Comparison of rectoanal axial forces in health and functional defecatory disorders

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CURRENT CONCEPTS SUGGEST that defecation is accomplished by increased intrarectal pressure coordinated with relaxation of the pelvic floor muscles. In addition to the internal and external anal sphincters, the pelvic floor muscles, especially the puborectalis, also relax during normal defecation (18). However, several aspects of the anorectal functions responsible for fecal continence and defecation are poorly understood, partly because our understanding is primarily based on manometry, which measures anorectal radial pressures but not axial forces that are responsible for defecation and contribute to fecal continence. First, although a functional disorder of defecation has been traditionally attributed to impaired relaxation of the anal sphincter and/or pelvic floor muscles (i.e., dyssynergia), recent studies suggest that inadequate propulsive forces may also be important (15, 16). These studies need to be confirmed. Moreover, the mechanisms responsible for generating the propulsive force during defecation, which is assessed by recording pressure in the rectum, are unclear. Specifically, the contributions of increased intra-abdominal pressure generated by voluntary effort (12) and rectal contraction (9) to this propulsive force have been disputed. This is an important issue because straining may increase intrarectal pressure but not improve evacuation (16), perhaps because the pelvic floor muscles also contract during straining (17). Second, though clinical observations suggest that the location of stool affects the ease of evacuation, it is unclear if axial rectoanal forces vary along the length of the rectum. Thus patients with a defecatory disorder often report it is harder to evacuate stool located in the upper rectum (i.e., the vault) than the lower rectum (i.e., the ampulla). Third, though defecatory symptoms are attributed to impaired pelvic floor relaxation during defecation, we recently demonstrated that pelvic floor motion assessed by dynamic MRI was abnormal not only during evacuation but also when patients contracted their pelvic floor muscles to retain intrarectal contents (3). These observations need to be confirmed by measuring anorectal forces during contraction and expulsion.

To address these questions, we measured anorectal axial forces exerted against a rigid sphere or a latex balloon at specified locations in the anorectum during rectal expulsion and inward traction (REIT) in healthy control subjects and experimental patients with symptoms of difficult defecation by a new device (i.e., the REIT device). Previous studies have evaluated axial rectoanal forces to assess the mechanisms of fecal continence, but not defecation (7, 8, 10). These studies have demonstrated that the axial force measured by an intrarectal solid sphere was correlated with anal pressures measured by manometry (7, 10). Moreover, the inward axial force, reflecting contraction of the anal sphincters and the pelvic floor, was reduced in patients with fecal incontinence (8, 10).

MATERIAL AND METHODS

Participants

Twelve healthy women (age $31.3 \pm 2.3$ yr, means $\pm$ SE) and 12 women with symptoms of difficult defecation (age $44.5 \pm 4.3$ yr, means $\pm$ SE) consented to participate in this study, which was...
approved by the Institutional Review Board of the Mayo Clinic. A clinical interview and physical examination were performed for all participants. Healthy control patients were recruited by public advertisement. Exclusion criteria for control patients included significant cardiovascular, respiratory, neurological, psychiatric, or endocrine disease, irritable bowel syndrome as assessed by a validated bowel disease questionnaire (4), medications (with the exception of oral contraceptives or thyroid supplementation), and abdominal surgery (other than appendectomy or cholecystectomy). In addition, healthy subjects who had any previous anorectal operations including hemorrhoid procedures or had sustained anorectal trauma during delivery (i.e., grade 3 or 4 laceration), as documented by obstetric records, were excluded. Experimental patients were recruited from a specialized clinic devoted to gastrointestinal motility disorders. All experimental patients had two or more symptom-based criteria for functional constipation (18). Colonic motor functions were evaluated by assessing colonic transit with scintigraphy in eight experimental patients (6) or by assessing colonic motility (i.e., tonic and phasic pressure activity in the descending colon under fasting conditions, after a meal, and after neostigmine by a barostat-manometric assembly) in one experimental patient.

Overall Study Design

On the morning of the study, subjects received two magnesium citrate enemas (Fleet; C. B. Fleet, Lynchburg, VA). Shortly thereafter, anorectal pressures and axial forces were measured by manometry and an axial force transducer, respectively. Prior to the anorectal assessments, an investigator, aided by a digital rectal examination, coached subjects to contract the anal sphincter and pelvic floor muscles, to simulate the process of expulsion, and to do a Valsalva maneuver.

During simulated expulsion, subjects were encouraged to mimic the process they usually employed to defecate. During a Valsalva maneuver, subjects were instructed to expire forcefully against a closed glottis.

Anal Manometry, Rectal Balloon Expulsion, and Rectal Sensation

After two sodium phosphate enemas (Fleet, C. B. Fleet), anorectal testing (i.e., manometry, assessment of rectal compliance and sensation by a barostat, and assessment of rectal traction) was conducted in the left lateral position by perfusion manometry. The manometric catheter assembly had eight sensors, i.e., four circumferentially oriented sensors at each of two levels separated by 2 cm. Average anal resting and squeeze pressures were measured by the distal group of four sensors using the station pull-through technique and summarized as described previously (5). The rectoanal pressure gradient was measured during expulsion; data were summarized by the difference between rectal and anal pressure, averaged over a 10-s interval during which anal pressure was at its lowest. The amount of external traction required to facilitate expulsion of a rectal balloon filled with 50 ml of warm water was also assessed in experimental patients (3, 14). Rectal compliance and sensation were recorded using previously validated techniques by an “infinitely” compliant 7-cm-long balloon with a maximum volume of 500 ml (Hefty Baggies; Mobil Chemical, Pittsford, NY) linked to an electronic rigid-piston barostat (Mayo Clinic, Rochester, MN) (2, 5). An initial or conditioning distension followed by a rectal staircase distension (0–32 mmHg in 4-mmHg steps at 1-min intervals) was performed. Rectal compliance and sensory thresholds for first sensation, desire to defecate, and urgency were recorded during the staircase distension; the threshold was the first sensation of each symptom. Rectal pressure-volume relationships were analyzed by a power exponential function and summarized by the pressure corresponding to half maximum volume (Prhalf) (2, 11).

Rectal Traction

Procedure. Rectoanal axial forces were measured by a customized REIT device adapted after a similar device described previously (7) (Fig. 1). This device comprised an intrarectal device (i.e., either a latex balloon or a rigid sphere 2.5 cm in diameter) that was connected to tension-compression (Transducer Techniques, Temecula, CA) and linear-displacement transducers (Novotechnik, Ostfildern, Germany) and interfaced to a computer. The intrarectal device was fixed at 8, 6, or 4 cm from the anal verge. We chose to use a sphere 2.5 cm in diameter because Bannister et al. (1) demonstrated that normal subjects could invariably expel a sphere of this size. The latex balloon was filled with 60 ml of water, and the intraballoon pressure was also measured during maneuvers. Each maneuver began with a baseline period of 20 s, during which the resting force was assessed. Thereafter, subjects were asked to squeeze (i.e., contract) their pelvic floor and anal sphincter muscles for 30 s, or to expel the device for 30 s, or to do a Valsalva maneuver for 20 s, in that order. A rest period of 30 s

Fig. 1. Rectal expulsion and inward traction (REIT) device. A sphere (thin arrow) or a latex balloon (not shown) were connected to a pressure transducer (thick arrow) and to axial-force and linear-displacement transducers (arrowhead).

Fig. 2. Representative example of rectoanal axial forces during squeeze, expulsion, and a Valsalva maneuver. During squeeze, forces were more negative (i.e., directed inward) when the sphere was located at 4 cm compared with 6 and 8 cm from the verge. During expulsion, the positive (i.e., outward) force during expulsion was considerably higher at 4 cm compared with 6 and 8 cm from the verge. During a Valsalva maneuver, outward forces were generated at all locations.
separated consecutive maneuvers. Data were acquired, displayed, and analyzed by a customized Labview-based program (National Instruments, Austin, TX).

Data analysis. In each subject, the baseline resting force was averaged over 10 s immediately prior to each maneuver. The force change during maneuvers was calculated by subtracting the baseline force from the force during maneuvers.

Statistical Analysis

Axial rectoanal forces at baseline and the force change during maneuvers (i.e., squeeze, expulsion, and a Valsalva maneuver) were analyzed by a mixed-model analysis of covariance, fitting terms for location, maneuver, and subject status (i.e., experimental patient or control patient). To validate the measurements of force, the relationship between force and pressure was assessed separately for each maneuver with a latex balloon in each subject. The relationship between the rectoanal pressure gradient during expulsion measured by manometry and the force change during expulsion was also assessed. All results are means ± SE.

RESULTS

Clinical Features

Consistent with the Rome II criteria, all experimental patients reported two or more symptoms of functional constipation for ≥25% of the time. Symptoms included excessive straining during defecation (92% experimental patients), hard stools (62%), sense of incomplete evacuation after defecation (92%), sense of anorectal blockage or obstruction (69%), infrequent stools (i.e., less than 3 times per week; 85%), and digital removal of stool from the rectum (77%). The duration of symptoms ranged from <1 yr (n = 2), 1–5 yr (n = 4), 5–10 yr (n = 2), or more than 10 yr (n = 4).

Anorectal Manometry, Standard Rectal Balloon Expulsion, and Colonic Motor Functions

Average anal resting pressures were comparable in control patients (66 ± 6 mmHg) and experimental patients (65 ± 7 mmHg). Average squeeze pressures were also comparable in control patients (150 ± 17 mmHg) and experimental patients (137 ± 16 mmHg). Ten experimental patients had an abnormal rectal balloon expulsion test and/or an abnormal rectoanal pressure gradient during simulated expulsion. The rectal balloon expulsion test was normal (i.e., ≤100 g traction required) in four and abnormal in eight experimental patients. The rectoanal pressure gradient during expulsion was also abnormal in eight experimental patients, including two patients who had a normal rectal balloon expulsion test. Seven experimental patients had normal colonic motility assessed by scintigraphy (6 patients) or by an intraluminal colonic barostat-manometric assembly (1 patient). Two experimental patients had delayed colonic transit.

Rectal Compliance and Sensation

During rectal staircase balloon distension, 9 of 12 subjects tolerated distension up to the highest pressure, i.e., 32 mmHg. Because of significant discomfort, this distension was terminated at 12 and 24 mmHg in 2 subjects, precluding an assessment of rectal compliance in these subjects. Among the remaining subjects, the Pr half for rectal compliance was within normal limits, i.e., 14.4 ± 0.5 mmHg. Three experimental patients had a stiff rectum, as evidenced by a Pr half that was above the 90th percentile value for healthy subjects in our laboratory.

During rectal staircase distension, the sensory thresholds for first sensation, desire to defecate, and constant urgency aver-
aged $11.5 \pm 1.4$, $15.7 \pm 1.1$, and $23.5 \pm 1.8$ mmHg, respectively; these values were within the 10–90th percentile of normal values for our laboratory. The corresponding volume thresholds were $110 \pm 20$, $150 \pm 17$, and $216 \pm 19$ ml, respectively. Although sensory thresholds expressed as pressure were within the normal range for all subjects, volume thresholds for the desire to defecate were above the 90th percentile value in two experimental patients.

**Assessment of Axial Forces with a Sphere**

Figure 2 provides representative tracings of axial forces recorded by a solid sphere during squeeze, expulsion, and a Valsalva maneuver. Axial forces directed inward (i.e., orad) and outward (i.e., caudad) were designated negative and positive, respectively. At rest (i.e., before maneuvers), the sphere recorded an inwardly oriented force at 4 and 6 cm and an outwardly oriented force at 8 cm from the verge (Fig. 3). Therefore, the resting force was influenced ($P < 0.0001$) by the location of the sphere in control patients and experimental patients. Moreover, the inward resting force was weaker ($P = 0.01$) in experimental patients compared with control patients (Fig. 3).

Both control patients and experimental patients exerted an outwardly directed force against a sphere during expulsion and a Valsalva maneuver (Figs. 3 and 5). Conversely, both control patients and experimental patients generated an inwardly directed force when they squeezed (i.e., contracted) their pelvic floor muscles and an outward force during expulsion and a Valsalva maneuver. Both control patients and experimental patients exerted a stronger outward force during expulsion against a latex balloon compared with a sphere (Figs. 3–5). Similar to a sphere, outward forces during expulsion and a Valsalva maneuver were weaker in experimental patients compared with control patients (Fig. 4).

During voluntary maneuvers, control patients and experimental patients generated an inward force when they squeezed their pelvic floor muscles and an outward force during expulsion and a Valsalva maneuver. Both control patients and experimental patients exerted a stronger outward force during expulsion against a latex balloon compared with a sphere (Figs. 3–5). Similar to a sphere, outward forces during expulsion and a Valsalva maneuver were weaker in experimental patients compared with control patients. However, in contrast to a sphere, 1) the inward force during squeeze was also weaker in experimental patients compared with controls, and 2) the force change during maneuvers with a balloon was not significantly different across locations (i.e., at 4, 6, and 8 cm from the verge) in control patients or experimental patients.

Table 1. **Rectoanal pressures measured by a balloon at rest and during maneuvers in healthy subjects**

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Controls 4 cm</th>
<th>Patients 4 cm</th>
<th>Controls 6 cm</th>
<th>Patients 6 cm</th>
<th>Controls 8 cm</th>
<th>Patients 8 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resting pressure (i.e., before maneuver)</td>
<td>25 (13, 36)</td>
<td>28 (17, 39)</td>
<td>22 (12, 34)</td>
<td>24 (14, 35)</td>
<td>38 (27, 50)</td>
<td>31 (20, 42)</td>
</tr>
<tr>
<td>Squeeze (during – before)</td>
<td>26 (16, 37)</td>
<td>11 (1, 20)</td>
<td>14 (3, 25)</td>
<td>8 (-2, 17)</td>
<td>-5 (-16, 6)</td>
<td>6 (-3, 16)</td>
</tr>
<tr>
<td>Expulsion (during – before)</td>
<td>17 (2, 32)</td>
<td>29 (16, 43)</td>
<td>29 (14, 43)</td>
<td>37 (24, 51)</td>
<td>35 (20, 50)</td>
<td>39 (25, 52)</td>
</tr>
<tr>
<td>Valsalva (during – before)</td>
<td>24 (12, 35)</td>
<td>13 (2, 24)</td>
<td>27 (16, 38)</td>
<td>13 (2, 24)</td>
<td>32 (20, 43)</td>
<td>11 (0, 22)</td>
</tr>
</tbody>
</table>

All values are means with 95% confidence interval in parentheses for pressure measured in mmHg.
ing pelvic floor contraction (8). Using a new device (REIT), we
jects squeezed, they exerted an inward axial force even when
10). Similar to previous studies, we observed that when sub-
contraction of the anal sphincters and the pelvic floor, was
manometry (7, 10). Moreover, the inward axial force, reflecting
solid sphere was correlated with anal pressures measured by
outwardly or contribute to continence when directed inward.
axial forces that are responsible for expulsion when directed
force during expulsion in experimental patients. These obser-

Relationship Between Force and Pressure Assessed by a
Latex Balloon

Table 1 provides the pressures recorded by a latex balloon at
rest and the change in pressure during maneuvers. Compared
with rest, rectal pressures generally increased during all ma-
neuvers. In control patients, the rectal pressure change during
expulsion and a Valsalva maneuver was comparable (i.e., 95%
confidence intervals overlapped). Among experimental pa-
tients, the axial force during a Valsalva maneuver was signif-
ically lower than during expulsion.

To validate force measurements, we examined the correla-
tion between axial forces and pressures measured by the latex
balloon. Figure 6 and Table 2 demonstrate that force and
pressure during maneuvers with a latex balloon were corre-
lated. These correlations were modest to excellent at all loca-
tions during expulsion and a Valsalva maneuver and at 4 and
6 cm during squeeze. During squeeze, these correlations were
negative because forces were negative (i.e., directed inward).

DISCUSSION

Anal manometry measures circumferential pressures but not
axial forces that are responsible for expulsion when directed
outwardly or contribute to continence when directed inward.
In previous studies, the axial force measured by an intrarectal
solid sphere was correlated with anal pressures measured by
manometry (7, 10). Moreover, the inward axial force, reflecting
contraction of the anal sphincters and the pelvic floor, was
reduced in experimental patients with fecal incontinence (8,
10). Similar to previous studies, we observed that when sub-
jects squeezed, they exerted an inward axial force even when
an intrarectal device was located above the anal canal, reflect-
ing pelvic floor contraction (8). Using a new device (REIT), we
measured axial forces not only during squeeze but also during
expulsion and a Valsalva maneuver at specified locations
within the anorectum. Consistent with the length of the anal
sphincter (i.e., between 2–5 cm from the anal verge), the
resting force was strongest at 4 cm from the anal verge, (i.e.,
within the anal canal). Moreover, the inward force was aug-
mented during squeeze to a greater extent as the intrarectal
device approached the anal verge. Simultaneous measurements
of axial force and pressure by a latex balloon during maneuvers
were significantly correlated at most locations, validating force
measurements by the REIT device against the existing standard
(i.e., pressure).

Four observations from this study provide insights into the
mechanisms of normal and disordered continence and expul-
sion. First, healthy subjects augmented the resting inward force
when they squeezed (i.e., contracted) their pelvic muscles and
exerted an outward force during expulsion and a Valsalva
maneuver. Second, compared with control patients, experi-
mental patients with defecatory symptoms exerted a weaker inward
force when they squeezed the pelvic floor and a weaker
outward force not only during expulsion but also during a
Valsalva maneuver, supporting the concept of generalized
pelvic floor weakness. Third, rectoanal forces were higher for
a latex balloon, which provides a closer approximation to a
normally formed stool than does a sphere. Last, forces were
influenced by the location of the device relative to the anal
verge. Thus the outward force during expulsion and a Valsalva
maneuver was strongest at 4 cm from the verge, perhaps
explaining why experimental patients find it easier to evacuate
stool located in the lower, compared with the upper rectum.

During a Valsalva maneuver in control patients, the axial
force, which reflects the net outward force, was comparable to
the outward force during expulsion. The intrarectal pressure,
which is a surrogate marker of the propulsive effort, increased
by an average of 31 mmHg during a Valsalva maneuver. This
increase in intrarectal pressure is similar to that reported in a
previous study in which intra-abdominal pressure increased by
36 mmHg during a Valsalva maneuver (13). Among experi-
mental patients, the axial force and intrarectal pressure change
during a Valsalva maneuver were lower than in control pa-
tients. Taken together, these observations suggest that the
lower outward axial force during a Valsalva maneuver in
experimental patients may be explained by a weaker propulsive
effort. The outward axial force during expulsion was correlated
with the rectoanal pressure gradient during expulsion measured
by manometry. However, in contrast to a Valsalva maneuver,
the intrarectal pressure during expulsion was comparable in
experimental patients and control patients, suggesting that
increased outlet resistance accounted for the weaker outward
force during expulsion in experimental patients. These obser-

Table 2. Relationship between axial force and pressure measured by a latex balloon during maneuvers

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Location</th>
<th>4 cm</th>
<th>6 cm</th>
<th>8 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squeeze</td>
<td></td>
<td>−0.71 (−0.97, −0.51)</td>
<td>−0.65 (−0.96, −0.44)</td>
<td>−0.01 (−0.61, 0.49)</td>
</tr>
<tr>
<td>Expulsion</td>
<td></td>
<td>0.62 (0.27, 0.9)</td>
<td>0.80 (0.72, 0.96)</td>
<td>0.69 (0.52, 0.97)</td>
</tr>
<tr>
<td>Valsalva</td>
<td></td>
<td>0.54 (0.15, 0.93)</td>
<td>0.87 (0.83, 0.96)</td>
<td>0.87 (0.85, 0.98)</td>
</tr>
</tbody>
</table>

All values are means with 95% confidence interval in parentheses for the correlation coefficient.
vations expand on the concept introduced by Rao et al. (16) that symptoms of obstructive defecation are associated with inadequate propulsive forces and/or with increased resistance to expulsion. They also reinforce the concept that impaired expulsion in obstructive defecation is not a fixed process but is strongly influenced by voluntary actions. Similar to anal manometry, forces were assessed in the decubitus position. Further studies are necessary to compare forces in the seated and decubitus positions.

In addition to a weaker outward force, the inward force during squeeze against a latex balloon was also weaker in experimental patients than in control patients. However, the inward force exerted against a sphere was not significantly different in experimental patients and control patients. These results confirm previous observations that the rectoanal axial force is influenced by the size of the intrarectal device (7). They also corroborate recent observations that pelvic floor motion during squeeze, assessed by dynamic MRI, was reduced in women with defecatory symptoms (3). Taken together, these findings (i.e., reduced axial forces during expulsion, Valsalva maneuver, and squeeze) are consistent with the hypothesis that a subset of patients with defecatory symptoms have generalized pelvic floor weakness, rather than an isolated impairment of pelvic floor relaxation during expulsion. This hypothesis needs to be substantiated by simultaneous assessments of abdominal wall activity, (e.g., by electromyogram) and axial forces during voluntary maneuvers.

The intrarectal sphere or balloon was connected to the transducers by a solid, inelastic segment, thus avoiding the drawback of an elastic connection that stretches and affects the force measured during maneuvers (10). In contrast to a previous study, the intrarectal latex balloon or sphere was fixed relative to the anal verge during assessments to avoid reflexive sphincter contraction induced by movement of the device (7). However, we cannot exclude the possibility that the resting axial force was influenced by proprioceptive input resulting from an object within the anorectum. The force change during maneuvers was substantially higher with a balloon compared with a sphere, perhaps because the balloon was in contact with, and therefore measured forces exerted by, a larger surface area (~100 cm²) compared with a sphere (16 cm²). It is also conceivable that a hydraulic effect (i.e., displacement of fluid within a balloon during a maneuver), also increased the axial force exerted against a balloon. From a practical perspective, a latex balloon may be preferable to a sphere because it approximates more closely to stool and also because it is easier to introduce a deflated balloon compared with a sphere into the rectum in subjects with high resting anal pressure. On the other hand, a sphere was more useful for characterizing the effects of location on rectoanal forces, probably because it had a smaller surface area than the balloon. Diamant and Harris (7) showed previously that the axial force was not influenced by friction, because similar forces were recorded by a regular sphere and another sphere with a smooth Teflon surface.

In summary, our studies demonstrate that the rectoanal forces responsible for defecation and contributing to fecal continence can be measured at specific locations within the anorectum by a new device. Rectoanal axial forces during voluntary actions (i.e., squeeze, expulsion, and a Valsalva maneuver) were influenced by device location within the anorectum. Both devices recorded weaker axial forces during expulsion and a Valsalva maneuver in experimental patients compared with control patients. The force during squeeze against a latex balloon was also weaker in experimental patients, consistent with the concept that some patients with defecatory symptoms have generalized abdomino-pelvic weakness, rather than an isolated impairment of pelvic floor relaxation.

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