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Development of a Peristaltic Pump Based on Bowel Peristalsis Using for Artificial Rubber Muscle

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***Abstract* —The global water shortage has recently been debated at the United Nations. The main cause of this shortage is the excessive use of water resources by humans. Therefore, a positive approach to saving water is needed. Much water is used to flush toilets in homes. Thus, it is necessary to develop a sewage disposal system that saves water. We focused on the bowel peristalsis as a model for a mechanism that can transport sludge with little water. In this paper, we suggest a mechanism that uses such a pump and confirmed its capability. In addition, we fabricated a peristaltic pump of six units, and conducted liquid transportation experiments as an operational check.**

***Index Terms* — Straight-fiber-type artificial muscle, Bowel peristalsis, Peristaltic pump.**

I. Introduction

SINCE the latter half of the twentieth century, the global water shortage has been debated at the United Nations [1]. The main reason for the shortage is the excessive use of water resources by humans. A positive water saving approach is needed because water resources on the planet will not increase in the future.

It has been shown that water used in restrooms accounts for most water use in ordinary households—about 30% of the total usage [2]. Furthermore, using drinking water for restroom washing is not an effective use of water since the water used for a toilet dose not typically come in contact with a person. We therefore focus on a sewage disposal system that saves as much water as possible.

The existing sewage disposal system commonly dilutes sludge, such as human waste and toilet paper, with water and flushes it. In other words, this is a conveyance system that creates a water current or whirlpool with large volumes of water to use for transportation. Thus, this system cannot function without large volumes of water—it is impossible to minimize water use in this system. Further the pump that can convey even high viscosity fluid and a solid–liquid mixture is necessary. In this study, we focused on a peristaltic pump as a mechanism that can convey the sludge even with little water.

The existing peristaltic pumps are earth auger type and electromagnetic type [3]-[6]. However, these types have a fault, respectively. The earth auger type cannot carry the low viscosity fluid and be made bent pipe. Further its maintenance is difficult and. The electromagnetic type is large-size and heavy against the conduit and the structure is complicated. Therefore, we focused on bowel peristalsis as a new mechanism that can convey the sludge even with little water.

Bowel peristalsis consists of the contraction and relaxation of the circular muscle located in the intestinal tract wall [7], [8]. Within the intestines, the conveyance of bolus is enabled by propagating the contraction of the circular muscle, one after another, in a backward series. This process makes the conveyance of bolus possible regardless of the amount of water. From this point of view, we thought that a mechanism based on bowel peristalsis could convey a solid–liquid mixture, such as sludge, with little water.

With this background, we developed a peristaltic pump based on bowel peristalsis. This paper consists of seven sections. In section II, we explain bowel peristalsis. In section III, we suggest a mechanism that has many units, and outline a straight-fiber-type artificial muscle and a cylindrical tube used for the mechanism. In section IV, we define the performance evaluation parameters of a unit, and show the results of the experimental evaluation. In section V, we describe the structure and the specification of the peristaltic pump. Section VI shows the result of transportation experiments. We present the conclusions in section VII.

II. Bowel Peristalsis

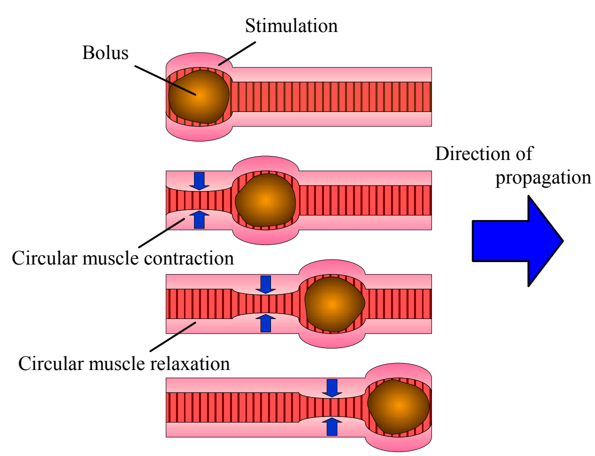

Fig. 1 Bowel peristalsis

Bowel peristalsis is a motion that uses the circular muscle located in the intestinal tract wall. This motion propagates toward the anus from the mouth. Fig. 1 shows the pattern of motion of bowel peristalsis. Bowel peristalsis can be described by three processes.

1) Bolus movement extends the circular muscle located in the intestinal tract wall, and stimulates that muscle.
2) The circular muscle stimulated by the movement of bolus contracts radially and pushes out the bolus.
3) After pushing out the bolus completely, the circular muscle relaxes and returns to its former state.

The bolus is conveyed in the intestines by repeating this process many times, using only the contractive force of the circular muscle. From this standpoint, we think that a sewage mechanism based on bowel peristalsis could transport a solid–liquid mixture using little water.

III. Mechanism of a Unit

A. Outline of a Unit

This mechanism has many units; each unit imitates the intestinal circular muscle. Fig. 2 shows the cross-section of a unit. The unit consists of a cylindrical tube, a straight-fiber-type artificial muscle, and flanges. The cylindrical tube is arranged inside the artificial muscle and the both ends are joined by the flanges. Then, the space enclosed by the artificial muscle, the cylindrical tube, and flanges forms a chamber. This chamber can be pressurized through an air vent.

Fig. 3 shows how the unit appearance changes when the unit is pressurized. Both the artificial muscle and the cylindrical tube expand during pressurization; the artificial muscle expands only in the radial direction, and the unit contracts in the axial direction. The cylindrical tube includes four fibers that become constrained when pressurizing the unit. Therefore, the fold lines occur on the cylindrical tube in four directions, and the expansion is divided into four parts. As seen from the axial direction, upon expansion the cylindrical tube takes the shape of four quarter circle that push out toward the center.

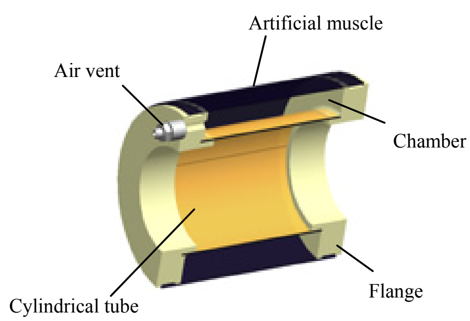

Fig. 2 Cross-section diagram of a unit

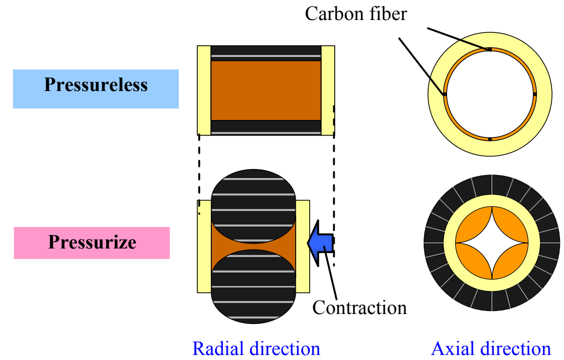

Fig.3 Appearance of pressurization

B. Straight-Fiber-Type Artificial Muscle

Fig. 4 shows a straight-fiber-type artificial muscle [9]. The artificial muscle consists of a tube made of low-ammonia natural rubber latex, and a carbon sheet. This artificial muscle has the carbon sheet arranged parallel to the axial direction of the tube. The carbon sheet is made of thin carbon fibers, and spreads across its width as rubber layers expand during pressurization. Upon pressurization of the artificial muscle, it expands only radially because the carbon fibers do not readily expand axially; thus, the artificial muscle contracts in the axial direction. The contractive force at this time serves as an actuator.

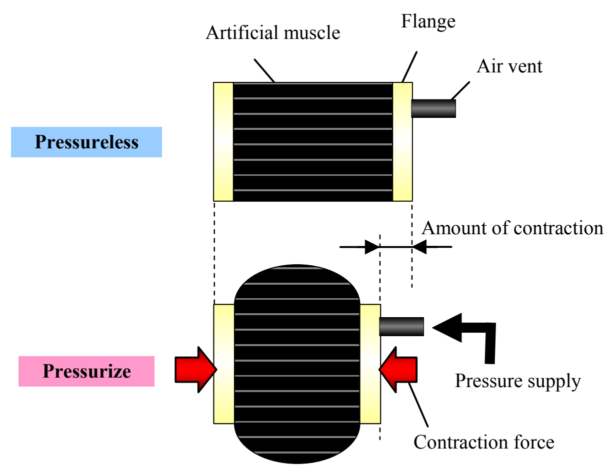

Fig.4 Straight-fiber-type artificial muscle

C. Cylindrical Tube

Fig. 5 shows the cylindrical tube made of low-ammonia natural rubber latex and thin carbon fibers. The cylindrical tube has its fibers arranged parallel to the axial direction of the tube. These fibers are also arranged at equal intervals along the circumference. The fibers in the cylindrical tube stabilize the expansion deformation inside the unit. The optimum number of fibers is considered by a geometric condition, and the optimum number of fibers is 4.

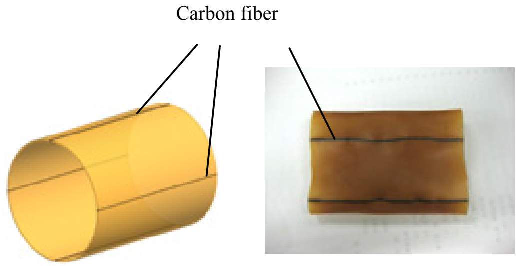

Fig. 5 Cylindrical tube

IV. Performance Evaluation of a Unit

A. Performance Evaluation Parameters

The prototype is shown in Fig. 6, and its specifications are shown in Table 1. In this study, we define the closing area and volume exclusion rates as performance evaluation parameters of the unit. Fig. 7 shows the schematic diagram of the closing area and volume exclusion rates.

The closing area rate C_a is defined using the percentage as

$$C_a = \frac{S_0 - S}{S_0} \times 100, \quad (5)$$

where S_0 is the unit-opening space viewed from the axial direction at the initial state, and S is the unit-opening space viewed from the axial direction at the time of pressurization. The closing area rate shows the performance of the unit as a valve. The volume exclusion rate E is defined using the percentage as

$$E = \frac{V_0 - V}{V_0} \times 100, \quad (6)$$

where V_0 is the internal volume of the unit at the initial state, and V is the internal volume of the unit at the time of pressurization. The volume exclusion rate becomes an index of the transportation efficiency of the peristaltic pump.

Fig. 6 Prototype of the unit

TABLE I
Specifications of the Unit

Length of cylindrical tube [mm]	70
Diameter of cylindrical tube [mm]	60
Length of artificial muscle [mm]	80
Diameter of artificial muscle [mm]	89

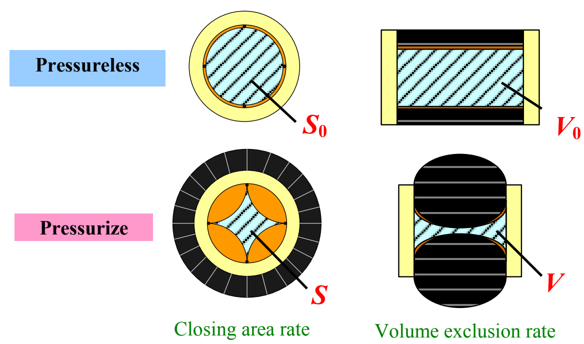

Fig. 7 Schematic diagram of parameters

B. Performance Evaluation

Fig. 8 shows the relationship between pressure and closing area rate, and Fig. 9 shows the relationship between pressure and volume exclusion rate. From these figures, it is confirmed that both the closing area and the volume exclusion rates are close to 100 %. Moreover, sufficient performance was demonstrated at a low pressure of about 0.03 MPa. In addition, when the thickness of cylindrical tube is changed, both the closing area and the volume exclusion rates have not changed.

Fig. 10 shows the relationship between rise time and closing area rate, and Fig. 11 shows the relationship between fall time and closing area rate. From these figures, it is confirmed that the rise time is 1 second and the fall time is 3 second. We think that the difference of this response time was observed because the drive of a unit depends only on elastic power of the cylindrical tube at the time of fall time. Moreover, when the rubber thickness of the cylindrical tube is changed, it is confirmed that the rise becomes late and the fall becomes early as the rubber thickness becomes high. We think that it is because the rigidity of the cylindrical tube becomes high and the elastic force becomes high at the time of the unit returning as the rubber thickness becomes high.

Therefore, we think that a pump using the suggested mechanism can demonstrate sufficient performance.

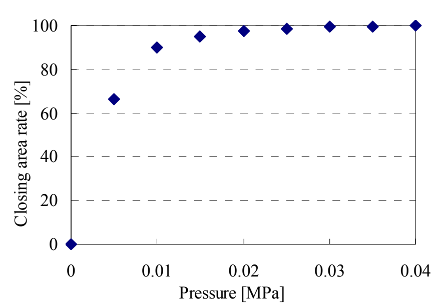

Fig.8 Relationship between pressure and closing area rate

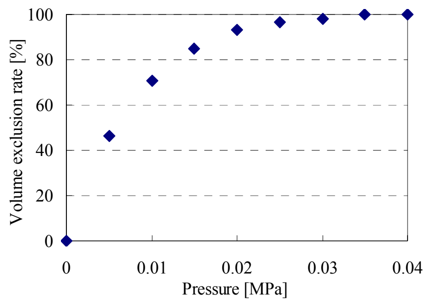

Fig.9 Relationship between pressure and volume exclusion rate

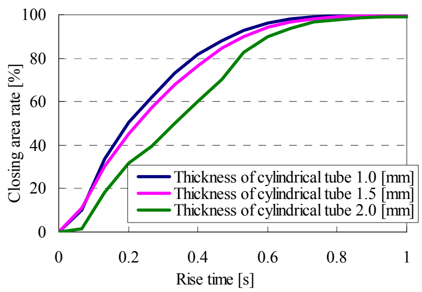

Fig.10 Relationship between rise time and closing area rate

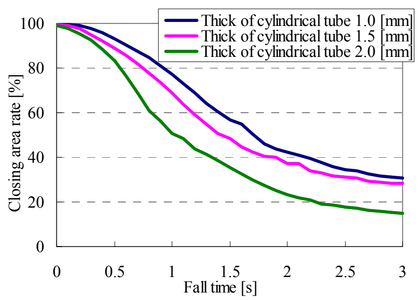

Fig.11 Relationship between fall time and closing area rate

V. Peristaltic Pump

A. Peristaltic Pump

The peristaltic pump developed in this study is shown in Fig. 12, and its specifications are shown in Table 2. Each unit of this pump can be contracted toward the center annularly as in the intestinal tract. The peristaltic action of the pump can be carried out by contracting each unit according to a pattern of regular motion. It is possible to transport the inclusion by this peristaltic action. In addition, the number of units can be easily changed in case of three or more units. In this study, we produced a peristaltic pump with six units

TABLE II
Specifications of Peristaltic Pump

Maximum length [mm]	561
Minimum length [mm]	484
Mass [g]	1356


Fig. 12 Peristaltic pump

B. Internal Structure of a Unit

The internal structure of a unit is shown in Fig. 13, and its specifications are shown in Table 3. When the units are connected, the chamber contains an air tube supplying air to each unit. The air tube is arranged so as to save space; Moreover, it is arranged in a circle to prevent it from breaking when the unit contracts. This structure prevents the air channel becoming cut. In this unit, flanges A and B form a pair. The cylindrical tube is fixed in place by interleaving one end of each unit between flanges A and B. Adopting this fixation method eliminates conveyance loss due to the influence of the thickness of the flanges.

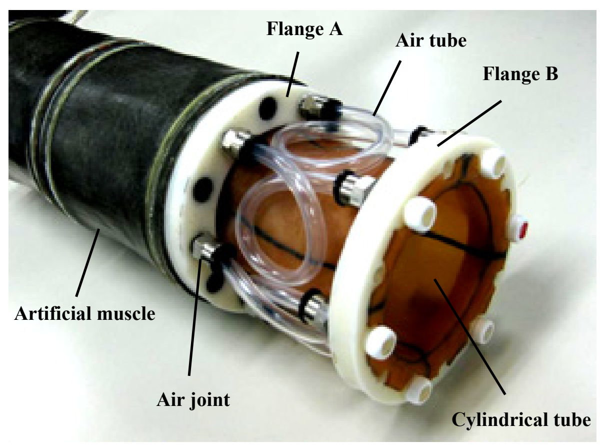

Fig. 13 Internal structure of the unit

TABLE III
Specifications of the Unit

	Extension	Contraction
Length [mm]	91.5	78.5
Maximum diameter [mm]	91.3	147.1
Bore [mm]	57.8	
Mass [g]	214	
Contraction rate [%]	14.2	

VI. Transportation Experiment

A. Experimental system

We performed a transportation experiment as an operational check of the peristaltic pump. Fig. 14 shows the outline of the experimental system. This system controls the air pressure through voltage signals. The pressure supplied to each unit is independently controlled using six electromagnetic proportional valves. The conveyance of the inclusion is enabled by supplying a controlled pressure to the peristaltic pump according to a specified regular motion pattern. In transportation experiment, the supply pressure was unified by 0.04 MPa. When the static pressure is measured, a pressure gauge is attached in the outlet of pump.

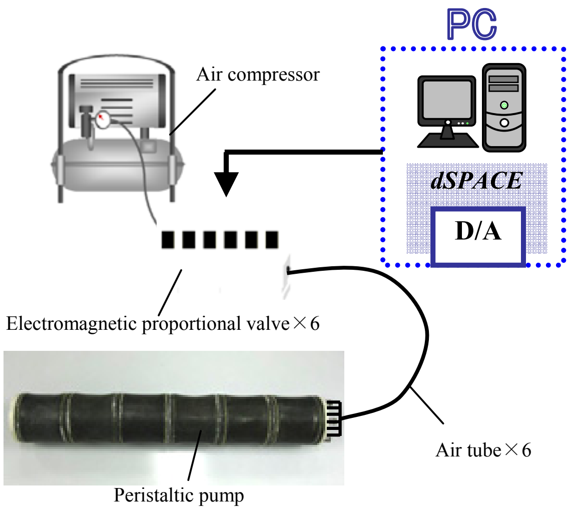

Fig. 14 Schematic diagram of experiment system

B. Experimental Arrangement

Fig. 15 shows a schematic diagram of the experimental arrangement. As shown in this figure, one end of the peristaltic pump is put into a tank containing conveyed fluid, and the fluid is transported upward θ degrees. We performed the transportation experiment with both one and two units immersed in fluid. The fluid flowing from the upper side of the pump accumulates in the reservoir, and the flow rate of the pump is measured using the scales. In this experiment, θ is 90 degrees.

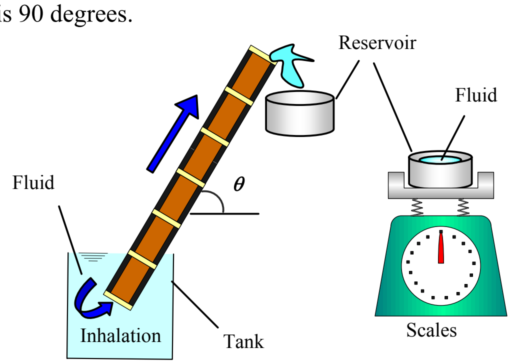

Fig. 15 Schematic diagram of the experimental arrangement

C. Motion Pattern

Fig. 16 shows the schematic diagram of the motion pattern used in the transportation experiment. In this figure, A–F shows each state of the pump motion pattern, and each state moves to the next state at a regular motion interval. The conveyance of the fluid becomes possible when each unit is pressurized according to this motion pattern. In the experiment, the change in the flow rate is examined with the motion interval varied.

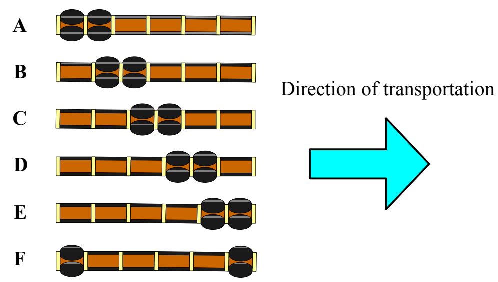

Fig. 16 Schematic diagram of the motion pattern

D. Result of Experiment

Fig. 17 shows the relationship between the motion interval and the flow rate per cycle of the peristaltic action, and Fig. 18 shows the relationship between the motion interval and the flow rate per minute. Here, water and rape oil is used in this experiment, and the viscosity of rape oil is 900 times water. From Fig. 17, the flow rate per cycle increase as motion interval become longer. From the result of Fig. 17, the necessary time for the stationary state of each unit is about 4 second. From Fig. 18, the flow rate per minute reaches maximum when the motion interval is set at about 0.8 second. Fig. 18 suggests that the flow rate per minute is influenced more by the peristalsis frequency than by the performance of the units. From the result of Fig. 17 and Fig.18, it turns out that the performance in high viscosity can be demonstrated.

Fig. 19 shows relationship between solid content percentage and flow rate (solid-liquid mixture). Here, sphere made of polypropylene (the diameter of 6 mm) is used as solid, and water is used as liquid. From the result of Fig.19, this pump can convey this fluid vertically, and the flow rate per cycle decrease as solid content percentage become larger.

Fig. 20 shows relationship between time and pressure when the motion interval is set to 0.4 second, and Fig. 21 shows relationship between time and pressure when the motion interval is set to 2.6 second. Here, water is used as fluid in this experiment. From these figures, it is confirmed that the pressure pulsation is generated in the fluid. Moreover, it is confirmed the pressure pulsation by the unit is generated when the motion interval is set to 2.6 second.

Fig. 22 shows relationship between motion interval and maximum pressure. From Fig. 22, we can see that the motion interval is increased with increasing maximum pressure, and maximum pressure of the fluid is close to the supply pressure that is supplied to the units (0.04 MPa). Moreover, it is confirmed that high enough pressure is obtained at motion interval being greater than or equal to about 1.5 second. Fig.22 suggests that maximum pressure of the fluid can be controlled by the supply pressure.

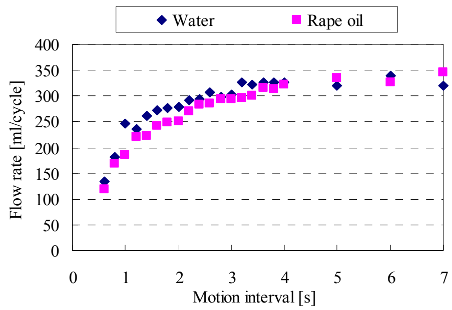

Fig. 17 Relationship between motion interval and flow rate (peristalsis cycle)

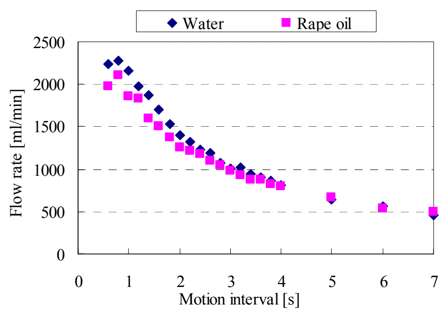

Fig. 18 Relationship between motion interval and flow rate (minute)

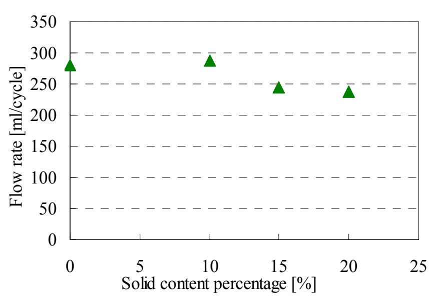

Fig. 19 Relationship between solid content percentage and flow rate (peristalsis cycle, motion interval 2.0 second)

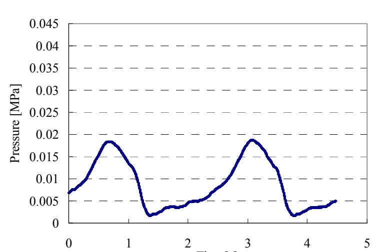

Fig. 20 Relationship between time and pressure (motion interval 0.4 second)

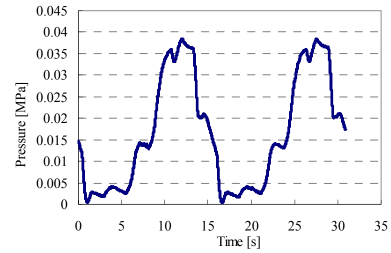

Fig. 21 Relationship between time and pressure (motion interval 2.6 second)

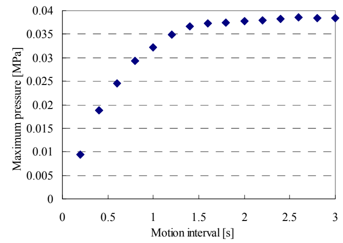

Fig. 22 Relationship between motion interval and maximum pressure

VII. Conclusion

We proposed the mechanism of a peristaltic pump based on bowel peristalsis, and confirmed its performance using performance evaluation parameters. Moreover, we fabricated a six-unit peristaltic pump, and showed that the transportation of high viscosity fluid and a solid–liquid mixture is possible without depending on gravity. In the future, we will consider a method of evaluating transportation efficiency in more detail.

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