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Simulation Analysis of Small Intestinal Peristalsis Based on Finite Element

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Abstract. Based on COMSOL Multiphysics, a two-dimensional model of the duodenum of the small intestine was established and simulated to obtain the flow rate of the duodenum under different chyme viscosity and different boundary loads. The results show that: when other conditions remain the same, the outlet flow rate decreases with the increase of the chyme viscosity with significant differences; the outlet flow rate increases with the increase of the boundary loads, and the flow rate only changes significantly when the boundary load is greater than 1.0×10^{-5} N/mm^2.

Keywords: small intestine, COMSOL, finite element analysis, fluid-structure.

1. Introduction

The intestine is the most important digestive organ in the human body. The intestine refers to the digestive tube from the pylorus of the stomach to the anus, and is the longest section of the digestive tube, as well as the most important section in terms of function. The mammalian intestine contains three major segments: large intestine, small intestine and rectum[1]. A large amount of digestion and absorption of almost all digestive products are carried out in the small intestine; the large intestine mainly concentrates food residues and forms feces, which is excreted through the rectum via the anus[2]. The modern biological definition of chyme is that the food eaten by the body mixes well with gastric juice to the point where it resembles a thin gruel, and we call this chyme. After the food and gastric juice are fully mixed to form the chyme, the chyme enters the small intestine from the stomach and starts the digestion in the small intestine. Due to the chemical digestion of pancreatic juice, small intestine juice and bile and the mechanical digestion of small intestine movement, the digestion of food is basically completed in the small intestine, and most of the digested nutrients are absorbed in the small intestine[3].

As an important organ of the body, small intestine has multiple functions such as digestion, absorption, secretion and motility[4]. Regarding small intestinal peristalsis, it is influenced by various aspects such as small intestine tube diameter, wall thickness[5], internal and external pressure[6], and viscosity of intestinal contents[7]. In recent years, there have been many simulations of the intestinal tract, such as the intestinal dynamics simulation by Xiao Dunxi et al.[8] and the force modeling and the fluid-solid coupling simulation of microcapsules in the simulated intestinal tract by Li Xiao et al.[9]. However, the models of these simulations are linear simulations of the intestine, while the internal structure of the intestine is sinuous. Therefore, in this paper, we established an S-shaped model using COMSOL Multiphysics software to simulate the peristalsis of the small intestine, and further analyzed the peristalsis of the small intestine through the changes of boundary load and chyme viscosity to derive the effects of both on the flow of the small intestine.

2. Establishing a Two-dimensional Model and Setting the Initial Conditions

2.1 Modeling

The small intestine is divided into three parts, namely duodenum, jejunum and ileum, and the structural parameters of the different parts vary from one another, shown as follows[10].

Table 1 Structural parameters of small intestine

Part	Diameter/cm	Wall thickness/mm

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Duodenum	4~5	1.9~2.7
Jejunum	2~3	1.6~2.4
Ileum	1.5~2.5	1.7~2.3

The duodenum is the beginning of the small intestine and is the initial place where the chyme reaches after entering the small intestine, so the geometry is modeled with reference to the duodenum of the small intestine.

First, an S-shaped two-dimensional model is created by COMSOL Multiphysics, as shown in Figure 1.

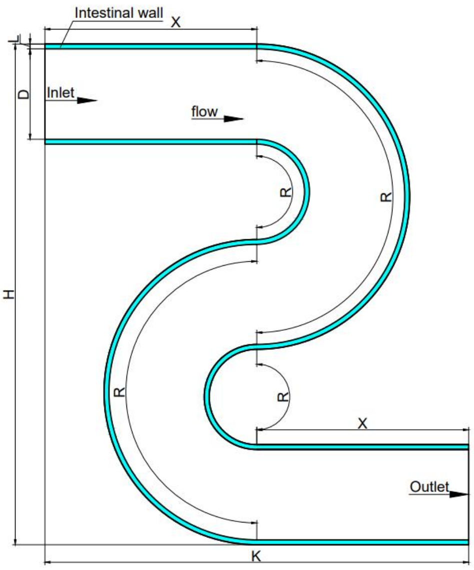

Figure 1 Schematic diagram of simulation model

The model geometric parameters are shown in Table 2:

Table 2 Geometric parameters of the model

D	45mm
X	100mm
R	180°
K	200mm
H	238.8 mm

The model contains two parts: the intestinal wall and the fluid flow. The intestinal contents are chyme, which enters from the inlet and exits from the outlet, and this paper mainly analyzes the flow variation at the exit under different conditions.

2.2 Parameter setting

The setting of the parameters of the solid and fluid parts of the model is a key process in the establishment of the model, and the variation of the parameters directly affects the simulation results of the model. Therefore, after the model is established and the geometric parameters of the model are determined, the remaining parameters of the intestinal wall and chyme should be established.

2.2.1 Solid part

A review of the literature shows that the Young's modulus of the small intestine wall tends to increase in a certain range with the increasing stress. In this paper, the Young's modulus (E) of the intestinal wall is 4.0 MPa[11,12], the Poisson's ratio v is 0.45[13] , and the density ρ is 1120.0 Kg/m^3 .

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The flow of chyme in this model is simulated by applying a boundary load on the model to simulate the peristalsis of the intestine. As the boundary load is applied, the intestinal wall will deform to drive the flow of chyme in the tube, thus simulating the peristalsis of chyme in the intestine. The boundary load is applied to the model on the red part of the intestinal wall, as shown in Figure 2, with the vertically downward direction.

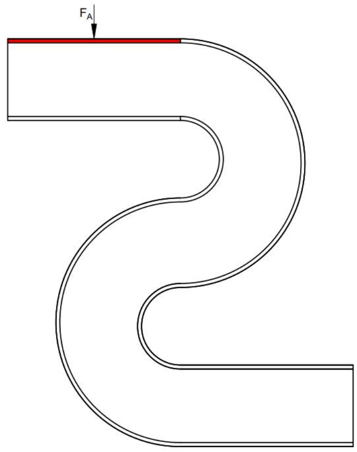

Figure 2 Model stress location

The boundary load is constantly changing in value and position on the model with time as follows Eq.

$$FA = -Lmax * load(x/width, t/dt)$$

where Lmax is the maximum boundary load, one of the variables studied in this paper; load is a function with a lower limit of 0 and an upper limit of 1. The load function is as follows:

$$Load = flc2hs(t\_off/dt - ts, 1) \cdot flc2hs(ts - t\_on/dt, 1) * \exp\left(-(xs - (x0 + v0 \cdot ts \cdot dt)/width)2/2\right)$$

The remaining parameters are listed in the following table:

Table 3.xs and ts are variables.

t_off	1.2s
dt	0.2s
t_on	0.3s
x0	-70mm
v0	30mm/s
width	-100mm

xs and ts are variables.

2.2.2 Fluid part

The chyme is mostly composed of water[14], and to simplify the calculations, we approximated the chyme as a Newtonian fluid. The density of the chyme was taken as 1000 kg/m^3. In the simulations, we adjusted the chyme viscosity (1～ 3 Pa· s) to study its effect on the flow rate.

3. Result Analysis

3.1 Net flow status at different moments in a cycle

First, in this paper, preliminary calculations were performed for the conditions when the boundary load was taken as 1.0×10^{-4} N/mm^2 , and the chyme viscosity was taken as 2 Pa·s. The time was set to 0.01 s to obtain more time nodes to make the results of the article more convincing. Through the simulation, a total of 151 data were obtained within one cycle of 1.5 s. These 151 data were line plotted to derive the variation of the net flow rate at the model outlet for each instant, as shown in Figure 3.

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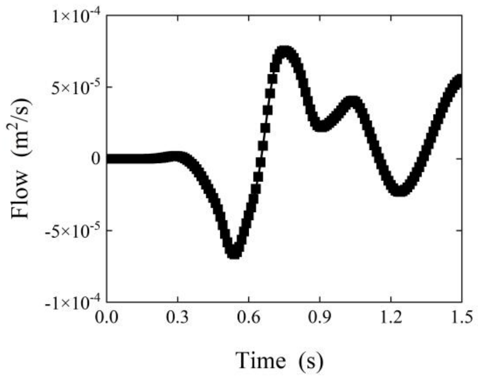

Figure 3 Flow change with time

From Figure 3, it can be seen that chyme flowed both out and back at the model exit during peristalsis with the intestine, but ultimately it was a net outflow. Based on this result, the following two additional analyses were performed.

3.2 Effect of change in chyme viscosity on net flow

The chyme viscosity was found to be at the range of 1～ 3 Pa· s, so the simulation results of the data under five sets of boundary load Lmax=1.0×10^{-4} N/mm^2 parameters were analyzed to obtain the relationship between viscosity and flow rate. Figure 4 shows the effect of viscosity change on the net flow rate.

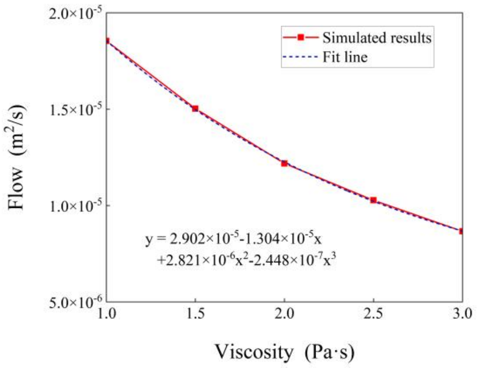

Figure 4 Effect of viscosity on flow

The results show that the net flow decreases with the increasing viscosity and increases with the decreasing viscosity.

3.3 Effect of boundary load variation on net flow

The boundary load also has an extremely important effect on the flow rate. Therefore, this paper starts from a lower boundary load and gradually increases, and finally analyzes the simulation results for 11 sets of data with viscosity of 2.0 Pa·s parameter conditions, and Figure 5 shows the effect of boundary load variation on the net flow rate.

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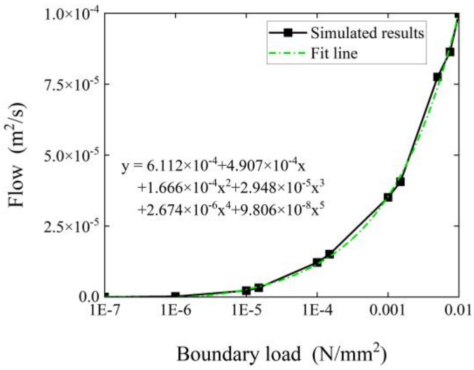

Figure 5 Effect of boundary load on flow

The results show that the net flow increases with large boundary load, and the net flow at the outlet is relatively small when the boundary load is less than 1.0×10^{-5} N/mm^2, and the flow changes significantly only when it is larger than this value.

4. Conclusion and Prospect

This experiment analyzed the peristalsis of the duodenum, and the model was numerically simulated by flow-solid coupling using Comsol Multiphysics software under different chyme viscosity and boundary load conditions. The results showed that:

1. The viscosity of chyme has a great influence on the flow rate. The flow rate at a viscosity of 1.0 Pa·s is about twice as high as that at 3.0 Pa·s. The lower the viscosity, the higher the flow rate, indicating that the conditions of low viscosity of intestinal contents are more conducive to intestinal peristalsis.
2. The flow of the intestine only increases significantly when the boundary load is greater than a certain value, and the greater the boundary load, the greater the flow. Therefore, only the peristaltic power of the intestine is large enough to ensure the normal realization of the intestinal function.

This experiment simulates intestinal peristalsis and the conclusions obtained can help to understand the peristaltic mechanism and the influence of the above two factors on peristalsis, and provide a basic theoretical analysis for the subsequent research. In the subsequent research process, more realistic models (such as 3D models) and more parameters can be set to further analyze the intestinal peristalsis and provide more ideas for related scientific and engineering applications.

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