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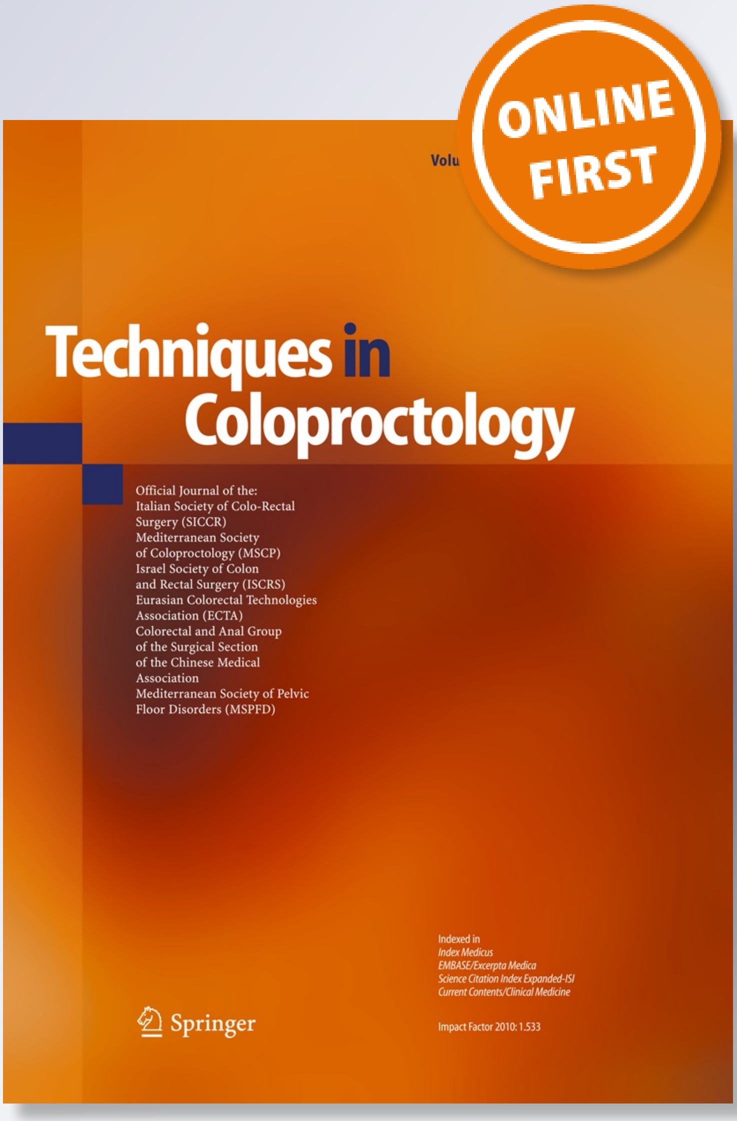

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ORIGINAL ARTICLE

Defecation 2: Internal anorectal resistance is a critical factor in defecatory disorders

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Abstract
Background The aim of this study was to test our hypothesis that the reason why imaging is of little assistance in diagnosing "constipation" causes may be related to the high sensitivity of internal anorectal flow resistance in defecation to small changes in geometry. We applied a mathematical model to describe the effects on flow mechanics of observed changes in the shape of the rectum and anus during defecation.
Methods Three groups of patients were studied with video proctograms. Group 1 comprised 4 patients with normal defecation studied with video proctography or magnetic resonance imaging (MRI). Group 2 comprised 8 patients with fecal incontinence, studied by video X-ray electromyography. Group 3 comprised 8 patients with constipation evaluated by video MRI.
Results Three muscle vectors open the anorectal angle prior to defecation, causing the anorectal luminal diameter to increase to approximately twice its resting size. These vectors are *forwards* (anterior wall), *backwards* and *downwards* (posterior wall). Resistance to passage of a fecal bolus through the anorectum is determined by viscous friction against the anorectal wall and by the energy required to deform the bolus as it flows. The observed changes in anorectal geometry serve to reduce both the viscous friction in the anus and the deformation of the bolus, which reduces the force required to facilitate its passage through the anus. For example, if the effective diameter of the anus is doubled during defecation, the frictional resistance is reduced by a factor of 8.
Conclusions The sensitivity of flow resistance to geometry explains why MRI or computed tomography (CT) scans taken during defecation are not often helpful in diagnosing causation. Small changes in geometry can have a disproportionate affect on flow resistance. Combining accurate directional measurements during dynamic MRI or CT scans taken during defecation with observations of bolus deformation, and if possible, simultaneous anorectal manometry, may provide clinically helpful insights on patients with anorectal evacuation disorders.

Keywords Mechanism of defecation · Constipation · Fecal incontinence · Pelvic floor disorders · Anorectal resistance · Lubricated flow · Yield stress · Mathematical model

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M. Bush (✉) · P. Petros
School of Mechanical and Chemical Engineering,
The University of Western, Perth, Australia
e-mail: mark.bush@uwa.edu.au

P. Petros
e-mail: pp@kvinno.com

P. Petros
St Vincent's Hospital, University of New South Wales,
Sydney, NSW, Australia

M. Swash
Department of Neurology, Royal London Hospital
and Queen Mary University of London, London, UK

M. Swash
Institute of Molecular Medicine, University of Lisbon,
Lisbon, Portugal

M. Fernandez
Department of Radiology, Clinica Las Condes,
Santiago de Chile, Chile

A. Gunnemann
Klinik für Urologie und Kinderurologie Klinikum Lippe,
Detmold, Germany

Introduction

We have shown that active opening of the anorectum during defecation is dependent on three muscle force vectors [1]. These muscle vectors were present in normal subjects, and also in patients with fecal incontinence or constipation. The muscle-derived vectors observed during defecation were similar to those demonstrated during opening of the urethral outflow tract in micturition [2].

There are other parallels between the anorectum and the urinary tract. The bladder and the rectum are essentially storage containers with emptying tubes, the urethra and anus. Frictional resistance to flow is a physical phenomenon, and it applies to all tubes, whatever their structure and function. Furthermore, frictional resistance is not linearly related to the diameter of the tube. As regards resistance to flow within the urethra, we have shown that, following the Darcy–Weisbach Law for non-laminar flow, it approximately varies inversely with the 5th power of the radius [3]. As a consequence, even a small change in the diameter of the urethral tube could have a major effect on urine flow. We hypothesized that resistance to fecal flow in the anorectal outlet tube would be subject to a similar exponential law, with the difference that defecation involves solid or semi-liquid material. In a similar study of flow through the anorectum, Farag [4] applied Poisseuille's law for laminar (viscosity dominated) flow. The anorectum was taken to be a tube of uniform diameter, carrying material of constant 'effective' viscosity (Newtonian fluid). Different values of viscosity were assumed for different states of the anorectal content. Under these conditions, Poisseuille's law predicts the flow resistance to be inversely proportional to the fourth power of the radius and proportional to the viscosity. There is no doubt that the flow resistance is sensitive to geometry. In the present study, we wished to investigate the effects not only of average tube diameter but also of the internal variations of geometry along the length of the anorectal canal. This required the non-Newtonian behavior of the bolus to be taken into account, along with other factors such as the effect of lubricating mucus. In particular, the resistance to the flow of feces through a duct of varying diameter is likely to be dominated by the yield stress behavior of the material, viscous effects being a secondary consideration.

Considered from a flow mechanics perspective, active opening of the anorectal tube as a component of defecation is an attractive concept. Contraction of striated musculature external to the rectum stretches the rectal walls, reducing the resistance of the mucosal folds. The resultant expansion of the diameter of the rectum, and reduced abruptness of changes in diameter along its length, will substantially reduce the expulsion pressure required for evacuation of feces. We set out to analyze the mathematical basis of defecation by analyzing our imaging observations [1] with reference to the flow mechanics of semi-solid matter through straight tubes, while recognizing the variable shape characteristics of the lower bowel, rectum and anus. We emphasize that this concept will require more detailed analysis, including accurate assessments of fecal flow rate, volume, consistency and deformation characteristics of the stool, lubricant consistency and accurate three-dimensional (3D) measurements of the volume changes of the anorectum.

Materials and methods

Three groups of patients were studied with video proctograms. Group 1: 4 patients with normal defecation had video MRIs; Group 2: 8 patients with fecal incontinence had video X-ray myograms; Group 3: 8 patients with obstructive defecation had video MRIs. These were described fully in the companion paper [1]. Typical images are reproduced in Fig. 1.

Mathematical methods

We applied a mathematical model based on well-established engineering principles to analyze resistance to flow of the stool by means of the anorectal geometry observed in video proctograms [1]. The resistance characterizes the amount of pressure required to force the stool to flow through the anus. The analysis is independent of the way the anorectal geometry comes about. Our aim was to understand the effect of changes to the geometry that may result from variations in elasticity (compliance) of the anorectum or the external active opening mechanism.

Feces of normal consistency behaves as a "plastic" material, in that fecal deformation leads to a permanent change in shape, with little or no elastic recoil, analogous to the behavior of a concentrated paste. Deformation is characterized by "flow stress", linked to the classic material property of "yield stress". If the applied stress is less than the flow stress, σ_f, the material will not deform, but once the stress exceeds σ_f, the material deforms plastically, that is, permanently. Resistance to movement of the fecal bolus through the rectum and anus is dominated by two factors: first, friction of the bolus against the wall of the duct (anorectum) resisting its motion and second, forces required to deform the bolus as it flows through physical restrictions or bends in the anorectum. A simplified representation of the flow of anorectal content is given in Fig. 2.

The flow of a fluid or plastically deforming solid through a duct has been very well characterized for many decades or centuries and can be described using simple mathematical expressions that link flow rate to the applied pressure gradient that is driving the flow, and parameters

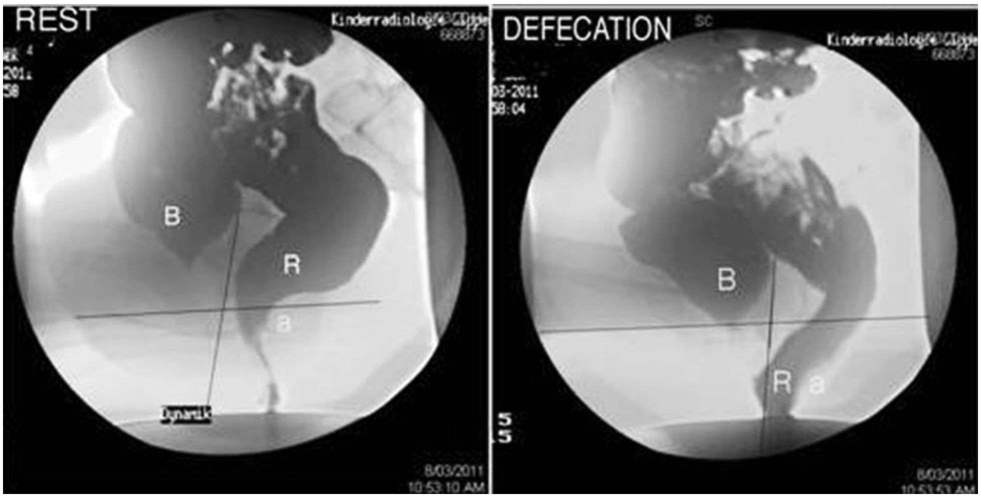

Fig. 1 MRI: Normal subject. *Left side at rest* the rectum 'R' is resting on the levator plate with a well-defined anorectal angle 'a' which is about 110 degrees. *B* bladder. *Right side defecation* the rectum and anorectal angle have descended below the horizontal bony co-ordinate; the anorectal angle 'a' has opened to approximately 150 degrees; the anterior rectal wall has been pulled forwards; the anorectal lumen has opened to at least to twice its resting diameter. Feces appear to run down the posterior wall of rectum

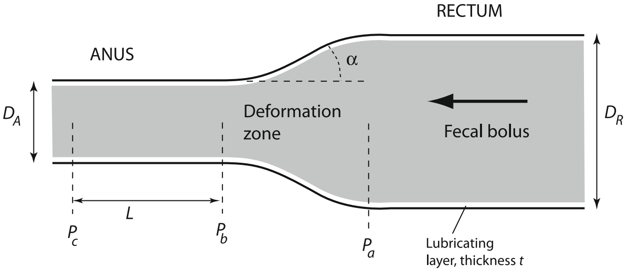

Fig. 2 Simplified representation of the rectum and anus. Note the necessary deformation of a fecal bolus when a change in diameter occurs, and the presence of a thin lubricating layer between the bolus and the duct wall

such as duct diameter and wall friction. The equations can be attributed to Stokes and Poisseuille [5] and have been modified to take into account complex fluid behavior, such as a yield stress [6]. Simple expressions of this sort are frequently applied to analysis of flow problems in bioengineering [7].

More detailed modeling of geometry and complex tissue behavior requires more complex numerical techniques, such as finite element analysis. This approach may be used to study the detailed behavior of a complex structure, such as the urethra [8] or the pelvic floor [9]. While the first of these studies takes into account the fluid pressure inside the urethra, the second does not deal with the nature of the flow through the anorectum; instead, it focuses on the interaction between structures in order to elucidate the mechanics of normal function in the pelvic floor. In the current paper, we focus for the first time on the effects of variations in the geometry of the anorectum on the forces required to expel feces. Direct observations of the shape and behavior of the anus and rectum obtained from various forms of imaging techniques are used to estimate the geometrical changes between resting and defecating conditions.

Although this model (Fig. 2) implies a simplification of the actual geometry (Fig. 1), it captures the key features of fecal flow, namely the presence of wall friction and the effect of geometrical changes along the anorectum. We have deliberately ignored the effects of bends in the duct. Flow through a bend will induce slightly higher wall friction and additional deformation resistance. However, this addition to the model would not add new insight to the key features of the analysis.

During defecation, the observed backward movement of the upper part of the anorectum, and forward movement of its lower part, effectively straightens the anorectal tube (Fig. 1), which helps us to derive clinical deductions from our calculations on a straight tube (Fig. 2). We have considered two possible scenarios regarding the mechanics of fecal flow in the anorectum: lubricated flow and flow with bolus deformation.

Results

Physical observations

In all three groups, both the anterior and posterior rectal walls appeared to be stretched during defecation. The dynamic changes in anorectal shape were similar in all three groups: the anorectal angle moved significantly downwards and began to open; the diameter of the anus enlarged to at least twice its resting size. In addition, the anterior wall of the anus was pulled forwards along with the distal part of the urethra (Fig. 1). These changes in anorectal position during defecation can be resolved as three muscle vectors. The anterior wall of the anus was pulled forwards; the posterior wall of the rectum was pulled backwards, opening the posterior anorectal angle and approximately doubling its resting diameter; and the anterior edge of the levator plate and coccyx were angulated downwards. Though quantitative differences appeared to occur between individual patients, these directional movements were seen, to a greater or lesser extent, in all patients in each of the three groups. We also consulted the works of Li et al. [10], which demonstrated in the coronal sections that the anus was actively opened out to almost 3 times its resting diameter.

Scenario 1: Lubricated flow

If the fecal bolus is forced to flow through a straight-walled duct in which there exists adhesion between the bolus and the wall of the duct (i.e., no slip), then flow would take the form of a classic yield stress material ("Bingham" plastic). The bulk of the bolus will move along the duct as a non-deforming plug. It is only in a relatively thin layer adjacent to the wall, where the stress in the material exceeds the flow stress, that the material will deform and flow. However, if the contact between the bolus and the wall is lubricated, then the flow mechanics will be quite different. In this case, it is likely that the bolus will remain largely un-deformed—instead the thin lubricating layer will flow.

The pressure (or driving force) required to overcome the resistance to move the bolus forward will depend on the viscosity of the lubricating fluid, which will be significantly less than the flow stress of the bolus itself. If the lubricating layer thickness is assumed to be much smaller than the diameter of the tube, then simple mechanics can be used to show that the pressure gradient $\Delta P/L$, for example, in the anal duct in Fig. 2, $(P_b - P_c)/L$, required to force the bolus to move with a flow rate Q, is inversely proportional to the cube of the diameter, D_A in Fig. 2. Specifically, $\Delta \mathrm{P}/\mathrm{L} = 16\,\mu\,\mathrm{Q}/\left(\mathrm{D}_{\mathrm{A}}^{3}\pi\,\mathrm{t}\right)$ where t is the thickness of the lubricating layer and μ is its viscosity.

According to this relationship, the pressure gradient will be highest in the anal canal, that is, where the duct diameter is the least, but more importantly, if the diameter of the anal canal was to be increased, for example by forward stretching of the anterior anal wall (as in Fig. 1), then the resistance to flow through the anorectum will decrease in proportion to D_A^3. If the diameter is doubled, the resistance falls by a factor of 8.

Scenario 2: Flow with bolus deformation

If the anal canal is narrower in diameter than the rectum, as illustrated in Fig. 2, forcing the bolus to deform as it flows through the zone of constriction, then the pressure required to drive the flow in this region (Fig. 2: $\Delta P = P_a - P_b$) is likely to be dominated by the deformation process, despite the presence of wall lubrication. This process is similar to well-known extrusion processes applied to metals and plastics, whereby, for example the diameter of a billet of metal is reduced. The pressure required to achieve this flow does not depend directly on the absolute diameter of the duct, but instead depends on the change in cross-sectional area of the duct, which can be expressed in terms of the ratio of rectum to anus diameter D_R/D_A (Fig. 2). The calculation of driving pressure is well established [11].

The pressure will be a function of the material flow stress (i.e., the yield stress), σ_f, the ratio of diameters, D_R/D_A, and the rate of change in diameter characterized by the angle α (in Fig. 2): $\Delta P = 2\,\sigma_f\,K(\alpha)\ln(D_R/D_A)$, where $K(\alpha)$ is a geometrical factor that depends on α, and *ln* refers to the natural logarithm of the diameter ratio. For example, a comparison of the deformation-induced flow pressure for the case of $D_R/D_A = 4$ (the anus diameter is 25 % of the diameter of the rectum) with the case of $D_R/D_A = 2$ (the anus diameter is 50 % of the diameter of the rectum) indicates that the required pressure decreases by a factor of 2 between these two geometries; that is, the flow pressure required in the second geometry is half that required in the first geometry.

Discussion

The total pressure required to force the stool to flow into and through the anus will be the sum of the two components: pressure required to overcome the frictional resistance in the anus (Scenario 1) and pressure needed to deform the bolus as it passes from the rectum to the anus (Scenario 2). It is possible to estimate the relative magnitude of the two components by inserting reasonable estimates of the material properties and flow rate into the equations above and taking dimensions from Fig. 1 (active defecation state). The result indicates that the deformation component is approximately an order of magnitude greater than the frictional component for the anorectal geometry shown on the right-hand side of Fig. 1—the pressure required to force the bolus to flow is dominated by the deformation of the material. This is a consequence of the exponential relationship between diameter and frictional resistance in the anus (Scenario 1). As the anus doubles in diameter between rest and active defecation, the frictional resistance falls by a factor of 8 for a given flow rate.

Furthermore, the reduction in diameter of the anus relative to the rectum evident in the comparison of the active state to the rest state in Fig. 1 is particularly important. In fact, as the diameter of the anus approaches the diameter of the rectum in active defecation, the deformation flow resistance diminishes to zero. If the observed changes in geometry between rest and active defecation were not to take place, the pressure in the rectum required to make the feces flow at the same rate would be at least an order of magnitude higher.

Our mathematical analysis is of more than theoretical interest, because any deficiency in this mechanism, whether muscle weakness or diminished muscle contractile force, caused by lax, stretched muscle insertion points [12–16], will impact on rectal evacuation by changing the flow geometry and hence the flow resistance. An example of the importance of this opening mechanism is evident in the urinary and bowel retention that occurs when this mechanism is disabled, as in spinal cord transection. Because of the sensitivity of flow resistance to anorectal geometry, even a minor degree of prolapse or intussusception may have a far greater functional impact than is evident on defecating proctography. Our clinical conclusion, therefore, is that non-surgical treatments should include pelvic muscle exercises to strengthen the muscle forces activating this opening mechanism. Any surgical treatment should at least prevent internal prolapse of the rectal mucosa, and at best restore the external opening mechanism (Fig. 1).

Correlation of imaging observations with the mathematical analysis

The anus is significantly larger during defecation compared to its resting state (Fig. 1), but there is often a focal bulge in the rectum just above the anus. Therefore, there must be deformation of the fecal bolus at this point, although this deformation may be less than would exist if there was no active opening of the anorectum. The ratio of average rectal to anal diameter is approximately 4 in Fig. 1 (resting), but approximately 2 during defecation. Assuming a constant flow rate, the deformation-related pressure would then decrease by approximately 50 % between the resting and defecation states, as in scenario 2 above. Furthermore, if active opening at least doubles the anal canal diameter, as suggested by comparison of resting and defecation in Fig. 1, the pressure required for defecation related to frictional resistance will decrease by a factor of more than 8, in accordance with scenario 1, described above. These two effects will facilitate the movement of the bolus, as in normal defecation.

In the absence of active external muscle opening, for example due to damaged muscles, lax ligaments or lax muscle insertion points, the anus would be narrower than it appears in Fig. 1 (defecation), so there would be major deformation pressure increase late in the process of defecation, requiring additional expulsive forces such as straining. The patient would experience this as difficulty in defecation, that is, constipation. Our model indicates that resistance to flow is highly sensitive to anorectal geometry. Therefore, patients may experience disordered fecal evacuation even with minor anatomical changes in clinical and MRI examination.

Role of the anal glands

The presence of a lubricating layer in the anorectum is fundamental to our calculations. Anal glands are well-known histological structures [17]. Our analysis implies the importance of lubrication of the anal walls, thus reducing frictional resistance to the passage of the fecal bolus, as shown diagrammatically in Fig. 2.

Role of muscle contraction

The concept of striated muscle vectors situated outside the rectum acting in a co-ordinated sequence to open it out is critical to this work. According to Li et al. [10] and others [1, 16], the morphological changes that occur during defecation (Fig. 1) are secondary to pelvic floor contraction. Furthermore, according to the Musculoelastic Theory [16], evacuation disorders in the female ultimately derive from laxity of the uterosacral ligaments. The downward vector contracts against a competent uterosacral ligament [16], and a lax uterosacral ligament may cause a deficiency in the downward muscle force, which opens out the anorectum (and urethra) during evacuation [2, 16]. This may lead to rectal (and urinary) evacuation disorders because of the increased resistance, which is encountered by the rectal (and bladder) detrusor. Abendstein et al. [18] reported surgical cure of evacuatory disorders and anterior rectal wall intussusception using a posterior sling to suspend the vaginal apex, with or without perineal body repair.

Limitations of the study

The model illustrated in Fig. 2 implies a simplification of the actual geometry (Fig. 1), as it does not take into account curvature of the anorectum. However, the model captures the key features of fecal flow, namely the presence of wall friction and the effect of geometric changes along the anorectum. Further complications in model geometry will increase the resistance, as additional deformation of the bolus will occur; however, the principles of the relationship between flow resistance and flow rate will remain relatively unchanged. Our aim here has been to demonstrate, only in a conceptual sense, the nature of the key factors that affect flow resistance without creating a detailed predictive model, which would require the application of detailed and complex numerical modelling techniques such as finite element analysis.

Furthermore, we did not attempt to characterize the full range of physiological variations in anorectal diameter between rest and during defecation, but have instead investigated the key changes that will occur if there are significant changes the anorectal geometry.

Conclusions

The relationship between geometry and flow resistance explains why MRI or CT scans taken during defecation are not often helpful in diagnosing causation. Small changes in the geometry of the anorectum can produce large changes in the forces required to expel feces.

Combining accurate directional measurements during dynamic MRI or CT scans taken during defecation with observations of bolus deformation, and if possible, simultaneous anomanometry, may bring clinically helpful insights to patients with anorectal evacuation disorders, especially when treatments using new surgical procedures such as a posterior sling are planned.

Conflict of interest The authors declare that no conflict of interest exists.

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