Viscoelastic modelling of Rectum tissue during short-term relaxation

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Abstract: The mechanical properties of rectum are highly time dependent as the result of the soft tissue's viscoelastic nature. Prediction of time-dependent mechanical properties can help enhance the design or performance of surgical instruments which interact with the rectum. In this paper the relaxation characteristics of rectum tissue were investigated along its longitudinal axis. The result of model fitting indicates that a Wiechert 5-element viscoelastic model provides a good approximation of rectum tissue behaviour at relaxation. The model coefficients enable calculation of the viscoelastic ratio which demonstrates a gradual increase of elasticity in rectum tissue under repeated loading-relaxation cycle.

Introduction: Most studies investigating the soft tissue of the rectum focus on tensile and expansion tests, but less has been focused on indentation techniques which are typical of the tool-tissue interface during surgical manipulation. Studies have characterised the effect of repeated loading and relaxation on the time-dependent response of other tissues such as collagen or skin [1, 2] yet this has not been studied for rectum tissue. Therefore, there is a need to determine the biomechanical response of rectum tissue in similar situations to typical surgical manipulation through repeated indentation tests.

Materials and Methods

Specimen preparation: 10 freshly excised porcine rectums were obtained from a local medical meat supply. To observe the behaviour of porcine rectum along its length, the specimens were cut circumferentially into 10 equally cut segments each measuring 4x4cm and stored in saline (PBS) solution. All the tests were conducted at controlled room temperature (22°) within 24 hours of dissection. Tissues were periodically sprayed with PBS during testing to replicate the conditions in open surgery or CO_2 insufflated colonoscopy procedures [3].

Instrumental set-up: A Modular Universal Surface Tester (Falex Tribology) was used to apply a controlled load to the tissue and monitor the resultant indentation depth. Displacement data are measured at a resolution of 1µm and force data at 1µN. A fine cylindrical indenter of diameter 5mm was attached to cantilever unit. Force and displacement data were recorded at 100 Hz for subsequent analysis.

Repeated interaction test: Twenty indentations were made in the same location on each segment, with no delay between cycles. This test was designed to evaluate tissue behaviour under repeated loading. The indentation process comprises three phases. Once the indenter tip makes contact with the tissue, the *loading phase* begins and the applied force increases linearly until a peak force is reached. The indenter is then held in this position for 10s in the *relaxation phase*. Finally, in the *unloading phase* the indenter is retracted back to the start position. To determine an appropriate peak force, tissue was loaded such that its behaviour remained in the linear region of strain and any tissue damage is avoided. From preliminary tests a peak load of 1N was found to achieve this objective. A strain rate of 0.2 mm/s was used for the loading and unloading phases in common with other studies [4].

Stress relaxation model fitting: In adopting a mechanical relaxation model, an investigation was performed to evaluate whether the complex structure of the rectum can be represented as a viscoelastic material. A linear combination of springs and dashpots are commonly used to explain the viscoelastic stress-relaxation behaviour of soft tissues [1, 5]. A 5-parameter Wiechert model was selected to model tissue response as it results in a good representation of soft tissue behaviour in a simple form [1, 6]. As illustrated in **Error! Reference source not found.**, the Wiechert 5-element model includes two relaxation processes, as defined in the relaxation modulus formula:

$$E(t) = E_1\, e^{-t/\tau_1} + E_2\, e^{-t/\tau_2} + E_3$$

Where E_1 and E_2 are elastic moduli (or elastic coefficients) of relaxation processes 1 and 2, E_3 is time-independent elastic moduli (or equilibrium moduli), and τ_1 and τ_2 are the corresponding relaxation durations for each relaxation process. The sum of the three moduli is the instantaneous modulus σ(0). Viscous coefficients η_1 and η_2 are calculated as $\tau = \eta_i/E_i$ where 'i' is the number of parallel Maxwell bodies.

Results and discussion: The 5-element Wiechert model provided a good fit to the experimental data with a mean ± SD fitting error of 0.16±0.08 kN/m^2. **Error! Reference source not found.** shows that the tissue relaxes less cycle by cycle, with a pronounced decrease of this effect for the first five cycles and then a gradual decrease in the remaining cycles (a red arrow shows the direction of cyclic progression). The parameters of the Wiechert model corresponding to **Error! Reference source not found.** are given in **Error! Reference source not found.**. The time- independent moduli (E3) increases between cycles 1-5 and then plateaus for the further cycles. A similar trend is seen for the time-dependent moduli (E1 and E2) while the time constants τ_1 and τ_2 remain relatively consistent. The ratio of the instantaneous modulus σ(0) and equilibrium moduli E3 is used as a measure of viscoelasticity ratio VR= σ(0)/ E3. VR=0 is an indication of a perfectly viscous material, VR=1 represents a perfectly elastic material and intermediate values specify a viscoelastic solid [5]. In comparison to other studies, the average viscoelastic ratio of porcine large intestine obtained in this study (VR=0.63) shows less elasticity to that of PS-4 polymer (VR= 0.89) and calf bone (VR=0.75), but more elastic than that of calf patella cartilage (VR=0.1) [5].

The typical trend of the viscoelastic ratio over repeated indentations is shown in **Error! Reference source not found.**. This shows that the tissue becomes more elastic during stress relaxation, as there is a progressive increase in the amount of viscoelastic ratio with each indentation. It is proposed that this is due to the molecular structure of the tissue becoming stiffer, cycle by cycle, as plastic deformation occurs in the direction of the applied load. This plastic deformation is more permanent for the first cycle as the most significant deformation to the tissue occurs during the first indentation. In addition the viscoelastic ratio increases rapidly with the initial cycles and by the 5th cycle this increase slows and shows a repeatable response. This trend agrees with other studies, which report reaching a repeatable state by the 5th cycle [2, 7].

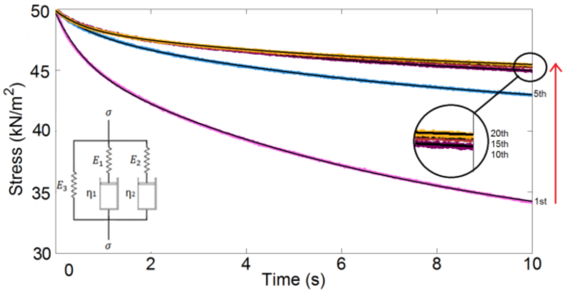

Figure 1: Typical stress relaxation curves (coloured lines) and Wiechert 5-element fits (black lines) for 20 consecutive indentations.

	E3 kN/m^2	E1 kN/m^2	E2 kN/m^2	τ_1 s	τ_2 s
1	31.7	4.0	15.8	0.6	7.7
5	44.2	1.9	7.3	0.8	8.5
10	45.8	1.5	4.9	0.7	8.1
15	46.5	1.6	4.2	0.7	8.0
20	47.6	1.6	3.8	0.6	7.1

Table 1: The average value of Wiechert parameters at 0.2 mm/s strain.

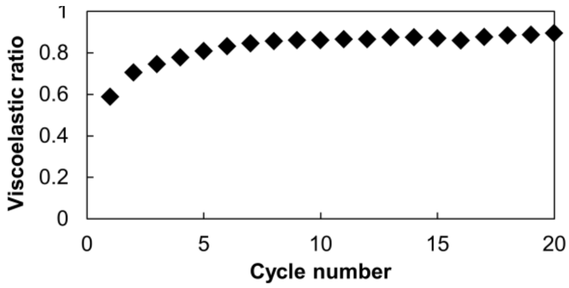

Figure 2: Typical trend of viscoelastic ratio obtained from the indentation test.

Conclusion: This study investigated time-dependent viscoelastic properties of porcine rectum through a repeated indentation test. A Wiechert viscoelastic model was employed to describe the stress relaxation behaviour. The parameters of the Wiechert model characterise the stress relaxation behaviour which can be employed for rectum tissue modelling and simulation. The result of indentation test shows that the repeated interaction substantially affects the viscoelastic response of the tissue. This has implications for the design of surgical instruments which interact with these tissues. For example repeated grasping of these tissues will require modulation of the tools contact force to achieve a consistent response.

References

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