Rectal tone, distensibility, and perception: reproducibility and response to different distensions

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Hammer, H. F., S. F. Phillips, M. Camilleri, and R. B. Hanson. Rectal tone, distensibility, and perception: reproducibility and response to different distensions. Am. J. Physiol. 274 (Gastrointest. Liver Physiol. 37): G584–G590, 1998.—Increasing interest is focusing on the role of intestinal tone, distensibility, and mechanosensation in the genesis of abdominal symptoms. Experimental approaches usually feature balloon distension of the bowel with measurements of perception, tone, and compliance and/or elastance; however, the methodologies are standardized incompletely. We examined the reproducibility of repeated assessments of sensory perception, basal tone, and compliance and/or elastance of the rectum during distension. We also evaluated the response to inflations that varied in regard to control of pressure or volume, pattern of distension, and rate of inflation. Five healthy volunteers were studied under two separate protocols. The first featured a series of experiments on each of 5 days; the other consisted of 2 separate days of study. Repeated distensions evoked reproducible responses of sensation and compliance and/or elastance on a single day, providing a conditioning distension preceded them. Day-to-day variability was also sufficiently small to allow valid comparisons to be made on different days in healthy persons. The configuration of the distension profile (phasic, staircase, or ramp) and the rate of inflation (from 1 to 40 ml/s) had little effect on distensibility or perception. Perceptions were sometimes transient and sometimes constant, but no relationship was found between these temporal features and the magnitude of the stimulus. These observations help provide a basis as to how the responses to rectal distension can be best studied.

rectal sensation; rectal compliance; rectal barostat

GASTROINTESTINAL MANOMETRY and transit are well-established experimental approaches to normal gut function and to the clinical evaluation of gastrointestinal symptoms. In particular, disorders of motility and transit have been implicated in the pathogenesis of the common functional bowel disorders (14). Interest has also focused on the role of disturbances of intestinal tone, distensibility, and mechanosensation in the genesis of gastrointestinal symptoms (3, 7, 9, 11, 12, 15, 16, 22). Mechanical distension of the bowel evokes perceptions that become more intense, often described as culminating as pain when the degree of distension is increased. Thus mechanostimulation with concurrent assessments of symptoms, wall tone, and compliance is being employed increasingly in the evaluation of intestinal symptoms, although the experimental methods and interpretations of results have not always been fully standardized.

Our aim in these experiments was to assess the reproducibility of measurements of rectal tone, distensibility, and perception to distension and to evaluate the influence of different forms of inflation on these indexes. The term “tone” has been used to describe the static pressure-volume relationship in a hollow viscus; decreases in tone are relaxations and vice versa. Tone in a viscus has usually been measured by monitoring volume changes in a highly compliant bag when the bag is inflated to a constant low pressure (1–3). Distensibility describes the dynamic reaction of a hollow viscus to changes in pressure or volume and is expressed as compliance or elastance. In physics, compliance describes volume changes that result from dynamic pressure changes and elastance summarizes the pressure changes that are the result of dynamic changes in volume (4). In materials with “ideal” physical characteristics and that behave passively in response to distension, elastance is the inverse of compliance; biological tissues react actively to distension and are therefore not ideal.

Two protocols addressed the following features: 1) day-to-day reproducibility of measurements of tone, elastance, and perception of distension; 2) order effect of repeated distensions on 1 day; 3) effects of different inflation protocols (pressure or volume controlled and ramp vs. phasic distension); 4) different rates of inflation (slow staircase and fast ramp distension); and 5) modulation of tone by neostigmine. The rectum was used in our studies because it is easily accessible and has been used in physiological and clinical studies (2, 7–9, 12, 15, 17). Furthermore, rectal distension results in distinct sensations that allow a grading by the commonly used descriptors, feelings of initial sensation, stool, and urgency (2, 7).

METHODS

Five healthy individuals (3 men and 2 women, 23–41 yr old) were recruited by public advertisement. Volunteers were excluded if they had a history suggestive of a functional bowel disorder, chronic or recurrent abdominal pain with altered bowel habits, intermittent or chronic diarrhea or constipation, urgency for evacuation, feelings of incomplete rectal emptying, or the passage of visible rectal mucus. Intra-abdominal or pelvic surgeries, except for appendectomy and cholecystectomy, or acute diarrheal disease within the last 4 wk were also reasons for exclusion. All signed informed consent before the study, and females were required to have a negative pregnancy test within 48 h. The studies were approved by the Institutional Review Board of Mayo Foundation (Rochester, MN).

Rectal Intubation

No bowel preparation was used, but subjects were asked to empty their rectums before the start of the study. They were placed in a left lateral decubitus position with the head lowered by 20 degrees, to reduce pelvic hydrostatic pressure (2). A two-lumen catheter with a 10-cm long cylindrical polyurethane bag was placed with the distal end of the bag 5 cm from the anal verge. One lumen was used for inflation of
the bag with air and the other was used to measure pressure within the bag. The catheter was connected to a barostat-distender assembly (Distender II, G + J Electronics, Toronto, Canada).

Measurement of Rectal Tone

During measurements of tone, the Distender II was in a pressure-controlled mode, at an operating pressure that was 2 mmHg above the pressure at which volume changes associated with deep breathing or coughing were noticed. The operating pressure was 10 mmHg in all but one person in whom it was 8 mmHg.

Rectal Distensions

Before the start of each distension, pressure within the rectal bag was lowered to 0.5 mmHg for 10 min; this was below the resting pressure in the rectum, allowing the bag to empty completely. Then the bag was inflated with air; volume-controlled and pressure-controlled distensions were used.

Volume-Controlled Distensions

The volume within the bag was increased using the Distender II, which was programmed as follows (Fig. 1). 1) Staircase distension: the rectal bag was inflated in steps of 10 ml at a rate of 1 ml/s. Each step was followed by a 50-s (see Study Protocol 1) or 20-s (see Study Protocol 2) observation period before the next 10-ml distension step was performed. 2) Ramp distension: the bag was inflated at a rate of 5 ml/s. 3) Phasic distension: the bag was inflated for 30 s and then completely deflated for 30 s before the next distension was performed. The inflation rate was 40 ml/s. With each distension step the volume that was used for distension was increased by 20 ml.

Pressure-Controlled Distensions

The Distender II was programmed to increase pressure in the bag by inflating it with air until a set pressure was achieved. The inflation rate was set at 40 ml/s. The following distensions were performed: 1) Staircase distension: starting at a pressure of 0.5 mmHg, the pressure within the bag was increased in steps of 1 mmHg. At each step the pressure was kept constant for 30 s. 2) Ramp distension: the rectal bag was inflated at a rate of 0.5 mmHgs. 3) Phasic distension: starting from a baseline pressure of 0.5 mmHg, pressure within the rectal bag was increased for 30 s and then lowered to the baseline pressure for 30 s. This cycle of pressure increase for 30 s and pressure decrease to baseline for 30 s was continued throughout the distension protocol. Pressures used to distend the bag were increased in increments of 2 mmHg.

All distensions were stopped and the rectal bag was deflated immediately if the sensation of urgency (see Sensory Assessment) persisted for 30 s.

Study Protocol 1

These experiments were designed to assess intraindividual variability of rectal tone, elastance, and thresholds of perception (Fig. 2). A 5 × 5 study design featured five volunteers, each volunteer was studied for 5 days, each study being separated from the next by 3–6 days. After rectal intubation, the operating pressure for measurement of rectal tone was determined; this was defined as the pressure 2 mmHg above that at which volume changes due to deep breathing or coughing were noted. A basal 30-min period, with the bag inflated at the operating pressure, was performed. We wanted to assess day-to-day variability. Thus there followed a 30-min period during which rectal tone was measured. Thereafter, pressure in the bag was lowered to 0.5 mmHg to completely empty the bag. A volume-controlled staircase distension was performed, followed by a 30-min recording of rectal tone. To assess the effect of repeated studies on one of the 5 study days, two additional distensions were performed. Each was preceded by a lowering of pressure within the rectal bag to 0.5 mmHg. Tone measurements were obtained for 15 min between the second and third distension and after the third distension.

Study Protocol 2

These experiments were separated from the first set by at least 4 wk. The same five volunteers participated in these experiments, which were performed on 2 days. These experiments were designed to assess the influence of different distension stimuli (volume vs. pressure controlled), distension modes (staircase vs. ramp vs. phasic), and distension rates (slow staircase vs. fast ramp) on distensibility and perception thresholds. Based on results from protocol 1, a volume-controlled continuous ramp inflation was performed as a "conditioning distension." Thereafter, three different volume-controlled distensions or, on a separate day, three different pressure-controlled distensions, were performed in randomized order. Distensions were separated by 10-min intervals (Fig. 2), during which time the bag was deflated completely by lowering the pressure in the bag to 0.5 mmHg. The interval between experimental days was at least 3 days, and the order of protocols, using volume- or pressure-controlled distensions, was randomized.

Sensory Assessment

Subjects were asked to note the onset and continuing presence of three sensations: 1) the first perception of the balloon, 2) the feeling of stool in the rectum, and 3) discomfort and/or urgency. The first sensation noted a feeling that something was within the rectum; for some subjects, this was a feeling of gas, whereas for others it was nonspecific. The sensation of stool was defined as a feeling of material being in the rectum, to be evacuated only if convenient. By contrast, urgency was defined as a feeling that would cause subjects to
Analysis of Data

Rectal tone. Rectal tone (protocol 1) was expressed as the mean barostat volume, averaged over the last 5 min of each interval of measurement. Day-to-day variability of tone was assessed by measurements that were obtained before distension on each of the 5 study days. The effect of repeated distensions on rectal tone was assessed by comparing tone measurements obtained before the first distension with those obtained after the first, second, and third distension. We used paired two-tailed t-tests, with Bonferroni correction for multiple comparisons.

Calculation of wall tension. Preliminary studies, in which a bag was coated with liquid barium before it was placed in the rectum, confirmed previous observations (2, 19) that the distended bag had a cylindrical shape within the bowel. The distending radius (r) was calculated according to the law for a cylinder, where volume equals height (10 cm in this bag) × \( r^2 \times \pi \). This formula was used to calculate r. Tension (T) in the rectal wall was calculated using Laplace's law applied to a cylinder, where \( T = P \times r \) (P is pressure).

Analysis of thresholds for perception. Thresholds were expressed as the volume, pressure, and tension at the onset of transient or constant sensations. Sensations were considered to be constant when an initial sensation or a feeling of stool lasted at least 60 s or when urgency lasted 30 s. During protocol 2, only thresholds for constant sensations were assessed. Paired t-tests were used for the responses to ramp and staircase inflations.

Analysis of elastance and compliance curves. Volume and pressure values were recorded on-line at a rate of 4 Hz. For the analysis of staircase and phasic distensions, the mean pressures and volumes during the middle third of the duration of each distension step were used. For the continuous ramp distensions, mean pressures and volumes were calculated for each of the consecutive 10-s periods of distension.

Elastance of the rectum in response to volume-controlled distension was calculated by linear regression starting at a distension volume of 100 ml, using pressure values transformed logarithmically. This yielded a curve with excellent fit (mean \( r^2 = 0.92 \pm 0.02 \)). Fit was significantly better (\( P < 0.01 \)) than it was for linear regressions, starting at a distension volume of 0 ml \( (r^2 = 0.87 \pm 0.02) \). Moreover, values below a distending volume of 100 ml were not relevant for sensory thresholds because symptoms usually occurred well above this volume. Curve fits for pressure-controlled distensions were calculated using logarithmically transformed pressure values starting at a distending pressure of 10 mmHg.

Assessment of day-to-day variability (protocol 1). Intraindividual day-to-day variabilities of rectal tone, elastance, and sensory thresholds were assessed for each of the five subjects by calculating the individual coefficient of variation (\( CV = \frac{SD}{mean} \times 100 \), expressed in %).

RESULTS

Rectal Tone, Elastance, and Sensory Thresholds: Effect of Repeated Distensions and Day-to-Day Variability

Rectal tone. Figure 3 illustrates four measurements of balloon volume (the inverse of rectal tone) on 1 day in five persons. Basal tone before the first distension of the day was significantly greater than thereafter. The greater volume of the rectal bag after the first distension (238 ± 35 ml) than before (161 ± 31 ml) represented a 48% decrease in rectal tone (\( P < 0.05 \)). After subsequent distensions, there were no further significant increases in rectal volume (263 ± 34 and 270 ± 30 ml). With any single distension, changes in tone were most obvious in the first minutes and tone was usually stable by 15–20 min.

Day-to-day reproducibility of rectal tone for each person was evaluated by comparing second, or subsequent, measurements of tone on separate days. There was no significant variability within healthy persons; the mean CV from five subjects was 18 ± 5%, with the range from 11 to 39%.
Rectal elastance. After the initial (conditioning) distensions, repeated inflations performed on the same day did not change significantly the slopes or the intercepts of the elastance curves. Similarly, day-to-day comparisons of slopes and intercepts yielded no statistically significant differences.

Thresholds for constant perceptions. Figure 4 shows individual sensory thresholds expressed as the volume, pressure, or tension at the onset of urgency, during three distensions on the same day in five subjects. Thresholds expressed as volumes did not change significantly between the first and the following distensions. In contrast, thresholds expressed as pressure or tension were significantly lower during the second and third distensions ($P < 0.05$). Figure 5 summarizes these data by showing mean thresholds for initial sensation, stool, and urgency during three distensions on the same day in five subjects. After the conditioning distension, there were no significant differences between any threshold when the third distension was compared with the second.

Day-to-day variability of thresholds for sensation are shown in Table 1. Tension thresholds showed significantly greater ($P < 0.01$) CVs than did pressure or volume thresholds. Thresholds for stool and urgency had better intraindividual day-to-day reproducibility (i.e., lesser CVs) than did those for the initial sensation.

Transient sensations. Transient sensations during rectal distension were assessed on the study day when three consecutive distensions were performed (protocol 1). Four of five volunteers had episodes in which an initial sensation, the feeling of stool, or urgency was a transient event. Mean threshold data for these sensations are shown in Table 2, where they are compared with the values for constant sensations. The data show that sensations occurred at the same degree of distension, regardless of whether they were brief or constant. On occasion, a transient sensation lasted for the duration of a phasic contraction of the rectum, but no statistically significant association between sensation and phasic rectal pressures was present. Episodes of transient sensation began during the distension step and during the early or later phases of the observation period. More than one-half of all sensations began during the observation period; thus the duration of the stimulus and the length of the observation period can be contributing factors to perception.

![Fig. 3. Rectal tone as measured by mean volume in barostat bag before and after 3 distensions. Individual data from 5 subjects.](http://ajpgi.physiology.org/)

![Fig. 4. Sensory thresholds expressed as volume (A), pressure (B), and tension (C) at onset of urgency during 3 distensions on same day. Individual data from 5 subjects.](http://ajpgi.physiology.org/)
As shown in Table 3, the mode of distension (staircase vs. ramp vs. phasic) and the rate (slow during staircase vs. fast during ramp) did not significantly influence the slope or intercept of the volume-pressure (or pressure-volume) relationship during volume-controlled or pressure-controlled distensions.

During volume-controlled distensions, sensory thresholds were not significantly influenced by the mode (ramp vs. phasic) or the rate (slow during staircase vs. fast during ramp) of distension (Table 4). By contrast, during pressure-controlled distensions, continuous ramp distension (fast) had significantly higher pressure and tension thresholds for urgency, and significantly higher tension thresholds for initial sensation, compared with stepwise ramp distension.

DISCUSSION

Increasing interest in afferent signaling from the intestine has led to mechanosensation being implicated as a pathophysiological or diagnostic feature of gastrointestinal disorders (3, 6, 7, 9, 11, 12, 15–18, 22). Distending protocols have utilized a variety of stimuli; much of the initial data were obtained using latex balloons (6, 15–18). The physical characteristics of latex balloons and polyurethane bags have been compared (21); latex behaves nonuniformly in tubular structures (21), and more recent reports have used the barostat technique, which features polyurethane bags with more predictable mechanics (1, 2, 21). Barostat bags are of very high compliance (2, 21), and they

Table 1. Day-to-day variability of thresholds for constant sensations

<table>
<thead>
<tr>
<th>Sensory Thresholds</th>
<th>Pressure</th>
<th>Volume</th>
<th>Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial sensation</td>
<td>40 ± 12</td>
<td>38 ± 11</td>
<td>52 ± 13</td>
</tr>
<tr>
<td>Stool</td>
<td>26 ± 2</td>
<td>18 ± 3</td>
<td>34 ± 3†</td>
</tr>
<tr>
<td>Urgency</td>
<td>23 ± 4</td>
<td>13 ± 3</td>
<td>28 ± 4†</td>
</tr>
</tbody>
</table>

Values are means ± SE in coefficient of variation percent; n = 5 subjects. *P < 0.01 vs. volume. †P < 0.01 vs. pressure.

Table 2. Thresholds for transient and constant sensations

<table>
<thead>
<tr>
<th>Volume thresholds, ml</th>
<th>Transient</th>
<th>Constant</th>
<th>Intraindividual Differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial sensation</td>
<td>144 ± 30</td>
<td>221 ± 57</td>
<td>77 ± 48</td>
</tr>
<tr>
<td>Stool</td>
<td>234 ± 40</td>
<td>236 ± 40</td>
<td>2 ± 2</td>
</tr>
<tr>
<td>Urgency</td>
<td>280 ± 36</td>
<td>286 ± 36</td>
<td>6 ± 4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure thresholds, mmHg</th>
<th>Transient</th>
<th>Constant</th>
<th>Intraindividual Differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial sensation</td>
<td>11 ± 2</td>
<td>13 ± 3</td>
<td>2 ± 2</td>
</tr>
<tr>
<td>Stool</td>
<td>14 ± 24</td>
<td>14 ± 3</td>
<td>0 ± 1</td>
</tr>
<tr>
<td>Urgency</td>
<td>19 ± 3</td>
<td>19 ± 3</td>
<td>0 ± 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tension thresholds, cm/mmHg</th>
<th>Transient</th>
<th>Constant</th>
<th>Intraindividual Differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial sensation</td>
<td>23 ± 6</td>
<td>37 ± 14</td>
<td>14 ± 11</td>
</tr>
<tr>
<td>Stool</td>
<td>41 ± 10</td>
<td>41 ± 12</td>
<td>0 ± 2</td>
</tr>
<tr>
<td>Urgency</td>
<td>58 ± 12</td>
<td>60 ± 14</td>
<td>2 ± 2</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 4 subjects (1 individual was excluded from this analysis because transient sensations were not noted).
usually have been used in conjunction with programmable electromechanical servo-systems. Some other aspects of methodology are also not uniform. Different means of inflation (syringes vs. barostat systems) have been coupled with different inflation protocols (ramp vs. phasic distension), pressure vs. volume control, and different inflation rates (ranging from 20 ml/min up to 40 ml/s). Relationships among pressure and volume have assessed pressure changes in response to volume changes, i.e., elastance, or have measured volume in response to pressure changes, i.e., compliance. Sensory thresholds have been expressed as the volumes, pressures, or tensions needed to elicit a variety of sensations. Finally, the reproducibility of repeated measurements has not been examined systematically.

Accordingly, we examined the tonic and sensory responses to repeated distensions of the rectum on a single day and also the day-to-day variability. Furthermore, we evaluated the influence of the mode and rate of distension on sensory thresholds. Our results provide observations that should help the design of experiments that examine the effects of various perturbations, psychological, physiological, or pharmaceutical, on mechanosensation. Thus repeated responses on a single day were most reproducible after a “conditioning” distension that reduced and stabilized basal tone. There may be other benefits, such as familiarizing subjects with the procedure and reducing response bias for the reporting of sensations; these we did not evaluate. Under these conditions rectal tone also had an acceptable day-to-day reproducibility, implying that observations made on more than 1 day should be comparable.

Indexes of compliance and/or elastance also did not change on a single day, after the conditioning distension, and day-to-day variation was not significant. The most robust finding was the change in basal tone that resulted from an initial inflation of the rectum. In this regard, thresholds for sensation, when expressed in the volume of distension, did not change between the first and subsequent distensions, whereas those incorporating a pressure measurement did. Thus there were parallel changes in tone- and pressure-related expressions of threshold values but not for volume thresholds. We have suggested that tone may be a contributing determinant of sensitivity (10). Musial and Crowell (13) demonstrated adaptive changes to rectal distension with relaxation continuing during 25 min of distension of sufficient magnitude to induce urgency.

Rectal distension evoked three distinct sensations. We defined the first perception as “something in the rectum”; this was least reproducible. Thresholds for the sensations of stool and rectal urgency varied less. On specific questioning after the study, all subjects denied the perception of actual pain during the study, even at the highest level of urgency and/or discomfort. Indeed, it could be argued that, unlike more proximal regions of the bowel, the rectum does not usually experience true pain from distension. Extreme urgency leads to evacuation, either voluntary or involuntary. Thresholds expressed as volume were more reproducible than those expressed as pressure or tension, although others have claimed that wall tension is critical for visceral sensitivity (4, 5). Sensory perceptions were either transient or constant and, although the differences between the respective thresholds were not significant, variable time courses of the sensations relative to the stimuli....

Table 4. Thresholds for constant sensations: influence of distension mode

<table>
<thead>
<tr>
<th>Volume-Controlled Distensions</th>
<th>Pressure-Controlled Distensions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial sensation</strong></td>
<td></td>
</tr>
<tr>
<td>Staircase</td>
<td>Vol, ml</td>
</tr>
<tr>
<td>119 ± 48</td>
<td>12 ± 3</td>
</tr>
<tr>
<td>Ramp</td>
<td>150 ± 37</td>
</tr>
<tr>
<td>Phasic</td>
<td>99 ± 20</td>
</tr>
<tr>
<td><strong>Stool</strong></td>
<td></td>
</tr>
<tr>
<td>Staircase</td>
<td>225 ± 63</td>
</tr>
<tr>
<td>Ramp</td>
<td>235 ± 39</td>
</tr>
<tr>
<td>Phasic</td>
<td>184 ± 30</td>
</tr>
<tr>
<td><strong>Urgency</strong></td>
<td></td>
</tr>
<tr>
<td>Staircase</td>
<td>281 ± 57</td>
</tr>
<tr>
<td>Ramp</td>
<td>333 ± 46</td>
</tr>
<tr>
<td>Phasic</td>
<td>308 ± 40</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 5 subjects. *P < 0.02 vs. stepwise ramp distension. †P < 0.05 vs. volume-controlled distension.
imply that the temporal features of stimulus-response should be specified.

When distensions featured volume-controlled protocols, there was no influence of the mode or rate of distension on thresholds of perception. Sun et al. (20), using a wider range of inflations, reported that the rate influenced the sensitivity to perception, and they used these data to infer different receptor mechanisms. Our experiments cannot, however, shed light on these issues. During volume-controlled distensions, thresholds can be expressed as the volume, or the pressure, at which perception begins because these had similar reproducibilities. Expression of thresholds as a volume may be advantageous because concomitant measures of pressure may be unnecessary if compliance and/or elastance is not to be measured. For the simplest clinical observations, volume-controlled staircase distensions can be performed with a hand-held syringe and a three-way stopcock. For research studies, even for such simple measurements of sensory thresholds, we recommend a highly compliant polyurethane bag with physical properties (19, 21) that need to be defined for each laboratory. Volume thresholds were most reproducible, and it might be speculated that volume (or tension) receptors are more integral to the firing of afferent signals from the rectum than are sensors of pressure.

Should basal tone and compliance and/or elastance be considered important, pressure-controlled inflation protocols are preferred, with a barostat system. We saw no major changes under any circumstances of the overall slopes and intercepts of these pressure-volume relationships. However, we excluded the initial nonlinear portions of our curves and, in some circumstances, these may be important (7). Our observations imply that an initial conditioning distension establishes assay conditions suitable for day-to-day comparisons or sequential observations on 1 day. The pattern of the distension protocol and the range of inflation rates we used were not critical determinants, and our data were more reproducible when pressure changes were determined in relation to volume stimuli (elastance).

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