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Low-resolution colonic manometry leads to a gross misinterpretation of the frequency and polarity of propagating sequences: Initial results from fiber-optic high-resolution manometry studies

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Abstract

Background *High-resolution manometry catheters are now being used to record colonic motility. The aim of this study was to determine the influence of pressure sensor spacing on our ability to identify colonic propagating sequences (PS).* ***Methods*** *Fiber-optic catheters containing 72–90 sensors spaced at 1 cm intervals were placed colonoscopically to the cecum in 11 patients with proven slow transit constipation, 11 patients with neurogenic fecal incontinence and nine healthy subjects. A 2 h section of trace from each subject was analyzed. Using the 1 cm spaced data as the gold standard, each data set was then subsampled, by dropping channels from the data set to simulate sensor spacing of 10, 7, 5, 3, and 2 cm. In blinded fashion, antegrade and retrograde PS were quantified at each test sensor spacing. The data were compared to the PSs identified in the corresponding gold standard data set.* ***Key Results*** *In all subject groups as sensor spacing increased; (i) the frequency of identified antegrade and retrograde PSs decreased ($P < 0.0001$); (ii) the ratio of antegrade to retrograde PSs increased ($P < 0.0001$); and (iii) the number of incorrectly labeled PSs increased ($P < 0.003$).* ***Conclusions & Inferences*** *Doubling the sensor spacing from 1 to 2 cm nearly halves the number of PSs detected. Tripling the sensor spacing from 1 to 3 cm resulted in a 30% chance of incorrectly labeling PSs. Closely spaced pressure recording sites (<2 cm) are mandatory to avoid gross misrepresentation of the frequency, morphology, and directionality of colonic propagating sequences.*

Keywords *Colon, Fiber-optic manomerty, High-resolution, Propagating pressure waves.*

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INTRODUCTION

The problems associated with sampling of periodic data have been known and understood since the early days of telegraph transmission and are largely described by the work of Nyquist and Shannon.[1,2] In brief, they defined the minimum sampling frequency needed to accurately describe a periodically varying signal as twice that of the signal itself. If a periodic signal is sampled at a lower frequency than this, then it is not possible to unambiguously determine the shape and frequency of the original signal.

Although this appears to be a far cry from the world of gastrointestinal research, it is becoming clear that,

until recently, we may have been confronted with this effect when analyzing data from colonic manometry studies. These studies generate hours of pressure wave recordings that are then scrutinized for the existence of propagating sequences (PSs; or propagating contractions). However, as the contractile activity of the colon cannot be seen readily, the identification of PSs is based upon the proximity of pressure waves to one another in both space and time. Commonly used criteria include pressure waves recorded over three or more adjacent channels that fit within a time window of 0.2–12 cm s^{-1}.[3] As most colonic manometry studies have recorded motility patterns with sensors spaced ≥10 cm apart,[4] detection of a PS requires that it span at least 20 cm of the colon. Utilizing a high-resolution manometry catheter[5] to record colonic pressures, we have recently shown that the majority of propagating events propagate <10 cm along the colon. Thus, widely spaced sensors can lead to an effect analogous to aliasing[1,2] in signal processing. In this sense, this process refers to the confusion that can result when a signal is sampled at sensor spacing greater than one-third that of the propulsive activity itself.

The aim of this study was to determine the influence of sensor spacing upon our ability to accurately identify colonic motility patterns. Specifically, we hypothesized that we can define a critical sensor spacing, at or below which we can be confident that we are: (i) detecting all meaningful propagating pressure waves, and (ii) we are correctly attributing their polarity (direction of propagation).

METHODS

Subjects

Data analyzed in this study were collated from our high-resolution fiber-optic manometry studies, conducted over the past 3 years from a large number of patients and healthy controls. Our study populations fall into four broad groups. (i) Constipated patients undergoing a sacral nerve stimulation trial[6] (8 h recording); (ii) assessment of colonic motility in patients with constipation (5 h recording); (iii) Patients with fecal incontinence who are undergoing sacral nerve stimulation[7] (8 h recording); and (iv) assessment of colonic motility in healthy controls (5 h recording).

All participants had given written, informed consent and the studies were approved by the Human Ethics Committees of the South Eastern Area Health Service, Sydney and the University of New South Wales (05/122, HREC/09/STG/107) and the South Adelaide Clinical Human Research Ethics Committee at Flinders Medical Centre (419.10). Pregnancy was excluded in all subjects prior to enrollment by urinary HCG testing. Studies were not performed in any particular phase of the menstrual period.

Controls All healthy subjects had a normal bowel habit, defined as between three bowel movements a day and one bowel movement every 3 days, with no symptoms of rectal evacuatory difficulty or any other gastrointestinal symptoms. None had a history of metabolic, neurogenic, or endocrine disorder(s) known to cause constipation. They were not taking regular medications including laxatives, and none had a history of prior abdominal surgery, other than appendicectomy.

Slow transit constipation The inclusion and exclusion criteria for selection of the constipated patients have been detailed in our previous publications.[6,8] Briefly, all patients were aged between 18 and 75 years, and had scintigraphically confirmed slow transit constipation.[9] All patients had undergone anorectal function studies and had no evidence of paradoxical sphincter contraction nor an inability to expel a rectal balloon.[10]

Fecal incontinence These were patients who were scheduled to undergo a trial of either temporary sacral nerve stimulation or a permanent stimulator implant, for the treatment of fecal incontinence.[7] Patients were aged between 18 and 80 years, and had failed conservative treatments, including dietary modifications, biofeedback, or medication. None had rectal prolapse. The severity of incontinence was measured using the St Mark's incontinence score.[11]

Fiber-optic manometry

Pressures along the length of the colon were measured using a high-resolution fiber-optic pressure sensing catheter as previously described.[6,7] A number of different fiber-optic catheters were used during the trial containing 72–90 sensors each spaced at 1 cm intervals. The signals were processed through a spectral interrogator unit (FOS&S FBG-scan 804. FOS&S, Geel, Belgium) and pressures were recorded in real time on a custom written LabVIEW program (National Instruments, Austin, TX, USA). Analysis of the fiber-optic data was performed manually on software (PlotHRM) developed by one of the authors (LW).

Catheter placement and data acquisition Cather placement has been described in detail previously[6,7] and the same procedure was performed in all patients and healthy controls. After a complete bowel preparation, the manometry catheter was taken into the colon with the aid of a colonoscope. A nylon loop on the catheter tip was secured to a fold in the ascending colon using two hemoclips (Olympus America, Melville, NY, USA).[12,13] The colonoscope was then removed, extracting as much air as possible.

After recovery from sedation (1–2 h), all subjects were transferred to a room where we commenced colonic manometry. Depending upon the study, the manometry continued for varying lengths of time from 6 h to 2.5 days. At the completion of the recording period, the catheter was removed by gentle traction, as previously described.[13,14]

A 2 h period was selected from each of the manometric recording periods. In each instance, a period was selected in which we would expect to see colonic activity. In patients undergoing sacral nerve stimulation, we examined the two hour stimulation period,[6,7] while in the remaining patients and all healthy controls we examined the colonic response to a high-calorie meal. For each data recording period, the catheter position was determined via an abdominal x-ray which was taken at the end of the recording period.

Data analysis

Overview Each data set, from each subject, was analyzed in six different ways by sub-sampling different sets of the full array to simulate inter-recording site distances of 10, 7, 5, 3, 2, and 1 cm. The identity of each data set was removed and given to the author PD for analysis. Each manometric trace was examined for the presence of antegrade and retrograde PSs. The location of each propagating event, identified at each test sensor spacing (2–10 cm) was then compared against the 1 cm spaced data (gold standard).

Analysis technique Each data set had the subject identification removed and the data was opened in PlotHRM. Within PlotHRM, the sensor spacing could be then selected. For example for 10 cm spacing, the manometric trace was analyzed assessing data collated from sensors 1, 11, 21, etc. Five test sensor spacings were analyzed; 10, 7, 5, 3, and 2 cm. The complete data sets (1 cm spacing) were used as the Gold Standard. At present, the 1 cm spacing is the closest that we can achieve with our current construction techniques, therefore we have made the assumption that the 1 cm spaced data will provide the best currently available resolution for viewing colonic manometry data. All 10 cm spaced data were analyzed first then 7, 5, 3, and 2 cm, before analyzing the data set at 1 cm spacing.

Each test-data set, and gold standard was then manually examined for the presence of PSs. A PS was defined as an array of three or more pressure waves recorded in adjacent recording sites. Each pressure wave within a PS was defined as a 'propagating pressure wave'. For senor spacing 7–10 cm, the PSs had to fall within a propagation velocity of 0.2–12 cm s^{-1}.[15] For the 1–5 cm spacing, the pressure waves were deemed to be linked as a propagating event if there was no period of quiescence between a pressure wave in one channel ending and the upstroke of the pressure wave in the adjacent channel beginning. If a pressure wave returned to baseline before a pressure wave in a proximal or distal adjacent channel began to form, then the pressures waves were not considered part of the same event.[7] If the PS traveled toward the rectum, it was labeled as an antegrade PS, conversely if the PS traveled toward the cecum it was labeled a retrograde PS.

For each identified PS, the following characteristics were recorded for each of the sensor spacing (Fig. 1); (i) site of origin; (ii) extent of propagation; (iii) velocity of propagation; (iv) direction of propagation. For each propagating pressure wave within each of the identified PSs, the maximal amplitude was marked with a time sample (Fig. 1). These data were recorded at 10 Hz (i.e., 10 samples per second) therefore each point of the trace has a time sample. Each time sample was also coded with a letter; for antegrade PSs the time sample was coded with an 'a' and for retrograde PSs each time sample was coded with an 'r'. These time samples and letter codes were later used to determine whether PSs identified at the test sensor spacing were also identified in the gold standard (see below).

Then, for the middle pressure wave of every identified PS, the following characteristics were detailed (Fig. 1).

i) maximal amplitude (trough to peak);
ii) Maximum gradient of the leading edge of the pressure wave;
iii) Maximum gradient of the falling edge of the pressure wave;
iv) Duration to half amplitude on the leading edge;
v) Duration to half amplitude on the falling edge.

These details were used to determine which characteristics, if any, were associated with PSs identified at all sensor spacings. All of these characteristics were calculated automatically in PlotHRM when a PS was manually selected.

Comparing PSs identified with each sensor spacing with the Gold Standard Utilizing additional software written in Matlab (The MathWorks, Natick, MA, USA), the PSs detected at each test sensor spacing were compared to the PSs detected in the corresponding gold standard (1 cm) trace. The software took the time sample and letter code for each pressure wave within a PS at each test sensor spacing and then scanned the corresponding gold standard data for a matching time sample and letter code. Each

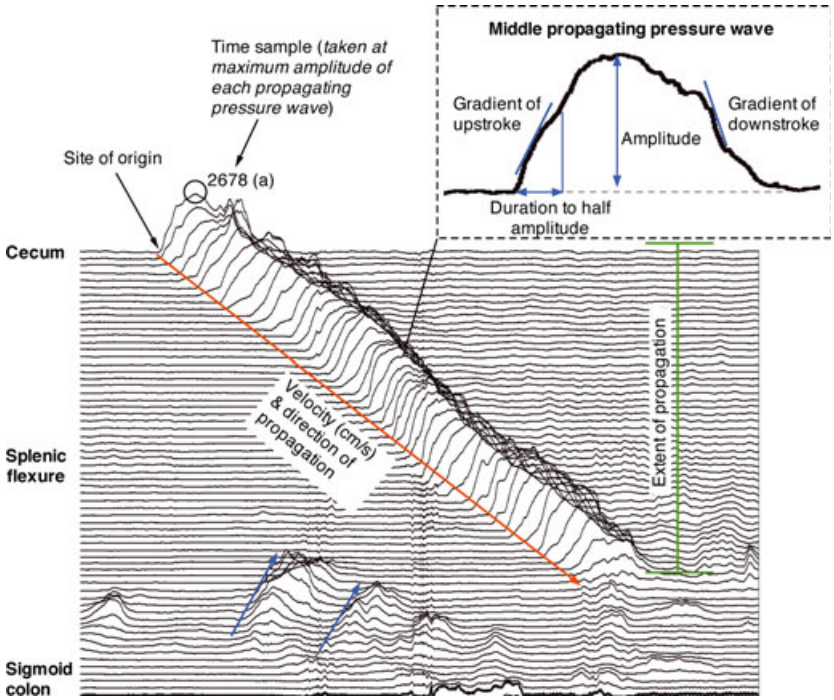

Figure 1 The characteristics collated for each propagating event. For each antegrade (red arrow) and retrograde (blue arrows) propagating sequence (PS), the site of origin, extent of propagation and velocity of propagation were recorded. The maximal amplitude of each component pressure wave was marked with a time sample and a letter 'a' for antegrade or 'r' for retrograde. From the middle propagating pressure wave of every PS, the amplitude, gradient of the upstroke and downstroke, and time taken to half amplitude were also recorded.

propagating pressure wave at each of the test spacings could then fall into one of the six categories; (i) AA – pressure wave that formed part of an antegrade PS in the test sensor spacing and the gold standard; (ii) RR – pressure wave that formed part of an retrograde PS in the test sensor spacing and the gold standard; (iii) AR – a pressure wave that formed part of an antegrade PS in the test sensor spacing and part of a retrograde PS in the gold standard; (iv) RA – a pressure wave that formed part of an retrograde PS in the test sensor spacing and part of an antegrade PS in the gold standard; (v) AN – a pressure wave that formed part of an antegrade PS in the test sensor spacing and did not form part of a PS in the gold standard; and (vi) RN – a pressure wave that formed part of an retrograde PS in the test sensor spacing and did not form part of a PS in the gold standard.

Propagating sequences were labeled as 'real' in each test sensor spacing if >75% of the component pressure waves were labeled with AA or RR. Propagating sequences were labeled as false if >25% of the propagating pressure waves were labeled with any of the following; AR, RA, AN, or RN.

Statistical analysis

The frequency of antegrade and retrograde PSs has been expressed per hour. The site of origin in which the PSs originated have been grouped into three broad regions; R1 = Ascending and transverse colon, R2 = descending colon; and R3 = sigmoid colon and rectum. Inferences regarding potential differences in the frequency of antegrade to retrograde PSs within healthy controls and within each separate patient group was made with the non-parametric Wilcoxon signed rank test. Comparison of the frequency of antegrade or retrograde PSs detected at each sensor spacing, within each subject group, was performed with the non-parametric Friedman Test with Dunn's multiple comparison test for comparison of PSs detected between sensor spacing.

Multivariate analysis Data were analyzed using a range of multivariate exploratory and analysis procedures in IBM SPSS 19. Unless otherwise stated, all data analyzed in this fashion came from the control group. Continuous variables included the following waveform characteristics: half maximum width of leading and trailing edges; maximum gradient of leading and trailing edges; maximum amplitude of the pressure waves; the velocity of the PS; and the extent of propagation of the PS. Categorical variables included sensor spacing (2, 3, 5, 7, or 10 cm interval), region of the gut (ascending-transverse colon, descending colon, or sigmoid colon-rectum), and observer classification of the propagating event as 'real' or 'false' based on inspection of the full data set at 1 cm spacing resolution (see above).

Initial data exploration was done with multivariate analysis of variance (MANOVA), principal components factor analysis and two-step cluster analysis. Classification and group membership prediction was done with discriminant analysis (for continuous variables) or logistic regression (for continuous and categorical variables). In both approaches, step-wise forward entry of variables was used to develop the predictive models.[16] The analyses were repeated with or without inclusion of the subjects as a categorical variable in order to check for and control variance between individuals. Post hoc comparisons of means following a significant overall MANOVA used Ryan-Einot-Gabriel-Welsch F-tests (REGWF) to identify homogenous groups and Bonferroni tests for pair-wise comparisons of means. Significance levels were set at $P < 0.05$ with corresponding 95% confidence limits on variable means and model parameters.

RESULTS

Data were analyzed from 11 patients with slow transit constipation (zero male; 51.5 ± 16.4 years), 11 patients with fecal incontinence (two male; 66 ± 13.9 years), and nine healthy controls (four male; 47.6 ± 15.3 years). The frequency and extent of propagation of the antegrade and retrograde PSs detected in the Gold Standard have been displayed in Table 1. In all three groups, retrograde PSs were detected at a significantly higher frequency than antegrade PSs ($P \leq 0.02$).

Impact of sensor spacing upon the detected frequency of PSs

Overall, there was a significant difference in the frequency of detected antegrade and retrograde PSs amongst the different sensor spacings ($P < 0.0001$; Fig. 2). In all groups, the frequency of antegrade and retrograde PSs detected at 1 cm spacing was significantly greater than their frequencies detected at 5, 7, and 10 cm spacing ($P < 0.05$). The frequency of detected events at 1 cm spacing did not differ significantly from the propagating events detected at 2 and 3 cm spacing. However, the accuracy of detecting 'real' propagating events dropped dramatically with sensors spaced at 3 cm and beyond (see below).

Of particular note was the dramatic decrease in the frequency of detected retrograde PSs as the sensor spacing increased (Fig. 2). At 1 cm spacing retrograde PSs were detected at a frequency of 36.5 ± 20.9,

Table 1 The frequency and extent of propagation of antegrade and retrograde PS

	PSs (h^{-1})		Extent of propagation (cm)	
Subject group	Antegrade	Retrograde	Antegrade	Retrograde
Healthy controls	18.9 ± 10.7	36.5 ± 20.9*	9.3 ± 2.9	8.4 ± 1.5
Constipation	13.8 ± 7.3	42.7 ± 37.8*	9.4 ± 2.1	7.8 ± 0.8
Fecal incontinence	18.5 ± 13.3	60.5 ± 40.9**	10.7 ± 5.3	9.3 ± 2.9

PS, propagating sequences.
*$P = 0.01$.
**$P = 0.02$.

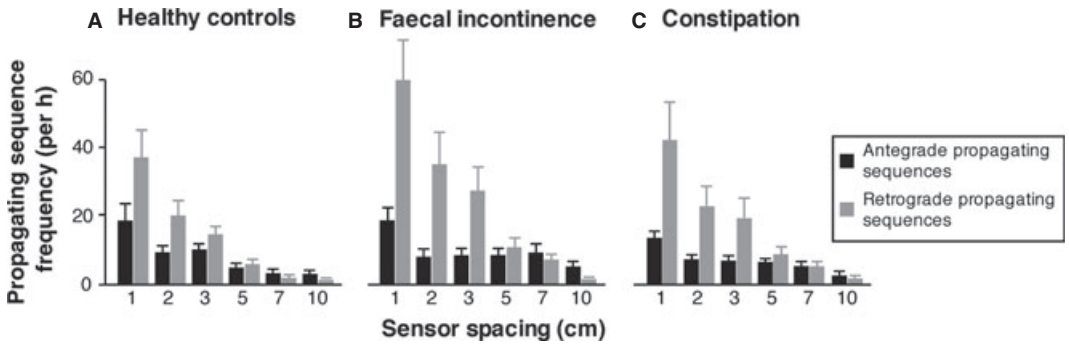

Figure 2 The frequency of antegrade (black) and retrograde (gray) propagating sequences identified at each sensor spacing for each of the three groups. In all the three groups, there was a significant difference ($P < 0.0001$) in the frequency of antegrade and retrograde events detected amongst the different sensor spacing. As the sensor spacing increased, the number of propagating events detected decreased.

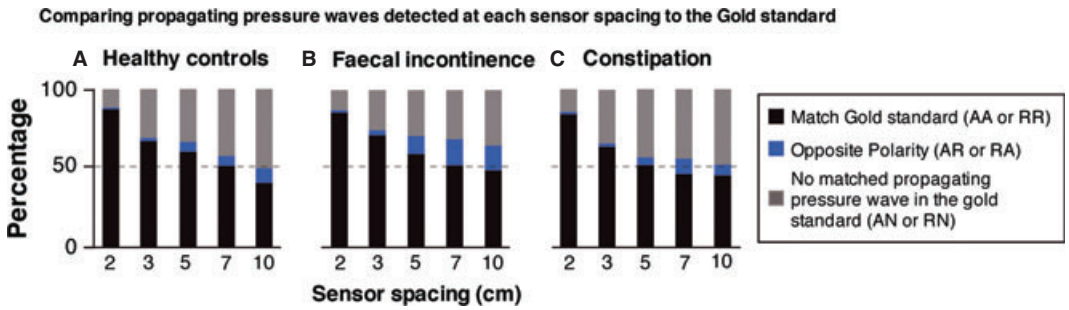

Figure 3 A comparison of the component pressure waves of each propagating sequence, identified at each sensor spacing, to those identified in the corresponding gold standard (1 cm) data. As the sensor spacing increases, the number of falsely labeled propagating pressure wave (blue and gray bars) significantly ($P < 0.0001$) increases. A, antegrade; R, retrograde; N, no propagating pressure wave detected at 1 cm spacing.

60.5 ± 40.9 and 42.8 ± 37.1 PSs h^{-1}, in healthy controls, fecal incontinence and constipation, respectively. At 10 cm spacing <5% of this activity was seem (controls; 0.7 ± 0.5, Fecal incontinence; 1.7 ± 2.2 and constipation 2.0 ± 1.9 PSs h^{-1}. As a result, in each of the groups the ratio of antegrade to retrograde PSs increased significantly as the sensor spacing increased ($P < 0.0001$).

Incorrectly labeled propagating pressure waves

In the next stage of the analysis, we compared all propagating pressure waves that formed the PSs in the section above, against the corresponding gold standard 1 cm spaced data. These data indicated that as the senor spacing increased so did the chances of including a pressure wave that did not form part of a PS in the 1 cm data. In all three groups, as the sensor spacing increased, the chances of a propagating pressure wave being labeled as false increased significantly ($P < 0.003$; Fig. 3).

At 2 cm spacing, the accuracy of detecting 'real' propagating pressure waves was ≥84% in all subject groups (Constipation 84%; Fecal Incontinence 87%; Health 88%). This fell (across all groups) to <72% at 3 cm spacing, <60% at 5 cm, and <52% at 7 cm. By 10 cm spacing, only 41% (healthy controls), 45% (constipation) and 49% (fecal incontinence) of all propagating pressure waves detected were identified as part of a PS at 1 cm spacing. (Figs 3–6).

Characteristics that define real events (multivariate analysis)

Based upon the characteristics of the component pressure waves in a PSs (amplitude, time course, slopes) we sought to determine if multivariate analysis could identify if any features that would separate real from false PSs. With wide spaced data (7, 10 cm spacing), logistic regression could correctly classify 80% of the PSs labeled as real PS and 70% of the PSs labeled as false events. This suggests that real & false PSs detected at wide sensor spacing do indeed have different characteristics. The major variables contributing to this were gut region and a combination of amplitude and the gradient of the falling edge of the pressure wave. As gut region was a significant indicator contributing to the classification of events derived

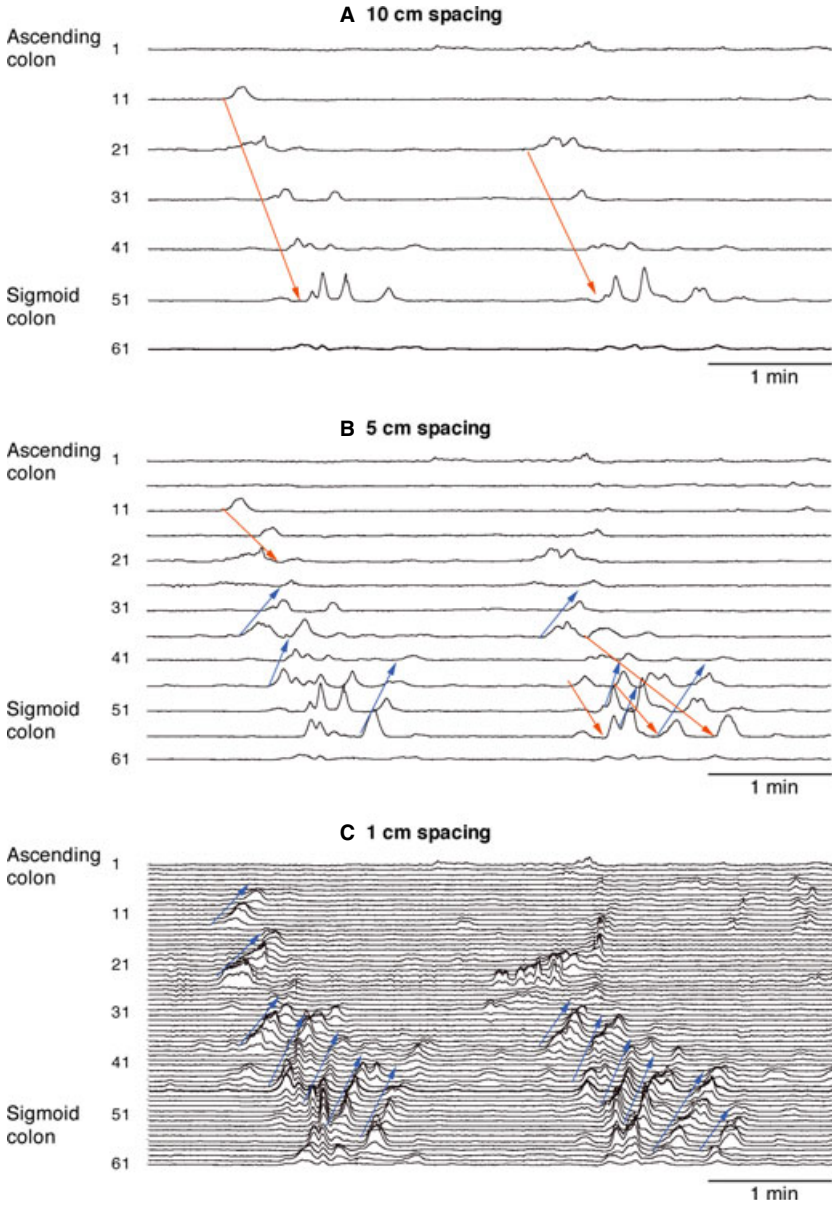

Figure 4 A section of a colonic manometry recorded in a patient with fecal incontinence. The data have been displayed with 10 cm (top), 5 cm (middle), and 1 cm spacing. At 10 cm spacing, two antegrade propagating sequences (PSs) can be seen (red arrows). Neither of these is visible at 5 or 1 cm spacing. At 5 cm spacing, there are several antegrade (red arrows) and retrograde (blue arrows) PSs and determining the direction of propagating is difficult. At 1 cm spacing, the direction of propagation is clear. Note the dramatic difference in interpretation of the data between 1 and 10 cm spacing.

from wide spacing data, logistic regressions were run again for PSs originating in the proximal colon (ascending and transverse). For this region, quantitative data from wide sensor spacing correctly predicted better than 90% of real and false PS, with amplitude and velocity being the most important predictor variables [real *vs* false amplitude: 138 *vs* 29 (± 12 SEM) mmHg; real *vs* false velocity: 5 *vs* 20 (± 3 SEM) mm s^{-1}]. A comparable classification outcome was achieved with discriminant analysis. These data therefore indicate that the real PSs detected at wide sensor spacing have large amplitude and travel slowly along the colon (i.e., wide-spaced sensors can accurately identify high-amplitude PSs). In contrast, the falsely labeled PSs have a much smaller amplitude and travel at a faster speed.

When logistic regression was applied to the data from the close spacing data (2 and 3 cm), it could correctly classify 90% of real, but only 35% of false PSs. This suggests that there were no distinguishing features associated with false PSs. For PSs originating in the proximal colon with close sensor spacing, the best logistic regression models correctly predicted more than 90% of real ones, but only about 50% of the false. Here, extent of propagation and maximum amplitude contributed most to the classification [real *vs* false extent: 14 *vs* 8 (± 2 SEM) cm; real *vs* false amplitude: 63 *vs* 28 (± 8 SEM) mmHg]. Discriminant

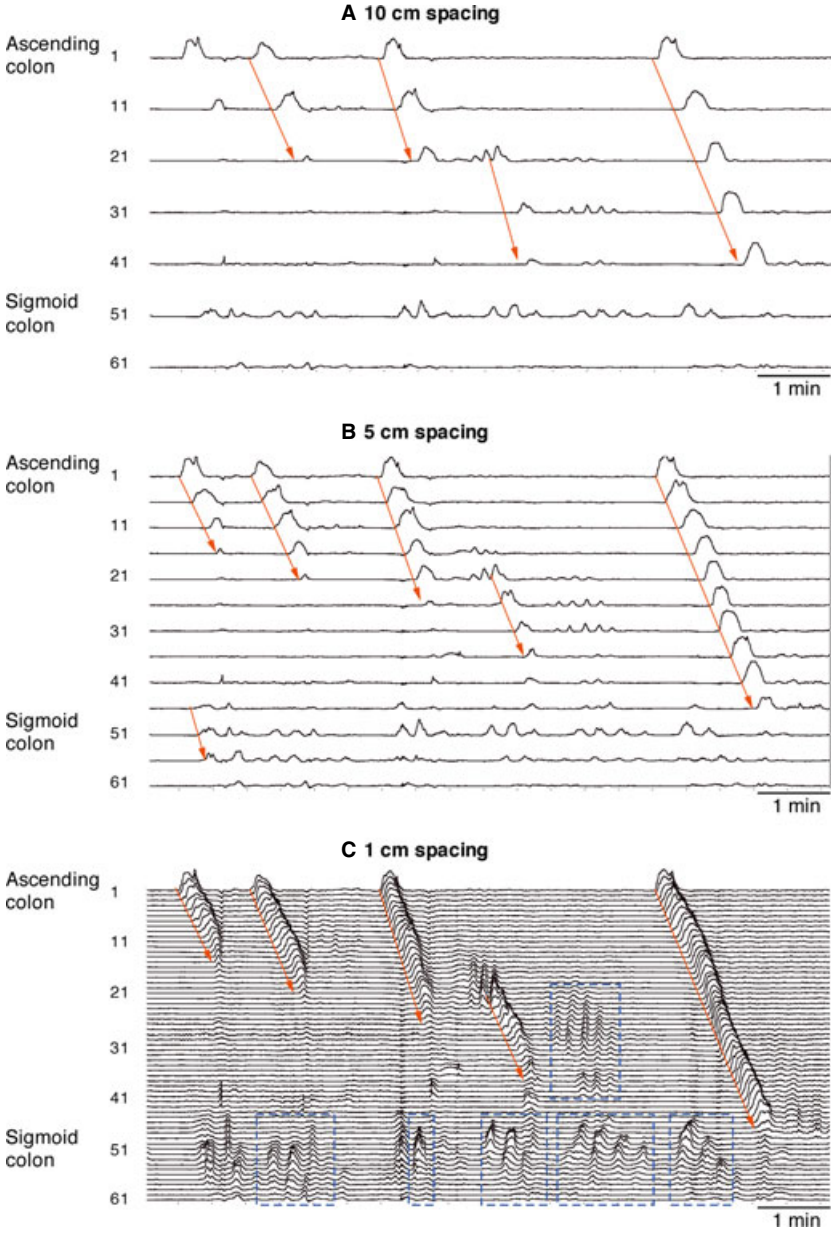

Figure 5 A section of a colonic manometry recorded in a healthy control. The data have been displayed with 10 cm (top), 5 cm (middle), and 1 cm spacing. At 10 cm spacing, four antegrade propagating sequences (PSs) can be seen, all of which are also observed in the gold standard 1 cm spaced data. At 5 cm spacing and additional two antegrade PSs are seen (left hand side of the middle trace). One of these propagating events (between sensor 41–61) is not visible in the 1 cm data. At 1 cm spacing, a cluster of retrograde PSs become apparent (blue hatched squares). None of the retrograde PSs are visible at 5 or 10 cm spacing.

analysis was not able to correctly classify the close sensor spacing data. Therefore with close sensor spacing (2–3 cm), the real PSs tend to have a greater amplitude and travel longer distances along the colon. However, they are no defining characteristics that define false PSs.

DISCUSSION

In this study, our data unequivocally indicate that as the spacing between recording sensors increases the accuracy with which we can identify both the presence and directionality of individual PSs decreases. At 10 cm spacing, <5% of the propagating activity observed at 1 cm spacing can still be seen. Arguably of more importance, is the ability to falsely label propagating events with widely spaced sensors. Approximately 30% of all propagating pressure waves identified as part of PSs with sensor spacing greater than 3 cm are labeled as false and this increased to >50% with the 7–10 cm spacing. The exception to this is the 2 cm spaced data. While some PSs may have been missed in analyzing the 2 cm spaced data, those PSs that were detected were nearly all (>84%) observed in the corresponding 1 cm data.

The benefits of high-resolution manometry have already been realized in the upper gut clinical and

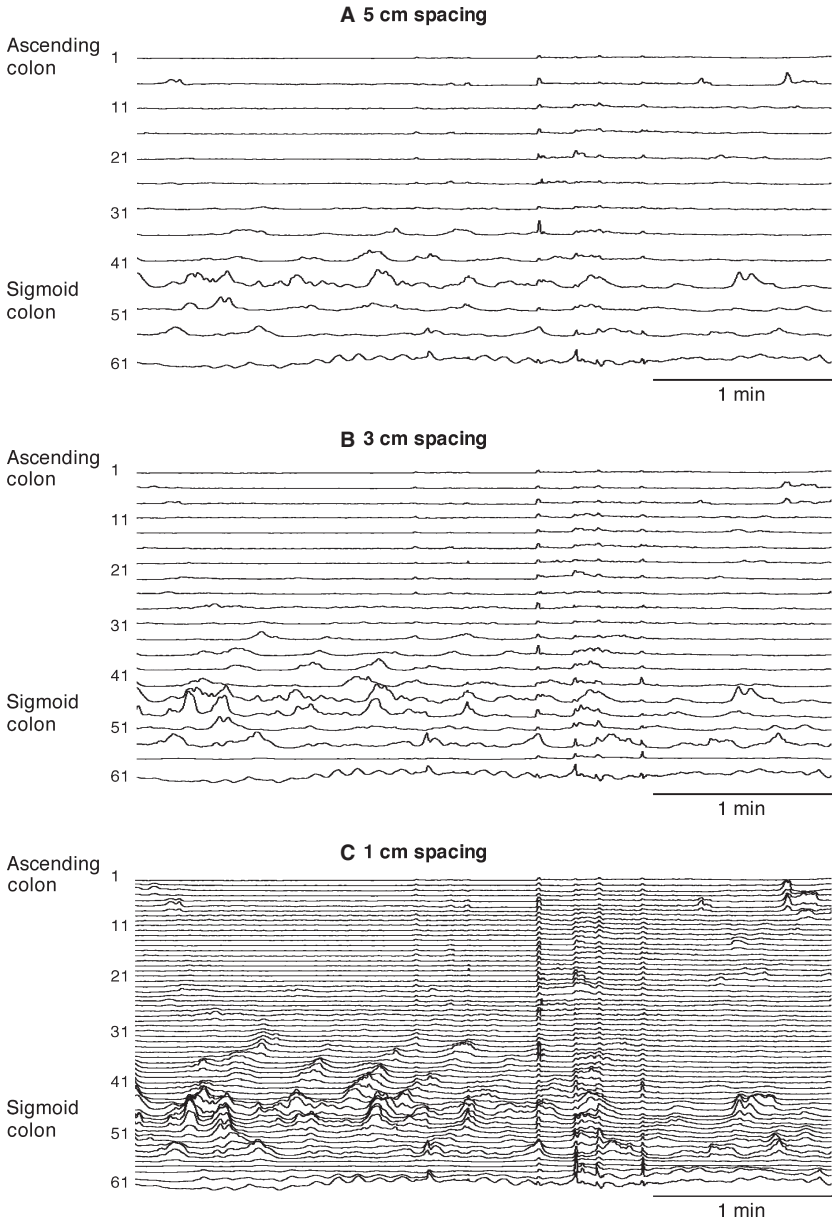

Figure 6 A section of a colonic manometry trace recorded in a healthy control. The data have been displayed with 5 cm (top), 3 cm (middle), and 1 cm spacing. Note that while pressure waves are clearly identifiable in all three traces, it is only at 1 cm spacing that the direction of propagation can clearly be identified.

research motility studies. Since the late 1990's, high-resolution manometry and subsequent spatio-temporal plots of pressure profiles, have been used to detail esophageal motility disorders. Such profiles draw out motility patterns making normal and abnormal motility patterns more easily identifiable.[17] Now, with the development of high-resolution colonic manometry catheters, we can create the same pressure profiles throughout entire regions of the colon. These pressure profiles are revealing motor patterns that, because of low sensor spacing, have been mostly invisible in previous studies. For example in all the three groups studied here, retrograde PSs were the dominant propagating motor pattern. As the average extent of propagation of these motor patterns was ~8 cm, previous studies using low resolution simply could not detect them.[15,18–21] The presence of these motor patterns is potentially important in helping to understand colonic physiology. For example with low-resolution colonic recording both here and in previous publications[22,] the antegrade to retrograde PS ratio per hour was 4 : 1. As transit through the colon is slower than in any other region of the gut such a ratio requires some explanation as to why transit is so slow. However, with high-resolution manometry retrograde PSs become the dominant motor pattern. The presence of this motor pattern, particularly in the distal colon may help to retard flow, thus allowing the colon to perform

its physiological functions. This is supported in a recent study in which we have shown that an increase in the frequency of short extent retrograde PS, detected with the high-resolution catheter in sigmoid and descending colon, during sacral nerve stimulation seemed to coincide with improved bowel function in patients with fecal incontinence.[7]

Traditional colonic manometry studies, utilizing low-resolution recordings, focuses largely upon the frequency of high-amplitude PSs.[8,15,23–25] These events are probably the most obvious of all colonic motor patterns and are of physiological importance. The multivariate analysis used in this study indicated that the specific characteristics associated with 'real' events in the wide sensor spaced data (7–10 cm) were PSs that originated in the proximal colon, contain high-amplitude pressure waves and travel at a slower speed. These are all characteristics of the high-amplitude propagating contraction.[8,15,23–25] Therefore, if the identification of high-amplitude propagating events is the main focus of the colonic manometry investigation, then low-resolution manometry catheters are adequate.

The problem arises when low-resolution manometry is unable to differentiate controls from patients with known motility disorders. For example, recently Singh *et al.*[26] published data on the manometric findings from 80 patients with confirmed slow transit constipation. Utilizing criteria based on data recorded from a catheter with six sensors spaced between 10 and 20 cm, they concluded that 41% of patients with slow transit constipation had normal colonic motility. In such instances, the differences between normal and abnormal motility may well exist in the detail of the events that are missed because the sensor are too far apart.

Whether 1 cm spacing is ideal for colonic motility still remains to be determined. We have not yet established diagnostic criteria and the benefits of identifying short extent propagating events require further detailed studies. However, we can say that for colonic manometry the preferred sensor spacing should be derived from the criteria used to identify the PSs in the first instance. For most groups, propagating events consists of three or more pressure waves present in consecutive sensors, with given upper and lower bounds on propagation velocity.[27,28] This effectively means that the sensor spacing needs to be, at most, 1/3rd the length of the expected propagation event being analyzed. Given the common existence of events as short as 6 cm seen during our colonic motility analyses, and the reasonable assumption that the very presence of these events must indicate some physiological purpose, a sensor spacing of 1–2 cm must be used in order to provide an accurate picture of activity within the colon; with 1 cm spacing being able to identify a greater frequency of propagating events.

Beyond 2 cm spacing, the chances of missing propagating events increase rapidly. This may be why, in contrast to this study, a retrograde PS frequency of near zero was reported in high-resolution pediatric colonic manometry study.[29] That study used sensor spacing of 2.5 cm, which may simply have been too large to clearly detect the short extent retrograde PSs the general noise of phasic pressure waves (see Fig. 6).

It needs to be recognized that in this study we only assessed periods in which we would expect to see colonic contractility (meal responses, response to sacral nerve stimulation). As such you could expect that by chance more isolated phasic pressure events would fit the criteria for a PS at all of the test sensor spacings, hence causing the potential for increased errors. During the periods of lower activity, the accuracy with which wider sensor spacing could accurately record propagating events may be improved. However, it is colonic response to a stimulus that is used as a measure of normal or abnormal motility[8,24,26,29,30] and therefore it is during these periods that we must be able to identify propagating motor patterns. Nevertheless given the fact that all previous colonic manometry studies may have missed much of the propagating activity, further studies will be required to re-establish normal ranges of propagating activity during both stimulated (meals, morning waking, chemical or mechanical stimuli) and unstimulated periods (fasted or nocturnal sleep). Furthermore, it also needs to be recognized that similar sensor spacing (10–15 cm) has been used to record small bowel contractions, and therefore the findings presented here for the colon will very likely be applicable to the small bowel. As the fiber-optic manometry catheters are able to incorporate up to 144 sensors spaced at 1 cm intervals, high-resolution measurement of intestinal contractions are now possible from large contiguous sections of the human gut, thus opening the door to redefine normal and abnormal intestinal motility.

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CONFLICTS OF INTEREST

No competing interest declared.

AUTHOR CONTRIBUTION

PD studied design, recording of colonic manometry studies at Flinders Medical Centre. Analyzed all data and wrote the paper; LW developed all of the software used to analyze the colonic manometry traces; IG performed all of the statistical analysis; VP recorded the colonic manometry studies at St.George Hospital in NSW; PB & DL colonoscopic placement of catheters at Flinders Medical Centre and St.George Hospital, respectively; IC critical manuscript review; JA fiber-optic catheter development, study design, critical manuscript review.

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