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Development of an In-pipe micro mobile robot using peristalsis motion [†]

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Abstract

Currently, many researchers from various fields are engaged in developing machines that move in a tubular cylinder. Many such machines are being developed for industrial purposes, such as for the examination of ruptures at the joints of gas and water pipes and those caused by cracks. Studies specifically focused on applications to the medical field, such as the realization of machines that can travel through the intestines and blood vessels, have also been reported. In this study, we propose a microscopic moving mechanism that can move in 2-3 mm-diameter blood vessels by peristalsis motion with repeated expansion and contraction using hydraulic pressure, particularly using a physiological saline solution as an acting fluid. Peristalsis motion, observed in earthworms and nematodes, induces shape variation and a shift in the center of gravity, causing extensional waves to propagate and thus achieving movement without damage to the vulnerable inner walls of blood vessels. When this moving mechanism is combined with catheters, we can realize an active catheter that can reach a diseased site by itself. In this study, we created a microrobot with pistonlike hydraulic pressure sources outside both its ends. The microrobot can move back and forth as follows. When the piston pumps, the acting fluid is repeatedly injected into and ejected from the driving body, while the microrobot changes the length and width of its rubber body. The development of our microrobot and the results of its evaluation are reported in this paper.

Keywords: In-pipe robot; Micro robot; Peristalsis; Hydraulic pressure

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1. Introduction

Moving mechanisms involving the rotation of wheels and other components are not appropriate for motion inside blood vessels because of the high viscosity and the rough wavelike surface of the inner wall. Moreover, the inner diameters of veins and venules are as small as 5 mm and 20 μm, respectively; thus, mobile devices that fit into such spaces receive weaker effects of gravity and inertia, but are increasingly affected by surface forces such as friction and surface tension (size effect). Peristaltic motion, observed in earthworms and nematodes, makes the best use of friction between the inner walls of a pipe and the mobile device by bringing as large an area as possible of the body surface into contact with the inner wall. It is also in good agreement with the theoretical prediction based on the size effect.

In this study, we propose a mobile device, a mobile microrobot, which has a pistonlike hydraulic pressure generator at its end and achieves peristaltic motion by changing its body length and width by injecting and ejecting a driving fluid into and from the driving section of the device. We have already succeeded in developing an in-pipe mobile device with peristaltic motion, which comprises two segments that are arranged in series in the direction of motion. Each segment is made of crude rubber or silicon, which is highly compatible with living bodies; therefore, only physiological saline solution, which serves as the driving fluid, and the crude rubber or silicon are inserted into living bodies. The details of the peristaltic motion are as follows. First, the driving fluid is injected into the rear segment to allow it to expand in both forward and circumferential directions; thus, the rear segment becomes thick and long. Next, the driving fluid is also injected into the front segment, causing it also to become thick and long. At this time, the thickened rear segment is in contact with the inner wall of a pipe and remains stationary because of friction, causing the front segment to be pushed forward. Subsequently, the driving fluid is evacuated from the rear segment to cause it to contract; thus, the rear segment becomes thin and short. At this time, the thickened front segment comes into contact with the inner wall of the pipe and is thus stationary because of friction; therefore, the contracted rear segment is detached from the inner wall and drawn forward owing to the decreased friction. Extensional waves propagate from the front to the rear segments during the repetition of these motions, causing the two-segment device to

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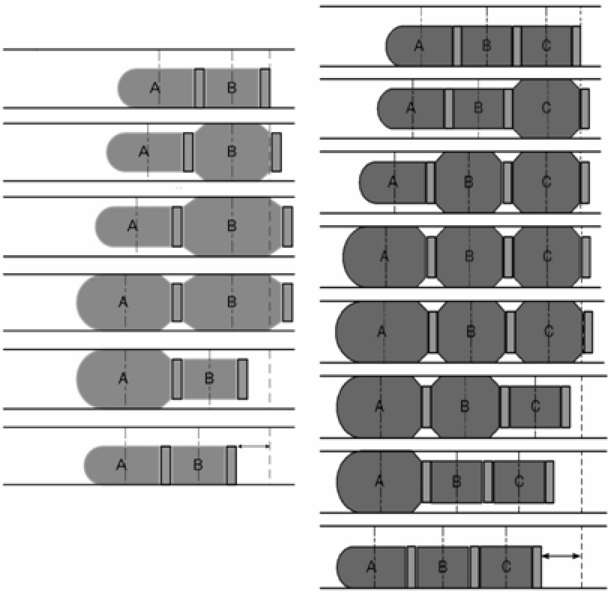
move by peristaltic motion. Fig. 1(a) shows a schematic of the principle of the two-segment mobile device.

However, it is difficult to achieve a sufficient driving torque to transport a catheter to a diseased site by the two-segment driving mechanism alone because our mechanism is driven only by friction force upon the expansion of the crude rubber segment. This problem is solved by creating a driving body with multiple segments, similar to earthworms, which envelopes a catheter, and then developing a device with segments that span the total distance to the diseased site. Unfortunately, installing the injection and evacuation mechanism of the driving fluid to each of the multiple segments is undesirable because it only results in a more complex mechanism. We propose that multisegment peristaltic motion can be realized by preparing an appropriate mouth at the cornea between two segments. That is, the driving fluid is injected into the rearmost segment of the driving body, and other segments are then sequentially thickened and lengthened. After the injection into the frontmost segment is completed, the driving fluid is evacuated from the rearmost segment, and the segments are sequentially thinned and shortened from the rear segment. The rear segments sequentially detach from the inner wall of the pipe, decreasing the friction, and are drawn towards the front segment. Similar to the case of the two-segment device, extensional waves propagate from the front to the rear segments during the repetition of these motions; thus, multisegment peristaltic motion is achieved. We fabricated prototype devices and examined them experimentally. Fig. 1(b) shows a schematic of the principle of the three-segment mobile device.

2. Mechanisms of prototype devices

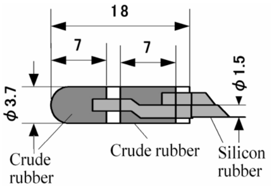
We fabricated two peristaltic mobile devices; one comprises two segments, and the other comprises three or more segments. The procedures described in Section 1 are experimentally examined. In this study, we fabricated a prototype five-segment peristaltic mobile device as a multisegment device. Figures 2 and 3 show the peristalsis mobile devices with two and five segments, respectively. As is clear from these figures, the system of pumping and evacuating the driving fluid is constructed using two tubes for the two-segment peristaltic mobile devices, whereas the system uses one tube for the five-segment peristaltic mobile device. To distinguish between them, the former is called a two-tube pumping method, and the latter is called a one-tube pumping method. Although the naming after the number of segments is considered to be easier to understand, the purpose of this study is to verify that a peristaltic mobile device having three or more segments can be realized by pumping and evacuating a simple driving fluid, rather than to examine the difference in performance depending on the number of segments.

In both methods, a 0.2 mm-thick crude rubber was used for the body surface of the devices, which were designed to have a body diameter of 3.64 mm and segments 7 mm long at contraction. The body weights of the devices, excluding the driving fluid and the pumping and evacuating systems, were 3.4 and 3.6 g for the two- and one-tube pumping methods, respectively.

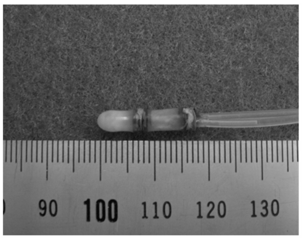


(a) Two segments (b) Multiple segments

Fig. 1. Schematic illustration of the principle of motion.

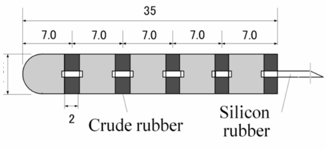


(a) Schematic illustration

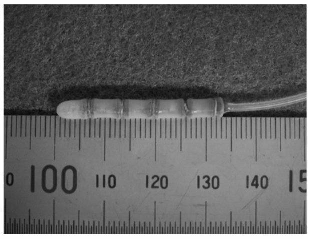


(b) Photograph of the mobile

Fig. 2. Mobile device driven by two-tube pumping



(a) Schematic illustration



(b) Photograph of the mobile

Fig. 3. Mobile device driven by one-tube pumping

3. Driving experiment

3.1 Outline of the system

Commercial syringes are connected to the bodies via silicon rubber tubes (inner diameter, 0.75 mm; outer diameter, 1.5 mm; length, 1 m) to allow the mobile devices to expand and contract. The crude rubber coating the bodies expands and contracts when the driving fluid that fills the syringes is pumped and evacuated. Electric actuators that move straight back and forth are connected to the piston sections of the syringes, thus establishing a system that can control the position

Table 1. Characteristics of blood and blood vessels, and mechanical properties of the materials used in the experiment.

	Human	Experimental materials
Artery: Outer diameter	8[mm]	8[mm]
Artery: Inner diameter	6[mm]	6[mm]
Young's modulus of blood vessel	1[MPa]	2[MPa]
Viscosity coefficient of blood	4.7[mPas]	5[mPas]

and velocity of the piston motion. Physiological saline solution was used as a driving fluid considering the minimization of the damage that may be caused by the leakage of the driving fluid inside blood vessels when our devices are used in practice. Moreover, silicon rubber tubes and a 5-mPas-viscosity mixture of glycerin and pure water were used in place of blood vessels and blood, respectively. Table 1 summarizes the mechanical characteristics of human blood vessels and blood and those of the silicon rubber tubes and the mixture used in this experiment.

3.2 Experimental methods

Silicon rubber tubes are placed almost horizontally in the mixture, as explained in Section 3.1, and the peristaltic mobile devices are moved forward by the two- and one-tube pumping methods in the experiments at room temperature. In particular, the behavior of the peristaltic mobile device driven by the one-tube pumping method, which is our proposal, is photographed using a video camera and observed by analyzing the obtained images.

The amounts of saline pumped into the syringes were 0.30 and 0.90 ml in the two- and one-tube pumping methods, respectively. These values, with which the maximum level of expansion is ensured without breakage of the device, were obtained in the preliminary experiment. The amounts of driving fluid are different between the two- and one-tube pumping methods; therefore, the rate of pumping the driving fluid (pumping rate) is fixed as described above, and the rate of evacuating the driving fluid (evacuation rate) per unit time is changed as a parameter in this experiment. The measurement was carried out in nine steps by changing the evacuation rate by 0.09 ml/s from 0.90 ml/s. The time required for the mechanism to move 30 mm in a pipe was measured using the front end of the device as the measurement point. The behavior is photographed using a video camera, and each measurement was carried out by analyzing the obtained images.

4. Experimental Results

Fig. 4 shows the operation behavior of the peristaltic mobile device driven by one-tube pumping. The time immediately before the start of expansion is set as t=0 s, and the typical operation behaviors are shown in Figs. 4(a)-4(g). First, the rearmost segment expands ((b) and (d)), and the expansion progresses sequentially toward the front segments. Here, the diameter of the rearmost and adjacent segments expands in the radial direction to approximately the inner diameter of the blood vessel, and the friction force between the mobile device and the inner wall increases; therefore, the rear segments push forward the front segments that are only in partial contact with the inner wall of the silicon rubber tube. Then the contraction starts from the rearmost segment ((e)-(g)), and progresses sequentially toward the front segments. Here, the diameter of the rearmost segment contracts to approximately its original size, and the friction force decreases; therefore, the front segments, which are in an expanded state, remain at the same position in the tube, pulling the rearmost segments. The mobile device again returns to its initial state in which expansion is started; thus, we observe that the front segments move forward.

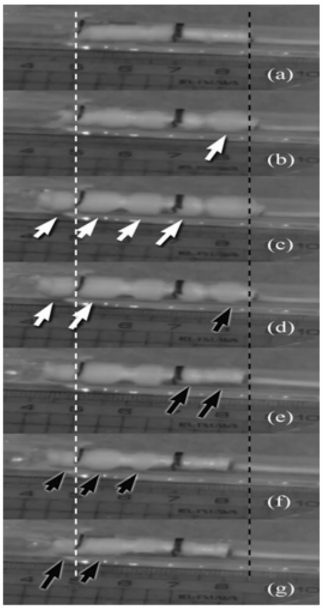


Fig. 4. Operation behavior of peristaltic mobile device.

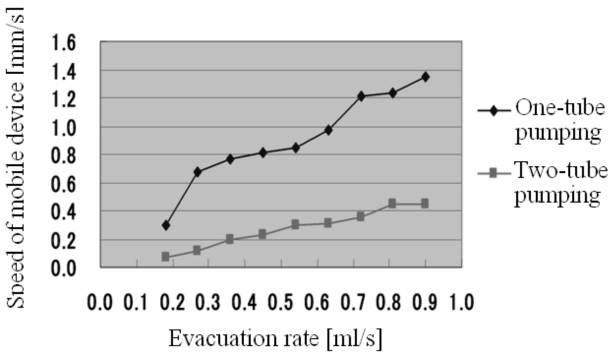


Fig. 5. Experimental results for mobile devices driven by two- and one-tube pumping methods.

Fig. 5 shows the experimental results for the peristaltic mobile devices driven by the two- and one-tube pumping methods. For both methods, the highest speed was obtained at the evacuation rate of 0.90 ml/s. Also, the speed of the mobile device by one-tube-pumping peristaltic motion is 3-4-fold faster than that in the case of the two-tube pumping method.

5. Discussion and conclusions

We proposed a microscopic mobile device that can move inside 2-3 mm-diameter blood vessels by peristaltic motion achieved by repeated expansion and contraction using hydraulic pressure, particularly with the use of a physiological saline solution as the driving fluid. In this study, a mobile device composed of five segments was proposed, and valuable findings were obtained through experiments using prototype devices. We confirmed that an in-pipe mobile microrobot having five segments can travel through blood vessels by peristaltic motion, similar to earthworms. Furthermore, a comparison of in-pipe mobile microrobots having five and two segments indicates that when the pumping rate of the driving fluid is kept constant, the moving speed of the former is 3-4-fold faster than that of the latter, although it also depends on the pumping and evacuation rates per second. On the basis of the above findings, the effectiveness of the in-pipe mobile microrobot having five segments was demonstrated, and the motion of the microrobot was confirmed experimentally.

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Yuichi Nakazato Dr. Nakazato is currently an Associate Professor at the Department of Mechanical Engineering at Nippon Institute of Technology in Saitama, Japan. Dr. Nakazato's research interests include medical and welfare robots and humanoid robots.