A Feasibility Study on the use of Concentric Tube Continuum Robots for Endonasal Skull Base Tumor Removal

Hunter B. Gilbert¹*, Philip J. Swaney¹*, Jessica Burgner¹, Kyle D. Weaver²
Paul T. Russell III², and Robert J. Webster III¹,²

¹Mechanical Engineering, Vanderbilt University
²Vanderbilt University Medical Center

Contact: philip.j.swaney@vanderbilt.edu, *Shared First Authorship

INTRODUCTION

We evaluate the ability of a robotic system with needle-diameter, tentacle-like manipulators [1] to remove pituitary tumors endonasally. The robot consists of precurved superelastic tubes that can be axially rotated and telescopically extended to create controllable bending and elongation of the manipulator.

Pituitary tumors account for 15-20% of all diagnosed primary brain tumors [2], and 1 in 5 people are likely to have one in their lifetime [2], with 1 in 120 of these growing large enough (>1cm) to require surgery [3]. In contrast to traditional transcranial and transfacial surgical approaches, the endonasal approach results in no disfigurement to the patient; rather than entering through large tunnels bored into the patient’s forehead or cheek, surgical instruments enter through the patient’s nostril(s). However, the endonasal procedure is only deployed in a small fraction of all pituitary tumor cases because of the challenge of manually manipulating multiple straight, rigid instruments through the constrained nostril entry port, while performing complex surgical motions at the skull base.

A robotic approach to this procedure has the potential to reduce technical barriers and bring the benefits of endonasal surgery to many more patients. As has been demonstrated in other surgical applications, robots can do this by accurately manipulating small tools (e.g. [4]) and enhancing dexterity (e.g. [5]) in constrained spaces inside the patient. Systems have recently been introduced specifically for middle ear surgery [4] and throat surgery [5], among others.

Endonasal surgery is a particularly challenging application for a robotic system, because of the small nostril access port and the dexterity required at the skull base. Some prior results exist on the use of robotic systems to aid in bone drilling to open access paths to the skull base (see e.g. [6]), and to assist in endoscope manipulation [7]. These are complementary to our approach [1], which is deployed after the surgical site is opened.

MATERIALS AND METHODS

Concentric tube robots, also called active cannulas in view of their uses in medicine, are a type of continuum robot that uses a series of concentric, precurved superelastic tubes (typically made of nitinol) that translate and rotate inside one another, creating “tentacle-like” motion (i.e. elongation and controllable bending) [8, 9]. The concentric tube manipulator used in this study (Figure 1) consists of three tubes, resulting in a six degree-of-freedom manipulator. The workspace required inside the skull for endonasal procedures and an example tube design method for endonasal surgery were given in [1], and our tube curvatures were selected to closely match the values suggested in that study. The robot is teleoperated using a resolved rates control approach [1] via a haptic device (Phantom Omni, Sensible, Inc., USA) with visualization provided by a standard endoscope (see Figure 2).

The robot shown in Figure 1 was used by two experienced skull base surgeons to resect simulated pituitary tumors from a skull model. Suction was used to remove the resected tissue, as is typical in endonasal skull base procedures. The phantom tumor tissue was made from a combination of 1 part SIM-TEST (Corbin, Inc., USA) ballistic test media, and 5 parts water. This mixture provided a soft phantom that the experienced endonasal skull base surgeons judged to be qualitatively similar to the consistency of a pituitary tumor. An anatomical skull model (#A20, 3B Scientific, Germany) was prepared using a bone drill by an experienced surgeon, to closely replicate conditions at the start of pituitary tumor resection. The simulated tumor was then inserted.

Figure 2 shows the experimental setup at the start of tumor resection, and Figure 3 the endoscope view. The surgeon operating the system was instructed to move the active cannula through the nasal passage to the pituitary and remove as much of the simulated...
tumor as possible, using only endoscope images for visualization. The skull and endoscope were held in place during the experiment, while the suction device was used periodically to clean the curette. The suction was not at any time used to directly remove the simulated tumor itself.

DISCUSSION
To the best of our knowledge, this experiment is the first robotic transphenoidal pituitary tumor phantom resection study. In assessing the results, it is important to note (1) that pituitary tumors are nearly always benign, and (2) that surgeons are often unable to remove 100% of the tumor using current surgical practices. However, clinical outcomes are good, because the goal is decompression of structures like the optic nerve and the carotid arteries (among other structures), and these tumors are often slow-growing. While percentage tumor removal is difficult to quantify in vivo, one clinical study revealed “definite tumor remnants or at least suspicious findings” in 42% of patients in post-operative MRI scans [10]. Thus, while numbers are not available for resection percentages in vivo (because there is no known way to accurately quantify them) we believe our resection percentages are likely in-line with current clinical results. Opportunities for enhancements to our system in future work include the use of a skull with a geometrically accurate sella (surgeons were not able to scrape along the back wall in our phantom as they typically would in vivo), enhancements to tube optimization [1] to include a dexterity metric in addition to reachability, and the potential for dexterity enhancement through the addition of a rotational degree of freedom for the curette about the cannula tip axis.

REFERENCES

RESULTS
Two phantom tumor resections were performed according to the procedure described in the Methods section above. In both cases, all tumor was removed other than a thin film of material on the bone surface and in crevices at the back of the sella. To determine the percentage of tumor removed, the skull was weighed before insertion of the simulated tumor, after resection, and after washing to remove tumor residue. In trial 1, one surgeon performed the procedure individually start to finish, with 308 milligrams of an initial tumor mass of 1.4 g remaining after resection (78% removal). In trial 2, two surgeons took turns performing the resection, and 693 milligrams of an initial tumor mass of 2.1 g remaining after resection (67% removal). While no time limit was suggested or imposed and the duration of the resections was not timed, both were completed in a time period comparable to that of a clinical endonasal pituitary tumor removal.

Figure 2 (a) The surgeon performing a resection used an endoscope view for visualization as shown. (b) The experimental setup consisted of the endoscope, suction, and the active cannula robot, with a Phantom Omni serving as the user interface for teleoperation of the cannula.

Figure 3 An endoscopic view collected during tumor removal – the tumor was located through the hole called out with an arrow on the endoscope view. The robot with curette tip is shown on the right side of the image, approaching the tumor.