The Viscoelasticity of Intestines by Dynamical Mechanical Analysis

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Abstract: The research for viscoelasticity of small intestine become significant in engineering due to the development of new medicine instruments such as the capsule robot and intellectualized endoscopy, which may help learn the unknown mechanical interaction between the intestinal tissue and the instrument. Therefore, a research of testing the mechanics of intestinal tissue in this paper is presented, which may help cognize intestinal viscoelasticity. As distinct from the conventional stress relaxation test, DMA (Dynamical Mechanical Analyzer) is applied in the experiment, and a large number of data is obtained by DMA, which have not been used in this area before, and is able to reveal directly the essential viscoelastic parameters of the intestinal tissue. The experiment result explicit the dissipated energy becomes larger when the strain amplitude increases. The DMA test and the experiment analysis introduce a particular angle of view in researching the viscoelasticity of intestinal tissue, and that is convenient for quantitative analysis and synthesis for deeper cognizing intestine in the future.

1 Introduction

The mechanical characteristics of intestine have been found particular and there must be important relationship between the intestinal tissue’s mechanics and the medicine instrument’s movement, e.g. the conventional endoscopy and the capsule robot which is supposed to apply in the future.

For the past years, the relative researches include two aspects: the “frictional force” and the biomechanics of GI tract tissue. The “frictional force” focuses on the friction between the capsulesbot and the intestine. The frictional resistance would change when the size, material, mass and shape is changed, and the capsule’s velocity should be taken into account too. It is learnt that when the capsule move at some low velocity, the intestinal wall deforms also slowly, and the stress relaxation makes the tested “frictional force” turn “smaller” [1]. The tissue’s viscoelasticity is considered to be an important factor which influences the frictional force between the tissue and the medicine instruments, however, the frictional characteristics of intestine’s tissue has not yet been represented essentially by law. The research on biomechanics of GI tract tissue comprises basic mechanical experiments and various constitutive models. Gregersen testified the residual stress within the GI tract under zero loading [2], and Jinbo Zhao found that each esophageal tissue layer have separate zero-stress state, which should be expressed in separate [3]. Fung’s exponential function is adopted widely in the biomechanical experiments to express the relationship between stress and strain. The GI tract’s stress-strain hyperelastic constitutive models are commonly derived from a strain energy function, e.g. pseudo-strain energy function (Fung) [4], esophageal hyperelastic model (Yang) [5] and hyperelastic model of anisotropic fiber reinforcements within intestinal walls (Ciarletta) [6]. Furthermore, viscoelasticite models are introduced to research the rate-dependence of GI tracts’ tissue. The conventional theory of linear viscoelasticity is applied, e.g. the five element model (Kim) [7], in the elongation test of stress relaxation, and five essential independent parameters are obtained. The Quasilinear Viscoelastic Model are introduced into the research of blood vessels and other organ’s tissue, e.g. the expression for efficiency of locomotion for the endoscopic robot [8], the experiment and theory research of viscoelasticity for porcine esophagus et.al. [9]
The researches above studied in part the factors which may influence the mechanical interaction about the medicine instrument inside the GI tract, while the limitations exist. The tested frictional force is complex and the frictional effect is affected strongly by the tissue’s material mechanics, in addition, it is difficult to describe exactly how the affection works, with lacking of the inner mechanism revealing out. The researches of constitutive models for the GI tract focus purely on the relationship between stress and strain, but that is not enough for solving the issue about the mechanical interaction between the medicine instrument and the tissue, besides, the FEA (Finite Element Analysis) is complex, and the absence of effective constitutive model of GI tract makes the FEA difficult, for instance, the QLV model is not feasible when solving dynamic partial differential equations in FEA [10].

The DMA is one apparatus that can test the dynamics of viscoelastic materials. The essential parameters on viscoelasticity are able to be obtained in direct, and the parameters display the mechanical response of intestinal tissue under forced oscillation. The DMA applies an effective method to research the mechanical interaction of medical instrument (for instance, the internal force-static friction capsule robot [11]) within the intestine’s lumen, and the test results may help design the control strategy of the capsule robot [12].

In this paper, we would like to present DMA, which have never been applied, for researching the viscoelasticity of the intestinal tissue from a noble angle of view. The theory of linear viscoelasticity is adopted, for it is simple and effective to explain the experiment, and have been adopted in common around the research of macromolecule materials, such as the rubber. The experiment procedure is presented, as well as the results, while hysteresis loops are introduced to explain the phenomenon.

2 Simple Shear test using DMA

The mechanics of intestines may root in the complex biological anatomy, both macroscopically and microscopically. The small intestine is composed of four concentric layers: the serosa, muscularis propria, submucosa, and mucosa. In fact, the major structural protein of connective tissue is collagen, and the most important properties of collagenous tissue is functionally mechanical. Therefore, we decided to test the mechanical parameters directly using DMA.

The theory of linear viscoelasticity is introduced in brief as follows.

The relationship between stress $\sigma$ and strain $\varepsilon$ is:

$$\sigma = Y^*(i\omega)\varepsilon$$

If the strain can be set by some experimental apparatus as custom forms, e.g. $\varepsilon = \varepsilon_0 e^{i2\pi ft}$, for $f$ the frequency, and $\varepsilon_0$ the strain amplitude, then we know that

$$\sigma = (Y_1 + iY_2)\varepsilon = \sigma_0 e^{i(2\pi ft + \delta)}$$

as according to the theory, the stress should lead the strain by a phase $\delta$ for the viscoelastic material, in which $Y_1$ is storage modulus, and $Y_2$ is loss modulus. The stress should lead the strain by a phase $\delta$ for the viscoelastic material, in which $Y_1$ is storage modulus, and $Y_2$ is loss modulus. The stress expression should be plural, in the same as the strain, and $\sigma_0$ is the stress amplitude.

The DMA (Q800, National Instruments Co.) is adopted to carry out the simple shear test.

The specimens of porcine intestine were prepared before the test. The size of each specimen was around 5×5 mm, and the thickness varied from 0.5 to 1 mm for individual specimens, for the dissection of each intestine segment is not in the same. It is estimated that this shear test of intestine in vitro was processed 6-10 hours later from the slaughter time, which was a pity because it was difficult to send the intestine in time from the slaughterhouse to our laboratory.

The clamp of DMA to fix the specimens is as follows. The stainless steel rod in the middle is driven by an actuator which is hidden bellow, and can move up and down. Specimens were pasted directly on both sides. The amplitude and frequency of vibration can be set in the manipulative program before the test.
We adopted the mode that fixed the frequency and changed the amplitude of vibration of the driver in DMA. The clamp and specimens were covered by a plastic mantle and the temperature of the sealing chamber was set to 37 °C before the test began.

3 Results

The stress-strain hysteresis loops are as Fig 2-3, in which the inner area of each ellipse represents the dissipated energy for the intestine specimen of a vibration cycle, at some amplitude. Table 1, 2 display the essential parameters, storage modulus (S.M. for short), loss modulus (L.M.) and Tgδ, which record the viscoelastic characteristics of the intestine specimens. The stress-strain hysteresis loops are drawn according to the corresponding table below.

Table 1

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<tr>
<td>1166.618</td>
<td>617.502</td>
<td>0.529309</td>
</tr>
<tr>
<td>1067.862</td>
<td>442.447</td>
<td>0.41433</td>
</tr>
<tr>
<td>1054.21</td>
<td>501.368</td>
<td>0.475587</td>
</tr>
<tr>
<td>972.835</td>
<td>492.227</td>
<td>0.505972</td>
</tr>
<tr>
<td>949.286</td>
<td>393.518</td>
<td>0.414541</td>
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Table 2

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<tr>
<td>673.573</td>
<td>772.342</td>
<td>1.146635</td>
</tr>
<tr>
<td>632.812</td>
<td>674.849</td>
<td>1.066428</td>
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<tr>
<td>627.688</td>
<td>587.322</td>
<td>0.935691</td>
</tr>
<tr>
<td>555.346</td>
<td>565.381</td>
<td>1.018071</td>
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<tr>
<td>533.822</td>
<td>521.267</td>
<td>0.976481</td>
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The results reveal that, the dynamic mechanical parameters of the intestinal tissue are not always steady, especially when the forced oscillation happens, which means the movement of the medical instrument would work in a changing environment. Besides, the mechanical modeling of the intestine is probably have to take the variation into account, which means a more complex model may be needed. In this paper, the linear viscoelasticity is adopted and the test results reveal the impossibility that using simply a set of parameters of linear viscoelasticity to describe the dynamic mechanical property of intestines.

4 Conclusions

In this paper, an effective apparatus DMA is adopted to test the viscoelasticity of intestinal tissue specimens. The experimental results are analysed applying the theory of linear viscoelasticity, and two hysteresis loops are drawn. The results imply that the mechanical interaction between both the intestinal tissue and the medical instrument are changing along with the variation of the viscoelasticity of intestines, and in the future, our work will focus on researches in quantification how the dissipated energy makes the motion of medicine instrument difficult.

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References

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