An Intestinal Propulsion Soft Robot for Enteral Ventilation

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***Abstract*— Enteral ventilation using perfluorodecalin (O_2-PFD), a liquid with high oxygen-carrying capacity, has been proposed for continuous gas exchange through the colon wall. We have developed a pneumatically driven soft robot designed to insert a PFD supply tube from the anus deep into the colon. In experimental evaluations, we assessed the robot's ability to self-propel within the porcine colon. We successfully achieved liquid flow from the deep colon to the anus through the supply tube inserted by the robot.**

Keywords—soft robot, pneumatic actuator, enteral ventilation

I. Introduction

Mechanical ventilation is a standard treatment for severe respiratory failure, but it carries the risk of lung injury[1]. ECMO (extracorporeal membrane oxygenation) offers an alternative by facilitating gas exchange outside the body; however, it is costly [2], requires highly skilled operators, and poses risks such as thrombosis and hemolysis. This highlights the need for a simpler and safer method of extracorporeal gas exchange.

Recent studies have explored enteral ventilation [3], which involves infusing oxygenated perfluorodecalin (PFD) into the large intestine to enhance gas exchange. This method has shown promise in improving oxygenation and reducing blood CO2 levels in hypoxic pigs. However, existing research has only examined the effects of a single dose. For enteral ventilation to be effective, O2-PFDs must circulate throughout a wide area of the large intestine.

To facilitate PFD circulation in the large intestine, a system is required to transport the PFD supply tube to the back of the large intestine, generate a flow of PFD from the back toward the anus, collect the PFD at the anus, re-oxygenate it, and reintroduce it into the system. This study aims to construct such an enteral ventilation system, and this paper reports on developing a soft robot designed to automatically transport the supply tube deep into the large intestine.

II. Prototype Large Intestine Propulsion Soft Robot

A. Pneumatic Soft Robot Driving Principle

Fig. 1 illustrates the design and driving principle of the intestinal propulsion soft robot. The robot's drive unit consists of three main components: elastic silicone tubes wrapped circumferentially with cotton thread, tubes that supply pressurized air to the elastic tubes, a PFD supply tube, a large intestine-sealing balloon, and a tube for inflating the balloon. Spirally attached elastic tubes around the liquid supply tube are sealed at both ends.

When air is supplied to one of the elastic tubes, it extends lengthwise, causing the entire drive unit to twist into a helical shape. By sequentially pressurizing each elastic tube, the robot propels itself forward through the large intestine, with each tube taking turns as the outermost part of the spiral. [4].

B. Prototype Soft Robot

Decreasing the helix pitch of the three tubes in the soft robot reduces the outer diameter (D) after inflation. A soft robot designed with a smaller pitch at the front and a larger pitch at the rear can navigate through tubes with varying diameters. [4].

We prototyped three types of soft robots using elastic tubes made of 12A silicone with an inner diameter of 1.5 mm and an outer diameter of 6 mm and PFD supply tubes having an inner diameter of 2.5 mm and an outer diameter of 5 mm, as shown in Fig. 2. Table I shows the robot's designs. An intestine-sealing balloon was attached to the robot's tip to limit the perfusion area.

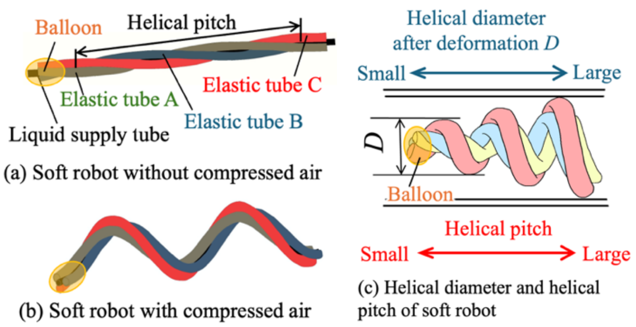

Fig. 1. Driving principle of soft robot

Fig. 2. Soft robots

TABLE I. SOFT ROBOT DESIGN

Soft Robot Type	Soft Robot Properties			
	Length	Helix pitch (tip)	Helix pitch (end)	Balloon [a]
a	730	120	400	Φ20（Φ45）
b	370	150	300	Φ20（Φ45）
c	620	120	480	Φ20（Φ45）

a. Latex sleeve diameter (*Diameter after inflation*). (mm)

III. EXPERIMENTS ON ANIMALS

A. Experimental Setup and Experimental Animals

Two experiments were conducted using two pigs, each weighing approximately 50 kg. As shown in Fig. 3, the setup consisted of a soft robot, a robot drive system, and a centrifugal pump (MD-30FY, Iwaki). The details of the soft robot are listed in Table 1.

Lead balls with a diameter of 2 mm were attached to the soft robot at 50 mm intervals to measure the soft robot's propulsion distance in the colon via X-ray fluoroscopy. The discharge flow rate and pressure of the PFD supply tube, as well as the flow rate of the fluid collected at the anus, were also measured.

B. Manual Insertion and Balloon Deployment Test

In the experiment, 1200 ml of oxygen gas was introduced into the large intestine to inflate the first animal. The robot, coated with lotion, was then manually inserted through the anus, without using the pneumatic drive, reaching a depth of 1500 mm. This was possible because the oxygen gas expanded the intestine, facilitating easier insertion.

Afterward, a balloon deployment test was conducted at the robot's tip. Water was pumped at a rate of 0.5 L/min through the fluid supply tube. Open surgery confirmed the balloon effectively blocked water flow toward the small intestine.

C . Soft Robot Propulsion Test

In the second animal test, the soft robot's automatic propulsion capabilities were evaluated in the colon of a pig without gas-induced dilation. The soft robot was manually inserted through the anus to the maximum achievable length, after which propulsion was initiated. The experiments used soft robot types A to C, as shown in Table 1. Each robot differed in the length of the soft actuator part and the pitch. All soft robots were operated at 180 kPa, with a 1.2-second cycle, a 0.47 duty ratio, and a 120° phase difference.

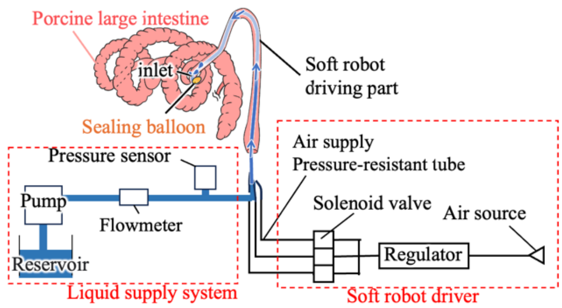

Fig. 3. Experimental equipment

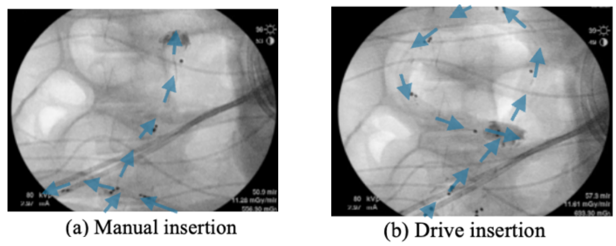

Fig. 4. X-ray fluoroscopic image of soft robot 3

TABLE II. SOFT ROBOT INSERTION RESULTS

No.	Insertion length by manual mm	Total insertion mm
a	400	800
b	500	550
c	700	1200

Table 2 summarizes the manual insertion limits and the final insertion lengths after the robots were activated. The manual insertion distances for all robots were significantly shorter than the 1500 mm achieved with gas-assisted colonic dilation. However, the soft robot propulsion increased the insertion distance for each robot.

The increased manual insertion distance from soft robot types A to C is likely due to the previous robot insertions pushing the intestine wider, making it easier for subsequent insertions. Additionally, for pneumatically driven automatic insertion, it was observed that a smaller outer diameter (D) after deformation of the soft robot facilitated better propulsion.

IV. CONCLUSION

In this study, we developed a soft robot to insert a PFD supply tube deep into the large intestine and seal the liquid for enteral ventilation. Animal experiments demonstrated that the tube could be inserted to a maximum insertion length of 1200 mm. The balloon at the tip of the soft robot could seal the large intestine. Water was delivered from the liquid supply tube at a rate of 0.5 L/min, successfully forming a flow from the back of the intestine to the anus.

Future challenges include optimizing the geometry and drive method for soft robot propulsion and improving the robustness of the drive performance to accommodate individual animal differences. Circulation-assisted experiments using PFDs are also needed.

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