Towards an assessment of rectal function by coupling X-ray defecography and fluid mechanical modelling

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***Abstract*— Despite the numerous available clinical investigation tests, the associated alteration of quality of life and the socio-economic cost, it remains difficult for physicians to identify the pathophysiological origins of defecation disorders and therefore to provide the appropriate clinical care.**

Based on standardized dynamic X-ray defecography, we developed a 2D patient-specific computational fluid dynamic model of rectal evacuation. X-ray defecography was carried out in a sitting position with a standardized paste whose yield stress matched that of soft human feces. The flow was simulated with lattice-Boltzmann methods for yield stress fluids and moving boundary conditions.

The model was applied for a patient with a normal recto-anal function. We deduced from the flow field that the main flow resistance during the defecation was due to the extrusion of the paste through the anal canal. We calculated also from pressure and stress fields the spatio-temporal evolution of the wall normal stress. This latter highlighted a gradient from the proximal to the distal part of the rectum.

We discussed how this new set of hydrodynamical and biomechanical parameters could be interpreted to gain new insights on the physiology of defecation and to diagnose underlying evacuation disorders.

***Clinical relevance*— If confirmed, our approach should allow clinicians to obtain other parameters from a classic clinical examination and thus better adapt the response of clinicians to the defecation disorders observed in patients.**

I. INTRODUCTION

Human defecation is the voluntary evacuation of faeces coordinated by sensory and motor activity of the rectum. Defecation disorders are worldwide problems observed in a significant part of the population (e.g. 15% in North America) and seriously affect the quality of life with significant socio-economic costs [1]. The health care pathway of these patients remains complex as the symptoms do not permit the physician to identify the pathophysiological origins of those trouble even with in-depth clinical investigations [2].

Moreover, significant disagreements remain between contemporary tests (e.g. manometry, imaging techniques, ballon explusion test) used to assess colonic and anorectal function and then establish a diagnosis and treatment pathway [3]. These diagnostic difficulties are compounded by our incomplete understanding of the normal and pathological process of defecation which has led to the continuing debate over the classification of defecation disorders [4], [5].

For these reasons, some biomechanical models of human defaecation emerged for a few years. By connecting muscle activity, anatomy of the recto-anal junction and the flow and rheology of feces, these models contribute to the renewal of the knowledge on rectal function, [6], [7].

In the present case-study report, based on a standardized dynamic imaging technique of human defecation (X-ray defecography, [8]), we report a 2D patient-specific computational fluid dynamic (CFD) model of rectal evacuation. We describe a model which allows to assess hydrodynamical and biomechanical factors controlling defecation, which could be used to gain new insights on the physiology of defecation and to diagnose underlying evacuation disorders.

II. MATERIALS AND METHOD

A. Videodefecography

The X-ray videodefecography used for CFD modelling was selected among about 2300 examinations performed by Dr. Alain Dubreuil during 28 years of professional medical career [9], [10]. Videodefecogrophy was performed in a sitting position of the patient. The rectum was visualized in the sagittal plane (Fig. 1-a) and filled with a standardized radio-opaque paste until the patient experienced rectal fullness [8].

The paste was prepared by mixing barium sulfate with a suspension of potato starch and cooked to obtain a paste, as described by Mahieu *et al.* [8]. The interest to use barium paste lies in the fact that its rheological properties corresponds to the one of a soft feces. In our previous study [7], we reported that the rheological properties of barium paste can be described by the Herschell-Bulkley constitutive model,

$$\begin{cases} \tau = \tau_0 + k|\dot{\gamma}|^n, & \text{if } |\tau| > \tau_0 \\ \dot{\gamma} = 0, & \text{if } |\tau| \leq \tau_0 \end{cases} \tag{1}$$

where τ_0 is the yield stress, k the consistency index, n the flow index, τ the shear stress and $\dot{\gamma}$ the shear rate. This constitutive equation corresponds to a fluid that can flow only if the stress is larger than the yield stress. For the barium paste, τ_0 = 350 Pa, n = 0.42 and k = 1000 Pa.s^n [7]. CFD simulations were carried out with these rheological parameters.

The videodefecography used in this study was carried out in 2001 on a female patient of 63 years old, who did not present any morphological abnormality. The patient was diagnosed with transit constipation with hard stools and her

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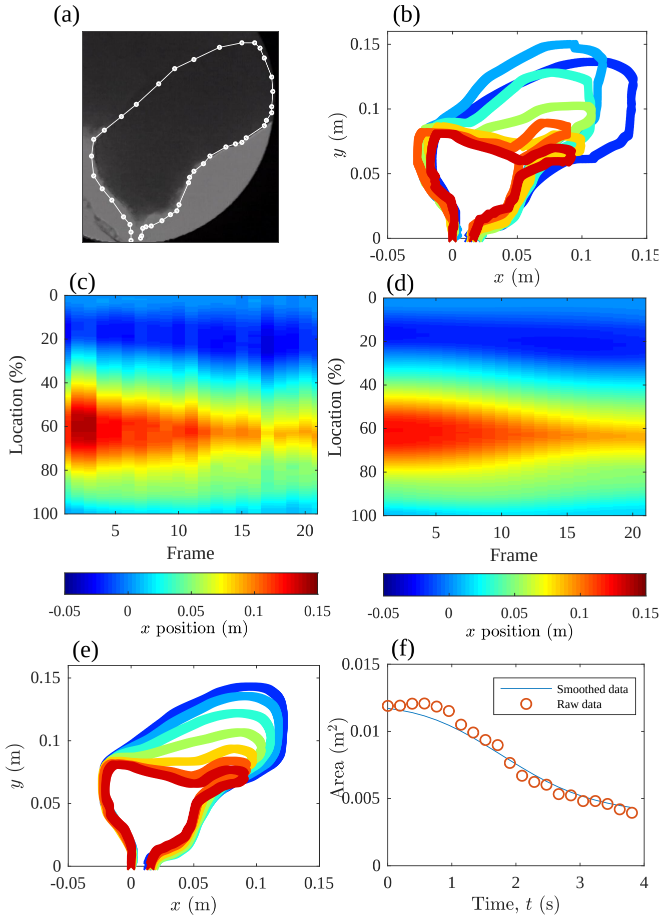

Fig. 1: a: Example of X-ray images segmentation. b: Raw profiles of the rectum after segmentation and interpolation for different time steps (time increasing from blue to red). c: Spatio-temporal map of the x position of the evenly spaced markers. The locations 0 and 100 % correspond to the anterior and posterior part of the anus, respectively. d: ST map after smoothing. e: Smoothed profiles of the rectum. d: Comparison of the area bounded by the raw boundaries (circles) and the smoothed boundaries (plain line).

rectal function was considered to be strictly normal by Dr. Alain Dubreuil. The patient experienced rectal fullness after the administration of 330 g of barium paste. The rectum was emptied at 90% in 4 s. The rectal length (10.2±2.3 cm), ano-rectal angle (120±9°), anal diameter (1.61±0.4 cm), were in accordance with dimensions reported for normal subjects on a large cohort [11].

Patient wa informed that her anonymized data might in the future be the subject of clinical research and could oppose this by informing the doctor. All procedures performed in this study were in accordance with the ethical standards research committee and with the Helsinki declaration. Ethics approval is not required for this retrospective study.

B. Image Analysis

X-ray analog images (HI-8) were first digitized using VLC media player software and process with the Image Processing Toolbox of Matlab R2019b (Mathworks). The boundaries of the rectum and the anus were manually segmented with approximately 40 points; white circles in Fig. 1-a. The selected x and y coordinates of the boundary were interpolated with a Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) method to increase the resolution for all the time steps, Fig. 1-b. For each time step, about 1000 points, evenly spaced along the boundaries, were selected. Fig. 1-c shows the spatio-temporal (ST) map of the x coordinate of these points. ST maps for x and y coordinates were smoothed with a 2D Gaussian filter, Fig. 1-d. Fig1-e shows the profiles of rectum boundaries after the smoothing process. This process allowed to suppress mass movements of the rectum when the patient was moving during the examination. The smoothed set of data was linearly interpolated for subsequent CFD simulations. To validate the image processing algorithm, the variations of the surface area bounded by the smoothed boundaries were compared to the one bounded by the raw data, fig1-f. The averaged outlet velocity of the barium paste in the anal canal V_{out} was given by the ratio of the temporal derivative of the area over the diameter of the anal canal.

C. CFD model

The barium paste flow during the defecation was simulated with D2Q9 lattice-Boltzmann methods (LBM) to solve mass and momentum conservation equations in 2D on a Cartesian mesh [12]. The viscosity at each lattice was calculated with the Papanastasiou's regularization of the Herschel-Bulkley model (Eq. 1) [13], i.e. $\eta = \frac{\tau_0}{|\dot{\gamma}|}[1 - \exp(-m|\dot{\gamma}|)] + k|\dot{\gamma}|^{n-1}$, where η is the viscosity, m is the stress growth exponent, and $|\dot{\gamma}| = \sqrt{\dot{\gamma}_{ij}\dot{\gamma}_{ij}}$ the second invariant of the rate-of-strain tensor. The two relaxation times LBM scheme was used to suppress numerical discrepancies associated to large variations of viscosity in one relaxation time LBM schemes [14], [15].

The moving boundary conditions were calculated by a computationally efficient combination of the bounce-back scheme and the transfer of momentum on the fluid by the moving wall [16]. Similarly, the velocity profile corresponding to the flow of a Herschell-Bulkley fluid of averaged velocity V_{out} was enforced at the outlet of the anal canal. The code was carefully validated with benchmark solutions for flows of yield stress fluids: Poiseuille flow and shear flow with a moving obstacle. The grid to solve the flow consisted in about 4000 lattices.

The stress applied in the normal direction by the fluid over the boundaries of the rectum, i.e the wall normal stress WNS, was calculated by

$$\text{WNS} = (-p\bar{\bar{I}} + \bar{\bar{\tau}}).\vec{n} \quad (2)$$

where p is the pressure on the rectum boundary, $\bar{\bar{I}}$ is the identity normal tensor, $\bar{\bar{\tau}}$ is the deviatoric part of the stress tensor and $\vec{n}$ is the normal unit vector to the boundary.

III. RESULTS & DISCUSSIONS

The patient-specific CFD model of rectal evacuation was used to calculate different hydrodynamical and biomechan-

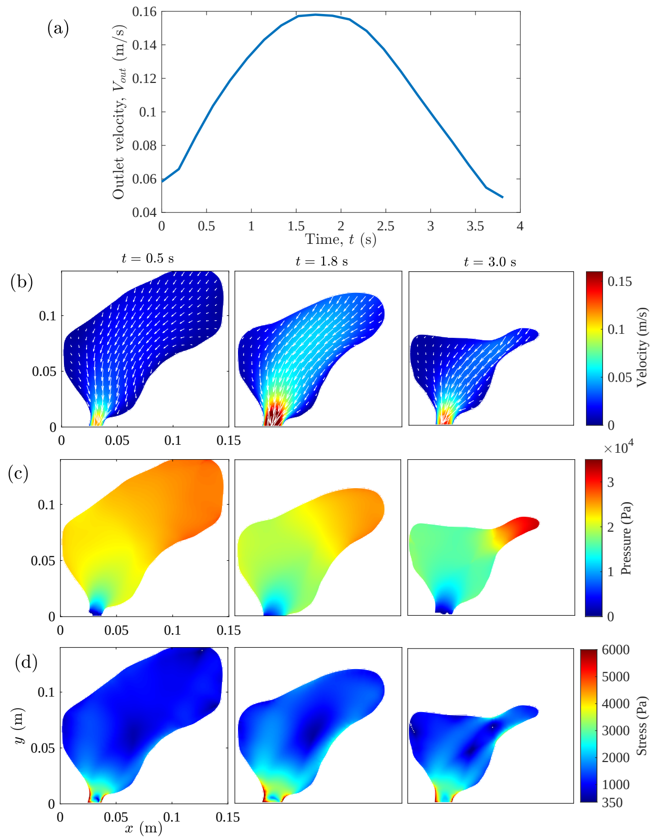

Fig. 2: Average outlet flow velocity V_{out} of the barium paste passing through the anus (a). Velocity (b), pressure (c) and stress (d) fields at 0.5, 1.8 and 3 s during the defecation of the barium paste.

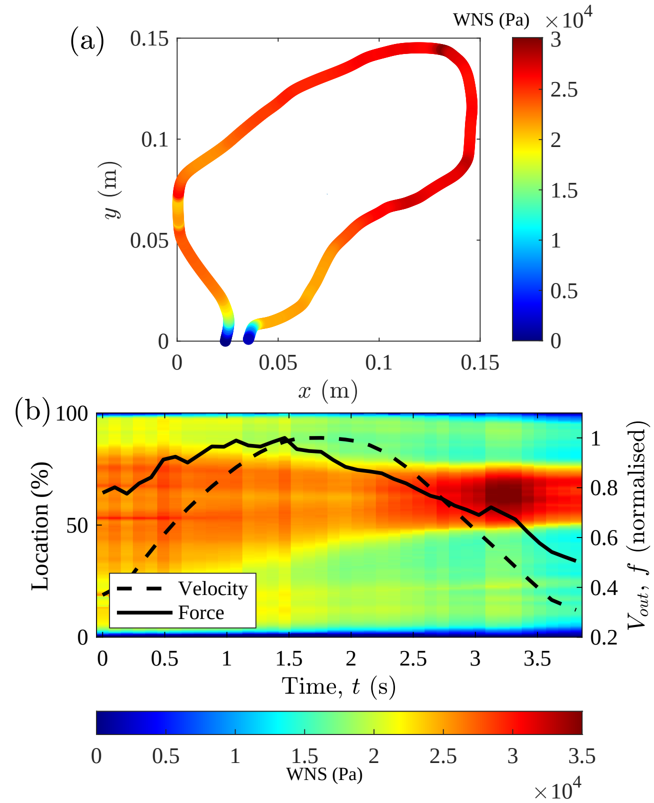

Fig. 3: a: Instantaneous variations of the wall normal stress (WNS) along the boundaries of the rectum at $t = 0.5$ s. The color code corresponds to the magnitude of WNS. b: Spatio-temporal map of WNS along the boundaries of the rectum. The location 0 and 100 % correspond to the anterior and posterior part of the anus, respectively. Plain and dashed lines show respectively the temporal variations of the magnitude of the force $\vec{f}$ and the outlet velocity V_{out}, which are scaled by their maximal value (right y-axis).

ical parameters during the defecation of the standardised barium paste for a patient who had a normal recto-anal function and anatomy.

A. *Hydrodynamics of defecation*

The averaged outlet velocity of the barium paste through the anus (V_{out}), calculated from image analysis, and time-sequences of the velocity field in the recto-anal cavity are shown in Fig. 2-a,b. The temporal evolution of V_{out} had a bell-like shape with a maximum of 0.16 m/s after 2 s of the beginning of the defecation. The velocity was oriented from the proximal (colo-rectal part) to the distal (ano-rectal part) parts. Its magnitude was maximal in the anal part and minimal in the cavity forming the anterior part of the rectum.

The pressure field shows a gradient from the proximal to the distal part, and was maximum at the distal part, Fig 2-c. The stress (i.e. second invariant of the stress tensor) was in average 10 times larger than the yield stress of the barium paste (350 Pa), and was maximal at the boundaries of the anus and relatively homogeneous in the rectum (Fig 2-d).

These results illustrated that the main flow resistance was related to the extrusion of the barium paste through the anal sphincter. Moreover, the stress was larger than the yield stress, meaning that all the barium paste was flowing. In pathological situations, the anterior part of the rectum can form a large cavity, called rectocele, in which the feces forms a cluster and accumulates [11]. Rectocele should be identified by regions of low stress and velocity, where the feces does not flow. A question to address in the future is to know if the presence of anatomical abnormalities, such as rectocele or enterocele, can impair the rectum function, i.e. create a supplementary flow resistance that could impair defecation. Also, we could hypothesize that the retention of feces in the rectocele might be the consequence of abnormal properties of the feces. Consequently, our model should help to know whether a surgical procedure is required.

B. *Muscle activity during defecation*

The wall normal stress (WNS), i.e. the normal force per unit of area that is exerted by the boundaries of the rectum over the barium paste, was calculated by projecting the stress field on the rectum boundaries (Fig3-a, Eq. 2). The WNS gradient from the proximal (maximum) to the distal (minimum) part was highlighted in the ST map of WNS

(Fig. 3-b). The gradient was always in a proximal to distal direction, regardless of the time of defecation. The maximum WNS of about 30 kPa observed at 3.2 s is coherent with manometric data, which reported a maximal pressure of about 40.2 kPa [17]. From these results, we can speculate that ST-maps of WNS for patients suffering of evacuations disorders should allow to identify an absence of muscle coordination [10], [18].

By integrating WNS along the rectum boundaries, we calculated the magnitude and the direction of the global force of the boundaries over the barium paste $\vec{f}$. On the ST map (Fig. 3-b), both amplitude of $\vec{f}$ and V_{out} are plotted as a function of time. Note that the amplitude of both variables were divided by their maximum. Both data were not in phase with the evolution of WNS: the temporal evolution of the force showed a bell-like shape, with a maximum almost in phase with V_{out} and preceding the maximum of WNS by 2 s. This phase shift is explained by the reduction over time of the contact surface of the barium paste with the mucosa of the rectum. Consequently, the force decreases for a steady value of WNS. Thus, any relaxation of the muscles would stop the flow. Moreover, the $\vec{f}$ orientation was equal to the recto-anal angle during defecation. In the clinical practice, the magnitude and the direction of the force could be used to detect any weakness of the muscles and/or a desynchronization of the muscles if the orientation of the force was different from the ano-rectal angle.

IV. CONCLUSION

In conclusion, this paper is a first step towards an assessment of the rectal function by coupling a well-established dynamic imaging of human defecation with a CFD model. Our model maps spatially and temporally the action of ano-rectal muscles. This information should be precious to identify problem of muscle strength or loss of coordination. Work is in progress to extend these simulations on a larger cohort of patients showing normal and pathologic defecation.

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