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Biomechanical wall properties of the human rectum. A study with impedance planimetry

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Abstract

Biomechanical properties of the rectal wall were studied in 17 healthy adult volunteers (nine men and eight women). With impedance planimetry it is possible to obtain simultaneous measurements of pressure and rectal cross sectional area (CSA) during balloon inflations. Rectal distensions were done with an intraluminal balloon using specified pressures up to 40 cmH_2O above baseline rectal pressure. Balloon inflation elicited a phase of rapid increase in rectal CSA followed by a phase of slow increase until a steady state was reached. Steady state occurred within 67 to 140 seconds with the shortest period at the highest distension pressures. Steady state rectal CSA values had a non-linear relation to increasing distension pressure. Rectal CSA values in women showed a tendency of being slightly higher than male values at all pressure steps with a significant difference at 3 and 5 cm H_2O. Biomechanical parameters were calculated from rectal CSA pressure relations. Circumferential wall tension increased in a linear way. Rectal compliance decreased in a non-linear way with no further decline between 30 and 40 cmH_2O. The pressure elastic modulus increased steeply until a distension pressure of 35 cmH_2O with no further increase to 40 cmH_2O. This suggests that rectal tone is reduced as the muscle fails to resist further distension at 35 cmH_2O and higher pressures. Impedance planimetry offers new possibilities for investigation of anorectal physiology through the study of segmental biomechanical wall properties of the human rectum.

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Changed anorectal function and innervation are commonly studied by pressure-volume relations by balloon distension, reflex investigations, characterisation of sphincter function, and registration of rectal sensation.[1-6]

Balloon distension elucidates the reservoir mechanism from a sensory point of view. It provides some information on biomechanical properties of the rectal wall. Commonly, rectal distensibility is determined as rectal compliance and calculated as the changes of volume and intrarectal pressure ($\Delta V/\Delta P$). Radial expansion, however, is not necessarily related to the volume infused because of the multidirectional expansion of the volume. Longitudinal extension of a compliant balloon is likely to occur during distension. This happens when tension, which has developed in the rectal wall, impedes further radial expansion.[7-9] The value of such compliance measurements is disputed.[7 10] To characterise segmental biomechanical properties of the rectal wall and regional thresholds of sensation new methods have to be introduced.

This study concerns a method named impedance planimetry by which it is possible to obtain segmental information on biomechanical properties at one specific circumference of the rectal wall. The aim was to describe these properties by measuring rectal cross sectional area (CSA) at the site of distension upon graded isobaric distension in healthy volunteers. We have used the technique in human and animal studies of intestinal wall properties.[11-15]

Methods

SUBJECTS

We studied 17 healthy volunteers without any history of bowel disease. The volunteers were nine men (age 28 (27–29) years, height 185 (179–187) cm, weight 80 (75–85) kg) and eight women (26 (23–29) years, 169 (166–172) cm, 58 (53–63) kg). Before the study we obtained informed consent from all subjects. The study was performed according to the second declaration of Helsinki and approved by the Ethical Committee of Aarhus county.

The study was conducted between 8 00 am and 1 00 pm. There was a period of at least 12 hours of fasting before the investigations. No laxative was used and subjects were asked to empty the rectum and bladder. Before the investigation a digital examination confirmed an empty rectum.

TECHNIQUE AND EXPERIMENTAL PROBE DESIGN

We used a specially constructed four electrode impedance measuring system located inside a balloon on a 20 cm long probe with an 8 mm external diameter (Fig 1). Two outer ring electrodes for excitation were placed with an interelectrode distance of 6 cm. A generator delivered a constant alternating current of 100 microamperes at 5 kHz for excitation.[9 15] Midway between the excitation electrodes we placed two ring electrodes with an interelectrode distance of 0·2 cm for measurement of impedance. We used copper electrodes wound around the probe in 0·5 mm wide grooves to ensure a smooth surface. The distance between the excitation and detection electrodes was chosen on the basis that the CSA can be measured up to a diameter of 4 to 5 times the interelectrode distance.[13]

We measured CSA according to the field gradient principle from the measurement of impedance of the fluid inside the balloon.[13 16-18] Rise time for measurement of CSA was 0·02

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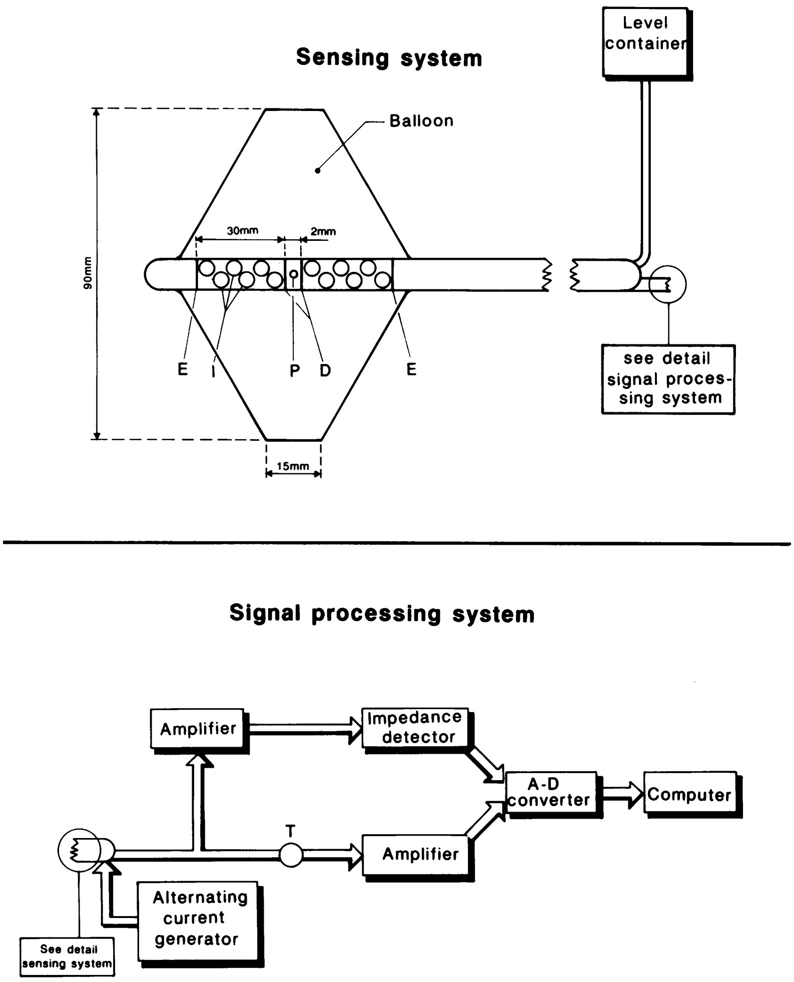

Figure 1: Upper drawing is a schematic diagram of the sensing system including the probe for measurement of rectal CSA. D=electrode for detection, E=electrode for exitation, I=infusion channels, and P=side hole for pressure measurement. Lower drawing shows the signal processing system for signals recording and online storing. T=pressure transducer.

(0·02–0·03) seconds.[19] We calibrated the CSA measuring system in PVC tubes with holes of known CSAs. Before the measurements we calibrated the measurement system with a two point minimum and maximum calibration.

The latex balloon was 6·9 cm long. To prevent longitudinal elongation of the balloon during distension we chose a balloon with a wall thickness of 0·2 mm. The balloon could be inflated with 37°C electrically conducting fluid (0·65 mM NaCl solution) through an infusion channel (diameter 4·5 mm) up to a CSA of 6361 mm^2 (diameter=90 mm and a volume of 200 ml) without stretching the balloon wall. The container was cylindrical with a surface area of 363 cm^2 ensuring a maximum reduction of the water level in the container of 0·55 cm in case of maximum balloon inflation. With a digitally controlled heating device (microprocessor HT 50, temperature sensor Pt 100, and heating tape BD 1194, Horst, Germany) we secured the temperature stability of the infusion fluid. A side hole for balloon pressure measurements was placed between the detection electrodes. The lumen and the side hole had diameters of 0·7 mm. We measured pressure with a low compliance perfusion system connected to an external transducer (strain gauge MX860, Medex Inc) with a perfusion rate of 0·16 to 0·20 ml min^{-1}. Rise time for measurement of pressure was 0·09 (0·08 to 0·10) seconds.[19]

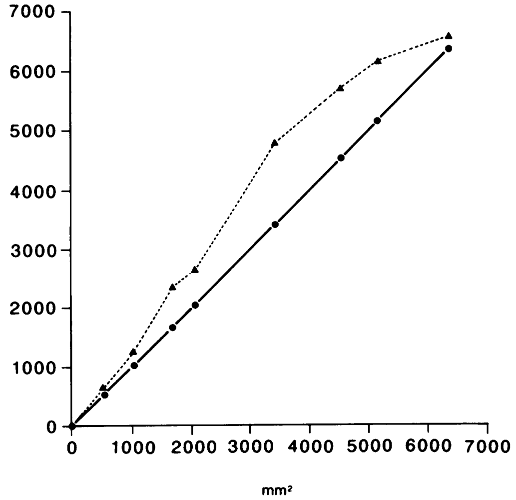

Figure 2: A diagram of an 8 point calibration. The calibration signals after the initial two point calibration (....) and after the final 8 point calibration (__) are shown.

INVESTIGATIONAL PROCEDURE

The subjects were placed in the left lateral position with hips and knees flexed to 90°.[20] Calibration of the measuring system was done before the insertion of the probe into the rectum. We secured the position of the prove by tape attached to the buttocks and measured the rectal CSA between 8·2 and 8·4 cm from the anal verge.

The balloon was inflated to a pressure of 30 cmH_2O to unfold the balloon before the measurements were recorded. There was a resting period of 20 minutes before the measurements were taken. After this period we did a series of rectal pressure distensions. We assessed the baseline rectal pressure by increasing the pressure column in steps of 1 cm. We continued until the inflation of the balloon caused an increase in rectal CSA. Raising a pressure column of consecutively increasing pressures at 3, 5, 10, 15, 20, 25, 30, 35, and 40 cm above the baseline rectal pressure provided the distension stimulus. Each distension lasted at least 1·5 minutes and until a steady state rectal CSA value. Five minute rest periods separated each rectal distension. We tested the in vivo reproducibility of the steady state values with repeated measurements at the pressure steps 10, 20, 30, and 40 cm H_2O in five subjects. After each rectal distension, the subjects described their sensation.

Records of rectal CSA and pressure were amplified and analogue to digital converted with a sample frequency of 10 Hz and stored online with software developed in our laboratory (Mingo).[21]

DATA ANALYSIS

Computer analysis was applied to the data.[21] The calibration curve was non-linear. Therefore we calibrated the results with an 8 point calibration curve to obtain a final linear calibration (Fig 2). We determined the steady state rectal CSA values for further analysis of the biomechanical parameters.

Definition of biomechanical parameters

Circumferential wall tension=R P_t, where R is the intraluminal radius (R=square root of rectal CSA π^{-1}) and P_t the transmural pressure difference (law of LaPlace).

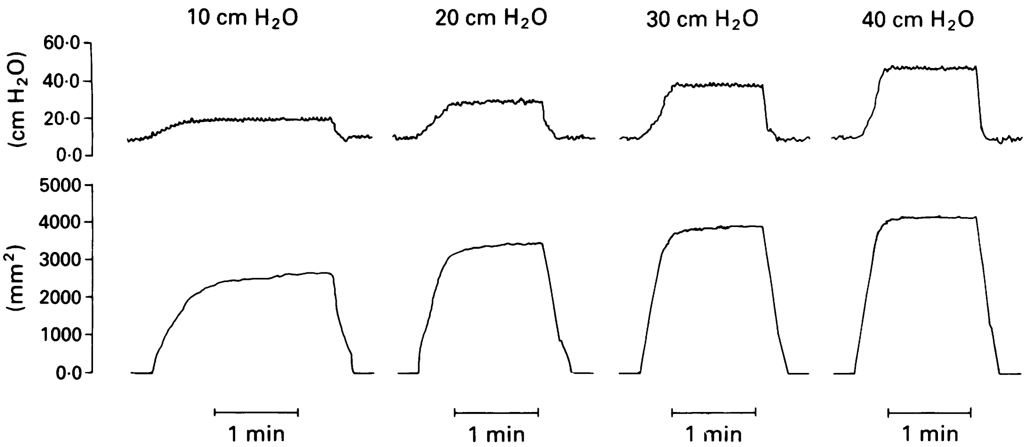

Figure 3: A series of rectal wall distensions with distension pressures of 10, 20, 30, and 40 cmH_2O above the baseline rectal pressure. BP is the balloon pressure. RCSA=rectal cross sectional area.

Compliance=Δrectal CSA ΔP^{-1}, where Δrectal CSA and ΔP are the changes in rectal CSA and pressure between two consecutive steps.

Pressure elastic modulus (wall stiffness)=ΔP R ΔR^{-1}, where ΔR and ΔP are the change in radius and pressure between one step and the value obtained two steps apart.

STATISTICAL ANALYSIS

Data are presented as medians and quartiles. We used the Mann-Whitney U test to compare the results of different groups. Results were significant if $p<0{\cdot}05$. Furthermore, we used a Wilcoxon signed ranks test to test the in vivo reproducibility of steady state rectal CSA values.

Results

The baseline rectal pressure was 4 (4–5) cmH_2O. Figure 3 shows recordings at different distension pressures and the resulting increase in rectal CSA from one subject. An initial rapid rectal CSA increase was followed by a phase of slow increase until steady state was reached. This was the configuration of the rectal CSA change seen in all the balloon inflations. Rectal reflex contractions elicited upon distensions were detected as deflections in rectal CSA, but no clearcut relation to the distension pressure could be established. The time to steady state rectal CSA was 67 to 140 seconds with the shortest period at the highest distension pressures. As Figure 4 shows, we found a good in vivo reproducibility of the steady state rectal CSA values ($p=0{\cdot}53$).

Steady state rectal CSA values had a non-linear relation to the increasing distension pressure (Fig 5). Rectal CSA values in women showed a tendency to be slightly higher than in men. The difference, however, was only statistically significant at distension pressures of 3 and 5 cm H_2O ($p=0{\cdot}037$ and $p=0{\cdot}012$). Rectal CSA values related to height, weight, and surface area showed no significant relation.

Among the calculated biomechanical wall parameters only wall tension showed significant differences at the lowest distension pressures between men and women. Therefore, we considered all subjects as belonging to one group when presenting the data for the these parameters. Rectal wall tension increased in a linear way with increasing distension pressures (Fig 6),

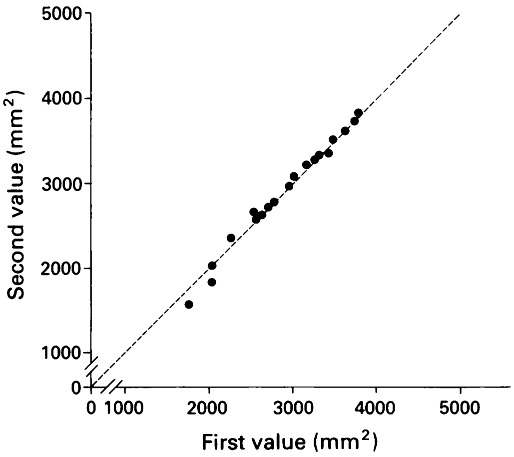

Figure 4: In vivo reproducibility of the rectal CSA measurement in five subjects at the distension pressures of 10, 20, 30, and 40 cmH_2O. Five minutes separated measurement of the first and second value at each step.

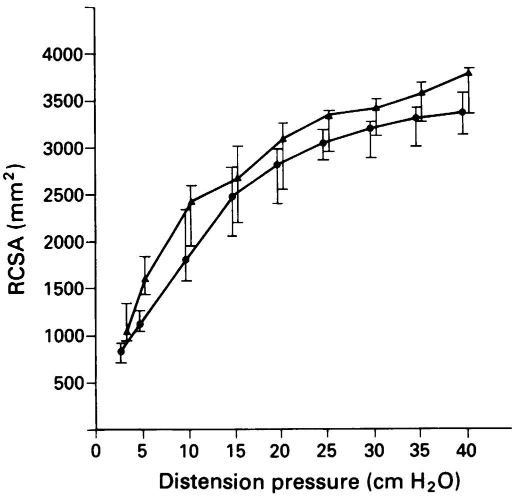

Figure 5: The steady state rectal cross sectional area (RCSA) as a function of the distension pressure. Medians and quartiles are shown. ▲=women (n=8), ■=men (n=9).

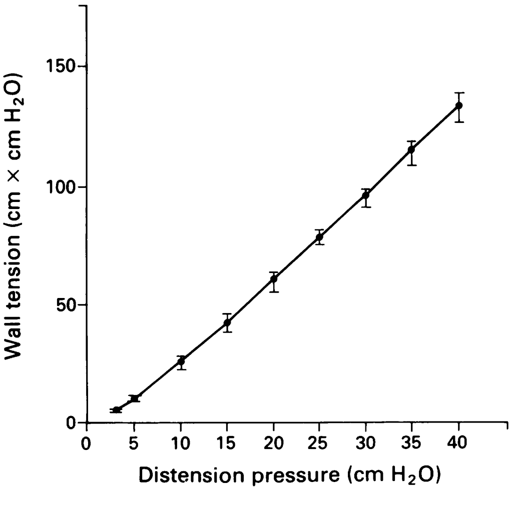

Figure 6: Wall tension as a function of the distension pressure. Medians and quartiles are shown (n=17).

whereas rectal compliance decreased in a non-linear way with increasing distension pressure. There was no further decline in rectal compliance between 30 cmH_2O and 40 cmH_2O (Fig 7). The pressure elastic modulus increased in an almost sigmoid way until a distension pressure of 35 cmH_2O. There was a small but insignificant decrease in wall stiffness between the distension pressures of 35 cmH_2O and 40 cmH_2O (Fig 8).

RECTAL SENSATIONS

Figure 9 shows data for rectal sensations. Only three subjects had a feeling of wind before a period of intermittent need for defecation. This feeling was followed by a feeling of continued need for defecation throughout the distension period. Only one subject had a feeling of urge at the highest pressure step. It was possible to classify rectal sensations into a group with no sensation, a group with intermittent need for defecation, and a group with continued need for defecation throughout the distension period. A comparison of men and women in terms of rectal CSA, wall tension, and pressure at the onset of intermittent need for defecation showed no significant difference ($p=0{\cdot}22$, $p=0{\cdot}26$, and $p=0{\cdot}49$, respectively). Furthermore, there was no significant difference at the onset of continued need for defecation throughout the distension period ($p=0{\cdot}26$, $p=0{\cdot}22$, and $p=0{\cdot}39$, respectively).

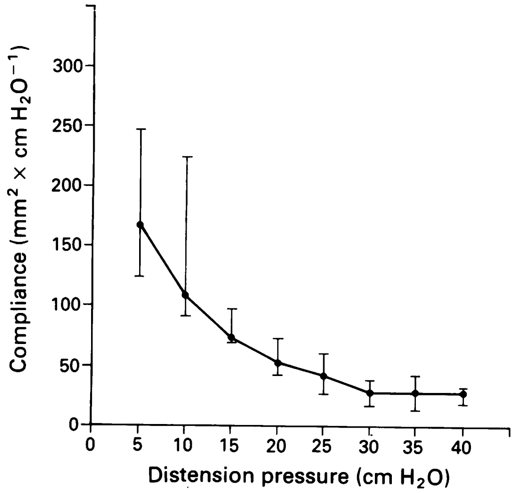

Figure 7: Rectal compliance as a function of the distension pressure. Medians and quartiles are shown (n=17).

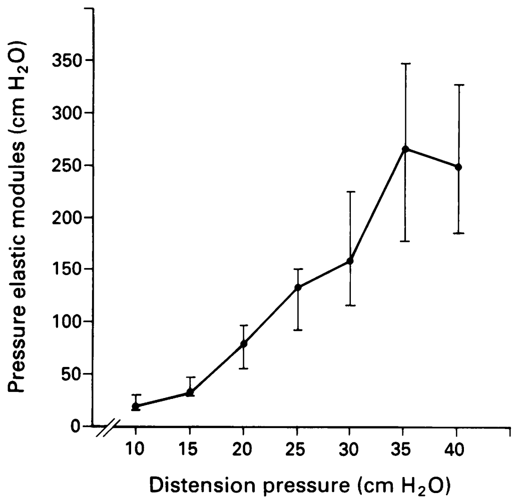

Figure 8: Wall stiffness stated as the pressure elastic modulus at the different distension pressures. Medians and quartiles are shown (n=17).

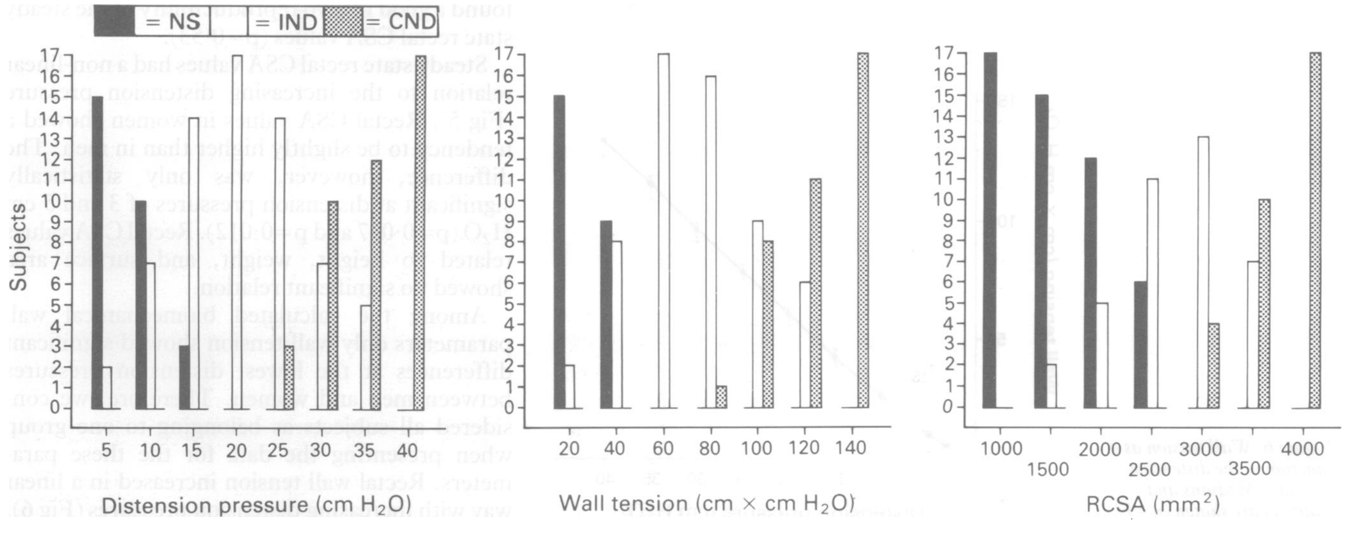

Figure 9: Rectal sensations elicited upon rectal distensions. Data are presented in groups. NS=no sensation, IND=intermittent need for defecation, CND=continuous need for defecation, and RCSA=the steady state rectal cross sectional area (n=17).

Discussion

Impedance planimetry is a novel technique offering possibilities to characterise biomechanical properties in vivo of the gut wall.[11 12 18] The principles of measurement and possible sources of error of this technique have been described in detail.[11-13 16 18 22 23]

The method provides an accurate segmental measurement of distension of tubular organs. From measurements of pressure and CSA the technique allowed us to derive several biomechanical parameters. The thickness of the rectal wall during distension could not be measured. Therefore, we calculated the circumferential wall tension, compliance, and the pressure elastic modulus rather than wall stress and Youngs elastic modulus.[24]

The validity of rectal distension measurements, usually determined with pressure-volume relations, is disputed.[7 8 25] Volume is a three dimensional variable. Studies of other tubular organs have shown that the major tensile stress during distension is in the circumferential direction.[24] Because volume is a three dimensional variable, it does not give exact information about a specific circumference. The advantage of pressure and volume relations seems more obvious in globular organs such as the bladder[26] and the stomach by use of a barostat.[27] With the rectal pressure as the zero pressure reference point, the applied distension pressure most probably equals the transmural pressure allowing the calculation of circumferential wall tension according to the law of LaPlace. The calculation is valid for the innermost layer of the wall at a constant transmural pressure and at steady state conditions. Furthermore, a uniformly cylindrical lumen and wall contact at the site of distension must be assumed during distensions. We achieved that in a previous study,[19] and before this study we showed these conditions with a vaginal ultrasonic probe during distension series of the rectum (unpublished data).

In this study the rectal CSA curve at each distension pressure could be described by an initial rapid phase followed by a slow phase of filling before reaching steady state. Previously, we have shown similar patterns in other intestinal segments by use of impedance planimetry.[19] It is a measure of viscoelastic properties, and not as previously stated a particular rectal phenomenon of accommodation to different volume loadings.[9] The rectal CSA values of men and women were significantly different at transmural pressures of 3 and 5 $\mathrm{cmH_2O}$. This shows that the rectal lumen is bigger and that the rectum is more compliant at low induced pressures in women. We need further investigations, however, including larger populations of men and women to confirm the tendency of higher low pressure distensibility in women than in men.

Despite a non-linear increase of luminal rectal radius similar to the rectal CSA increase, the increase of the circumferential wall tension with increasing distension pressures was linear. This suggests a major influence of the transmural pressure on this parameter calculated according to the Law of LaPlace. Calculation of stress-strain relations seems more appropriate to estimate the load of distension on a rather thick walled human rectum.

Compliance showed no linear relation to the distension pressure (Fig 7). The rectum was most compliant at low pressures and declined with increasing distension pressure until no further progress in compliance between the pressures of 30 to 40 $\mathrm{cmH_2O}$. Because nonlinearity it is doubtful if rectal compliance should be characterised by a single value. The pressure elastic modulus showed a similar non-linear pattern. This parameter is more appropriate than compliance to describe biomechanics because it measures the changes in rectal CSA and pressure and also considers the actual degree of distension.

Variations in rectal tone as shown by Bell *et al* might change rectal distensibility upon distension.[28] The influence of smooth muscle cells within the wall of a tubular organ upon intraluminar distensions is shown in studies of vascular distensibility. Variations in vascular muscle stiffness change arterial distensibility, for example, when the arterial muscle contracts, the vessel is less distensible.[24] In this study, the rectal pressure elastic modulus (wall stiffness), increased steeply until a distension pressure of 35 $\mathrm{cmH_2O}$ with no further increase to 40 $\mathrm{cmH_2O}$. At 35 $\mathrm{cmH_2O}$ and higher pressures muscle tone may be reduced as the muscle fails to resist further distension. If only passive properties determine the pressure elastic modulus, an exponential increase would have been expected. We showed this in a previous study of the isolated perfused porcine duodenum.[19] Studies of the human oesophagus and duodenum showed the same influence of intestinal tone upon the pressure elastic modulus during distension.[29 30]

Sensations elicited by rectal distensions are the subject for research by several investigators. Volume is commonly the independent variable. Previously, another group performed isobaric distensions with simultaneous registration of the infused volume.[31] In this study we classified rectal sensations elicited by isobaric distensions according to the segmental steady state values obtained. Previous results have shown a higher threshold of rectal sensation in men than in women.[32 33] This could not be confirmed by this study. This may be caused by the use of different techniques, for example, continuous rectal filling with a certain infusion rate up to the maximal tolerable volume.

The method may be a future tool in studies of rectal biomechanical wall properties and anorectal motility elicited by intraluminal distensions. Furthermore, in combination with new techniques, for example, high resolution ultrasound systems, it permits the measurement of and an estimation of stress-strain relations of the rectal wall thickness during distensions.

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1 Denny-Brown DE, Robertson EG. An investigation of the nervous control of defaecation. *Brain* 1935; **58**: 256–310.

2 Goligher JC, Hughes ESR. Sensibility of the rectum and colon. Its role in the mechanism of anal continence. *Lancet* 1951; i: 543–8.

3 Schuster MM, Hendrix TR, Mendeloff AI. The internal anal sphincter response: manometric studies on its normal physiology, neural pathways, and alteration in bowel disorders. *J Clin Invest* 1963; **42**: 196–207.

4 Scharli AF, Kiesewetter WB. Defecation and continence: some new concepts. *Dis Colon Rectum* 1970; **13**: 81–107.

5 Haynes WG, Read NW. Ano-rectal activity in man during rectal infusion of saline: a dynamic assessment of the anal continence mechanism. *J Physiol* 1982; **330**: 45–56.

6 Arhan P, Faverdin C, Persoz B, Devroede G, Dubois B, Dornic C, *et al*. Relationship between viscoelastic properties of the rectum and anal pressure in man. *J Appl Physiol* 1976; **41**: 677–82.

7 Kendall GPN, Thompson DG, Day SJ, Lennard-Jones JE. Inter- and intraindividual variation in pressure-volume relations of the rectum in normal subjects and patients with the irritable bowel syndrome. *Gut* 1990; **31**: 1062–8.

8 Sun WM, Read NW, Prior A, Daly JA, Cheah S, Grundy D. Sensory and motor responses to rectal distension vary according to rate and pattern of balloon inflation. *Gastroenterology* 1990; **99**: 1008–15.

9 Dall FH, Jørgensen CS, Djurhuus JC, Gregersen H. Biomechanical wall properties of the porcine rectum. A study using impedance planimetry. *Dig Dis* 1991; **9**: 346–52.

10 Madoff RD, Orrom WJ, Rothenberger DA, Goldberg SM. Rectal compliance: a critical reappraisal. *Int J Colorect Dis* 1990; **5**: 37–40.

11 Gregersen H, Jensen SL, Djurhuus JC. Changes in oesophageal wall biomechanics after portal vein banding and variceal sclerotherapy measured by a new technique. An experimental study in rabbits. *Gut* 1988; **29**: 1699–704.

12 Gregersen H, Kraglund K, Djurhuus JC. Variations in duodenal cross-sectional area during the interdigestive motility complex. *Am J Physiol* 1990; **259** (Gastrointest Liver Physiol 22): G26–31.

13 Gregersen H, Andersen MB. Impedance measuring system for quantification of cross-sectional area in the gastrointestinal tract. *Med Biol Eng Comput* 1991; **29**: 108–10.

14 Gregersen H, Djurhuus JC. Impedance planimetry. A new approach to biomechanical wall properties in the intestine. *Dig Dis* 1991; **9**: 332–40.

15 Gregersen H, Jørgensen CS, Dall FH, Jensen SL. Spontaneous and evoked motility in the isolated perfused porcine duodenum. *J Appl Physiol* 1992; **73** (1): 9–19.

16 Harris JH, Therkelsen EE, Zinner NR. Electrical measurement of ureteral flow. In: Boyarsky S, Tanagho EA, Gottschalk CW, Zimskind PD, eds. *Urodynamics*. London: Academic Press, 1971: 465–72.

17 Colstrup H, Mortensen SO, Kristensen JK. A probe for measurements of related values of cross-sectional area and pressure in the resting female urethra. *Urol Res* 1983; **11:** 139–43.

18 Gregersen H, Stødkilde-Jørgensen H, Djurhuus JC, Mortensen SO. The four electrode impedance technique: a method for investigation of compliance in luminal organs. *Clin Phys Physiol Meas* 1988; **9** (suppl A): 61–4.

19 Gregersen H, Jørgensen CS, Dall FH. Biomechanical wall properties in the isolated perfused procine duodenum. An experimental study using impedance planimetry. *J Gastrointest Motility* 1992; **4:** 125–35.

20 Åkervall S, Fasth S, Nordgren S, Öresland T, Hultén L. Manovolumetry: a new method for investigation of anorectal function. *Gut* 1988; **29:** 614–23.

21 Andersen MB, Stødkilde-Jørgensen H, Gregersen H. Versatile software system for analysis of gastrointestinal pressure recordings. *Dig Dis* 1991; **9:** 382–8.

22 Lose G, Colstrup H, Saksager K, Kristensen JK. A new probe for measurement of related values of cross-sectional area and pressure in a biological tube. *Med Biol Eng Comput* 1986; **24:** 488–92.

23 Mortensen SO, Djurhuus JC, Rask-Andersen H. A system for measurements of micturition urethral cross-sectional areas and pressures. *Med Biol Eng Comput* 1983; **21:** 482–8.

24 Dobrin PB. Mechanical properties of arteries. *Physiol Rev* 1978; **58:** 397–460.

25 Varma JS, Smith AN. Reproducibility of the proctometrogram. *Gut* 1986; **27:** 288–92.

26 Coolsaet B. Bladder compliance and detrusor activity the collection phase. *Neurourology and Urodynamics* 1985; **4:** 263–73.

27 Azpiroz F, Malagelada JR. Intestinal control of gastric tone. *Am J Physiol* 1985; **249** (Gastrointest Liver Physiol 12): G501–9.

28 Bell AM, Pemberton JH, Hanson RB, Zinsmeister AR. Variations in muscle tone of the human rectum: recordings with an electromechanical barostat. *Am J Physiol* 1991; **260** (Gastrointest Liver Physiol 23): G17–25.

29 Orvar KB, Gregersen H, Christensen J. Biomechanical characteristics of the human esophagus. *Dig Dis Sci* 1993; **38:** 197–205.

30 Gregersen H, Orvar KB, Christensen J. Biomechanical properties of the duodenal wall and tone during phase I and phase II of the MMC. *Am J Physiol* 1992; **263:** G795–801.

31 Åkervall S, Fasth S, Nordgren S, Öresland T, Hultén L. Rectal reservoir and sensory function studied by graded isobaric distension in normal man. *Gut* 1989; **30:** 496–502.

32 Loening-Baucke V, Anuras S. Effects of age and sex on anorectal manometry. *Am J Gastroenterol* 1985; **80:** 50–3.

33 Sun WM, Read NW. Anorectal function in normal human subjects: effect of gender. *Int J Colorect Dis* 1989; **4:** 188–96.