More Ports = Less Invasive? A Multi-Needle Robot for Lung Ablation

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INTRODUCTION

There has been a great deal of interest in single-port robot surgical systems based on their promise to reduce invasiveness by reducing the number of incisions needed to perform a surgical procedure. While reducing the number of incisions is a worthy goal, invasiveness is also a function of incision size. Some surgeons use needlescopic (< 3mm diameter) instruments to eliminate incisions and sutures all together. However, the approach is limited by the low stiffness of small-diameter tools [1].

In this paper, we present a system that addresses this problem by using needle-diameter tools, yet enabling them to grasp one another within the patient's body to form parallel structures for greater stiffness (Fig. 1). The needles and flexible instruments (e.g., thin endoscopes, ablation probes, and other interventional instruments) grasp one another within a body cavity with snares as shown in Fig. 2. The parallel structure formed by the needles can be maneuvered inside the body via coordinated motion of the needles' bases outside the body using robot manipulators (Fig. 1). The snares can be released and retightened to reconfigure the needle structure into different topologies inside the body to satisfy changing task requirements. This reconfigurable robotic multi-needle concept was first introduced in [2] with the motivating example of diagnostic palpation.

Here, we address therapy delivery for the first time, performing a feasibility study on percutaneous thermal ablation of a partially deflated lung from within the pleural cavity. This is motivated by the high incidence of lung cancer, which kills more than 158,000 Americans each year [3]. Percutaneous thermal ablation is a useful tool for treating inoperable lung tumors, but challenges remain with targeting, particularly in the typical case where multiple overlapping ablation zones are needed to fully cover the tumor. Accurately targeting a lung tumor with needles is challenging due to needles' tendency to unpredictably deflect along the insertion path. Small aiming misalignments can cause an ablation needle to entirely miss the desired target [4]. These issues are compounded when attempting to overlap ablation zones since repositioning typically requires new transthoracic needle insertions. To address this, we propose a thoracoscopic paradigm in which the lung is partially deflated to create an open cavity (i.e., the pleural space) for tools. In this context, the multi-needle concept can be viewed as a platform for dexterously maneuvering and re-aiming ablation needles from within the pleural space that facilitates greater ablator placement accuracy through a single set of thoracic entry points.

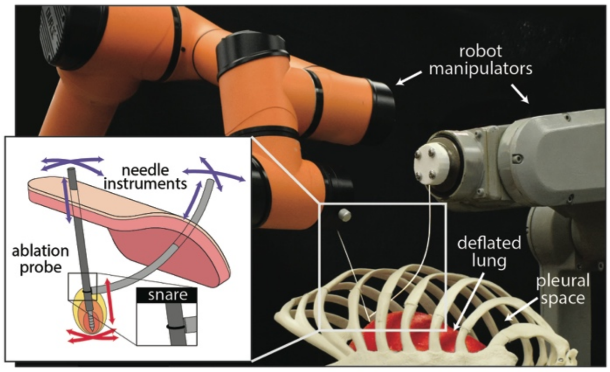

Fig. 1: A multi-needle system is assembled inside a body cavity and is maneuvered by manipulating the needles outside the body using robot manipulators. The needles bend each other to produce coordinated motion inside the body.

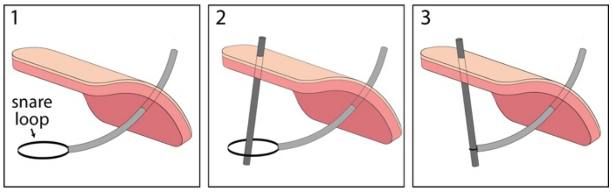

Fig. 2: A multi-needle structure is assembled inside a body cavity using snares that form structural grasps when tightened. The assembly of a two-needle structure is shown in three steps.

This paper investigates the aiming dexterity and needle insertion stiffness of the multi-needle concept in this thoracoscopic setting. We demonstrate dexterity with a mechanics-based simulation that directs an ablation probe through a trajectory in a patient's chest. We experimentally demonstrate the ability of a multi-needle structure to aim and insert a radiofrequency ablation probe into ex vivo chicken tissue. This provides the first feasibility study of interventional capability in our new robotic paradigm that focuses on minimizing the size of individual ports rather than the number of ports.

MATERIALS AND METHODS

We fabricated a benchtop multi-needle system using superelastic Nitinol tubing (OD 1.78mm, ID 1.20mm). Through one of the needles, we inserted a snare made of braided Dyneema line. Through the other needle, we inserted a prototype RF ablation needle (OD 0.82mm). The ablation needle was created out of Nitinol and a Smith & Nephew Vulcan RF Generator was used for ablation experiments. The system was placed in static configurations using Noga articulated holders that will be replaced by robot manipulators in future work.

Assembly and Therapy Delivery: The multi-needle system was assembled by (1) inserting a snare needle

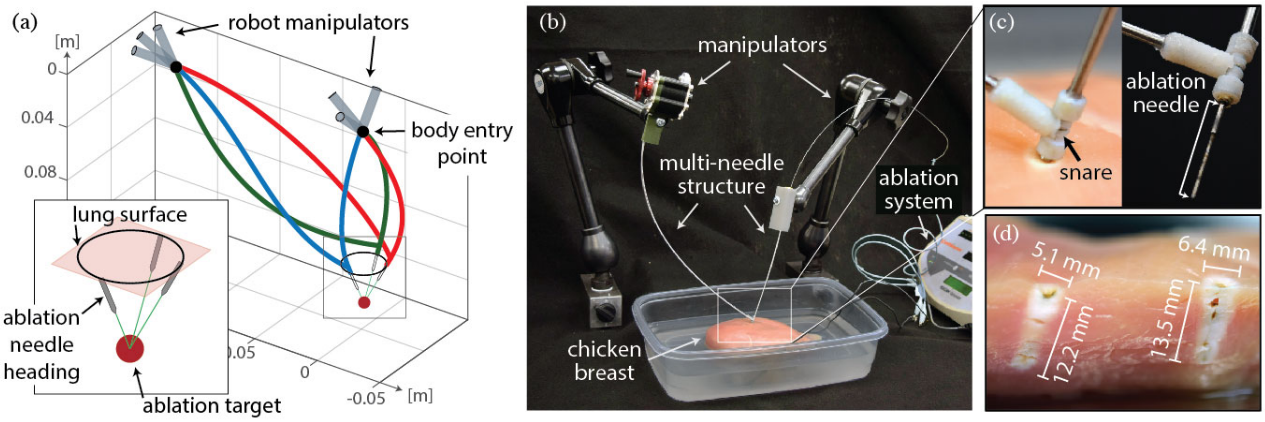

Fig. 3: (a) Simulation experiments demonstrate aiming dexterity by illustrating how the tip of the prototype multi-needle system can be maneuvered along a circular trajectory on a simulated lung surface while keeping it aimed at a subsurface lung nodule. (b) The prototype multi-needle structure is sufficiently stiff to insert an ablation needle (c) into chicken breast for ablation tasks (d).

with an open snare, (2) inserting a guide needle for the ablation probe and directing its tip into the open snare, (3) closing the snare, (4) delivering the ablator through the guide needle and into tissue, and (5) applying ablative energy. The assembly process is illustrated in Fig. 2.

Modeling: We investigate the dexterity of a two-needle prototype in simulation using a mechanics-based model. The model inputs are the needles' entry points into the body $\boldsymbol{r}_i$, their quaternion orientations $\boldsymbol{q}_i$ at the entry points, and their insertion lengths L_i into the body (the subscript $i \in \{1,2\}$ describes the needle in question). The model outputs are the needles' shape inside the body.

The constituent needles of a multi-needle structure can be modeled as Cosserat rods with a state vector $\boldsymbol{x}_i$ that propagates along the needles' backbones in arc length s_i according to the arc length derivative $\boldsymbol{x}_i{}'$ as

$$\boldsymbol{x}_i = \begin{bmatrix}\boldsymbol{p}_i{}^T & \boldsymbol{q}_i{}^T & \boldsymbol{m}_i{}^T & \boldsymbol{n}_i{}^T\end{bmatrix}^T \quad \text{and} \quad \boldsymbol{x}_i{}' = \boldsymbol{f}(\boldsymbol{x}_i, s_i),$$

respectively. The needles' states are also functions of arc length s_i and describe their position $\boldsymbol{p}_i$, quaternion orientation $\boldsymbol{q}_i$, internal moment $\boldsymbol{m}_i$, and internal force $\boldsymbol{n}_i$. The arc length derivatives of the states are formulated into a multi-point boundary value problem that can be solved numerically to produce the structure's shape [2].

RESULTS

To illustrated the aiming dexterity of the benchtop multi-needle system, we used the model to simulate a trajectory where the tip of an ablation probe is commanded to follow a circular trajectory on the surface of a simulated lung while always pointing at a simulated lung tumor beneath the lung's surface. Three configurations from this trajectory are shown in Fig. 3(a). Such a trajectory could be useful for guiding an ablation needle to a lung nodule from multiple angles but through only two insertion points in the chest wall. This would be impossible with a single ablation needle on its own.

To demonstrate tissue ablation, we constructed a benchtop experiment where an ablation needle was deployed through one of the parallel structure's needles into a chicken breast, which is qualitatively comparable to the density of lung parenchyma (Fig. 3(b)). Two insertions and ablations were performed with the multi-needle structure arranged in two different configurations (one is shown in Fig. 3(b)). This experiment indicates the feasibility of therapy delivery using a multi-needle system for the first time.

DISCUSSION & CONCLUSION

There is evidence that a thoracoscopic approach where the lung is deflated will enhance ablation effectiveness. For example, lung ablation is hindered by blood flow that convectively cools the ablation zone – this is reduced in deflated lung and results in larger ablation volumes [5]. Deflating lung can also increase safety. For example, ablating peripheral lung tumors risks incidental ablation of the sensitive mediastinum and chest wall. Deflating the lung displaces nodules away from these areas, creating safe space for ablation [5]. Further safety improvements are enabled by the multi-needle concept's potential for targeting multiple ablation sites through a single set of thoracic entry points, reducing the risk of painful damage to intercostal nerves. Future work will investigate these potential benefits in animal models.

As a platform for percutaneously delivering needles through open cavities like the pleural space, the multi-needle concept offers the potential for better aiming dexterity and enhanced stiffness over a single ablation needle on its own. We anticipate these benefits will open the door to more effective ablation in the lung.

REFERENCES

[1] D. M. Krpata and T. A. Ponsky, "Needlescopic surgery: what's in the toolbox?" *Surg. Endosc*, vol. 27, no. 3, pp. 1040–1044, 2013.

[2] A. W. Mahoney, et al., "Reconfigurable Parallel Continuum Robots for Incisionless Surgery," *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2016, pp. 4330-4336.

[3] R. L. Siegel, K. D. Jemal, and A. Miller, "Cancer statistics, 2016," *CA Cancer J. Clin.*, vol. 66, no. 1, pp. 7-30, 2016.

[4] R. Bale, et al., "Stereotaxy: Breaking the limits of current radiofrequency ablation techniques," *Interventional Radiology*, vol. 75, no. 1, pp. 32-36, 2010.

[5] R. S. Santos et al., "Microwave ablation of lung tissue: impact of single-lung ventilation on ablation size," *Annals of Thoracic Surgery*, vol. 90, no. 4, pp. 1116-1119, 2010.