Peristaltic flow characterization of shear thinning fluid through elastic tube by UVP

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In-vitro small intestinal flow characteristics of a non-Newtonian fluid are investigated by transient '2-wave'-squeezing of an elastic tube under different speed of peristalsis. Such peristaltic flow is the essential physiological transport mechanism in the gastro-intestinal tract. The peristalsis involves both expansion and contraction type of flow (crest and trough of a wavelength). We met the challenge of implementing the UVP technique for monitoring the velocity fields during appropriate peristaltic propulsion of a shear thinning fluid through an elastic tube (*in vitro* modeled small intestine). The higher wave speed of peristalsis results in higher magnitude of back flow velocity (negative) both in the wave crest and trough regions with positive value being near the tube wall. The higher value of back flow is expected to be responsible for the improved mixing and convection leading to higher mass transport through the intestinal wall. The measured pressure difference between crest and trough of a peristaltic wave increased, as the wave speed got faster. However, the crest region showed a higher pressure compared to the trough region since the magnitude of back flow velocity in the wave trough is found to be much higher compared to that in the wave crest.

Keywords: Elastic tube, *in vitro*, peristaltic flow, shear thinning fluid

1 INTRODUCTION

The detail understanding of steady and unsteady flow characteristics of non-Newtonian fluids in collapsed elastic tube [1] followed the interest to investigate experimentally the flow behavior of a shear thinning fluid during peristaltic propulsion through an elastic tube (*in vitro* modeled small intestine). Peristaltic flow is a primary physiological transport mechanism encountered in the most tubular organs of the human body (e.g. transport of food through the esophagus, and carrying & mixing motion of chyme in the small intestine). Some experimental and theoretical features of peristaltic flow have been studied for Newtonian fluids as described in [2-3]. In addition, an *in-vivo* study has been carried out to characterize and visualize the flux over time in small bowel segments [4]. For more realistic non-Newtonian fluid systems, systematic work is still missing. Most of the physiological fluids and foods are known to be non-Newtonian and their rheological properties (shear and extensional viscoelasticities) play an important role in the peristaltic flow characteristics. The theoretical investigation of a power-law has been studied involving the influence of shear-thinning and shear-thickening properties under peristaltic motion [5].

Present study involves the measurements of axial velocity profiles using pulsed ultrasound Doppler based velocity profile (UVP) technique under various speeds of peristalsis. In addition, the pressure difference between crest and trough within a wavelength is also measured under peristaltic motion of a shear thinning fluid through an elastic tube.

2 EXPERIMENTAL

2.1 Set up for peristaltic flow experiment

A silicone elastic tube (Lindemann GmbH, Germany) with 20 mm inner diameter, 1 mm thickness and 1165 mm long is mounted between two aluminum pipes and immersed in a water filled open tank (width 250 mm and length 1300 mm). The schematic diagram of the experimental setup with the positions of pressure sensors (P_1 & P_2) is given in Figure 1a. In addition, three distinct UVP measuring lines (ML1L, ML1 and ML1R) both horizontal and vertical positioning of ultrasound transducer and wave troughs are also inserted as in Figure 1b and 1c respectively. Three pairs of rollers (outer diameter of 30 mm) are placed (both top and bottom surface of the tube) to induce the peristaltic motion on the elastic tube. The distance between two adjacent rollers along tube length as well as the gap (4 mm) between top and bottom rollers are so adjusted that generates the peristaltic wave with wavelength of 82 mm. The speed of the rollers is controlled by an electric motor (MCD EPOS 60W, maxon motor) for the variation in peristaltic motion while squeezing of the elastic tube. The elastic tube is filled with a non-Newtonian 1.5 % carboxymethyl-celullose aqueous solution (with 0.3% polyamide) and two outlets are connected to an aqueous solution filled reservoir. Two optical fiber based pressure transducers with a control unit (Samba sensors, Sweden) are used for the measurement of local and total pressure difference in a wavelength at different speeds of peristalsis. The velocity profiles are monitored by UVP technique with an ultrasound transducer (5 mm outer diameter and 2 mm beam or active diameter) of 8 MHz emission frequency. The measured sound velocity in the test fluid is 1499 m/s at 22 °C.

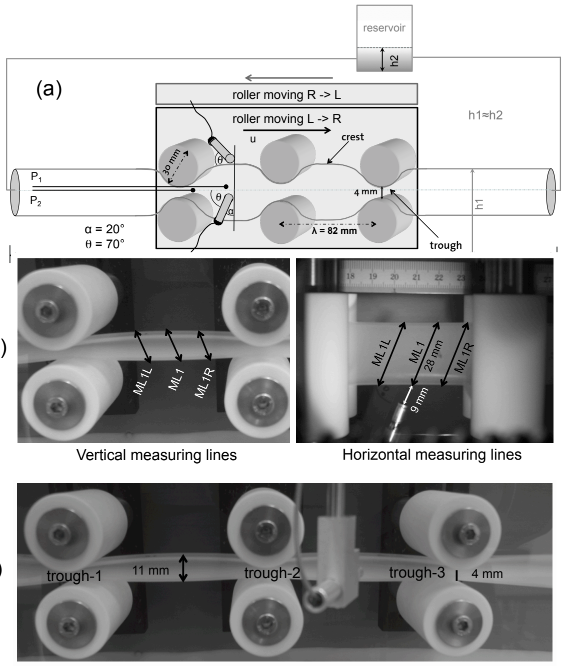

Figure 1: (a) Schematic representation of the experimental set up showing peristaltic squeezing of an elastic tube with the positions of pressure sensors (P_1 & P_2) and ultrasound transducer, (b) Three distinct vertically & horizontally adjusted measuring lines (ML1L, ML1, ML1R), (c) three wave troughs of the '2-wave'-squeezing of an elastic tube.

2.2 Shear thinning fluid

A carboxymethyl-cellulose (CMC; Blanose CMC 7MF, IMCD Switzerland AG) at 1.5 % w/w (with 0.1 M NaCl; $M_W = 2.5 \times 10^5$ g/mol) aqueous solution is used in the peristaltic flow experiment. In addition, polyamide particles (ρ = 1030 kg/m^3; and 20 µm diameter; Dantec Dynamics, Skovlunde, Denmark) at 0.3 % w/w are added to the CMC aqueous solution (velocity magnitude is relatively low under peristalsis) for better resolution of UVP measurement. CMC aqueous solution represents an inelastic shear thinning behavior as demonstrated in [6]. The viscosity flow curve is not altered after adding the polyamide particle in the CMC aqueous solution, since small mass fraction (0.3 %) of the added particles, which lead to negligible particle-particle interaction.

2.3 UVP in peristaltic flow

The main study challenge is to investigate the velocity fields under peristalsis (squeezing of an elastic tube), which are not measured previously due to lack of applicable methods. Consequently we successfully applied the UVP technique for monitoring the steady and unsteady flow fields through a collapsible elastic tube as demonstrated elsewhere [1]. We met the challenge of implementing the UVP method for investigating the velocity fields during appropriate peristaltic propulsion of a shear thinning fluid through an elastic tube. The details of the UVP technique applied here can be followed as described in Nahar et al. [1].

The velocity profiles are monitored by UVP both in the crest and trough region (of the '2-wave'-squeezing of an elastic tube) while ultrasound transducer placed at three distinct measuring lines (ML1L, ML1, ML1R, positioning the ultrasound transducer both horizontally and vertically at the crest, and only horizontally at the trough as shown in Figure 1) with a Doppler angle of 70° in a moving frame. In the moving frame, the transducer is moving longitudinally at the same speed as the wave speed in both directions (left to right, L→R or right to left, R→L) depending on the study interest. The measured velocity profiles are found to be uniform and stable for the entire measurement (in both directions). All the measured velocity profiles shown later are transformed into the laboratory frame by adding or subtracting of the wave speed respect to the wave direction (as $v_{real} = v_{meas} + v_{wave}$ for L→R and $v_{real} = v_{meas} - v_{wave}$ for R→L, where v_{real}, v_{meas} and v_{wave} are the actual, measured and peristaltic wave velocities respectively).

3 RESULTS AND DISCUSSION

3.1 Velocity profiles in the wave crest

The measured velocity profiles in a wave crest at the measuring line ML1 (horizontal) are represented as a function of distance inside the tube in Figure 2 under different wave speeds (as 3 to 10 mm/s). The results show that higher wave speed of peristalsis develop in higher velocity being of specific interest for improved mixing and mass transfer conditions of nutrients. A positive velocity is detected near the tube wall while moving the peristaltic wave from L→R (Figure 2a) or R→L (Figure 2b), since the moving rollers to impose the peristalsis are in direct contact with the tube wall. In contrast, the velocity magnitudes are gradually becoming larger and negative (representing a back flow) towards the tube center due to forward movement of the peristaltic wave from L→R (Figure 2a) and correspondingly the fluid is moving backward. The reason is that the pressure rises inside the leading wave (fluid ahead the roller) than that in the lagging wave (fluid behind the roller) during peristalsis, which can lead to a mixing mechanism near the wave trough. The behavior is vice versa when the peristaltic wave is moving from R→L (Figure 2b), where the obtained positive velocity magnitudes are represented as negative values by correction with relative of roller-speed. In both cases, when the wave speed of peristalsis got faster that is velocity near the tube wall is more positive and correspondingly the velocity magnitude at the tube center becomes more negative (back flow) due to higher pressure drop depending on the wave speed.

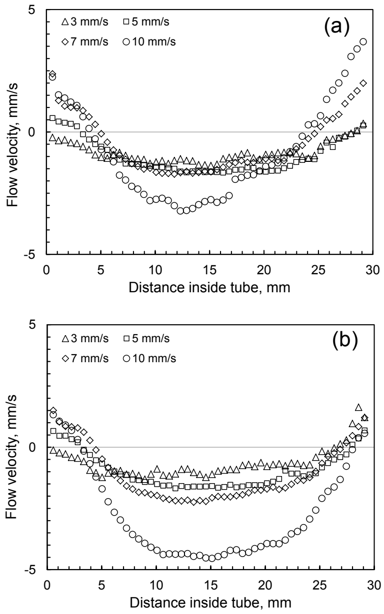

Figure 2: Experimentally measured velocity profiles in the wave crest under different speed of peristalsis, while the peristaltic wave moving left to right (a), or right to left (b).

The accuracy of the measurement is confirmed by symmetric and overlapping of the normalized (by velocity at crest center) velocity profiles at different peristaltic speeds as shown in Figures 3a and 3b. The measured velocity fields are found to be influenced by the memory of the traveling waves and wave speeds. It is seen that the normalized velocity profiles during peristaltic wave moving from L→R are having little deviation for variation in speeds of peristalsis (Figure 3a), where the measured velocity profiles are affected by lagging of a wave respect to the direction of wave speed. On the other hand, the wave moving from R→L is leading a wave that shows a more symmetric and overlapping normalized velocity profiles (Figure 3b) under various peristaltic speeds.

In addition, velocity profiles are also measured at two other measuring lines ML1L and ML1R in the crest, which are 20 mm back and forth from ML1 respectively, while the peristaltic wave moving from L→R at the wave speed of 10 mm/s.

The results (Figure 4a) depict that the maximum velocity magnitude (negative) inside the tube is much higher while measuring horizontally at ML1L compared to those measured at measuring lines ML1 and ML1R and a higher positive velocity value is observed at the tube wall. The reason is that the measuring line ML1L is close to and leading the wave crest which has much higher contraction (smaller cross sectional area) in the first half measuring region from the tube center resulting to a higher negative velocity values at that regime. On the other hand, the second half measuring region from the tube center is showing a less negative velocity values, which confirms a region of bigger cross sectional area. In contrast, the measuring line ML1 is aligned at the center of the wave crest with a uniform cross sectional area along the measuring line showing more symmetric velocity profile.

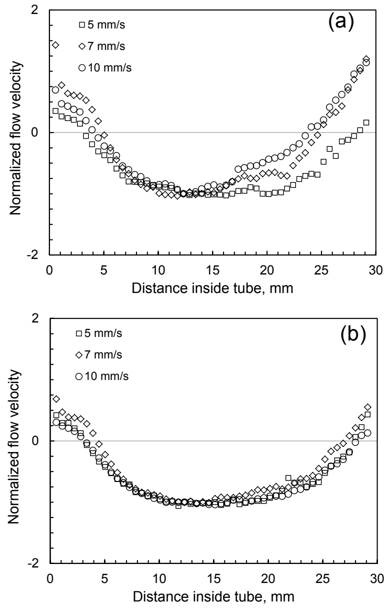

Figure 3: The normalized velocity profiles in the wave crest under different speed of peristalsis (as in Figure 2), while the peristaltic wave moving L→R (a), or R→L (b).

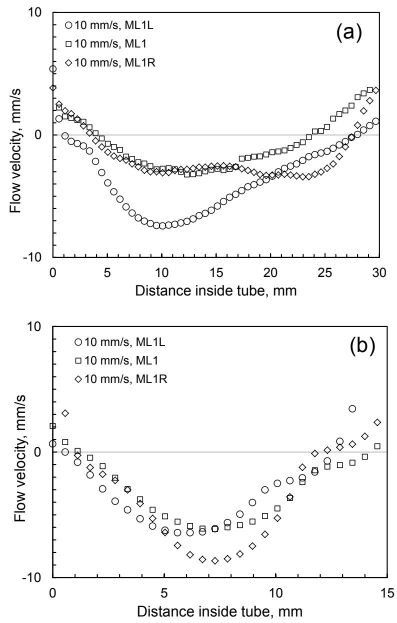

Figure 4: Experimentally measured velocity profiles in the wave crest as monitored by positioning of ultrasound transducer both horizontally (a) and vertically (b) at the wave speed of 10 mm/s.

Furthermore, the measuring line ML1R is fixed at the end of the wave crest with a small contraction in the second half of the measuring line, representing a more negative velocity magnitude than that obtained in the first half with more uniform tube shape. The velocity profiles measured at ML1R is showing slightly higher negative value at the end part of the measuring line since it starts in leading to the wave crest with little contraction (small cross sectional area). Hence, the resultant velocity magnitude differs depending on the corresponding tube deformation (tube cross sectional area), so the target and actual measuring lines for UVP measurement do not remain identical. In contrast, the larger velocity magnitude (negative) inside the tube is observed at ML1R while measuring vertically compared to those measured at measuring lines ML1 and ML1 (Figure 4b). The reasons can be speculated as explained for the horizontal measurements.

3.3 Velocity profiles in the wave trough

The velocity profiles are also measured at the first and second wave trough (trough-1 & trough-2) with same history of wave propulsion moving from L→R as shown in Figure 5.

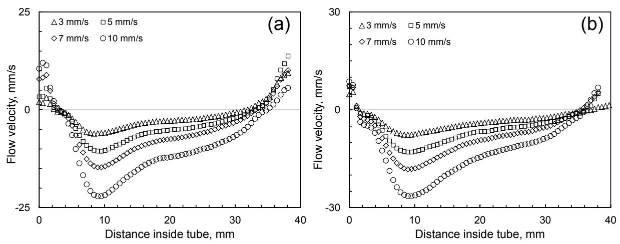

Figure 5: Measured velocity profiles in two wave troughs (of the ‘2-wave’-squeezing of an elastic tube), trough-1 (a) and trough-2 (b) under different speed of peristalsis.

The higher wave speed of peristalsis results in higher velocity magnitude (negative) inside the tube, which corresponds to higher back flow with a positive velocity value at the tube wall. The measured velocity profiles are representing a higher velocity magnitude in the first half of the investigated region along the adjusted measuring lines in the wave troughs (trough-1 & trough-2), indicating more contraction of the squeezed tube at that region (so the target and actual measuring lines are seen to be different by UVP). The velocity magnitude measured in the second trough is observed to be more negative than that of the first trough, as trough-2 is forwarded by the trough-1 along the wave direction.

3.4 Pressure difference under peristalsis

The local pressure in a wavelength is measured by placing pressure sensors (P_1 & P_2) in direct contact with the fluid as shown in Figure 1a. The speeds of peristalsis are varied as 2, 4, 6, 8 and 10 mm/s. The two pressure sensors are also connected with moving part of the peristalsis (the sensors are always seen to be at the same position as the peristaltic wave travels). The distance between two sensors are about 25 mm. The pressure difference between tube crest and its corresponding two troughs is measured. The crest region shows a higher pressure compared to the trough region, since the magnitude of back flow velocity in the wave trough is much higher (negative) compared to that in the wave crest. Therefore, a higher velocity head corresponds to a lower pressure head as in the wave trough according to Bernoulli’s law. The pressure difference between crest and trough of a peristaltic wave is found to be increased with increasing the wave speed as expected (Figure 6).

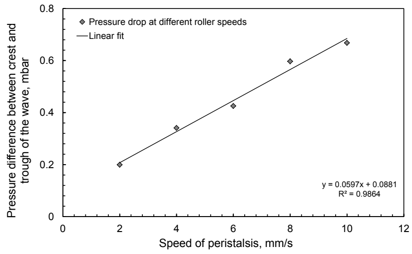

Figure 6: Variation in the pressure difference with different speeds of peristalsis.

However, the pressure difference between center of crest and trough is found to be low about 0.2 - 0.7 mbar due to low mean fluid velocity and relatively large gap in the trough (required to locate the pressure sensors).

4 CONCLUSIONS

The velocity profiles and pressure differences are investigated experimentally under peristaltic flow of a shear thinning CMC aqueous solution in an elastic tube. The higher wave speed of peristalsis results in higher magnitude of back flow velocity both in the wave crest and trough regions with positive value adjacent to the tube wall. The higher value of back flow is expected to be responsible for the improved mixing and convection leading to higher mass transport through the intestinal wall. The pressure in the tube crest is found to be higher than that at the trough. The detailed knowledge gained about non-Newtonian peristaltic flow is aimed to use in future for mass transport investigations across the elastic membrane tube wall.

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