Transoral Steerable Needles in The Lung: How Non-Annular Concentric Tube Robots Can Improve Targeting

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INTRODUCTION

Lung cancer is one of the most profound current public health challenges, with more than 150,000 lives lost to it each year in the United States alone [1]. A major challenge is early diagnosis, since life expectancy drops precipitously as the tumor grows. While small nodules (which may or may not be cancerous) are being identified with increasing frequency due to better imaging and new guidelines that dramatically increase the frequency of screening, many cannot currently be biopsied. Surgeons have a low diagnostic yield rate (< 52%) with nodules less than 1.5 cm in size using hand-held needles [2]. Furthermore, traditional percutaneous approaches risk lung collapse, which is a serious complication that can even be fatal to patients with various co-morbidities.

Transoral targeting for biopsy and therapy delivery is a better approach, since the lung's outer wall is not punctured, reducing the risk of lung collapse. While a few academic and commercial systems exist for this purpose (e.g. Medtronic's superDimension system http://superdimension.com/), they are typically limited to nodules that occur in or near the bronchial tree. We recently described a robotic system designed to exit the bronchial tree and steer through the soft tissue of the lung [3]. The system, shown in Fig. 1, combines three steerable surgical devices: a tendon-driven redundant mechanism (the bronchoscope), a concentric tube robot [4], and a flexure-based bevel tip steerable needle [5]. Concentric tube robots have been used to augment the dexterity of rigid [6] and flexible endoscopes [7] in prior work, but this is the first time all three steering technologies have been combined into one system. The intended workflow for our system is (1) deploy the bronchoscope manually to the desired location in the bronchi, (2) use a puncture mechanism [3] to make a small opening in the bronchial wall, (3) deploy the concentric tube robot through it into the soft tissue of the lung, and (4) deploy the bevel tip needle and steer it to the desired target under closed loop control [8].

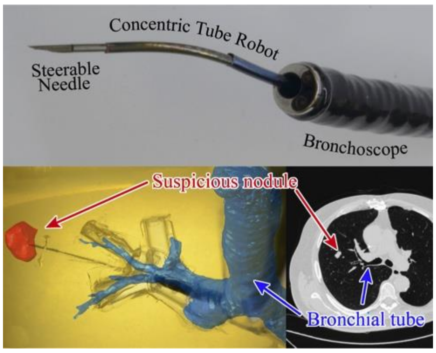

Fig. 1. Our transoral lung access system consists of three stages: a tendon-actuated bronchoscope, a concentric tube robot, and a steerable needle. The system was designed to target hard-to-reach nodules in the peripheral lung.

In this paper we focus on improving step (3). Our objective is to provide a way for the concentric tube stage to use high curvatures, while minimizing tissue damage and deformation. We aim to achieve this via follow-the-leader deployment, in which the shaft of the device remains perfectly in the path traced out by the device's tip as it advances through tissue. See [9] for a discussion of this as it relates to concentric tube robots. Achieving follow-the-leader deployment with our system is a challenge, because the long transmission lengths required for the tubes to pass through the bronchoscope are subject to substantial torsional windup as the curved tubes elastically interact. This can cause elastic instabilities and snap-through, in which the tubes suddenly snap from one configuration to another [10,11]. This makes a range of axial tube rotation angles inaccessible, unless tubes are only gradually curved, or are deployed such that their curved sections do not overlap when relative axial tube rotations are applied.

Non-annular tube cross sections provide a way to achieve follow-the-leader deployment with higher tube curvatures, or at currently inaccessible relative angles. Non-annular tubes prevent relative rotation of the tubes with respect to one another, avoiding the snapping behavior caused by elastic instabilities. This idea was first developed in a collaboration between the last author and Philips, Inc. Yet to date, it has only been described conceptually in the patent literature [12]. Thus, the contribution of this paper is the first physical realization of non-annular concentric tubes.

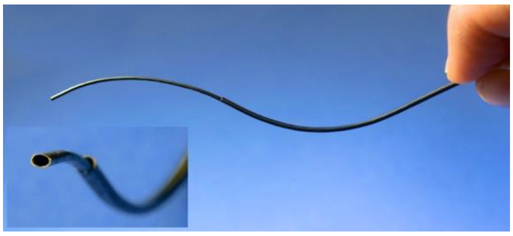

Fig. 2. Our prototype concentric tube robot with elliptical cross sections. This design can achieve configurations that would be unstable for annular tubes, facilitating follow-the-leader deployment with higher curvatures.

MATERIALS AND METHODS

To create a set of non-annular tubes, we modified a set of annular tubes. We used an outer tube with an outside diameter (OD) of 1.60 mm and an inside diameter (ID) of 1.40 mm, and an inner tube with an OD of 1.16 mm and an ID of 0.99 mm. Mandrels made from nitinol wire (0.79 mm and 0.48 mm, respectively) were inserted into each tube, and a hot air gun was used to heat each tube to approximately 600° C. We then mechanically deformed the tube onto the mandrel with a set of pliers, yielding an elliptical cross section. We then precurved the tubes (curvature of 31.5 m^{-1}, curved length ≈55 mm). Fig. 2 shows the tubes placed concentrically. The elliptical cross sections prevent relative tube rotation.

RESULTS

The complete system introduced in the previous section, and described in [3], is illustrated in Fig. 3. The enhancement to the system that is the main result of this paper is the prototype shown in Fig. 2. The elliptical cross sections enable tubes to deploy with curvatures opposed to one another (see Fig. 2), in configurations that would be unstable for annular tubes [10,11]. For example, annular tubes of the same dimensions, precurvatures, and curved lengths, with transmission lengths long enough to pass through a bronchoscope (e.g. 735 mm and 835 mm), would wind up torsionally and be unable to achieve this configuration. In fact, the maximum overlapped arc length of the precurved portions of these annular tubes for which stable opposed curvatures could be maintained would be 0.9 mm [10]. Furthermore, when the precurved sections of these annular tubes are fully overlapped and extended from the bronchoscope, the maximum stable rotation angle of the inner tube relative to the outer is 53°, and this requires a tube base angle of approximately 3083°, more than 8.5 revolutions! In contrast, the use of non-annular tubes enables higher curvatures and previously inaccessible relative tube angles (e.g. the 180° case shown in Fig. 2) to be employed.

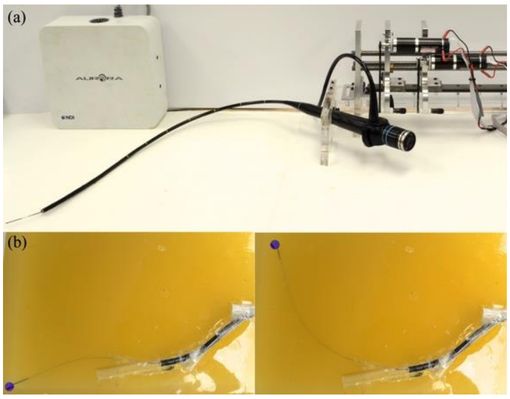

Fig. 3. (a) Our complete system, in which the concentric tube robot and steerable needle pass through the bronchoscope port. (b) Photographs of phantom targeting experiments with the system, in which magnetic tracking feedback was used to steer the needle to targets [3].

CONCLUSION

While non-annular tube cross sections would not be useful in contexts where the concentric tube robot is intended to act as a manipulator (see [4]), they can be a good option when one desires the concentric tube robot to act like a steerable needle. By locking the relative axial rotation of the tubes, elastic instability is prevented, and configurations inaccessible to annular tubes become possible. This is potentially useful in any procedure where the robot acts like a steerable needle.

REFERENCES

[1] American Cancer Society. Cancer facts & figures 2014. Accessed Oct. 21, 2014.

[2] N. Kothary, et al. "Computed tomography–guided percutaneous needle biopsy of pulmonary nodules: impact of nodule size on diagnostic accuracy." Clinical Lung Cancer, vol. 10, no. 5, pp. 360-363, 2009.

[3] P. J. Swaney, A. Mahoney, et al., "Tendons, concentric tubes, and a bevel tip: Three steerable robots in one transoral lung access system", IEEE Int. Conf. on Robotics and Automation, 2015. In Press.

[4] H. B. Gilbert, D. C. Rucker, and R. J. Webster III, "Concentric tube robots: state of the art and future directions", Int. Symposium on Robotics Research, 2013. Springer Tracts in Advanced Robotics, In Press.

[5] P. J. Swaney, J. Burgner, H. B. Gilbert, and R. J. Webster III, "A flexure-based steerable needle: high curvature with reduced tissue damage", IEEE Trans. on Biomedical Engineering, vol. 60, no. 4, pp. 906-909, 2013.

[6] R. J. Hendrick, et al., "A multi-arm hand-held robotic system for transurethral laser prostate surgery", in IEEE Int. Conf. on Rob. Autom., pp. 2850-2855, 2014.

[7] E. J. Butler, et al., "Robotic neuroendoscope with concentric tube augmentation," IEEE/RSJ Int. Conf. Intel. Rob. and Sys., pp. 2941–2946, 2012.

[8] D. C. Rucker, J. Das, et al., "Sliding mode control of steerable needles", IEEE Trans. on Robotics, vol. 29, no. 5, pp. 1289-1299, 2013.

[9] H. B. Gilbert, et al., "Concentric tube robots as steerable needles: achieving follow-the-leader deployment", IEEE Transactions on Robotics, In Press.

[10] R. J. Hendrick, et al., "Designing snap-free concentric tube robots: A local bifurcation approach", IEEE Int. Conf. on Robotics and Automation, 2015. In Press.

[11] J. Ha, F. Park, P. E. Dupont, "Achieving elastic stability of concentric tube robots through optimization of tube precurvature", in IEEE/RSJ Int. Conf. Intelligent Robots and Systems, pp. 864-870, 2014.

[12] E. Greenblatt, et al. "Interlocking nested cannula", US Patent Application Number 20110201887. 2011.