarce (4, 26, 27). While the advent of high-resolution fiber-optic manometry (2) makes it possible to create pressure profiles along >100-cm-long sections of gut, ethical constraints prohibit detailed correlation between pressure and flow using fluoroscopy. Therefore, interpreting how intraluminal pressures relate to gut wall movements and flow in the small and large intestines has been problematic. This was made possible, in the present study, by the use of isolated preparations in vitro.

**Longitudinal muscle contractions.** The first questions addressed in this study were whether longitudinal muscle contractions (in the absence of circular muscle contractions) were associated with detectable rises in intraluminal pressure and whether longitudinal muscle contractions themselves are propulsive. In the absence of intraluminal distension, the rabbit...
small intestine exhibits rhythmic pendular movements, solely attributed to longitudinal muscle rhythmic contractions (20). Counterintuitively, these rhythmic longitudinal contractions were reliably associated with local small passive increases in gut diameter due to the localized thickening of the gut wall. This study revealed that these small bulges (and, hence, the longitudinal muscle contractions that underlie them) may, in fact, propagate. They can propagate anterogradely or retrogradely, or in both directions simultaneously, at different points in the preparation. In the great majority of cases, such pendular movements were associated with small, but detectable, increases in intraluminal pressure. Clearly, some of the force generated by longitudinal muscle shortening must be transferred to the luminal content, as pressure detectable by intraluminal manometry. However, as the pressure changes evoked were small and the lumen was not occluded, it is not surprising that these movements were not propulsive, as the intraluminal pressure (0.5–1.5 mmHg) was less than the back-pressure from the outflow (2.9–4.4 mmHg). This is significant, inasmuch as it demonstrates that manometric catheters readily detect pressure change evoked by non-lumen-occlusive contractions. It is likely that longitudinal muscle contractions, without simultaneous circular muscle contractions, are predominantly involved in mixing content and facilitating its turnover at the mucosal surface (23).

Circular muscle contractions. The great majority of large propagating pressure events were associated with corresponding propagating circular muscle contractions. This is hardly unexpected, but it directly answers the following outstanding question: Are propagating waves of intraluminal pressure the result of propagating circular muscle contractions? These propagating events frequently resulted in outflow of fluid from the aboral cannula, indicating that they are, as long suspected, highly propulsive patterns of motor activity. Consistent with this, the intraluminal pressures associated with circular muscle events were significantly higher than those generated by the longitudinal muscle contractions alone.

It has been well established in vitro that neurally mediated, propagating circular muscle contractions elicited by distension (often called peristalsis) are very effective in emptying isolated segments of intestine (18, 29). The present study represents a first step in quantifying manometric pressure profiles in relation to changes in gut length, diameter, and intraluminal flow. We observed a strong correlation between propagating pressure sequences and propagating circular muscle contractions. Intraluminal manometry certainly detects increases in intraluminal pressure, even when the luminal diameter is greater than the catheter diameter, since pressure increases were readily detected in common cavities where the gut was dilated. The manometric catheter also registered much larger increases in pressure when local contraction of the circular muscle was lumen-occlusive and squeezed against the surface of the catheter. The high pressure peaks, caused by squeeze against the catheter, are unlikely to directly control the propulsion of luminal fluid, since fluid is displaced from the segment well before the muscular walls press on the catheter. Interestingly,

Fig. 5. Anterogradely propagating circular muscle events associated with outflow. A: $D_{\text{map}}$ of a series of propagating circular muscle events that extends the majority of the length of the preparation (white dashed arrows). Initial propagating muscle event is temporally associated initially with a common cavity. Propagating muscle events terminate with a common-occluded contraction through the distal region of the segment. B and C: $P_{\text{map}}$ and pressure trace of a series of rapidly propagating pressure events that terminate in synchronous pressure changes resulting from circular muscle contractions. Amplitude of these synchronous pressures changes is higher than during the common cavity that precedes them.
the duration of the pressure peaks, during lumen-occluding circular muscle contractions, was four to eight times shorter than the duration of the circular muscle contractions, indicating that a relaxation of the muscle is not necessarily associated with a distension of the lumen, unless there is a net inflow of content into that segment.

In fact, a more important pressure-controlling propulsion is the pressure that results from the displacement of fluid from contracted regions into a dilated, compliant, noncontractile receptive segment. Within the resulting common cavity, there is a pressure gradient, determined by the resistance to outflow (in our case, due to the nonreturn valve and outflow level) and the compliance and capacitance of the muscular walls. Indeed, in the present study, we observed in fully filled segments that any circular muscle contractions along the preparation caused outflow, even though intraluminal pressure was often smaller than the high pressures recorded directly under lumen-occluding contractions. This is important for the interpretation of in vivo manometric recordings of pressure. Our data suggest that high-amplitude propagating pressure events are likely to be due to the gut wall squeezing against the catheter. However, significant flow of contents can also be evoked by much smaller pressure profiles, which are considerably harder to identify. Our data show that propulsive low pressure excursions can be caused by circular muscle activity at distant sites.

The present study was carried out in specimens of rabbit small intestine with a resting luminal diameter of 6–10 mm. Whether in larger-diameter gut, as in human large bowel, there is such a close temporal and spatial association between circular muscle contractions and high-amplitude pressure events remains uncertain. There is in vivo evidence to suggest that manometry is less sensitive when the resting diameter of the gut exceeds 5.6 cm (32), and we have shown that the degree of association between flow and propagating pressure sequences was significantly reduced in ascending compared with transverse colon (14), perhaps indicating that manometry was unable to detect many propulsive events in the large-diameter section of the human colon.

In the present study, circular muscle contractions propagating for distances \(<3\) cm were often not detected as propagating pressure events in the \(P_{\text{maps}}\), because they were not detected by three consecutive pressure sensors. This highlights the importance of adequate sensor spacing for recording of intraluminal pressure. A recent study with the high-resolution fiber-optic catheters in the human colon has highlighted this (2). It demonstrated the potential to misidentify colonic propagating sequences. Many colonic manometric studies have probably attempted to measure motor phenomena that propagate over distances shorter than the spacing between the sensors. Our understanding of the events contributing to colonic motility may therefore contain significant inaccuracies (8).

Our experiments also provide insight into the underlying motor events associated with common-cavity phenomena. Hydrodynamic principles suggest that a rapid inflow of liquid into a noncontractile, enclosed receptive segment of gut will lead to a near-simultaneous increase in pressure along the entire cavity. This occurs when a segment of intestine is closed aborally by a lumen-occlusive contraction, receives fluid displaced by a

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**Fig. 6.** A and B: propagating pressure events recorded in a human colon and a rabbit small intestine (taken for comparison from Fig 4). In rabbit small intestine in Figs. 4 and 5, common cavities and/or common-occluded contractions are shown. Note similar signatures in human in vivo manometric recording. In A, 2 large “propagating pressure events” are recorded; both events terminate with a simultaneous increase in pressure waves in the rectum. The 1st propagating event does not result in stool expulsion; however, a signature that is likely to be a common cavity can be seen. This is likely to result from the rectum filling with fecal content. The 2nd propagating event ends with a larger simultaneous contraction, which is associated with stool expulsion. Thus, laboratory-based studies on isolated preparations may help interpret manometric signatures recorded in the human gut. [Human data are from Dinning et al. (16).]
propagating circular muscle contraction orally, and can only empty when the intraluminal pressure reaches the backpressure imposed by the nonreturn valve and the level of the outflow cannula. In some \( D_{\text{maps}} \) in the current study, we observed an elongated dilated section ahead of the advancing circular muscle contraction. The corresponding \( P_{\text{map}} \) revealed a synchronous (nonpropagating) increase in intraluminal pressure in this dilated region, signifying a common cavity. The conclusion is that the fluid displaced from the contracted region passively distended the downstream region and detectably raised its pressure in inverse proportion to wall compliance. Alternatively, propagating events in the proximal region of the segment could be associated with a common-occluding contraction in the distal region of the segment. On the \( P_{\text{maps}} \), these events appear to be similar to the common cavities, but they were of a much higher amplitude as a result of the circular muscle contractions squeezing the catheter.

We have recorded similar manometric signatures in the human colon in vivo. In these instances, propagating pressure events (referred to in those studies as propagating sequences) originating in the proximal colon terminate at the sigmoid colon, at which point the pressure waves become synchronous (Fig. 6). These events are often associated with an urge to defecate, as well as actual episodes of defecation (3). On the basis of our in vitro data presented here, we speculate that these human propagating pressure events initially move luminal contents (solid, liquid, or gas) into the rectosigmoid colon, dilating the region and giving rise to the common-cavity phenomenon, thus triggering receptors that give rise to the urge sensation. The subsequent propagating sequence applies a greater circular muscle contraction (radial squeeze), which overcomes the resistance produced by the rectum and anal sphincter, resulting in defecation (Fig. 6).

The combination of methods of recording simultaneously patterns of motor activity measured as kinetic changes (intraluminal pressure changes and flow of contents) in parallel with kinematic changes (diameter and length changes) represents a formidable tool to investigate the physiological and biomechanical changes (diameter and length changes) represents a formidable tool to investigate the physiological and biomechanical changes (diameter and length changes). Kinematic changes (diameter and length changes) represent a formidable tool to investigate the physiological and biomechanical changes (diameter and length changes) represent a formidable tool to investigate the physiological and biomechanical changes (diameter and length changes). Kinematic changes (diameter and length changes) represent a formidable tool to investigate the physiological and biomechanical changes (diameter and length changes). Kinematic changes (diameter and length changes) represent a formidable tool to investigate the physiological and biomechanical changes (diameter and length changes).


