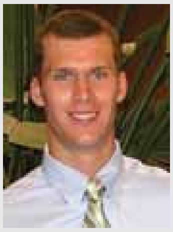
A robot for transnasal surgery featuring needle-sized tentacle-like arms

Expert Rev. Med. Devices Early online, 1–3 (2014)

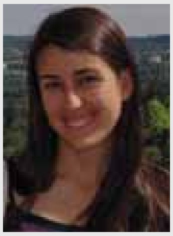
Hunter Gilbert

Vanderbilt University – Mechanical Engineering, 2301 Vanderbilt Place PMB 351592, Nashville, TN 37235, USA



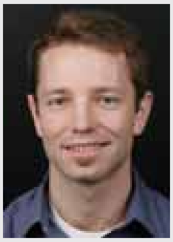
Richard Hendrick

Vanderbilt University – Mechanical Engineering, 2301 Vanderbilt Place PMB 351592, Nashville, TN 37235, USA



Andria Remirez

Vanderbilt University – Mechanical Engineering, 2301 Vanderbilt Place PMB 351592, Nashville, TN 37235, USA



Robert Webster III

Author for correspondence:
Vanderbilt University – Mechanical Engineering, 2301 Vanderbilt Place PMB 351592, Nashville, TN 37235, USA
robert.webster@vanderbilt.edu

This paper discusses a new class of robots known as concentric tube robots and their application to transnasal skull base surgery. The endonasal approach has clear benefits for patients, but the surgery presents challenges that strongly motivate the use of robotic tools. In this paper, the concentric tube robot concept is described, and preliminary experimental results for transnasal skull base surgery are reviewed. Just as the da Vinci robot has revolutionized many laparoscopic surgeries, we expect concentric tube robots will enable the advancement of skull base surgery and the development of other minimally invasive procedures that require access through constrained paths.

Robotic minimally invasive surgery has become the standard of care in many laparoscopic surgeries. One of the key benefits of adding surgical robots to the operating suite is to make technically challenging procedures easier to perform for the surgeon. The da Vinci® system, for example, has enabled more doctors to provide the benefits of minimally invasive surgery to more patients in laparoscopic radical prostatectomy and abdominal surgeries than was possible before its introduction. Research points to the fact that the robot allows less experienced surgeons to feel more comfortable with complex laparoscopic tasks [1]. As with abdominal and pelvic laparoscopy, endoscopic transnasal skull base surgery is a minimally invasive procedure that is known to reduce collateral damage to healthy tissues and the rate of complications when compared with traditional open surgery approaches [2]. The most common clinical indication for the transnasal approach is pituitary adenoma. Approximately 17% of the population will develop a pituitary adenoma at some time in their lives, and about 1 in 120 of those tumors will become a macroadenoma, that is, a tumor larger than 10 mm in diameter, which is an indication for surgical resection [3].

Traditionally, access to these tumors is provided by either craniotomy or an approach through the facial bones. However, over the past several years, a transnasal approach to the pituitary gland has been developed, which is much less invasive and thereby speeds healing for the patient. The surgery begins with the surgeon widening the nasal passages as necessary to access the anterior wall of the sphenoid sinus. After drilling through the anterior wall, the posterior wall is drilled to provide access to the tumor, which is then resected. This workflow leaves patients with no visible scars and a short recovery time. However, despite these advantages, less than half of cases are performed transnasally [4]. The primary reasons for this lack of wider adoption are the limitations imposed by the access channel through the nostrils. Current surgical tools have poor dexterity at the end of straight shafts, and visualization of the surgical site is limited [5–7]. These issues make the surgery challenging because a team of surgeons must coordinate the motions of several instruments through one or both nostrils, leaving little space for preventing tool collisions during complex surgical maneuvers.

The known benefits for the patient combined with the challenges for the

Expert Reviews

Keywords: concentric tube robot • continuum robot • endonasal surgery • minimally invasive surgery • robotic surgery • skull base surgery

 10.1586/17434440.2013.854702 ISSN 1743-4440

surgeon presented by endonasal skull base surgery provide ample motivation for robotic tools, but existing surgical robots are not good choices for skull base surgery. Their tool shaft diameters are large relative to the nostril opening and robot arm collisions force tool shafts to remain far from parallel. The recently invented concentric tube robot allows shaft diameters to be small enough for multiple tools to pass through a single nostril while maintaining dexterity and fine control at the instrument tip. Concentric tube robots are tentacle-like, needle diameter devices composed of multiple precurved tubes arranged concentrically. The tubes interact elastically and bend one another to form a final curved shaft shape (for more information on modeling these elastic interactions between tubes, see [8,9]). By independently translating and rotating each tube about its axis, the overall shaft shape of the device can be controlled. Construction of the robot from superelastic Nitinol metal facilitates elastic interaction of tubes and still enables the overall robot to deliver adequate forces for interaction with tissues at the surgical site. These robots have shaft diameters of 1–3 mm (this diameter can be changed to suit the needs of various instruments since Nitinol tubes are commercially available at a wide range of diameters). Various end effectors such as endoscopic cameras, grippers, curettes and suction and irrigation can be added at the distal end of the robot by means of the open center channel of the innermost tube. The overall system integrates a hardware design optimized for skull base surgery with image guidance software, which provides the surgeon with visualization of tool positions with respect to preoperative images [4]. Using this information, the system can, in principle, be programmed to avoid 'no-fly' zones demarcated on the preoperative images. Additional benefits of the robot are motion scaling, which enables the surgeon to make precise motions, and tremor reduction, which reduces the chance of accidental collision of the tool with critical anatomical structures such as the carotid arteries and optic nerves.

Preliminary trials have been conducted in which experienced surgeons operated the robot under endoscopic visualization to remove a phantom tumor from a model skull. The tumor was constructed of a combination of ballistic test media and water and placed in an anatomical skull model. The tissue was resected by a curette, the standard tool used in endonasal pituitary surgeries, attached at the end of a concentric tube robot. The resected tissue was removed from the curette with suction. In two trials, an average of 73% of the tumor phantom was removed [10]. These results constitute successful simulated surgeries because the goal of surgery is decompression (pituitary adenomas are typically benign and slow growing, so removing 100% of the tumor is not necessary). We also note that in current surgical practice, there are 'definite tumor remnants or at least suspicious findings' in 42% of postoperative MRI scans after transsphenoidal pituitary surgery [11]. Additional cadaver and phantom experiments are now underway in which a one degree-of-freedom wrist has been added to the tip of the robot, allowing the surgeon to rotate the curette as desired. This modification appears likely to improve resection percentages.

Beyond endonasal surgery, the concentric tube robot concept provides advantages in many other kinds of surgery. Examples include decompression and removal of clots in response to intracerebral hemorrhage [12], transoral biopsy and therapy delivery for lung tumors [13], delicate 'beating-heart' cardiac procedures [14], thermal ablation of large or multiple liver tumors through a single liver capsule entry point [15] and fetal surgery [16]. In the case of intracerebral hemorrhage, needle diameter entry paths can replace open brain surgery for clot removal. In lung biopsy, transoral access appears likely to lower the risk of lung collapse in comparison to inserting a needle through the chest wall. In cardiac procedures, miniaturized tools carried by these robots may enable complex surgical repairs on a beating heart. In the liver, multiple overlapping ablation regions can be created without multiple needle insertions. In fetal surgery, defects in growing fetal structures may be corrected before birth so that normal development can follow.

In summary, the concentric tube robot is an emerging technology, which appears poised to revolutionize not only skull base surgery but also other procedures as well. These needle-sized, tentacle-like robot arms have the potential to bring the benefits of surgical robots to many places in the human body where the current da Vinci robot cannot reach. The combination of small size and improved control and dexterity over existing tools will give surgeons the ability to perform minimally invasive surgeries that they could not otherwise perform. It is our hope that this robot will extend the benefits of the endonasal approach to many more patients in the context of pituitary surgery and also enable other new minimally invasive procedures to be developed. Just as the da Vinci has driven improvements in the standard of care for laparoscopic surgeries, we expect concentric tube robots to enable a similar leap forward in transnasal surgery and other surgeries requiring very thin instruments that can enter the body through curved trajectories and provide dexterity at the surgical site.

Financial & competing interests disclosure

R Webster is the inventor on US Patent No. 8152756 which describes concentric tube robots. The authors have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed.

No writing assistance was utilized in the production of this manuscript.

doi: 10.1586/17434440.2013.854702

References

1. Lee D. Robotic prostatectomy: what we have learned and where we are going. *Yonsei Med. J.* 50(2), 177–181 (2009).
2. Nogueira JAF, Stamm A, Vellutini E. Evolution of endoscopic skull base surgery, current concepts, and future perspectives. *Otolaryngol. Clin. North Am.* 43(3), 639–652 (2010).
3. Ezzat S, Asa SL, Couldwell WT *et al.* The prevalence of pituitary adenomas: a systematic review. *Cancer* 101(3), 613–619 (2004).
4. Burgner J, Rucker DC, Gilbert HB *et al.* A telerobotic system for transnasal surgery. *IEEE Transac. Mechatronics* (2013) (In Press).
5. Barker FG. Transsphenoidal surgery for pituitary tumors in the United States, 1996–2000: mortality. *J. Clin. Endocrinol. Metabol.* 88(10), 4709–4719 (2003).
6. Central Brain Tumor Registry of the United States (CBTRUS) (2011).
7. Kohler BA, Ward E, McCarthy BJ *et al.* Annual report to the nation on the status of cancer, 1975–2007, featuring tumors of the brain and other nervous system. *J. Natl Cancer Inst.* 103(9), 714–736 (2011).
8. Rucker DC, Jones BA, Webster RJ III. A geometrically exact model for externally loaded concentrictube continuum robots. *IEEE Transac. Robotics* 26(5), 769–780 (2010).
9. Dupont PE, Lock J, Itkowitz B. Design and control of concentric-tube robots. *IEEE Transac. Robotics* 26(2), 209–225 (2010).
10. Gilbert HB, Swaney PJ, Burgner J, Weaver KD, Russell PT III, Webster RJ III. A feasibility study on the use of concentric tube continuum robots for endonasal skull base tumor removal. Presented at: *Hamlyn Symposium on Medical Robotics*. Royal Geographical Society, London 1–2 July 2012.
11. Fahlbusch R, Ganslandt O, Buchfelder M, Schott W, Nimsky C. Intraoperative magnetic resonance imaging during transsphenoidal surgery. *J. Neurosurg.* 95(3), 381–390 (2001).
12. Burgner J, Swaney PJ, Lathrop RA., Weaver KD, Webster RJ III. Debulking from within: a robotic steerable cannula for intracerebral hemorrhage evacuation. *IEEE Transac. Biomed. Eng.* 60(9), 2567–2575 (2013).
13. Torres LG, Webster RJ III, Alterovitz R. Task-oriented design of concentric tube robots using mechanics-based models. Presented at: *IEEE/RSJ International Conference on Intelligent Robots and Systems*. Vilamoura, Algarve, Portugal 7–12 October (2012).
14. Gosline AH, Vasilyev NV, Veeramani A *et al.* Metal MEMS tools for beating-heart tissue removal. Presented at: *IEEE International Conference on Robotics and Automation*. Vilamoura, Algarve, Portugal 7–12 October (2012).
15. Burdette EC, Rucker DC, Prakash P *et al.* The ACUSITT Ultrasonic ablator: the first steerable needle with an integrated interventional tool". Presented at: *SPIE Medical Imaging*. San Diego, CA, USA 13–18 February 2010.
16. Furusho J, Ono T, Murai R, Fujimoto T, Chiba Y, Horio H. Development of a curved multi-tube (CMT) catheter for percutaneous umbilical blood sampling and control methods of CMT catheters for solid organs. Presented at: *IEEE International Conference on Mechatronics and Automation*. Niagara Fails, Ontario, Canada 29 July-1 August 2005.

doi: 10.1586/17434440.2013.854702