Luminal Robots Small Enough to Fit Through Endoscope Ports: Initial Tumor Resection Experiments in the Airways

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INTRODUCTION

In this paper, we present the first resection experiments with a new kind of luminal continuum robot that is small enough to fit through the port of a conventional flexible endoscope, yet provides a large open central lumen through which surgical instruments can pass. This robot enables dexterity at the tip of a flexible endoscope for port-delivered instruments (see Figure 1). These capabilities can be useful in a wide range of surgical procedures where flexible endoscopes are used, including those in the colon, lung, brain, and other natural orifice procedures throughout the body. Historically, obtaining this type of dexterity has required re-engineering the endoscope, increasing its diameter (e.g. the EndoSamurai from Olympus or the Anubiscope from Karl Storz, both of which are 16mm).

Our new luminal robot concept consists of two tubes, each of which has had material selectively removed from one wall [1]. The tubes are placed within one another and axially rotated so that the non-machined faces of each are opposite one another. The tips are then attached, so that these faces can act as push-pull actuation elements that make the overall structure bend. This actuation principle is analogous to the multiple backbones in the designs pioneered by Simaan et al. [2] but packages them into a thin, tubular form factor suitable for delivery through standard endoscope ports (see Figure 2.)

Here we perform the first tumor resection experiments with this new kind of robot. Specifically, we explore their potential for removing central airway tumors, which affect 80,000 patients per year in the USA [3, 4] and pose a life-threatening risk of asphyxiation. Surgery to remove these tumors is normally performed using either an open approach or a rigid endoscope. The latter approach, while less invasive, still has a 32% complication rate [5], with complications including broken teeth, damage to the neck, or in rare cases even death from ruptured blood vessels. Many of these complications are related to the need to tilt the patient's head back to straighten the throat so that the endoscope can reach the lung, combined with the fact that endoscope angulation is currently the only way to aim tools delivered through the rigid endoscope's port.

Figure 1: Conceptual drawing of a dual-channel flexible endoscope with our luminal manipulators delivered through its ports.

In this paper, we explore whether our dexterous manipulators can take the place of rigid endsocope angulation for instrument aiming, thereby enabling the procedure to be performed through a flexible endoscope with no wrenching of the patient's neck.

ROBOT PROTOTYPE

We created our luminal robot by machining two PEEK tubes using the method used for unidirectional wrists in [6]. The inner tube had an ID of 1.25 mm and an OD of 1.65 mm. The outer tube had an ID of 1.80 mm and an OD of 2.31 mm. We cut five 2.3 mm wide notches, 1.6 mm apart, at a depth of 70% of the outer diameter for each tube. After machining, the tubes were arranged concentrically and cyanoacrylate was used to attach their tips to one another.

Figure 2: Prototype luminal manipulator delivered through a 6 mm diameter bronchoscope.

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Figure 3: (a) Initial obstruction, (b) Removal of tumor with the manipulator, (c) Sheep trachea after tumor removal.

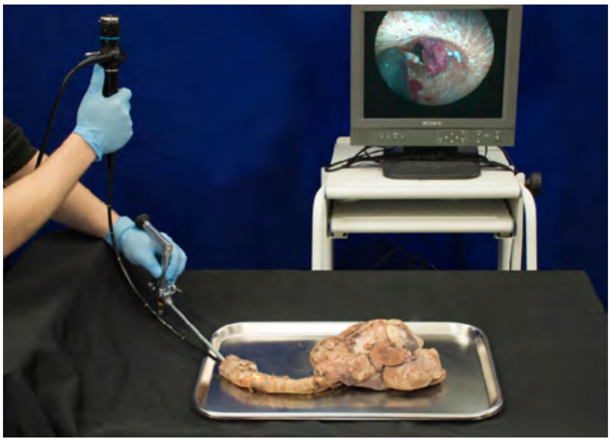

Figure 4: Experimental Setup: The bronchosope was used to deploy the luminal manipulator into the sheep trachea. A rigid endoscope was introduced beside it to capture the images shown in Figure 3.

EXPERIMENTS

To create a model of a tumor obstructing the central airway, we used a sheep trachea and attached a small piece of chicken liver to its inside wall with cyanoacrylate to simulate the tumor (see Fig. 3(a)). Once the obstruction was fixed in place, we deployed the luminal manipulator through the working channel of a commercial flexible bronchoscope (Olympus BF-1T20D) (see Fig 3(b)). The tip of the luminal manipulator was fitted with a blade for sharp dissection. Two people collaborated to operate the device in these experiments, one operating the endoscope controls and the other manually controlling extension and curvature of the port-delivered manipulator by coordinating the linear motions of both its tubes. After separation of the obstruction from the wall, the blade was removed, and a suction tube was placed through the lumen of the device to remove the excised tumor, resulting in the image shown in Fig 3(c). We note that in a clinical implementation this blade would likely be replaced by a fiber laser and the tumor removed intact by grasping it with forceps, to remove it from the body.

DISCUSSION

The results in this paper represent the first resection experiments using our new luminal manipulator. They also represent the first steps toward a new paradigm for central airway tumor resection using a flexible endoscope rather than a rigid one, an approach that is expected to reduce complications that come from wrenching the patient's head and neck as is required in the current rigid endoscopic approach. Future work will involve performing experiments similar to those in this paper using a flexible fiber optic laser for cutting, with en bloc removal of the tumor. The new manipulator itself also can be enhanced even further with optimization of materials, dimensions, and tolerances. A robotic actuation system is in development for this device; the experiments in this paper revealed the usefulness of it, since it was challenging for two different people to coordinate endoscope and manipulator motions. These proof-of-concept experiments, combined with the scalability and adaptability of this design, present exciting possibilities for enhancing dexterity in a wide variety of current flexible endoscopic procedures.

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