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Abstract

Background: Rectal evacuation involves multiple mechanisms that are not completely understood. The aim of this study was to quantify the rheologic property, i.e. yield stress, that governs the ease of deformation of a range of faeces of differing consistency and understand its influence on the pathophysiology of defaecation.

Methods: Yield stresses of faeces of differing consistencies and Bristol scores were determined by the Vane test. We then explored the effects of this property on ease of defecation using a simple static model of the recto-anal junction based on the laws of flow for yield stress pastes and checked the conclusions by X-ray defaecography experience.

Results: The yield stress of faeces increased exponentially with their solid content, from 20 to 8000 Pa. The static model of the recto-anal junction showed that evacuation of faeces of normal consistency and yield stress is possible with moderate dilatation of the anal canal, whilst the evacuation of faeces with higher yield stress requires greater dilatation of the anal canal. X-ray defaecography showed that such increases occurred in vivo.

Conclusions: The diameter of the recto-anal junction is increased to enable the passage of feces with high yield stress. The finite limits to such dilation likely contribute to fecal impaction. Hence difficulties in defaecation may result either from unduly high yield stress or pathologies of reflex recto-anal dilatation or a combination of the two.

Key words: defaecation - X-ray defaecography - rheology - yield stress

Introduction

Defaecation is the voluntary evacuation of faeces from the rectum. Disorders of defecation occur frequently in the population with, for instance, an incidence of about 15% of the population in North America [1], and can seriously degrade the quality of life [2]. However, the classification of these disorders and the relevance of the current tests for evaluating colonic and anorectal function are subject to ongoing debate as our understanding of the process of defaecation is currently incomplete [3-7]. This is exemplified by the absence of consensus in the attendant aetiological terminology, for example the term dyschezia has multiple meanings [6].

There is a general consensus that there is a need for greater understanding of the mechanisms that govern defecation by modeling the relative contributions of colo-recto-anal forces, motility, and motricity and the effects of structural and physiological abnormalities. This could enable identification of disease phenotypes and optimize the management of patients with disorders of defaecation [4, 6, 8-10].

Ultimately defaecation involves the physical resistance of faeces to flow [11-15], i.e. the flow rate in relation to the intrarectal pressure generated by motility and motricity and depends, largely, on the relative geometry of the rectum and anus. Hence it is well established that high flow resistance due to anatomical abnormalities (e.g. internal rectal intussusception) or a high anorectal angle can hamper defecation [4]. Motor dysfunctions that include recto-anal dyssynergia have been shown to reduce intrarectal force / pressure and impair fecal expulsion [8, 16]. However, whilst the visual assessment of the consistency of feces is well established as an aid to the diagnosis of abnormalities in bowel function [17], relatively little work has been done on the rheological properties of faeces [12, 18-20], which will directly influence their resistance to flow and hamper evacuation.

Distal colonic digesta, from which faeces are formed, consist of indigestible particulate residues of food suspended in a watery fluid. Rheology of digesta governs the ease with which digesta flow [21] and depends on the relative proportion of the fluid and particulate fraction [22] and physical properties of the particles [23]. Progressive absorption of water from the colonic digesta contained between successive slowly propagating haustral contractions results in the formation of semi-solid colonic pellets [24]. The progressive accumulation and impaction of colonic pellets in the rectum lead to the formation of the rectal faecal mass which must be forced through the anal canal to achieve defaecation. The process of defaecation requires application of a sufficient pressure to deform the faecal mass as it transits from the rectum through the anal canal. The principal rheological property that governs the ease, with which semi-solid materials, i.e. pastes, may be deformed, is the yield stress [25, 26] which governs the minimal pressure that is required to induce permanent deformation. Contrary to what occurs in purely viscous materials, such as water and oil, flow is not induced in pastes such as faeces unless the pressure that is applied exceeds a threshold that depends on both geometry and yield stress.

If we consider the flow of soft matter within a geometrically defined space such as the recto-anal junction, the relationships between pressure, flow rate, geometry and yield stress can be determined mathematically by the use of appropriate flow laws [12, 14]. Hence models which incorporate colo-recto-anal motility and motricity (pressure), anatomy (geometry) along with the relevant yield stress (rheology) of the faeces allow us to evaluate the principal parameters that govern faecal evacuation (flow rate) and the aetiology of associated pathophysiological disorders.

The aim of the current study was to evaluate the role of faecal yield stress in the aetiology of disorders of defaecation. Firstly, we used an ex-vivo rheometrical technique to determine the yield stresses of a range of faeces of various visual consistencies and correlate these with their water content. Secondly, we modelled the deformation of feces through the recto-anal junction using a model that incorporated the relevant flow laws for yield stress fluids. Thirdly, based on the 28-year experience of one of the authors (AD), who had performed more than 2 300 video dynamic defaecographies examinations before starting this study [27], we discussed how these new physical insights may be used to rationalize current terminology and classifications of disorders of defaecation and the relative contribution of faecal rheology.

Materials and methods

Samples

Faecal samples were collected from 17 volunteers who had attended the Departments of Colorectal Surgery and Hepato-Gastroenterology at Grenoble University Hospital. The selection of these subjects was designed to obtain samples that covered a wide range of consistencies. Hence some subjects had undergone colostomy, ileostomy or had been diagnosed by clinicians as severely constipated. All samples were anonymized by coding following collection and subsequently characterized by rheometry within one hour of their collection. Subsamples were taken for determination of water and solid content with a desiccant Sartorius balance and were each given a Bristol score [28] by an experienced blinded clinician.

The thick suspension of barium that was subsequently used for X-ray-defaecography was prepared by mixing barium sulfate suspension with a suspension of potato starch and cooked to obtain a paste [29]. The yield stress of the resulting paste was determined by rheometry.

Videodefaecography

The clinical comments in this article were based on the experience of one of the authors (AD), who has 28 years of experience and had performed more than 2 300 video defaecography examinations before starting the study [27].

Rheometric technique

The Vane test is an established rheometric technique to determine the yield stress of pasty materials [30-33]. It employs a rotary rheometer (Haake VTK 550, Thermo Scientific) with a vane geometry that is immersed in the sample. A low velocity of rotation (about 10^{-3} rad/s) is used so as to deform the sample under quasi-static conditions, the resulting torque being measured as a function of time. Determination of the maximal torque T_{max} under these conditions allows the yield stress σ of the material to be determined given that $\sigma = cT_{max}$ with the constant c depending on the geometry of the vane [31]. All measurements were performed at 20±2°C with 2 to 3 replicates of each of the 17 faecal samples. Validation of this method with a number of standardized formulated pastes (Carbopol gel and plasticine) of known yield stress showed an accuracy of ± 20%. This technique preserves the structure of the stool unlike the techniques usually used in the measurement of viscosity of feces [19]. Indeed, the latter techniques crush the faeces to small gaps, which not only modify the structure but also can introduce artifacts if the constituents of the faeces are too large in respect to gap.

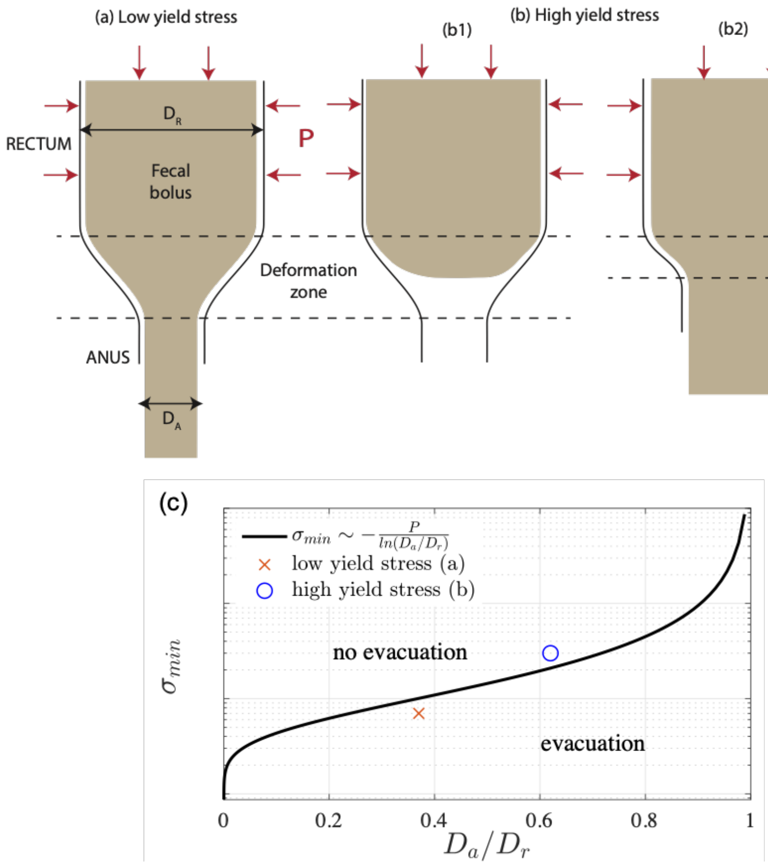

Figure 1. Modeling of the evacuation of faeces with low and high yield stress
a-b: Evacuation of faeces with low yield stress (a). For higher yield stress, evacuation is not possible for the same diameter of the anal canal (b1). Greater widening is required to evacuate the faeces (b2). c: Minimal yield stress σ_{min} that is required for evacuation of faeces as a function of the ratio of the diameter of the anus D_a over the diameter of the rectum D_r. For yield stress below the plain line, flow laws predict that evacuation is not possible. In this situation, evacuation is made possible if the intrarectal pressure P and/or the diameter of the anus D_a increase.

Modeling of faeces evacuation using flow laws

This method of analysis followed that introduced by Bush *et al.* [14] to explain the role of anorectal geometry in evacuation disorders and is based on the fact that evacuation of the rectum results from pressure-induced plastic deformation of the content by squeezing it through the anal canal [13, 34]. We extend their analysis to show the consequences of a high yield stress on evacuation in a geometric model. The anorectal geometry is modeled as a constriction characterized by the ratio of the diameters of anal canal and rectum, D_a and D_r respectively (Fig. 1-a). The faeces must be extruded through this constriction and must transit the zone of deformation in the bulk of faeces i.e. between the upper and lower limits shown as dotted lines in Fig. 1-a. Hence the main flow resistance is provided by the plastic deformation of the faeces within these limits. The physical relationship between the minimum yield stress σ_{min} necessary for passage though the geometric model and the principal geometric parameters is given by $\sigma_{min} \propto -P/ln(D_a/D_r)$, where D_a is the diameter of the residual anal canal, D_r is the diameter of the rectum, and P is a uniformly applied pressure acting on the walls and the proximal lumen of the rectal canal. In fact the expression $P/ln(D_a/D_r)$ is multiplied by a coefficient that depends on the shape of the passage zone from the rectum to the anus [35, 36].To estimate the total pressure required for the stool to flow by the anus, it is necessary to add the pressure to overcome the friction of the stools against the wall of the anus. This contribution is much smaller than that required to deform the stool during the passage from the rectum to the anus.

Statistical analysis
Linear regression analyses were performed with Matlab7.0 (The Mathworks, Natick, MA, USA). The best fit curve for yield stress against solid content was negative exponential of the form y = a exp (bx) which gave a correlation coefficient r of 0.83 and a standard error of 10.65. The best fit curve for yield stress against Bristol score was of quadratic form which gave a correlation coefficient r of 0.94 with an se of 0.68.

The study was conducted in accordance with the principles of the Declaration of Helsinki. According to the recommendations relative to the steps and means to be used for evaluation and diffusion of innovations published by an international panel of methodologists and surgeons, this study of the faeces of 17 patients can be classified as a phase 1 study [37]. Therefore, submission of the data to a Committee for the Protection of Individuals was unnecessary.

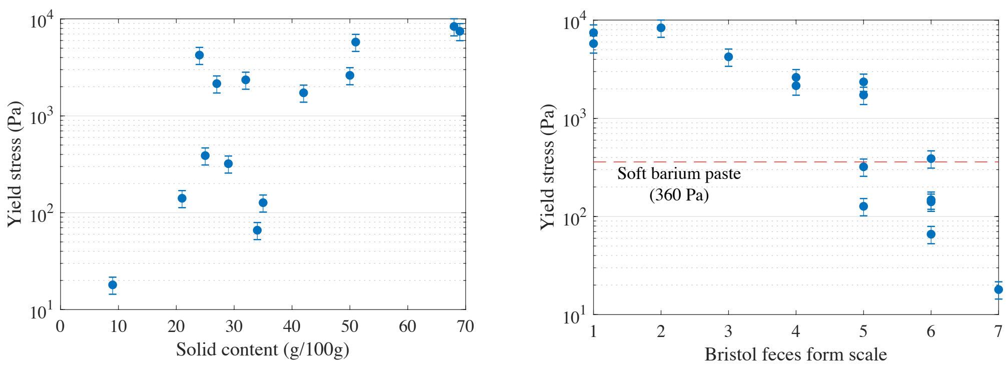

Figure 2. Yield stress of human faeces
Left: Yield as a function of solid content (p=0.0002, r=0.82). Yield stress increases over several orders of magnitude as solid volume content increases. Right: Yield stress is correlated with the score on the Bristol faeces form scale17 (from the hardest "7" to watery "1"). The red dotted line indicates the yield stress of the barium/potato starch paste (360 Pa) used in X-ray defaecography. Error bars show measurement uncertainty (standard error +/- 20%).

Results

Yield stress of human feces
Plots of yield stresses of the various samples against their solid volume contents (Fig. 2a) showed a broadly positive and significant linear regression (N=17, p=0.0002, r=0.82) over the range in solid content between 10 and 70 g/100g and yield stress between 20 and 8000 Pa. Hence, yield stress increased exponentially with solid volume content presumably as reduction in inter-particulate fluid increased the packing of particles.

Plots of yield stresses of the various samples against their Bristol scores (Fig. 1b) showed that yield stress decreases with the Bristol score. Further, the mean ranges for yield stress for the various Bristol scores were significantly different (ANOVA, N=10, p<0.0001). Hence

“watery faeces” (n°7 on the Bristol scale) had a yield stress of <20 Pa. Regular faeces (Between n°5 - 4) had yield stresses between 200 - 2000 Pa and faeces that exhibited “cracks” (and thus scored between n°1-3) had a yield stress between 5000 - 8000 Pa.
The barium paste prepared according to Mahieu et al. [29] that was subsequently used in X-ray defaecography had a yield stress of 360 Pa, which was between the scores of 5 and 6 on the Bristol scale, and thus was in the range of that the yield stress of regular faeces.

Flow law modeling of the evacuation of faeces
Given that faecal material can deform into the constriction represented by our model only if the yield stress is lower than a threshold [35, 36, 38] and that this threshold depends on the geometry (diameters, length, angle) and the applied pressure, plotting the relationship between the minimal yield stress σ_{min} and D_a/D_r shows that as D_a/D_r decreases, the minimal yield stress σ_{min} for which evacuation is possible, decreases over several orders of magnitude (Fig. 1-c). Hence, evacuation of faeces of high yield stress requires greater dilatation of the anal canal: the functional diameter of the faecal material of higher yield stress following extrusion through the anus is higher than that of faecal material of lower yield stress (Fig. 1-a, b). Thus, evacuation of faeces of normal consistency and yield stress is possible with moderate dilatation of the anal canal (red cross on Fig.1-c), whilst the evacuation of faeces with higher yield stress (blue circle on Fig. 1-c) requires greater dilatation of the anal canal. Again, faecal impaction will occur if yield stress exceeds the capacity for dilatation and faecal incontinence will appear if yield stress drops below the capacity of anal constriction.

X-ray defaecograms of soft barium paste and faecoliths
On X-ray defecography sequences of soft barium paste of yield stress of 360 Pa carried out in more than 2 300 patients with defaecation disorders with or without pelvic floor disorders such as full-thickness rectal prolapse, internal rectal prolapse, peritoneocele, or enterocele, results showed that the accompanying dilatation of the junction of the rectum with the anal canal, measured as the length of a line on the lateral view between the anterior and posterior limits of the recto-anal junction can be within the normal range .
In some cases, attempts to evacuate the remaining faecolith require several ‘abdominal thrusts’ over a period of almost 40 seconds, producing extreme transverse dilatation of the junction of rectum with the anal canal with accompanying lengthwise shortening of the anal canal, and are then described by the patient as painful. We have already described this condition as rectal akinesia [39]. Hence the diameter of the anal canal as determined by the length of a line between the anterior and posterior limits of the recto-anal junction during attempted defaecation increased by several times (2 to 4 times) the normal value. Further, regular evacuation is recovered once the fecolith is evacuated [39] .

Discussion

Pathophysiology of evacuation and rheology of faeces
To the best of our knowledge this is the first study that measures the yield stress of human faeces and investigates its relationship with evacuation. The determination of the yield stresses of a range of feces of differing water and solid volume content by rheometry allowed us to determine the range of yield stress that is represented by the Bristol feces form scale [17, 28]. Further, our study demonstrated that yield stress increased exponentially with reduction in solid volume content in line with more general work on particulate suspensions [22, 40] and digesta [23, 41]. In this context, it is important to note that the considerable variation in yield stress for a given solid volume ratio between subjects (Fig. 2) most likely arises from differences in the subjects’ diets and hence in the characteristics of the particles.

The work examining the influence of geometrically based flow laws and yield stress on flow through anatomically defined sites, in this case the recto-anal junction, indicates that an increase in the diameter of the anal canal relative to that of the rectum reduces the level yield stress that is necessary to achieve defaecation. Further, that with a finite level of increase in anal diameter there will be an upper limit where the yield stress is too high to achieve defaecation. It is important to bear in mind that the model contains a number of assumptions, firstly that, at a given diameter ratio that is necessary for successful defaecation, the walls of the rectum contract uniformly to elevate rectal intraluminal pressure and that the walls of the anal canal relax uniformly to a finite diameter in order to accommodate inflowing feces. This is an approximation since the muscular actions that are associated with defaecation are complex and under continuing debate [42]. Hence for example, some evidence suggests that rectal contraction occurs in two phases, an initial shortening of longitudinal muscle to reduce length followed by a uniform contraction of the circular muscle to increase diameter [43]. Again recent evidence from computed tomography scans suggests that the levator ani muscles, that run from the perianal region to the walls of the pelvis and form a basin–like structure that surrounds the rectum and anal canal, also contract in two phases, an initial phase where they assume a plate like configuration that squeezes the rectum followed by a phase in which they assume a basin–like form that may contribute to the opening of the anal canal [44]. Further, whilst the conclusion that an increase in anal dilatation is necessary for successful defaecation of harder faecal material is likely to be valid, it remains to be seen whether this increase is achieved passively as faecal material is expelled into the anal canal or whether flow is assisted by active 'anticipatory' anal shortening and dilatation via the mechanoreceptor mediated reflex activation of the perianal musculature and the second phase of levator activity [45].

Our work raises the possibility that the yield stress of faeces may on occasion rise to a sufficient level to exceed the capacity of the recto-anal musculature to dilate to a sufficient degree to allow defaecation in a normal subject. Such an incapacity should be fully reversible if faecal yield stress returns to normal i.e. below ~500 Pa providing that the conditions that precipitated the situation do not persist, such as in the case of a subject with a rectocele. However, it the broad threshold at which faecal yield stress exceeds the defaecatory capacity of subjects with normal recto-anal anatomy and physiology has yet to be established. Once such data have been obtained, subjects who experience difficulty in the defaecation of faeces with yield stresses below that threshold, who are likely to have an underlying anatomical or physiological abnormality will be easier to identify.

Terminology and aetiology of disorders of defaecation

Our findings that the yield stresses of faeces vary over several orders of magnitude i.e. from 20 to ~8000 Pa, that an increase in the functional diameter of the anorectal junction is predicted by our model to facilitate defaecation of material of higher yield stress, and that such variation is recorded on X-ray defaeocograms, may help to clarify the etiology of constipation and the shortcomings of current terminology [39].

Evaluation of defaecatory disorders

As the rheology of faeces has clinical implications, the idea to evaluate faecal consistency is reinforced [17, 46]. Several authors have proposed empiric techniques to assess faecal consistency [47-49]. However, we observed a good correlation between yield stress measured with well-established rheometrical techniques and the Bristol scale. This suggests that an instrumental measurement of faecal yield stress for functional exploration is probably too sophisticated and this kind of accurate technique is relevant for research and clinical studies.

As was illustrated in this study, defaecography of a barium paste of yield stress that is within the range of that of normal faeces can be used to establish the integrity of the normal neuromuscular reflexes associated with defaecation and focus the investigation on other causes [27, 50]. Similarly, it is useful in identifying subjects who would benefit from administration of agents that directly reduce faecal consistency e.g., softening and bulking agents such as ispagula.

Conclusions

The Vane test is a useful method to measure the yield stress of feces. Our findings that the yield stresses of faeces vary over several orders of magnitude from 20 to ~8000 Pa., that an increase in the functional anorectal diameter can facilitate expulsion of material of higher yield stress, and that such variation can be seen on X-ray defaecograms, may help to clarify the aetiology of constipation and the shortcomings of current terminology for, and treatment of patients with difficulties in defecation. Quantification of the yield stress will make it possible to construct an accurate biomechanical model of human defaecation to investigate mechanisms of continence and constipation.

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Conflict of interest

The authors declare that no conflict of interest exists.

Ethical approval: The study has been performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments.

Informed consent: For this type of study formal consent is not required.

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