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Traditional measures of normal anal sphincter function using high-resolution anorectal manometry (HRAM) in 115 healthy volunteers

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Key Messages

- High resolution anorectal manometry (HRAM) is an emerging method for examination of anal sphincter function, however at present there are few published data of findings in health using this technique;
- HRAM assessments were performed during rest, squeeze, cough and simulated defecation (push) maneuvers with analysis using Solar GI HRM v9.1;
- This study provides normal data of traditional measures of sphincter function in a large cohort of healthy volunteers (n = 115);
- A number of novel qualitative phenomena were identified, the significance of which may become apparent with comparison to disease states.

Abstract

Background *High-resolution anorectal manometry (HRAM) is a relatively new method for collection and interpretation of data relevant to sphincteric function, and for the first time allows a global appreciation of the anorectum as a functional unit. Historically, traditional anal manometry has been plagued by lack of standardization and healthy volunteer data of variable quality. The aims of this study were: (i) to obtain normative data sets for traditional measures of anorectal function using HRAM in healthy subjects and; (ii) to qualitatively describe novel physiological phenomena, which may be of future relevance when this method is applied to patients.* ***Methods*** *115 healthy subjects (96 female) underwent HRAM using a 10 channel, 12F solid-state catheter. Measurements were performed during rest, squeeze, cough, and simulated defecation (push). Data were displayed as color contour plots and analysed using a commercially available manometric system (Solar GI HRM v9.1, Medical Measurement Systems). Associations between age, gender and parity were subsequently explored.* ***Key Results*** *HRAM color contour plots provided clear delineation of the high-pressure zone within the anal canal and showed recruitment during maneuvers that altered intra-anal pressures. Automated analysis produced quantitative data, which have been presented on the basis of gender and parity due to the effect of these covariates on some sphincter functions. In line with traditional manometry, some age and gender differences were*

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seen. Males had a greater functional anal canal length and anal pressures during the cough maneuver. Parity in females was associated with reduced squeeze increments. ***Conclusions & Inferences*** *The study provides a large healthy volunteer dataset and parameters of traditional measures of anorectal function. A number of novel phenomena are appreciated, the significance of which will require further analysis and comparisons with patient populations.*

Keywords *anal sphincter, anorectal function, high-resolution anorectal manometry (HRAM), high-resolution manometry (HRM), manometry.*

Abbreviations: GI, gastrointestinal; HRAM, high resolution anorectal manometry; HRM, high resolution manometry.

INTRODUCTION

Anorectal manometry is the most widely performed test for the assessment of anal sphincter function and anorectal co-ordination.[1] Nevertheless, both recording equipment and methodology remain unstandardized, which can significantly impact interpretation of results.[2,3] Traditionally, manometry has been performed using either solid-state or water-perfused catheters incorporating a limited number of recording channels (typically ≤6).[2,4] However, the last decade has seen the development of high-resolution manometry with key improvements being: an increased number of closely spaced microtransducers greatly enhancing spatial resolution; the ability to measure pressure changes circumferentially; and software development to allow interpolation between adjacent microtransducers providing the operator with the option of detailed topographical plots of intraluminal pressure events relative to time and location[5]; data can be displayed as a color contour plot, in contrast with a conventional line tracing.

Such technology has resulted in a paradigm shift in manometric testing of the upper gastrointestinal (GI) tract, with high-resolution manometry now having replaced traditional manometry as the gold-standard investigation of esophageal function.[6] However, despite recognized benefits, uptake of high-resolution manometry for the assessment of anorectal function (typically referred to as high-resolution anorectal manometry: HRAM) has been less enthusiastic. Nevertheless the ability to visualize the anorectum as a dynamic structure during test maneuvers should intuitively allow for a better appreciation of normal physiology and hopefully enhance our understanding of the pathophysiology of defecatory dysfunction.[7,8]

One of the principle challenges to adopting HRAM is to establish new normative data sets of an adequate size for recognized measures of anal sphincter function, and to promote standardization of the technique so that results are transferrable between institutions; a problem that has bedeviled traditional practice.[2] To date, the only study examining sphincter function in health using HRAM have been performed in Northern America[7] on 62 female volunteers using the Manoview AR v1.0, Sierra Scientific Instruments system. Given that equipment setup, catheter configuration and software analyses may affect results, the primary aim of this study was to provide a large dataset of parameters of normal anal sphincter function using an alternative, widely available HRAM system. The secondary aim was to qualitatively report phenomena noted during investigations that were previously difficult to recognize or overlooked using traditional manometry.

MATERIALS AND METHODS

Subjects

Healthy, asymptomatic male and female subjects were recruited at Barts and the London School of Medicine and Dentistry, London. Ethical approval was granted by the Queen Mary University Research Ethics Committee (ref QMREC 2010/74 and QMREC 2013/12), and written informed consent obtained. A general and focused clinical history (including obstetric history in females) and examination was performed in all participants. Of note, structural integrity of the anal sphincter was not assessed as endoanal ultrasound was not performed.

Equipment

High-resolution anorectal manometry was performed using a solid-state catheter (UniTip: UniSensor AG, Attikon, Switzerland), of external diameter 12F, incorporating 12 microtransducers, each of which measured circumferential pressure by means of a unidirectional pressure sensor embedded within silicone gel. Ten of these sensors were spaced 0.8 cm apart, spanning 7.2 cm. The most proximal microtransducer was located within a non-latex balloon 3.3 cm proximal to these. The most distal sensor (located 2 cm below the most distal of the central 10 sensors) was used as an external reference.

Before every study, the catheter was immersed in tepid water for at least 3 min to prewet the sensors. Sensors were then zeroed to atmospheric pressure. Data acquisition, online visualization, and signal processing were performed using a commercially available manometric system (Solar GI HRM v9.1; Medical Measurement Systems (MMS), Enschede, The Netherlands).

Protocol

Each subject was instructed to defecate if required prior to investigation. No bowel preparation given. All subjects were studied in the left-lateral position with knees and hips flexed. Prior to catheter insertion, a digital rectal examination was performed and the ability of the subject to understand the commands 'squeeze' and 'push' were confirmed.

All test maneuvers were performed in accordance with published guidelines.[2] To perform the study, the catheter was inserted into the anorectum with the distal two microtransducers visible (the second most distal being located immediately outside of the anal verge). This is important, as if the second most distal sensor is inserted past the anal verge; interpolation of recorded pressures would provide an artificially elongated anal canal length. Following a 3-minute run-in period for the purposes of familiarization, maneuvers were performed in a standard sequence with a 30 s recovery period between each maneuver (Fig. 1): *Rest* – Anorectal pressures were measured with the subject relaxed, lying still and not speaking for a period of 1 min; *Squeeze* – The subject was instructed to squeeze the anal canal as strongly possible for a period of 5 s; *Endurance squeeze* – The subject was asked to squeeze the anal canal as strongly as possible for a period of 30 s; *Push (simulated defecation)* – Whilst still lying in the left lateral position, the subject was asked to bear down for 5 s as if to defecate; *Cough* – The subject was asked to cough forcefully once on two occasions.

Duration of the familiarization period and minimum maneuver number were determined following a pilot study of extended protocol in 50 volunteers. For squeeze, push, and cough maneuvers, the first attempt was used as practice, and the second attempt used for analysis. In the unusual event of poor participant compliance a further attempt was allowed at the practitioner's discretion.

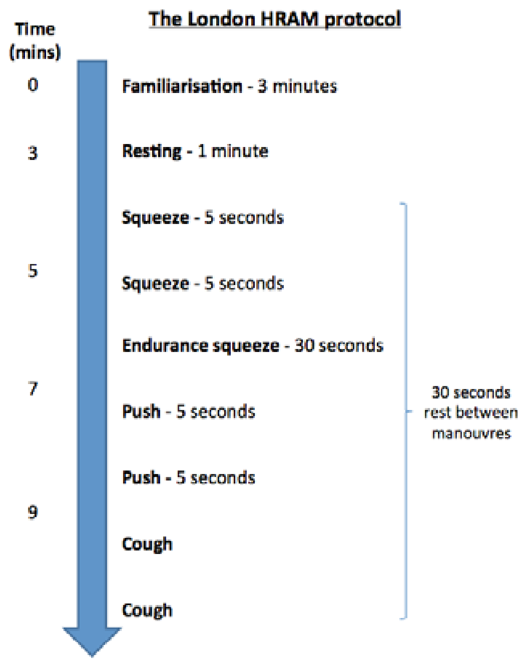


Figure 1 Schematic of standardized high-resolution anorectal manometry protocol.

Data analysis

For each maneuver period, the anal canal area was highlighted as an 'area of interest' using the e-sleeve box (Fig. 2). This allowed the software to derive the maximum pressure recorded over this anal length at each point in time (sampling rate 10 Hz). Averages were then calculated automatically over the duration of the maneuver. The variables recorded together with their respective definitions are shown in Table 1.

Statistical analysis

Variables were summarized using number of observations, mean, standard deviation, median, minimum, and maximum values.

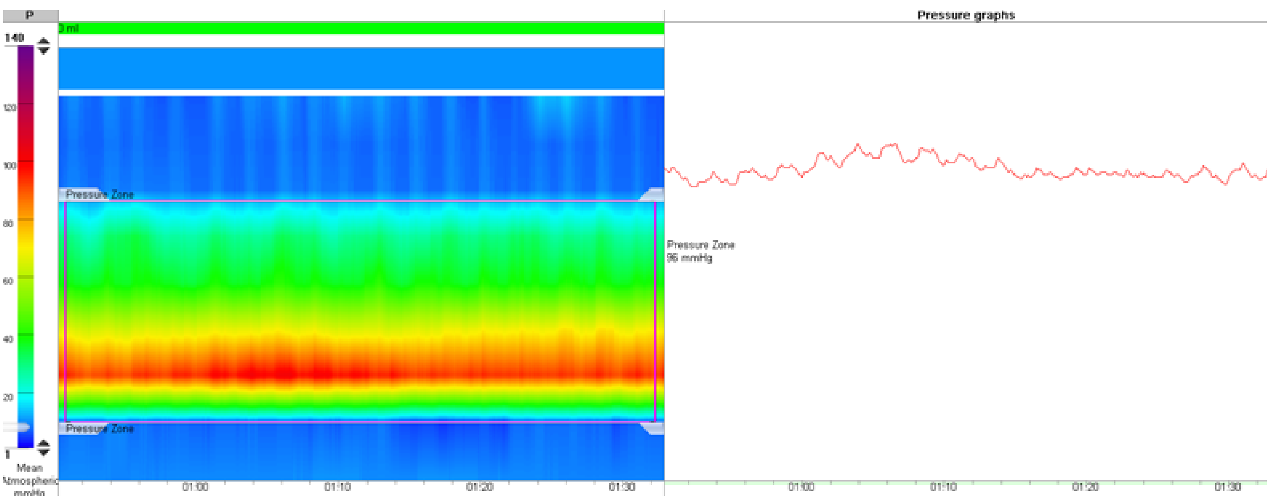


Figure 2 Representative color contour plot at rest, demonstrating use of the e-sleeve function. The left pane shows a color contour data display with a pressure of 140 mmHg depicted red and 0 mmHg as blue (pressure scale to the extreme left). The anal canal length is clearly displayed as a green band, and superimposed red/yellow pressure variations (slow pressure waves) can be seen. Within the rectum, pressure is low (blue). On the right pane, the manometric trace is derived from the maximum pressure within the anal canal e-sleeve ('area of interest' box overlying the distal and proximal borders of the anal canal length – within the color contour plot). This also shows small variations in maximum pressure over time.

Table 1 Analysis parameters and definitions

Maneuver	Definition
Functional anal canal length (FACL)	length of anal canal (cm) in which pressure exceeded rectal pressure by >5 mmHg
Average anal resting pressure	average maximum pressure (mmHg) over the FACL during the 1 min period of rest
Maximum absolute anal squeeze pressure	highest recorded pressure (mmHg) at any point during the squeeze maneuver
Maximum incremental anal squeeze pressure	maximum recorded pressure (mmHg) at any point during voluntary squeeze, minus the mean maximum resting pressure prior to the maneuver (over 5 s)
Average absolute anal squeeze pressure	mean maximum pressure (mmHg) sustained over the duration of the 5 s squeeze maneuver minus the mean maximum resting pressure prior to the maneuver (over 5 s)
Endurance squeeze duration	length in time (sec) over which a pressure at or above 50% of the highest recorded squeeze pressure [2] was sustained. The endpoint was determined as the point at which the pressure first dropped below this threshold
Residual anal push pressure	lowest maximum pressure (mmHg) recorded within the anal canal over the duration of the 5 s push maneuver
Push relaxation percentage	maximum relaxation percentage achieved over the duration of the 5-second push maneuver
Maximum absolute anal cough pressure	highest recorded pressure within the anal canal (mmHg) at any point during the cough maneuver
Maximum incremental anal cough pressure	highest recorded pressure within the anal canal (mmHg) at any point during the cough maneuver, minus the maximum resting pressure prior to the maneuver (over 5 s)

Reference ranges for maneuver variables were estimated directly from the 5th and 95th percentiles of the measurements. To assess the impact of age, sex, and parity on these parameters (and thus the reporting strategy for normal ranges), initial Mann–Whitney *U*-tests were employed with further analysis using linear regression models as required. Statistical analyses were performed using a commercially available software package (SPSS Statistics Version 20: IBM, New York, NY, USA). A $p < 0.05$ was considered statistically significant.

RESULTS

Subjects

A total of 115 volunteers were recruited for the study. All subjects tolerated the procedure without complication. Basic demographics are shown in Table 2. Recruitment was weighted toward parous females, as this is representative of the patient cohort that usually present for assessment of anal sphincter function.[9,10]

Table 2 Subject demographics

		Age		
Demographics	*N*	Min	Max	Median
Female all	96	18	68	45
Nulliparous	34	18	68	34
Parous	62	25	68	47
Male all	19	21	72	32

Parous females were significantly older than nonparous females ($p = 0.001$). Within the parous group ($N = 62$), 16 had more than two vaginal deliveries, three had two or more deliveries requiring instrumental assistance, six had two or more deliveries associated with episiotomy, and four had two or more deliveries associated with a perineal tear. Quantitative values for each maneuver are shown for all females, nulliparous females, parous females, and males in Table 3.

Effect of gender, age, and parity on conventional measures

Although the primary aim of this observational study in health only was not to subanalyse normative data on the bases of demographics, traditional anal manometry has always been approached from the perspective that males and females differ and that parity has an effect on anal sphincter function. Thus, secondary analyses were performed to study the influence of these possible explanatory variables on the cohort as a whole.

Contrary with some previous literature, age had no affect on anal resting pressures (linear regression; $R^2 = 0.005$, coefficient = −0.1, $p = 0.47$, CI −0.38 to 0.17). However, consistent with previous studies, hypothesis tests demonstrated significantly greater functional anal canal length in males *vs* females (Table 4) and reduced absolute and average squeeze pressures in parous *vs* nulliparous females (Maximum incremental and average incremental squeeze pressure in nulliparous *vs* parous females 191 ± 77 mmHg and 134 ± 62 mmHg *vs* 149 ± 81 mmHg and 102 ± 60 mmHg $p = 0.005$ and 0.007 respectively). As parous females were significantly older than nulliparous females, further modeling with multiple linear regression analysis demonstrated that when squeeze pressures were modeled on both age and parity, age was not a significant predictor of reduced squeeze pressures ($R^2 = 0.09$, coefficient = −0.36, $p = 0.54$, CI −1.53 to 0.81).

On this basis, subsequent data have also been presented by gender and parity. This subdivision notes

Table 3 Summary of values for traditional measures of anorectal function using HRAM (A) all females, (B) nulliparous females, (C) parous females, and (D) males

	Summary statistics					
	N	Mean	SD	Median	Min	Max
(A) All females						
Functional anal canal length (cm)	96	3.5	0.8	3.4	1.6	6
Average anal resting pressure (mmHg)	96	65	19	63	25	111
Maximum absolute anal squeeze pressure (mmHg)	96	225	89	221	76	503
Maximum incremental anal squeeze pressure (mmHg)	96	164	81	161	27	429
Average absolute anal squeeze pressure (mmHg)	96	173	71	167	24	387
Average incremental anal squeeze pressure (mmHg)	96	113	62	105	20	281
Endurance squeeze duration (s)	96	11	9	6	2	30
Residual push pressure (mmHg)	96	43	21	43	12	110
Push relaxation percentage (mmHg)	96	24	22	23	0*	83
Peak rectal push pressure (mmHg)	96	64	31	57	18	200
Maximum absolute anal cough pressure (mmHg)	96	174	68	164	58	460
Maximum incremental anal cough pressure (mmHg)	96	113	64	100	7	408
(B) Nulliparous females						
Functional anal canal length (cm)	34	3.6	0.9	3.6	2.3	6
Average anal resting pressure (mmHg)	34	69	17	66	46	111
Maximum absolute anal squeeze pressure (mmHg)	34	259	90	244	81	503
Maximum incremental anal squeeze pressure (mmHg)	34	191	77	187	43	387
Average absolute anal squeeze pressure (mmHg)	34	203	74	199	63	387
Average incremental anal squeeze pressure (mmHg)	34	134	62	130	29	271
Endurance squeeze duration (s)	34	12	10	6	2	30
Residual push pressure (mmHg)	34	47	19	44	13	87
Push relaxation percentage (mmHg)	34	27	25	23	0*	83
Peak rectal push pressure (mmHg)	34	66	38	57	18	200
Maximum absolute anal cough pressure (mmHg)	34	186	66	174	82	316
Maximum incremental anal cough pressure (mmHg)	34	120	59	104	32	243

Table 3 Continued

	Summary statistics					
	N	Mean	SD	Median	Min	Max
(C) Parous females						
Functional anal canal length (cm)	62	3.4	0.8	3.4	1.6	5.2
Average anal resting pressure (mmHg)	62	62	19	62	25	107
Maximum absolute anal squeeze pressure (mmHg)	62	207	84	196	77	479
Maximum incremental anal squeeze pressure (mmHg)	62	149	81	141	27	429
Average absolute anal squeeze pressure (mmHg)	62	157	65	151	24	337
Average incremental anal squeeze pressure (mmHg)	62	102	60	92	20	281
Endurance squeeze duration (s)	62	10	9	6	2	30
Residual push pressure (mmHg)	62	45	22	42	12	110
Push relaxation percentage (mmHg)	62	23	20	23	0*	68
Peak rectal push pressure (mmHg)	62	62	27	57	21	140
Maximum absolute anal cough pressure (mmHg)	62	168	69	159	58	460
Maximum incremental anal cough pressure (mmHg)	62	109	67	96	7	408
(D) Males						
Functional anal canal length (cm)	19	3.9	0.8	3.8	2.4	5.3
Average anal resting pressure (mmHg)	19	73	23	67	38	136
Maximum absolute anal squeeze pressure (mmHg)	19	290	155	268	94	732
Maximum incremental anal squeeze pressure (mmHg)	19	219	153	176	61	643
Average absolute anal squeeze pressure (mmHg)	19	215	118	190	86	563
Average incremental anal squeeze pressure (mmHg)	19	144	116	124	40	474
Endurance squeeze duration (s)	19	16	11	19	3	30
Residual push pressure (mmHg)	19	57	23	57	20	104
Push relaxation percentage (mmHg)	19	16	33	21	0*	60
Peak rectal push pressure (mmHg)	19	71	33	77	20	140
Maximum absolute anal cough pressure (mmHg)	19	250	124	218	109	576
Maximum incremental anal cough pressure (mmHg)	19	179	123	136	29	434

*Substitute value of 0 as lowest relaxation percentage was negative i.e. representing a paradoxical anal contraction during push.

Table 4 Summary of differences between male/female and parous/nulliparous female groups

Group differences	Males *vs* females	Parous females *vs* nulliparous females
Functional anal canal length (cm)	0.024	n.s.
Average anal resting pressure (mmHg)	n.s.	n.s.
Maximum absolute anal squeeze pressure (mmHg)	n.s.	0.002
Maximum incremental anal squeeze pressure (mmHg)	n.s.	0.005
Average absolute anal squeeze pressure (mmHg)	n.s.	0.001
Average incremental anal squeeze pressure (mmHg)	n.s.	0.007
Endurance squeeze duration (secs)	n.s.	n.s.
Residual push pressure (mmHg)	0.031	n.s.
Push relaxation percentage (mmHg)	n.s.	n.s.
Peak rectal push pressure (mmHg)	n.s.	n.s.
Maximum absolute anal cough pressure (mmHg)	0.013	n.s.
Maximum incremental anal cough pressure (mmHg)	0.044	n.s.

P values obtained using a Mann–Whitney U analysis based on data summarized in Tables 3(A–D). A $p < 0.05$ was considered as statistically significant with values presented. n.s. = not significant.

that the sample studied was based on feasibility with demographic division to reflect patient referral patterns (as the cohort presenting for anorectal physiology assessment are typically older parous females) rather than a prestudy calculation of power to detect differences between binary groups. Post hoc testing for these variables confirms low power to detect differences, given the distribution of the cohort (ratio of males: females; parous: nulliparous) and wide standard deviations. For example, mean resting pressures males *vs* females, power = 30%; squeeze pressures males *vs* females, power = 22%, resting pressures nulliparous *vs* parous, power = 46%; mean squeeze incremental pressures nulliparous *vs* parous, power = 69%.

Normal values for use in clinical practice

Tests of normality demonstrated that some data (particularly measures of squeeze pressure) were not normally distributed. For this reason, suggested normal ranges have been based on 5th and 95th percentiles rather than 95% confidence intervals (Table 5).

Qualitative color contour plot findings

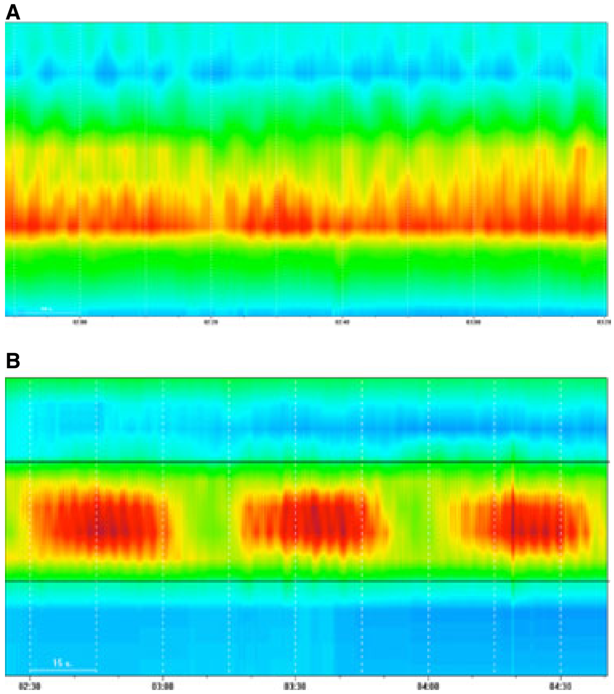
Rest Data displays with the color contour plots allowed clear appreciation of varying pressures within the anal canal (Fig. 2). In the majority of subjects, an intra-anal high-pressure zone was appreciated. In 44% of subjects, slow pressure waves were recorded at a frequency of 9–19 cycles/minute, and were seen to be superimposed on the basal resting pressure (Fig. 3A). Also, in 13%, more dramatic ultra-slow pressure waves (at a frequency of 1–2 cycles/minute) were observed (Fig. 3B).

Squeeze Inspection of squeeze morphology using the color contour plots revealed marked heterogeneity of squeeze pattern between individuals. Contribution to squeeze did not necessarily involve the whole anal canal. In some, contribution by (presumed) puborectalis appeared predominant; in others, squeeze

Table 5 Table of suggested normal values for use in clinical practice

	All females		Parous females		Nulliparous females		Males	
Suggested normal values	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper†
Functional anal canal length (cm)	2.3	5	2.3	4.9	2.3	5.3	2.4	5.1
Average anal resting pressure (mmHg)	33	101	31	100	47	110	38	114
Maximum absolute anal squeeze pressure (mmHg)	90	397	86	387	89	447	94	590
Maximum incremental anal squeeze pressure (mmHg)	45	324	43	313	52	352	61	525
Average absolute anal squeeze pressure (mmHg)	73	314	71	310	74	348	86	430
Average incremental anal squeeze pressure (mmHg)	29	235	24	232	32	247	40	366
Endurance squeeze duration (secs)	2	30	3	30	2	30	3	30
Residual push pressure (mmHg)	16	88	15	99	16	79	20	93
Push relaxation percentage (mmHg)	0*	66	0*	64	0*	81	0*	51
Peak rectal push pressure (mmHg)	21	122	22	129	19	144	20	132
Maximum absolute anal cough pressure (mmHg)	82	298	70	276	82	315	109	498
Maximum incremental anal cough pressure (mmHg)	34	224	35	221	34	230	29	413

Lower limit values are estimated from the 5th percentile and upper limit values estimated from the 95th percentile.
*Substitute value of 0 as 5th percentile for relaxation percentage was negative i.e. representing a paradoxical anal contraction during push.
†90th percentile quoted due to low sample size in males.

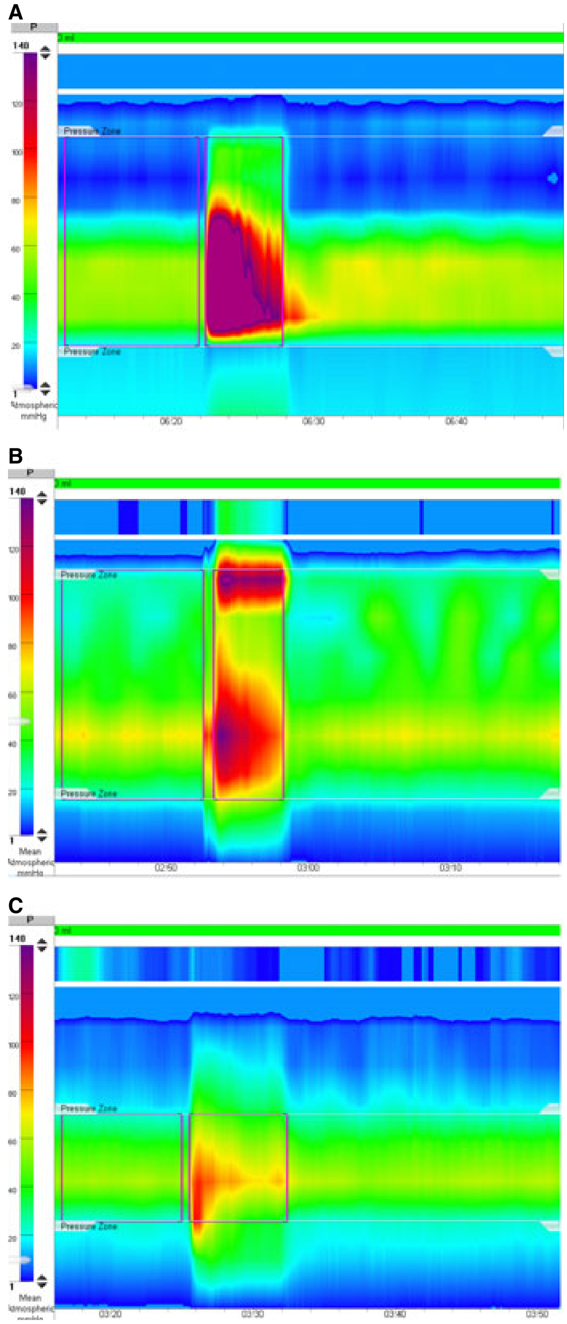


Figures 3 (A and B) Representative color contour plots during the resting maneuver. (A) The presence of slow waves (rhythmic red/yellow pressure patterns, seen as 'stripes' overlying the green of the anal canal) at a rate of ~17 cycles/minute. (B) The presence of ultra slow waves at a rate of 1.5 cycles/minute (rhythmic bursts of red demonstrating more prolonged increases in mid anal canal pressure).

appeared mainly as a result of contraction of the distal portion of the anal sphincter (Fig. 4). Due to the use of the e-sleeve function (that records only the maximum pressure within the selected area at each point in time) these differences were not highlighted quantitatively.

Push The use of the color contour plots clearly highlighted co-ordinated recto-anal events during the push maneuver. Qualitative interpretation of anal pressures relative to rectal pressures was aided by the ability to use the color display to show either 'absolute' or 'relative to rectal' pressures (Fig. 5). As previously demonstrated, there was failure of some healthy volunteers to increase the rectoanal gradient during push; however, in some, a delayed relaxation of the anal canal was seen which could be considered a normal variant.

Cough Qualitative inspection of cough maneuvers clearly demonstrated the anal response to cough (Fig. 6A). In all volunteers, pressures within the anal canal exceeded rectal pressures during this maneuver. However, some volunteers appeared to exhibit a post



Figures 4 (A–C) Representative color contour plots from 3 different individuals demonstrating the heterogeneity of squeeze morphology in health. (A) Contribution from the whole anal canal (observed as an extension of the red 'high pressure zone' length); (B) increase in anal canal pressure showing two distinct high pressure zones, the upper being (presumably) secondary to puborectalis contraction, and the lower being due to external anal sphincter contraction; (C) poorer increase in anal canal pressure predominantly secondary to contraction of the distal external anal sphincter.

cough relaxation of the upper segment of the anal canal (Fig. 6B), a finding previously unrecognized with conventional manometry.

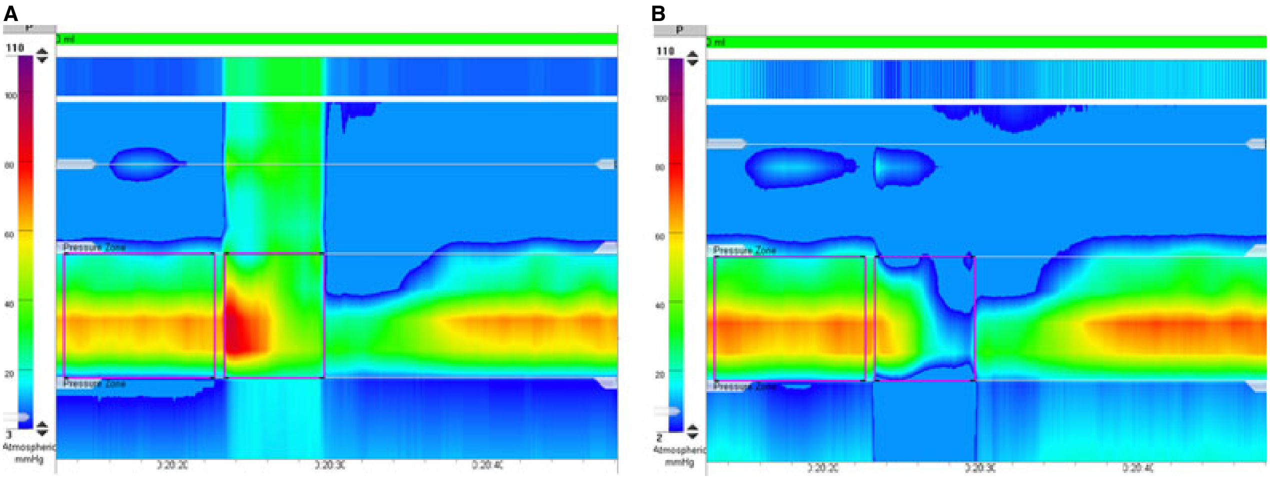


Figure 5 Two images of the same push in the same individual. Inspection of image (A) shows an increase in both anal and rectal pressures during push (which could led to the mistaken interpretation of dyssynergia). However, when the same event is displayed relative to rectal pressure (B), this more clearly reveals an appropriate change in the recto-anal gradient.

DISCUSSION

Anal manometry is the most widely used physiological test of anorectal function and in current practice can be performed using a variety of techniques. To date, experts have failed to reach consensus with regard to either the optimal test protocol or method of reporting, despite several 'position statements' and 'working party reports' being published on the topic.[2,3,11,12] A large share of this historic difficulty must be attributed to the paucity of appropriately large normative data sets,[4,5,7,13] all of which used variable methodology. Such a situation makes comparison between centers problematic, as it becomes difficult to determine whether an individual's test results are normal or abnormal, the endpoint of any clinically useful investigation.

One of the principal advantages of high resolution manometry is the ability to more clearly display pressure events within the structure of interest.[7] Color contour plots provide a more intuitive understanding of pressure profiles and synchronized events over time than traditional line traces.[14,15] When applied to the anorectum, the ability to observe this structure as a single unit is likely to allow the practitioner to more accurately appreciate the subtleties of co-ordinated anorectal events during a variety of maneuvers.[8] The introduction of HRAM now presents an opportunity, similar to that of the Chicago process[6] (which has revolutionized the use of manometry in the upper GI tract), to reach consensus regarding standardization of this new and promising technique. Such consensus may then avoid the pitfalls that have bedeviled standard ARM (and all other tests of anorectal function).

The first part of the current study presents results of a large (to the authors' knowledge, largest within the literature) healthy volunteer dataset with studies performed using a standardized HRAM protocol, which may prove a starting point for discussion, collaboration, and ultimately standardization. The following limitations are nevertheless acknowledged. First, the dataset only included a small number of healthy male subjects and although this cohort more seldom presents for investigation, recent epidemiological studies may suggest that symptoms (such as fecal incontinence) in this group are more common than previously recognized.[9,16] Secondly, the authors' did not perform endoanal or other structural investigations of sphincter integrity in this healthy volunteer cohort and therefore asymptomatic structural abnormalities of the sphincter complex (especially in the parous female cohort) cannot be excluded. Thirdly, anal manometry provides limited information about the integrity of the anorectal complex and clinical application will require contextualization to the overall clinical picture alongside the results of other diagnostic tests.

Comparisons of the findings from this study with previously published literature highlight the already appreciated point that reported values have relevance and validity primarily to the technology employed and population studied. A table summarizing findings from manometric studies of anal function in healthy cohorts (minimum $N = 50$) can be found below (Table 6). The mean resting pressure and mean squeeze increment reported in this article are very similar to that reported

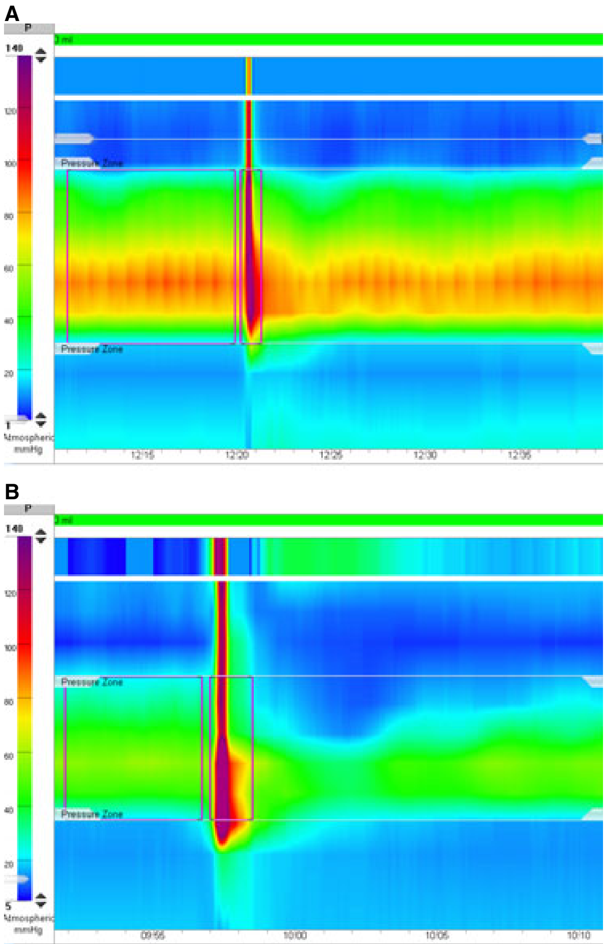


Figure 6 Representative color contour plots from two individuals during the cough maneuver. (A) demonstrates clear increase in anal canal pressure, the duration of which exceeds increase in rectal pressure. (B) shows a post cough relaxation of the anal sphincter complex.

by Gundling *et al.* in 2010 (who performed a study of conventional water perfused manometry of 72 women and 74 men using an eight lumen, 15F water perfused manometry catheter)[17] however, squeeze pressures appear to significantly higher than those reported recently by Noelting *et al.* in 2013 (who used the Manoview system in 62 females).[7] There are several possible reasons for these observed differences. First, it is generally agreed that equipment set-up is likely to have an impact on absolute reported values as (for example) water perfused manometric systems are generally regarded to have lower fidelity than those that utilize solid-state technology.[1,18,19] Secondly, data from previous studies may reflect a cohort with different demographics (the relationship between age and parity on anorectal function is well-documented).[17,20,21] Thirdly, as anal manometry is a dynamic investigation partly of voluntary function, it is well-appreciated that nuances of study protocol are likely to impact derived results.[2,4,22,23] Indeed, a recent study in 70 patients with defecatory dysfunction demonstrated that enhanced instruction and verbal feedback significantly improved squeeze pressures when compared with standard instruction.[22] It is certainly conceivable that this may account for some of the differences during comparison with previous studies.

Although in this study sample size was based on feasibility without formal sample size calculation (and differences reported between demographic groups should therefore be interpreted with caution), the already appreciated reduction in sphincter function associated with parity[24] has, however, once again been highlighted in this dataset. It is possible that further longitudinal investigation of healthy parous females with poor sphincter function using HRAM may prove useful, particularly given the fact that onset of incontinence commonly occurs up to two decades following obstetric trauma, at around menopausal age.[25]

Examination of the reference ranges presented in this study demonstrates that at least three traditional measures (residual push pressure, maximum rectal push pressure, and endurance squeeze duration) are unlikely to have diagnostic utility due to wide variations in health. This highlights the fact that traditional metrics themselves have limitations and indicates the need for new parameters of anal function. This study particularly highlights deficiencies in current measures used for the definition of dyssynergia. Were currently accepted definitions for dyssynergia applied to this cohort of healthy volunteers (i.e. the presence of a negative recto-anal gradient is indicative of defecatory dysfunction[7]), 33 (28%) of individuals would have been classified as having an abnormal result. Whether such a large proportion of asymptomatic individuals should be classified as having an abnormal test result (or whether the test itself should change) is a philosophical question that requires further investigation.

In the upper GI tract, the application of high resolution manometry has led to the development of several novel parameters such as the distal contractile integral and integrated relaxation pressure of the lower oesophagus, both of which have led to changes in the classification of oesophageal dysmotility.[6]

On this basis, the second part of the current study explored qualitative findings in sphincter function that may subsequently be shown to have disease relevance. A number of novel phenomena were

Table 6 Table outlining results of previous studies examining anorectal function in healthy cohorts

			Catheter configuration						
Author (year)	Manometry type	System type	⊘ (mm)	Channel N	Spacing	*N*	Sex	Anal resting pressure (mmHg)	Average squeeze increment (mmHg)
Poos (1986)	Conventional	Balloon	2	1	n/a	72	F	50 ± 3*	120 ± 11*,†
						103	M	54 ± 3*	121 ± 11*,†
Pedersen (1989)	Conventional	Water perfused	2	3	Equally spaced radially	23	F	46 (40–58)‡	103 (78–190)†,‡
						35	M	60 (51–98)‡	163 (76–234)†,‡
Felt-Bersma (1991)	Conventional	Water perfused	n.s.	4	n.s.	40	F	63 ± 19*	102 ± 36*
						40	M	68 ± 21*	183 ± 73*
Cali (1992)	Conventional	Water perfused	n.s.	8	Equally spaced radially	21	NF	75§,¶	114†,§,¶
						18	PF	60§,¶	103†,§,¶
						20	M	75§,¶	144†,§,¶
Chaliha (2007)	Conventional	Solid state	n.s.	n.s	n.s	283	NF	59 ± 15[a]	107 ± 28*
Corsetti (2010)	Conventional	Water perfused	4.7	7	Variable**	22	NF	73 ± 16*	185 ± 66*,†
						30	M	82 ± 15*	243 ± 53*,†
Gundling (2010)	Conventional	Water perfused	4.8	8	n.s.	72	F	54 (17–126)††	151 (64–418)††
						74	M	67 (30–142)††	201 (69–413)††
Schuld (2012)	Conventional	Solid state	3.3	1	n/a	66	F	63 (58–69)‡	114 (106–212)‡
						106	M	68 (63–72)‡	137 (132–142)‡
Li (2013)	Hi-resolution (3D)	Solid state	10	256	4 mm axial	46	F	60 (56–65)‡	167 (151–184)†,‡
					2 mm radial	64	M	61 (57–66)‡	195 (181–209)†,‡
Noelting (2013)	High-resolution	Solid state	4.2	8	6 mm axial	30‡‡	F	88 ± 3¶¶	73 ± 6¶¶
						32§§	F	63 ± 5¶¶	96 ± 12¶¶
Carrington (current study; 2013)	High-resolution	Solid state	4	10	8 mm axial	34	NF	66 (46–111)††	130 (39–271)††
						62	PF	62 (25–107)††	92 (20–281)††
						19	M	67 (38–136)††	124 (40–474)††

*Mean ± SD.
†Reported as absolute maximum squeeze pressure, not increment.
‡Median (95% CI).
§Mean.
¶Reported as cmH_20 but converted to mmHg in this table for purposes of comparison ($1cmH_20$ = 0.7356 mmHg).
**4 radial ports at 5 cm with 1 port 5 mm proximally and 1 port 5 mm distally.
††Reported as median (range).
‡‡Age <50.
§§Age >50.
¶¶Reported as mean ± SEM.
n.s., not specified; n/a, not applicable; F, females; M, males; NF, nulliparous females; PF, parous females.

observed, including the presence of postcough relaxations in some individuals. Further exploration of this may be interesting, as the presence of this feature in those with poor sphincter tone may be an important feature in the pathophysiology of fecal incontinence. Qualitative observations also included synchronous recordings of rectal pressure acknowledging that disturbances of defecatory function usually represent the summation of anal and rectal dysfunction (and often colon).[26] Further studies in health and disease using short and prolonged duration studies are underway to determine the clinical significance of these findings and their incorporation to a future recording protocol.

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AUTHOR CONTRIBUTION

EVC prepared ethical approval, collected data, analysed data, wrote manuscript, and edited manuscript; AB prepared ethical approval, collected data, analysed data, wrote manuscript, and edited manuscript; WJ assisted with protocol design; GSD assisted with study design; HC analysed data; NZ assisted with study design and prepared ethical approval; EJH collected data; SP collected data; CHK assisted with statistical analysis and edited the manuscript; PJL assisted with study design and edited manuscript; SMS study principal investigator, conceived study design, assisted in preparation of ethical approval, collected data, analysed data, wrote sections of the manuscript and edited manuscript.

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