Ambulatory 24-h colonic manometry in healthy humans

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Rao, Satish S. C., Pooyan Sadeghi, Jennifer Beaty, Renae Kavlock, and Kris Ackerson. Ambulatory 24-h colonic manometry in healthy humans. Am J Physiol Gastrointest Liver Physiol 280: G629–G639, 2001.—Our aim was to investigate motor activity of the healthy, relatively unprepared colon in the ambulatory state. Twenty-five age- and gender-matched adults had a six-sensor solid-state probe inserted into the proximal transverse colon without sedation. Subjects ambulated freely and ate standard meals. In 528 h of recording, we found a lower (P < 0.05) area under the curve during the night. Waking induced a threefold increase in motility, whereas meals induced a twofold increase. Women showed less activity (P < 0.05) in the transverse/descending colon than men. The transverse/descending colon showed more (P < 0.05) activity than the rectosigmoid colon. Seven patterns were recognized; predominantly, they were simultaneous, propagated, or periodic bursts of 3-cycles/min (cpm) waves. A specialized propagating pressure wave with a high amplitude (>105 mmHg) and a prolonged duration (>14 s) occurred in all subjects (mean 10/day), mostly after waking, after meals, or with defecation. A 3-cpm motor activity was seen in the rectosigmoid region predominantly at night. The colon exhibits a wide spectrum of pressure activity around the clock, with gender and regional differences and circadian rhythm. This comprehensive study provides qualitative and quantitative normative data for colonic manometry.

Studies of colonic motility have reported inconsistent results in humans (3, 30) and in animal models (54). Among these, several patterns have been described that include short- and long-duration contractions (54), patterns of types I–IV based on duration and amplitude of contractions (58), rectal motor complexes (33, 41) or periodic rectal motor activity (42, 47), giant migrating contractions (54, 55, 58), propagating sequences (24), and high-amplitude propagating contractions (4, 39). These descriptions are confounded by electromyographic recordings (21, 54) that have shown long spike bursts, short spike bursts (7), and migrating spike bursts (23). How these electromyographic findings correlate with colonic pressure activity remains unclear (22, 54).

These discrepancies may be caused by methodological shortcomings such as the use of nonambulatory subjects (4, 7, 21, 24, 33, 39, 41, 42, 59), recordings from short segments (rectosigmoid region) (9, 11, 13, 33, 41, 42, 45, 59) or for short periods (9, 11, 45), or the use of different recording systems (4, 7, 9, 11, 13, 21, 23, 24, 33, 39, 41, 42, 45, 47, 58, 59). Also, a majority of studies were performed after the colon was cleaned. Unlike the rest of the gut, the colon normally contains digestive residue, whose presence may be critical for its normal function (14, 49). If feces are removed, then the colonic milieu and, consequently, its motor function (16, 25, 35, 49, 56) are altered. The precise effect of cleansing remains unclear because reduced (25), unchanged (35), or altered (16, 56) motor activity has been described. The motor activity of the unprepared healthy human colon has rarely been examined (27, 35, 60). Colonic motor activity is intermittent, and it differs between colonic segments (18, 26, 31, 48). Therefore, a recording should be performed over prolonged periods, and with enough sensors to sample from different segments, to comprehend the spectrum of normal colonic motility.

To date, there has been no comprehensive assessment of both colonic pressure activity and motor patterns in the same individual. Thus our aim was to study colonic pressure activity over a 24-h period in healthy humans under ambulatory conditions and to characterize the patterns of motor activity.

METHODS

Subjects

Twenty-five healthy volunteers (13 men, 12 women; mean age 39 yr, range 25–57 yr) were recruited through a hospital advertisement. All subjects gave written informed consent, and the study protocol was approved by the Human Ethics Review Board and the Radiation Protection Committee. The volunteers were in good health, had no previous history of gastrointestinal symptoms or surgery, were not taking any medications, and had normal physical examinations. They all reported normal bowel function.

Manometry Assembly

We used a 6-mm-diameter flexible probe containing six strain-gauge pressure transducers (Gaeltec, Dunvegan, UK)
that were located ~7, 14, 25, 35, 45, and 60 cm from the anus. The purpose of differential spacing of sensors was to ensure that pressure activity could be recorded from the rectum, sigmoid colon, descending colon, and transverse colon. The probe was attached to a portable recorder (type 7-MPR, Gaeltec), 18 × 12 × 5 cm in size, with a sampling frequency of 8 Hz. Although it had a memory of 1 MB, it used a selective data acquisition algorithm that acquired data without losing any recorded pressure activity. After the study, the data were transferred to an IBM PC and stored on diskettes for future analysis. The memory space on the recorder was checked every 4–6 h. If >90% of the memory was full, the data were downloaded and a fresh recording was begun. This resulted in a loss of data for 15–20 min.

**Experimental Design**

Subjects were admitted to the Clinical Research Center after an overnight fast. At 7:00 AM, they received a tap water enema. Thereafter, with the use of the following technique, the manometry probe was placed in the colon. A silk thread was tied to the tip of the probe. The thread was grasped by a polypectomy snare that was introduced through the biopsy channel of a pediatric colonoscope (Olympus GIFC10). The snare was pulled back so that its tip lay 2–3 cm inside the distal end of the instrument. No sedation was used. The probe and the colonoscope were advanced under direct vision up to the hepatic flexure, with minimal air insufflation. Once the location of the probe was confirmed by fluoroscopy, the silk thread was released, freeing the probe. The snare and the colonoscope were withdrawn, and care was taken to remove as much air as possible. The probe was then taped securely to the gluteal region. Fluoroscopy was repeated the next morning and again at the end of the study to assess the location of each sensor. The total radiation exposure for each individual did not exceed 1,144 μrad.

The recorder was placed in a shoulder bag, and the subjects were free to move about throughout the study. At 9:00 AM, all subjects received a 400-kcal snack. Around 6:00 PM and again the next morning at 11:00 AM, they received a standardized 1,000-kcal meal. The subjects were allowed free access to water (maximum 1.5 l/24 h) but were prohibited from drinking alcohol. The subjects slept overnight at the Clinical Research Center beginning at 10:00 PM. The next morning, they were awakened at 6:00 AM. The motility recording was continued until 2:00 PM, and thereafter the probe was removed. An event marker was attached to the recorder, and the subjects were encouraged to click the button to mark the time of events such as eating, walking, and sleeping or to indicate the occurrence of symptoms such as abdominal pain, passing flatus, etc. They were also provided with a diary in which they described the event(s) or the symptom(s) and recorded its time and duration. If the subject had a bowel movement, then the perineum was cleaned and under fluoroscopy the position of sensors was rechecked. If feasible, the probe was advanced to previous locations and fresh adhesive tapes were applied. During the course of the study, if the tip of the probe had shifted by >15 cm from its original location and could not be repositioned or was expelled, the data from that subject were excluded.

**Data Analysis**

The pressure activity that was recorded at each sensor was analyzed both by observation of the manometry tracings on the monitor and with the aid of a software analysis program (AMBB, Gaeltec). Pressure waves with an amplitude of ≥8 mmHg and a duration of ≥3 s were included in the analysis. For each hour and at each pressure sensor, we measured the number of waves, the area under the curve of pressure waves, the duration of each wave, and the percentage of time occupied by pressure activity. Additionally, to examine regional variation, we measured the number of waves and the area under the curve of pressure waves in the proximal four channels (transverse/descending colon, channels P1–P4) and in the distal two channels (rectosigmoid colon, channels P5 and P6). Physical activity such as walking or coughing was associated with movement artifacts. These segments were excluded from the computer analysis but were analyzed manually.

Because colonic pressure activity was complex and variable, we displayed pressure activity at gain settings ranging from 25 to 400 mmHg and at recording intervals ranging from 30 s/page to 16 min/page. In this way, we were able to identify seven different patterns of pressure activity that were mutually exclusive. 1) Isolated pressure waves were defined as those that occurred randomly without any associated pressure activity within the same channel or in adjacent channels for at least 30 s. 2) Propagating pressure waves were defined as waves that migrated aborad across three consecutive channels with a velocity >0.5 cm/s; this window was chosen on the basis of our previous studies (47, 48). 3) Specialized propagating pressure waves (SPPWs) were defined as waves that migrated aborad across at least three consecutive channels with an amplitude of ≥105 mmHg and a duration of >14 s. These parameters were chosen because they represented values higher than the 95% confidence limit for ordinary propagating pressure waves. 4) Simultaneous pressure waves were defined as pressure waves that occurred simultaneously in at least three consecutive channels with a wave onset time of <1 s between channels. 5) Retrograde pressure waves were defined as waves that migrated oral across three or more consecutive channels with a velocity of >0.5 cm/s. 6) Periodic colonic motor activity (PCMA) was defined as discrete random bursts of phasic and tonic pressure waves with a frequency of ≥3 min⁻¹ and a cycle duration of ≥3 min⁻¹. These bursts occurred either in one channel or in multiple channels. 7) Periodic rectal motor activity (PRMA) is a unique pattern of periodic motor activity seen in the rectosigmoid colon, which consisted of discrete bursts of phasic and tonic pressure waves with a frequency of ≥3 min⁻¹ and a cycle duration of ≥3 min⁻¹ (47). We measured the incidence and the maximum amplitude for each sequence of pressure waves. Wherever appropriate, we measured the duration, propagation, or length of periodic events.

To exclude the potential effects of instrumentation and probe placement on colonic motility, we discarded the manometric recordings taken from 8:00 AM to 2:00 PM. For the purposes of examining the diurnal variation, we divided the 24-h recording into three epochs of 8 h each. The pressure activity that was recorded between 2:00 PM and 10:00 PM was taken as an index of day 1 motor activity. The motor activity that was recorded between 10:00 PM and 6:00 AM was taken as an index of nighttime motor activity. The following day, the pressure activity that was recorded between 6:00 AM and 2:00 PM was taken as an index of day 2 motor activity. For each of these time periods, we calculated the incidence of the aforementioned patterns and the various parameters of pressure activity.

**Statistical Analysis**

The data are expressed as means and 95% confidence intervals (CI). Statistical differences for the area under the curve, the number of waves, and percentage of activity that
was recorded on day 1 were compared with those recorded during the night and during day 2 using multiple-factor ANOVA with Bonferroni correction. Statistical differences for the pressure activity 1 h before and for each of the 2 h after meals were also compared using multiple-factor ANOVA with Bonferroni correction. Statistical differences for the pressure activity between the transverse/descending and rectosigmoid colon were also compared for the three periods using the multiple-factor ANOVA with Bonferroni correction. We compared the incidence of each pattern of motor activity that occurred during day 1, at night, or during day 2 using multiple-factor ANOVA with Bonferroni correction. The differences in pressure activity between men and women for each period were calculated using Student’s t-test.

RESULTS

Subjects and Technical Aspects

The data from 3 of the 25 healthy volunteers were excluded for technical reasons. In one subject, the probe shifted and became accidentally disconnected from the recorder. In another subject, the probe was expelled during defecation, and in one other subject, there was significant migration. In three other subjects, the probe was pushed out by ~10 cm during a bowel movement but could be readvanced under fluoroscopy. Thus we analyzed 528 h of recording from 22 subjects [11 men and 11 women; mean age 36 and 37 yr, respectively (range 25–57 yr)]. At the end of the study, fluoroscopy showed that the tip of the sensor was situated in the distal transverse colon in all 22 subjects, and when removed, the probe was coated with stool. In all subjects the hepatic flexure was reached, as confirmed by fluoroscopy.

Colonic Pressure Activity

Effects of gender. Women showed less pressure activity than men, and this difference was particularly significant in the transverse/descending colon and during the day. This included a lower incidence of pressure waves, percentage of activity, and area under the curve (Table 1).

Number of waves, percentage of activity, and area under the curve. During the night, there was a significant reduction (P < 0.0002) in the number of waves (Fig. 1), the percentage of time occupied by colonic motor activity [mean% (CI) of day 1, night, and day 2: 34 (4.6), 16 (2.7), and 32.4 (3.9)%, respectively], and area under the curve compared with either day 1 or day 2 (Fig. 1). There was no difference between day 1 and day 2. A 24-h profile of the area under the curve of pressure waves is shown in Fig. 1. On waking, there was an approximately threefold increase in pressure activity (Fig. 1). Ingestion of a meal was also associated with an increase (P < 0.05) in all three parameters during the first postprandial hour (Table 2). The meal-induced increases in colonic motor response persisted during the second hour (Table 2). During the third hour, they were similar to those in the preprandial hour (data not shown).

Regional variation. The transverse/descending colon (channels P1–P4) showed an increase in the number of waves and the area under the curve of pressure waves (P < 0.05) during the day compared with the rectosigmoid colon (channels P5 and P6) (Table 3). There was more (P < 0.05) activity in the rectosigmoid colon during the night compared with the transverse/descending colon largely because of higher motor activity in the rectosigmoid colon from periodic rectal motor activity.

Colonic Motor Patterns

There was no well-defined or recurring cyclical pattern. Largely, the pressure waves were nonpropagating and occurred randomly. Often, they overlapped. Not uncommonly, different patterns occurred at the same time in different channels. However, seven different patterns were recognized. The incidence of colonic motor patterns over a 24-h period is shown in

![Fig. 1. A 24-h profile of the incidence of pressure waves and the area under the curve (AUC) of pressure waves in healthy humans.](http://ajpgi.physiology.org/)

Table 1. Effects of gender on colonic manometry

<table>
<thead>
<tr>
<th></th>
<th>Day 1</th>
<th>Night</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No. of waves</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse/descending</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>141.5(21.4)*</td>
<td>68.5(12)</td>
<td>149(27.6)*</td>
</tr>
<tr>
<td>Women</td>
<td>103.4(24)</td>
<td>49(19.6)</td>
<td>107.5(21.1)</td>
</tr>
<tr>
<td>Rectosigmoid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>109.8(20.1)</td>
<td>78.3(25.3)</td>
<td>123.9(25.6)</td>
</tr>
<tr>
<td>Women</td>
<td>105.9(27)</td>
<td>49.7(13.3)</td>
<td>114.1(24.1)</td>
</tr>
<tr>
<td><strong>% Activity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse/descending</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>42.6(8.5)*</td>
<td>17.2(3.9)</td>
<td>38.7(5.7)*</td>
</tr>
<tr>
<td>Women</td>
<td>29.6(7.8)</td>
<td>12.5(5.4)</td>
<td>27.4(6.2)</td>
</tr>
<tr>
<td>Rectosigmoid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>30.9(4.8)</td>
<td>19.5(5.8)</td>
<td>30.3(5.8)</td>
</tr>
<tr>
<td>Women</td>
<td>33.9(9.2)</td>
<td>14.5(4.1)</td>
<td>32.3(7.3)</td>
</tr>
<tr>
<td><strong>AUC, ×10^3 mmHg</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse/descending</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>16.6(3.8)*</td>
<td>9.0(3.4)</td>
<td>23.1(5.9)*</td>
</tr>
<tr>
<td>Women</td>
<td>10.5(2.1)</td>
<td>6.1(3.1)</td>
<td>13.2(4.1)</td>
</tr>
<tr>
<td>Rectosigmoid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>12.5(2.9)</td>
<td>9.3(2.5)</td>
<td>14.1(3.0)</td>
</tr>
<tr>
<td>Women</td>
<td>13.9(4.0)</td>
<td>7.1(2.8)</td>
<td>15.5(3.8)</td>
</tr>
</tbody>
</table>

Values are means (95% confidence intervals). AUC, area under the curve of pressure waves. *P < 0.05, men vs. women.

Fig. 1. A 24-h profile of the incidence of pressure waves and the area under the curve (AUC) of pressure waves in healthy humans.
pressure waves comprised the predominant pattern of occurred within 15 min before defecation. SPPWs occurred during defecation and, of these, 81% study. In these nine subjects, 40% (38/97) of their total subjects (40%) had spontaneous defecation during the fort, and 7% were associated with urination. Nine movement, 8% were associated with cramps or discom- passage of flatus, 19% were associated with a bowel SPPWs were asymptomatic, 26% were associated with the anus. Symptom diary analysis showed that 40% of found to abort in the rectosigmoid colon. The remain- ing (transverse/descending colon) vs. P1–P4 Rectosigmoid AUC, ×10³ mmHg·s Transverse/descending AUC, ×10³ mmHg·s Rectosigmoid AUC, ×10³ mmHg·s

Values are means (95% confidence intervals). *P < 0.05, control vs. 1st hour; †P < 0.05, control vs. 2nd hour.

Fig. 2. The most common patterns were simultaneous pressure waves, propagating pressure waves, and genetic bursts of phasic pressure waves.

Propagating pressure waves Propagating pressure waves (Fig. 3) occurred throughout the 24-h period, including at night (Fig. 2), but the incidence was almost four times higher (P < 0.0001) during either day 1 or day 2 compared with the night (Table 4). In particular, immediately after waking (at the beginning of day 2) and after meals there was a significant inc- crease (P < 0.0001) in the number of propagating waves (Fig. 2). Overall, there was no difference be- tween waves 1 and 2. Although not significant (P = 0.1), the amplitude of propagating waves tended to be higher during day 2 compared with day 1 (Table 4). The duration of each propagating pressure wave varied between 8 and 14 s, with a mean duration of ~11 s.

SPPW. All subjects exhibited SPPW (Fig. 4); 216 sequences were observed in 22 subjects. On average, we observed 10 SPPWs per subject over a 24-h period (Table 4). Eighty percent (173/216) of SPPW sequences were identified at the most proximal sensor, suggesting that they commenced at or proximal to the transverse colon. Interestingly, 64% (138/216) of SPPWs were found to abort in the rectosigmoid colon. The remaining 36% (78/216) of SPPWs propagated all the way to the anus. Symptom diary analysis showed that 40% of SPPWs were asymptomatic, 26% were associated with passage of flatus, 19% were associated with a bowel movement, 8% were associated with cramps or discom- fort, and 7% were associated with urination. Nine subjects (40%) had spontaneous defecation during the study. In these nine subjects, 40% (38/97) of their total SPPWs occurred during defecation and, of these, 81% occurred within 15 min before defecation.

Simultaneous pressure waves. Overall, simultaneous pressure waves comprised the predominant pattern of motor activity in the colon (Figs. 2 and 5). Compared with either day 1 or day 2, the simultaneous waves were half as frequent (P < 0.0001) during the night (Table 4). After waking, there was a significant (P < 0.0001) increase in the simultaneous pressure waves. The mean amplitude of simultaneous waves was similar throughout the day or night (Table 4). The dura- tion of individual simultaneous pressure waves varied within the range of 6–14 s with a mean of ~9 s.

PCMA. Compared with nighttime incidence, the incidence of this pattern (Fig. 6) was similar during day 1 but was higher (P < 0.05) during day 2 (Table 4). Also, the mean duration of these waves was not affected by the circadian rhythm (Table 4). Approximately 70% (540/768) of these events were confined to a single channel. The remaining 30% (228/768) occurred at more than one channel. Of these, 18.7% propagated aborad, 66% occurred simultaneously, and 15.3% migrated retrogradely.

PRMA. A distinct cyclical activity that was confined to the rectum or rectosigmoid region (channels P5 and P6) was seen in all normal subjects. Detailed charac- teristics of this pattern, such as its propagation and relationships to proximal colonic activity, were pub- lished previously (47). Although the present study in- cluded more subjects, the results were comparable to our previous data. There was a significant increase (P < 0.0001) in the incidence of PRMA during the night compared with the day 1 and day 2 periods (Table 4).

Table 2. Regional variation in colonic manometry

<table>
<thead>
<tr>
<th>Time of Day</th>
<th>Day 1</th>
<th>Night</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse/descending</td>
<td>141(9)*</td>
<td>61(9)*</td>
<td>139(13)*</td>
</tr>
<tr>
<td>Rectosigmoid</td>
<td>119(8)</td>
<td>69(9)</td>
<td>123(10)</td>
</tr>
<tr>
<td>AUC, ×10³ mmHg·s</td>
<td>Transverse/descending</td>
<td>14.3(0.9)*</td>
<td>8.9(0.6)*</td>
</tr>
<tr>
<td>Rectosigmoid</td>
<td>12.7(1.3)</td>
<td>8.2(1.1)</td>
<td>15.7(1.7)</td>
</tr>
</tbody>
</table>

Values are means (95% confidence level). *P < 0.05, control vs. 2nd hour.
The incidence of PRMA was not affected by the ingestion of meals (Fig. 2).

Retrograde pressure waves. In general, retrograde pressure waves occurred infrequently (Fig. 7). Their incidence was lower \( P < 0.03 \) during the night compared with either day 1 or day 2 (Table 4). The waking hour showed a slight increase in the incidence of retrograde pressure waves (Fig. 2). After meals, there was a twofold increase in the incidence of retrograde waves, particularly during the first hour (Fig. 2).

**DISCUSSION**

We performed prolonged recordings at multiple sites in the relatively unprepared colon without sedation in healthy age- and gender-matched subjects and analyzed 528 h of recording. Previous studies were performed in younger subjects, \( 32 \) yr, and either exclusively (24) or predominantly (5, 39) in men or in women (13, 27). These studies may not represent the normal spectrum of colonic motor activity, because both gender (36, 46, 50) and age (2, 38) may affect gastrointestinal motor function. Furthermore, colorectal disorders are more common in women. Hence, we examined normal gender-matched subjects.

We found differences in colonic pressure activity between men and women. During daytime hours, women showed lower incidence of pressure waves, percentage of activity, and area under the curve of pressure waves in the transverse/descending colon. This inherent tendency for less motor activity could be one reason why women are prone to colonic problems such as constipation. The gender difference also underscores the need for performing gender-matched comparisons. Previous studies have reported decreased colonic motility in constipated patients (5). However, these patients were invariably women whose data were compared with those of a normal group of predominantly young men. Such findings should be interpreted with caution.

To minimize the effects of intubation and enema preparation on colonic motility, we excluded the initial 5 h of recording. Also, subjects were allowed to move about freely, and a few managed to pursue secretarial and administrative jobs. Whether ambulation affects

<table>
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<tr>
<th>Table 4. Colonic motor patterns</th>
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<tr>
<td></td>
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<tr>
<td>No. of propagating waves</td>
</tr>
<tr>
<td>Amplitude of propagating waves, mmHg</td>
</tr>
<tr>
<td>No. of SPPW</td>
</tr>
<tr>
<td>Amplitude of SPPW, mmHg</td>
</tr>
<tr>
<td>No. of simultaneous waves</td>
</tr>
<tr>
<td>Amplitude of simultaneous waves, mmHg</td>
</tr>
<tr>
<td>No. of retrograde waves</td>
</tr>
<tr>
<td>Amplitude of retrograde waves, mmHg</td>
</tr>
<tr>
<td># of PCMA</td>
</tr>
<tr>
<td>Duration of PCMA, min</td>
</tr>
<tr>
<td>No. of PRMA</td>
</tr>
</tbody>
</table>

Values are means (95% confidence intervals). SPPW, specialized propagating pressure waves; PCMA, periodic colonic motor activity; PRMA, periodic rectal motor activity. *P < 0.05, day 1 vs. night; †P < 0.05, day 2 vs. night; ‡P < 0.05, day 1 vs. day 2.
Colonic motor activity is unclear (10, 30, 43) but prolonged immobilization is nonphysiological. In one study, graded aerobic exercise decreased phasic colonic motility in healthy, untrained subjects (43), but after exercise there was a resurgence of predominantly propagating pressure waves, suggesting that exercise may enhance stool transit (43). Previous ambulatory studies have been fraught with methodological problems such as intubation (27, 60), lack of adequate sensors (13, 60), inconsistent location (13, 27, 60), memory limitations (13), or colon cleansing (13). Because psychological and physical stress can affect colonic motility (20, 40, 42), we also sought to minimize the influence of stress or of the laboratory environment. Subjects were invited to stay overnight in a private room rather than in a laboratory and often stayed with a family member. Finally, during probe placement stool material was encountered in all subjects, and when the probe was removed it was uniformly stained with feces. Thus our studies were performed under more optimal physiological conditions.

The colon is believed to be a quiet organ (60). In contrast, we found that the colon was active around the clock, although its activity varied both within and between subjects and at different regions within the colon. Previous studies quantified motor activity using the motility index, a product of mean amplitude and the sum of durations (39), or the area under the curve of nonpropagating waves (24), both of which can underestimate the overall pressure activity. Interestingly, in our subjects the profiles for the number of waves per hour correlated well with those of the area under the curve. However, there was considerable intersubject variability in the amplitude and duration of
pressure waves. This variability accounted for the lack of any change and, if anything, a lower percentage of activity on day 2 compared with day 1, although the number of waves and the area under the curve were higher on day 2. Hence, it was our impression that the area under the curve is a more robust method of quantifying colonic motility.

The 24-h profile showed a well-established circadian rhythm with marked diminution of pressure activity at night, confirming previous observations (4, 21, 24, 27, 39, 60), and it concurs with similar changes in small bowel motor activity (32, 34). We also observed intra- and intersubject differences in nocturnal motor activity, possibly caused by the influence of different stages of sleep (24). Immediately after waking, there was a threefold increase in colonic pressure activity. This reaffirms that the colon is primed to empty early in the morning (4). Nine patients had a bowel movement during the study, five of these in the morning. The colonic pressure activity also increased after meals, confirming previous observations (29, 37, 39, 64). This increase in postprandial pressure activity persisted for 2 h and reverted to the basal state in the third hour. A bimodal response that was seen in dogs (55) was not observed in humans.

The colon also exhibited regional variation in pressure activity, confirming previous reports (18, 19, 48). During daytime hours, the transverse/descending colon exhibited more pressure activity, confirming its role as an organ that mixes, stores, and salvages digestive residue (49). In contrast, although the overall colonic pressure activity decreased at night, the...
rectosigmoid region was more active, largely because of the occurrence of periodic rectal motor activity (33, 41, 42, 47). This regional variation emphasizes the importance of studying the colon at multiple sites, failing which important differences may be missed. For example, if we had examined only the rectosigmoid region, the gender differences in colonic motility might not have been recognized.

Periodic rectal motor activity, also termed rectal motor complex (41), occurred primarily during the night. Previously, we (47) showed that the periodic activity is often triggered by a propagating pressure wave from the proximal colon; this suggests that it occurs in response to movement of stool or gas into the distal colon. Also, a majority of these cyclical events were either localized to the rectosigmoid region or moved retrogradely (<5% propagated aborally) (47). Hence, this burst of intense, localized segmental activity may serve as an intrinsic nocturnal brake that prevents untimely movement of stool or flatus from the proximal colon into the sensitive rectum, particularly during sleep, when a person’s awareness is somewhat impaired (47).

Although complex, overlapping, and sometimes occurring together at different channels, seven different patterns of pressure activity were recognized. Because of their temporal and spatial variations, the software program was unable to detect these patterns reliably. Hence, these analyses were performed manually. Unlike the cyclical interdigestive migrating motor complex (MMC) of the small bowel (32, 34), there was no cyclical recurring pattern of motor activity. Hence, although MMCs have been described in the canine colon (54, 55), our findings concur with other human studies (27, 60) that an MMC-like activity does not occur in the colon. Also, most descriptions of colonic pressure activity have focused on one pattern, the specialized propagating or high-amplitude propagating contractions (3–5, 13, 27, 35, 62). However, we found that the most common pattern of pressure activity was simultaneous pressure waves. Like other patterns, its incidence was higher after meals and after waking. These waves occurred randomly, either singly or in short clusters of three to six waves across three or more channels. On average, their amplitude was 50 mmHg. Although their incidence was lower at night, the mean amplitude was similar. The other prominent pattern was a burst of periodic colonic motor activity. Approximately 70% of periodic phasic events were confined to a single channel, and the rest occurred in two or more channels. Also, they were seen mostly during the day as opposed to the periodic rectal motor activity. Thus, together, the simultaneous and the periodic colonic motor activity constituted the predominant motor activity in the colon. These patterns may be involved in slowing transit, facilitating the mixing of ileal effluent with colonic secretions and bacteria, and creating conditions for bacterial proliferation, fermentation, and absorption of fluid, electrolytes, and short-chain fatty acids (14, 49, 54, 55). They are akin to the ringlike contractions described previously in radiological studies (52).

Propagating pressure waves were seen intermittently throughout the day and especially after meals or after waking. Their amplitude, duration, and length of propagation were, however, quite variable. But it should be pointed out that the mean amplitude of these waves (range 54–104 mmHg) was substantially higher than that described previously (4, 13, 39). This must be caused by the higher fidelity of our manometry system and the physiological study conditions. In an elegant review, it was stated that propagated contractions that migrate >10 cm and are <50 mmHg in amplitude are typical of high-amplitude propagated contractions (3). If these criteria were applied to our study, almost all of the ordinary propagating waves would be classified as high-amplitude propagating contractions. This highlights the importance of study conditions when interpreting and classifying manometry.

In this context, the terms high-amplitude propagating contractions (4, 13, 39), mass movements (5), or giant migrating contractions (31, 58) merit further thought. We confirm that these propagating events do occur. However, on the basis of current trends in nomenclature (6) and the motor characteristics of this pattern, we, like others (1), believe that the aforementioned descriptive terms are inconsistent and misleading. Although the term “contraction” has been used interchangeably with “pressure wave” in the motility literature, the latter is a more accurate description. To use the term contraction there ought to be visual confirmation (6). This was not possible in our study and in most previous studies. Also, this unique pattern consisted of propagating sequences that were not only of high amplitude but also of prolonged duration, often exceeding 20 s. We found that their amplitudes were higher than those described previously with perfused systems (4, 5, 13, 39), possibly because of the higher fidelity of a solid-state system. In fact, 40% of these pressure events had an amplitude that was >223 mmHg, the highest pressure that could be recorded with our device. Hence, the mean amplitude (164–190 mmHg) was an underestimate of the true amplitude. Also, they propagated at a higher velocity than the ordinary propagating pressure waves. In view of these distinct characteristics, we have proposed the term “specialized propagating pressure waves” (SPPWs), to distinguish them from the ordinary propagating pressure waves. We found that during a 24-h period there were ~10 SPPWs per subject, mostly after waking, after meals, or associated with defecation. This incidence is also higher than the previously quoted number of four to six per subject in 24 h (4, 13, 39). Both the propagating pressure waves and the SPPWs may be involved in the movement of gas or feces, as demonstrated recently by combining manometry with transit of radionuclide material (12). The former possibly shifts material over short distances and the latter over longer segments (28, 29, 53). This is substantiated by our observations that 45% of SPPWs were associated with the passage of flatus or stool. Consequently, the
SPPW may be involved in the initiation of defecation. However, it is worth noting that although an SPPW precedes a bowel movement, this accounted for only 19% of the overall incidence of these waves, and 40% of SPPWs were in fact asymptomatic. Occasionally, they were seen when the individual was asleep, as confirmed recently (12). Also, two-thirds of SPPW tended to abort in the rectosigmoid region, and only one-third reached the anus. Because we did not measure transit alongside manometry, we are unable to assign a more specific function for these propagating events.

On the basis of animal studies, it has been suggested that retrograde pressure waves occur frequently and that they move contents orad toward the cecum (8, 17). In humans, scintigraphic studies have shown retrograde movement of radiotracers (12, 51), but the occurrence of retrograde pressure waves has scarcely been documented in the healthy human colon. However, we found that these waves occurred infrequently, and their highest incidence was after a meal and during the morning waking response. One possibility for a lower incidence in our study could be that this pattern may occur more commonly in the cecum/ascending colon (12), a segment that was not examined. Even when seen, only 10% of such events were associated with retrograde movement of isotope (12), suggesting that this pattern may not play a crucial role in stool transport.

The optimal technique for placing a probe in the colon is unclear. Three methods have been described: nasal intubation (1, 35, 60), guide wire-assisted probe placement (4, 20, 27, 61, 62), and retrograde direct probe placement (4, 5, 39, 43, 48). In the latter two techniques, a colonoscope is used either to place a guide wire or to advance the probe under direct vision. The first technique requires no bowel preparation but is fraught with problems such as prolonged intubation time (2–3 days), inconsistent sensor location (60), and fecal contamination of the upper gut and nasopharynx during probe removal (1, 35, 60). Consequently, this method may not be acceptable for routine clinical use. With the guide wire-assisted technique, in one study, the goal was to reach the transverse colon, but in 50% of subjects the tip was located in the descending colon (27), although another group was more successful (24). With the direct placement technique, the proximal transverse colon (desired location) was reached in all subjects, both in our study and in others (4, 39). Furthermore, the probe remained in place in >80% of studies (4, 39, 43, 48). Technically, although arduous, the use of a pediatric colonoscope facilitated placement and made the procedure more acceptable to our subjects. All of our subjects tolerated the procedure without any adverse events. Thus this technique may offer some advantages over the indirect techniques, but it warrants comparative studies.

Whether solid-state manometry provides a more reliable recording is controversial. In vitro studies showed that the water-perfused system can be unreliable when a perfusion rate of <0.2 ml/min is used compared with a solid-state system, particularly in the presence of viscous luminal contents (57). This observation is important because previous prolonged studies used perfusion rates of <0.2 ml/min (1, 4, 12, 24, 39). Although the colon can absorb several liters of water (15), not only does a water-perfused system instill more fluid into the distal colon but its side holes can become occluded by fecal matter, compromising its sensitivity. Also, the subjects must be immobilized and hospitalized, which renders this technique nonphysiological and unsuitable for routine clinical studies. In contrast, the solid-state system is bereft of these drawbacks. However, its transducers are fragile, expensive, and prone to corrosive damage either from moisture or from irritants in stool (28), especially when placed without colon cleansing.

One of the limitations of our study was that the pressure activity was recorded from the distal two-thirds of the colon. In part, this was because of technical limitations such as the length of the probe and our objective of studying a relatively unprepared colon. Another limitation was probe migration, and because of this, we excluded three subjects. However, this problem can be overcome by clipping the probe to the colonic mucosa (63). Another possibility is that the pressure signals may be dampened by stool coating the transducers. Our pilot studies showed that the sensors retained their preprocedure calibration signals. Also, the colonic pressure activity on day 2 tended to be higher than on day 1. Hence, it is unlikely that the coating of transducers with stool dampened our ability to record colonic manometry.

This study confirms that it is feasible to perform prolonged studies under physiological conditions and without significantly disturbing the colonic milieu. It underscores the fact that technical differences and regional variation can influence manometric results. Although we confirmed some of the previous observations, here we have quantified for the first time both the pressure activity and the motor patterns in the colon in the same individual over a 24-h period. This assessment provides much-needed normative data, including gender differences.

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