On the Merits of Using Angled Fiber Tips in Office-based Laser Surgery of the Vocal Folds

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ABSTRACT

Office-based endoscopic laser surgery is an increasingly popular option for the treatment of many benign and premalignant tumors of the vocal folds. While these procedures have been shown to be generally safe and effective, recent clinical studies have revealed that there are a number of challenging locations inside the larynx where laser light cannot be easily delivered due to line-of-sight limitations. In this paper, we explore whether these challenges can be overcome through the use of side-firing laser fibers. Our study is conducted in simulation, using three-dimensional models of the human larynx generated from X-ray microtomography scans. Using computer graphics techniques (ray-casting), we simulate the application of laser pulses with different types of laser fibers and compare the total anatomical coverage attained by each fiber. We consider four fiber types: a traditional "forward-looking" fiber - not unlike the ones currently used in clinical practice - and three side-firing fibers that emit light at an angle of 45, 70, and 90 degrees, respectively. Results show that side-firing fibers enable a ∼70% increase in accessible anatomy compared to forward-looking fibers.

Keywords: Office-based Surgery; Surgical Simulation; Vocal Folds Surgery; Flexible Endoscopy; Laser Surgery; Laser Fiber.

1. INTRODUCTION

Office-based laser surgery is an emerging trend in Otolaryngology, where it is used to treat a variety of benign and pre-malignant tumors of the vocal folds.[1–3] These procedures are performed with the approach illustrated in Fig. 1: a laser fiber is deployed through the endoscope's operating channel to deliver laser pulses and thermally coagulate diseased tissue. This approach represents a paradigm shift from traditional tumor management strategies, which are normally based on surgical resection in the operating room. Prior studies have found office-based laryngology procedures to enable considerable savings for patients.[4,5] Furthermore, office procedures can be simply carried out under local anesthesia without sedation or using only a mild sedative,[1,3] therefore enabling the treatment of patients who are ineligible to receive general anesthesia, e.g., elderly patients.

Despite their documented benefits, office-based procedures are still underutilized because of how challenging they can be to perform with available instrumentation. One of the key challenges is that the laser fibers used to deliver treatment can only emit light forward in a line-of-sight fashion, making it hard to reach disease that lies off the longitudinal axis of the fiber. Consider, for instance, the scenario depicted in Fig. 1(b): it is not uncommon for a tumor to form immediately below the free edge of one of the vocal folds,[6–8] an area where the laser fiber cannot be easily aimed to. Patients presenting with disease in these "unfavorable" locations are not considered candidates to receive in-office treatment.[9]

The limitations described above could be tackled by developing new laser fibers capable of directing light at different angles. Custom angled fiber tips that can redirect light laterally have been used in other biomedical applications,[10,11] including some minimally-invasive surgical procedures,[12] but to the best of our knowledge, they have never been evaluated for use in office-based laser surgery of the vocal folds. In this paper, we present a comparative study of four different laser fiber designs: a traditional forward-looking fiber, and three side-firing fibers that emit light at an angle of 45, 70, and 90 degrees, respectively. We test these fibers in simulation, using

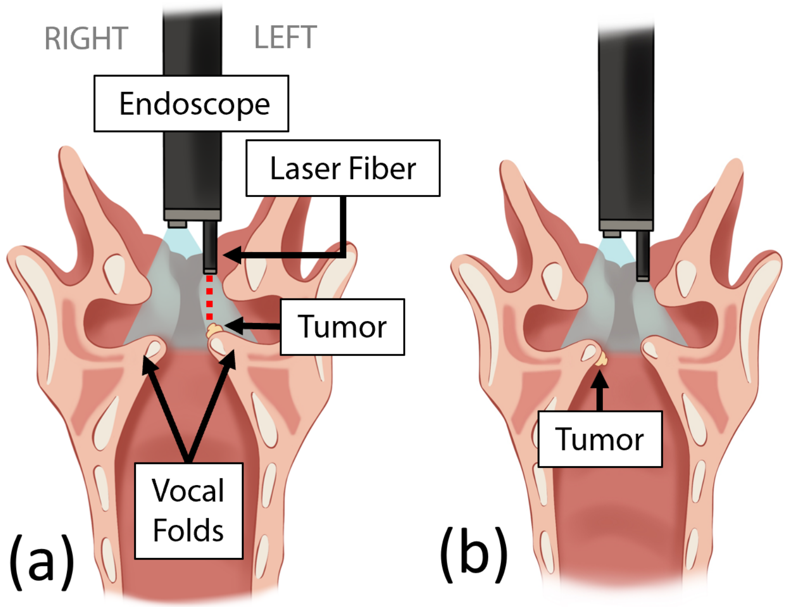

Figure 1. Frontal cut of the human larynx illustrating the approach used in office-based vocal folds laser surgery: (a) An endoscope is deployed in proximity of the vocal folds and a laser fiber is used to thermally treat diseased tissue. The blue cone represents the field of view of the endoscopic camera, while the dashed red line shows the line of sight between the laser fiber and the target tumor. (b) In some instances, a tumor may grow below the free edge of one of the vocal folds, where the laser fiber cannot be easily aimed to. Patients who present with disease in unfavorable locations are not candidates for office treatment.

three-dimensional models of the human larynx generated from microtomography X-ray scans of cadavers.[13] A ray casting procedure simulates the application of laser pulses from the fiber tip. We let a computer program manipulate the endoscope and the laser fiber, and perform an extensive exploration of the reachable workspace. The output of this process is a three-dimensional map indicating what tissue can be accessed by each fiber type.

2. METHODS

The simulation environment is shown in Fig. 2(a). A virtual flexible endoscope carrying a laser fiber is deployed into a three-dimensional model of the larynx, and a computer program is used to control the endoscope and explore the reachable anatomy (more on this in the following paragraphs). Fig. 2(b) illustrates the types of fiber considered in the current study. One is a standard forward-looking fiber, while the other is a side-looking fiber that emits light at an angle ϑ from its tip. We simulate side-firing fibers with $\vartheta = 45°, 70°$, and $90°$. All the fibers considered in this study are assumed to have a diameter of 0.6 mm and to emit a cone-shaped beam with a divergence angle $\alpha = 40°$.

The endoscope we simulate in this study is the Pentax VNL-1570STK[14] (Fig. 3), a trans-nasal flexible laryngoscope with a diameter of 4.9 mm and a working channel of 2 mm. In its standard orientation, the endoscope is positioned into the larynx with the chip-tip camera above the right vocal fold, and the laser fiber pointed on the left vocal fold[8] (as illustrated in Fig. 1). The endoscope can be axially translated, rotated, and bent in-plane. To model the motion of the endoscope, we assume that bending occurs in the shape of a constant curvature arc (see Fig. 3(b)) and use well-known kinematics relations from the robotics literature.[15] The endoscope range of motion was determined based on the clinical experience of one of the authors, a trained laryngeal surgeon. In the simulations, the endoscope bending ranges between (-120°, 120°), and the axial rotation is limited in the (-100°, 100°) interval.

To simulate the larynx anatomy, we use a set of tomography images recently published by Bailly et al.[13] These images were acquired with an X-ray microtomograph, with voxel sizes varying between 25 and 45 µm. We processed the scans with a custom MATLAB script to generate a three-dimensional stereolithography (STL)

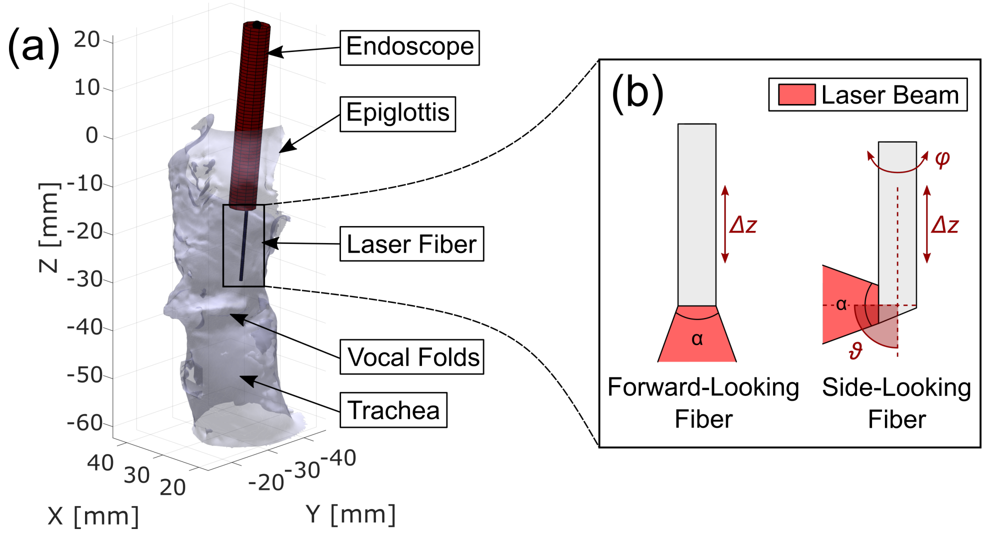

Figure 2. (a) Simulation Environment: an endoscope is deployed into a virtual larynx model and controlled by a sampling-based motion planning algorithm, i.e. Rapidly-Exploring Random Trees (RRT); (b) the two types of laser fiber considered in this study, which can be axially translated (Δz) independently of the endoscope. The side-looking fiber can also be rotated (φ) to change the direction of the laser beam. Both fibers are assumed to emit a cone-shaped beam of light with divergence $\alpha = 40°$.

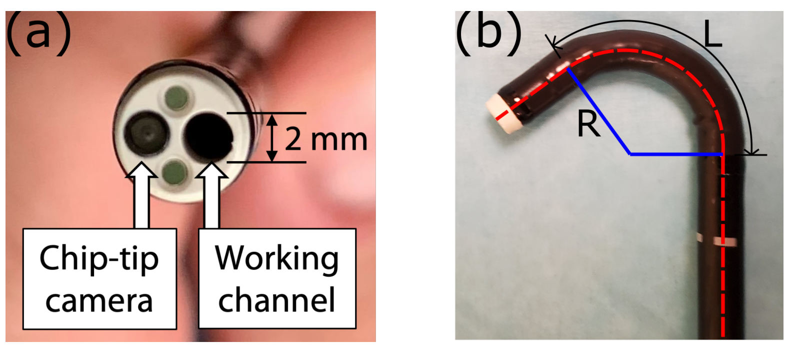

Figure 3. Pentax VNL-1570STK video laryngoscope: (a) This flexible endoscope includes a chip-tip camera and a 2 mm side working channel; (b) View of the endoscope showing constant-curvature bending, with R being the (variable) bending radius and $L = 25.7$ mm being the length of the bending section.

model. The STL models were subsequently post-processed with the Quadric Edge Collapse Decimation filter in Meshlab[16] to reduce the number of vertices, with the goal of reducing the computational cost of the simulations.

To build a map of the reachable tissue, we generate a large number (10,000) of reachable endoscope configurations with a sampling-based motion planning algorithm, i.e., Rapidly-Exploring Random Trees (RRT).[17] From each configuration, we run a ray casting algorithm to simulate the application of laser light. We generate 1,000 virtual rays from the tip of the fiber in a cone that mimics the laser beam. With each of these rays, we use the Möller–Trumbore ray-triangle Intersection algorithm[18] to detect what faces of the STL larynx model are visible in a direct line of sight. STL faces that are located too far away from the tip of the laser fiber (> 3 mm) would not be irradiated with a sufficient power density due to the divergence of the laser beam[3] and are therefore not marked as reachable. A video of the simulations is available at https://youtu.be/G1q8HMk9s3M.

3. RESULTS

Results are shown in Fig. 4. The two larynx models used in the simulations are based on the anatomy of two deceased individuals who donated their bodies for research purposes.[13] Larynx 1 reproduces the anatomy of an 86-year-old female, while Larynx 2 is a 94-year-old male. In both subjects, side-firing laser fibers were able

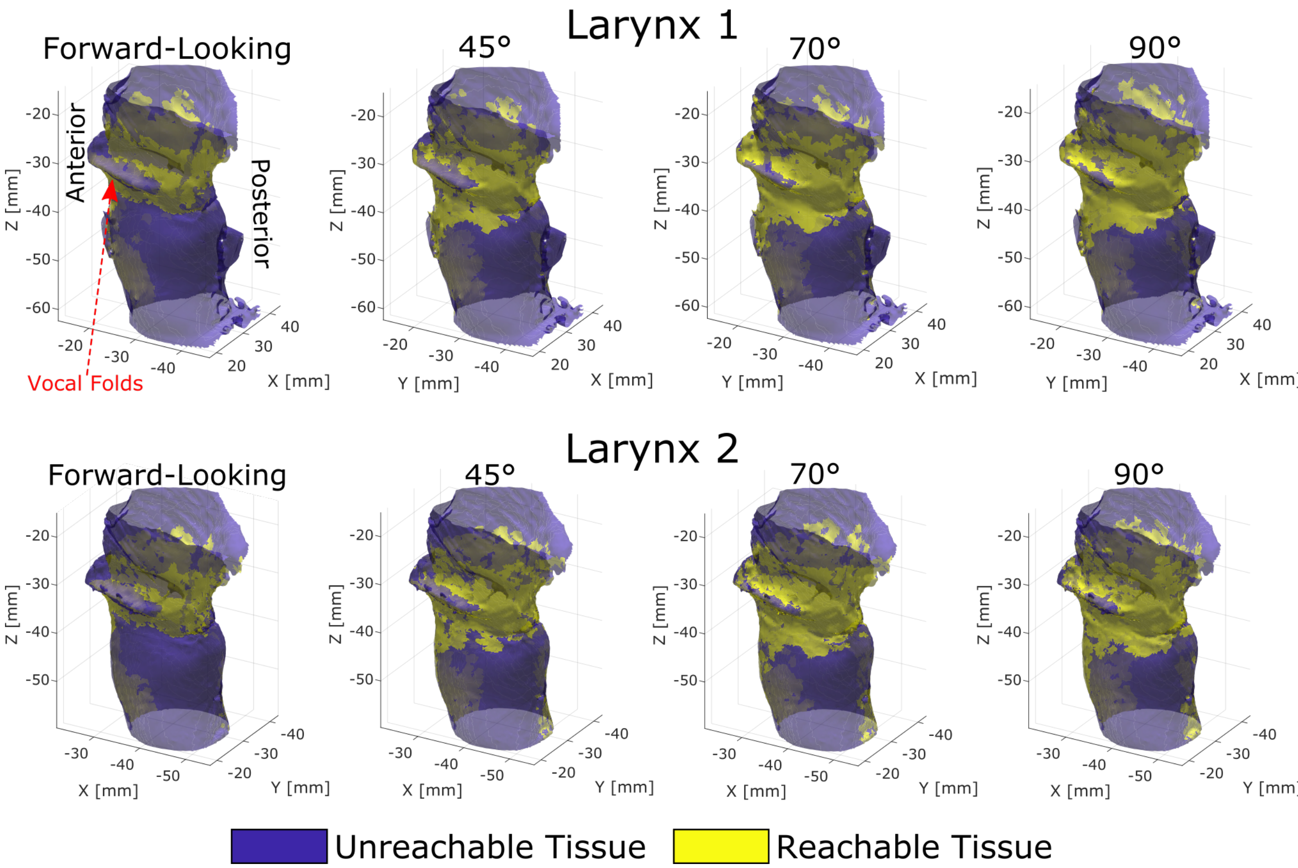

Figure 4. Estimation of the reachable tissue in two different larynx models. Yellow surfaces mark areas that were found to be reachable by the laser fiber. Results are shown for a traditional forward-looking laser fiber and for three laser fibers with angled tips ($\vartheta = 45^\circ, 70^\circ$, and 90°).

Table 1. Total tissue area covered by each fiber type. All results are in square centimeters (cm^2).

	Forward-Looking Fiber	Side-Firing Fibers		
		45°	70°	90°
Larynx 1	9.23	12.20	14.65	15.45
Larynx 2	8.48	12.52	14.45	15.02

to achieve more extensive coverage than the forward-looking fiber. The side-looking fibers performed better particularly in the regions immediately above and below the vocal folds (refer to Fig. 4). The total coverage afforded by each fiber type is reported in Table 1. The total tissue area coverage was observed to increase with the deflection angle ϑ. Compared to the forward-looking fiber, the 90° side-firing fiber enabled 67% more coverage in Larynx 1, and a 77% increase in Larynx 2.

Further analysis of the simulation output revealed an interesting result, namely the presence of a well-defined gap in the point clouds representing the set of spatial locations reached by the tip of the laser fibers (see Fig. 5). This gap was observed in all the simulations, and it was always located on the right side of the larynx. After reviewing the simulation code to exclude the presence of programming errors, the finding was discussed with the clinical expert on our team, who confirmed that the right side of the larynx is, in fact, more challenging to access during an in-office procedure than the left side. This issue has been previously reported in the medical literature,[8] and it is attributed to the way in which channeled video laryngoscopes are designed and operated. As it was shown earlier in section 2, the standard orientation for a laryngoscope is such that the chip-tip camera is positioned on the right side of the patient, while the laser fiber is on the left side (refer to Fig. 1). To aim the

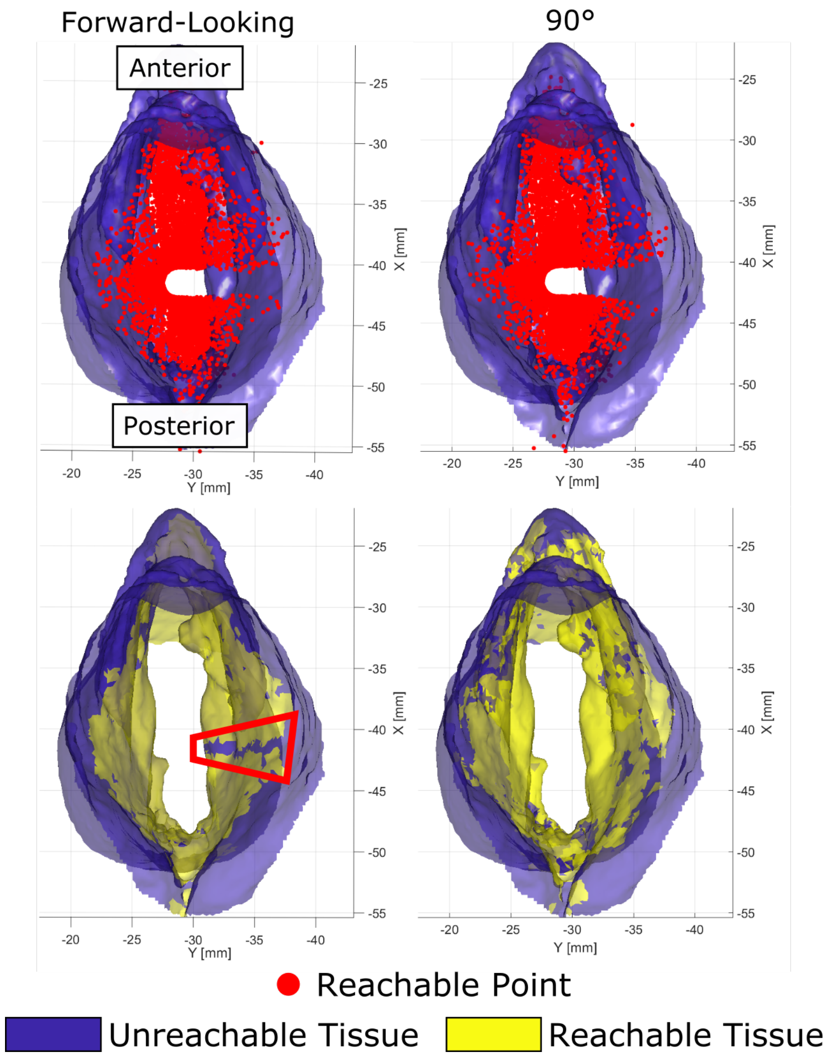

Figure 5. Axial views of Larynx 2 showing (top row) the points reached by the fibers in simulation, and (bottom row) the corresponding reachable tissue maps. In all the simulations (including those on Larynx 1), we observed the presence of a gap in the point clouds, extending towards the right side of the larynx. These gaps indicate the presence of an inaccessible region within larynx volume, which is consistent with prior observations reported in the clinical literature.[8] For forward-looking fibers, this inaccessible region causes an entire part of the larynx to become impossible to reach and treat (region highlighted in red), while side-firing fibers do not seem to suffer from the same issue.

laser fiber on the right vocal fold, the endoscope could in principle be axially rotated by 180°. In practice, such a maneuver is rarely performed, as it would require the operating physician to (1) flip the endoscope handle and hold it upside-down, and also (2) work with an inverted view of the anatomy. Both these things would make the procedure counter-intuitive to perform.

When using a forward-looking fiber, the gap in the reachable volume causes a region on the right side of the larynx to become inaccessible — this region is highlighted in red in Fig. 5. By contrast, none of the side-firing laser fibers were found to suffer from this issue.

4. DISCUSSION

The results of our study suggest that side-firing optical fibers have the potential to augment the accessible anatomy during office-based vocal folds laser surgery. The extent of accessible tissue was found to significantly increase with the use of a 90° angled fiber, as compared to a standard forward-looking fiber. Intermediate options, i.e., 45° and 70° were also found to outperform forward-looking fibers. Side-firing fibers appear to offer enhanced access to the regions immediately above and below the vocal folds; these regions are among the most challenging to access clinically.[6–8]

Another area where side-firing fibers offer enhanced access is the right side of the larynx. Our results show that currently available instruments for office-based surgery have significant kinematic limitations (i.e., the workspace gap illustrated in Fig. 5), which, among other things, make it difficult to reach and treat lesions that develop on the right side of the larynx. These limitations were well-known in the clinical world,[8] but they had not been quantitatively elucidated in the engineering literature yet. The results of our study help to fill this knowledge gap between clinical laryngoscopy and engineering, and they provide quantitative evidence that can be used in the future to guide the design of new laser fiber types for office-based vocal folds procedures.

This study is not without limitations. First and foremost, simulations were only run in two larynx models, which may not be representative of the anatomical variability that could be found in a large population sample. To further corroborate the findings of this paper, additional simulations would have to be run with new larynx models. The challenge here is that generating high-definition models of the larynx from conventional medical images (e.g. CT or MRI images) is not straightforward. The vocal folds are relatively small anatomical structures, and accurate imaging of these organs requires the use of micro-imaging techniques.[13] Another limitation of the present study is that it does not account for the physiological motion that may occur during an office-based procedure. As noted earlier, office-based surgery is often carried out in awake patients, and the shape of the larynx may undergo alterations due to breathing or speaking. The STL models used to represent the shape of the larynx in this study are static objects, and they are thus not suitable to capture such shape changes.

5. CONCLUSIONS

This paper presented the results of simulation studies aimed to evaluate the benefits of using side-firing laser fibers in office-based laryngeal surgery of the vocal folds. Results suggest that introducing angled fibers in the armamentarium for office-based laryngeal procedures has the potential to help physicians reach and treat disease in regions that are currently hard to access, thereby expanding the pool of patients that can be treated in the office.

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