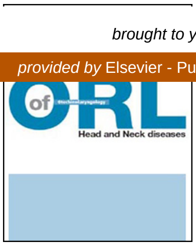
European Annals of Otorhinolaryngology, Head and Neck diseases (2013) **130**, 201—207

ELSEVIER MASSON
Available online at
SciVerse ScienceDirect
www.sciencedirect.com
Elsevier Masson France
EM|consulte
www.em-consulte.com/en



REVIEW

Robotic endoscopic sinus and skull base surgery: Review of the literature and future prospects

V. Trévillot[a,b,*], **R. Garrel**[b], **E. Dombre**[a], **P. Poignet**[a], **R. Sobral**[a], **L. Crampette**[b]

[a] *LIRMM, CNRS, université Montpellier-2, 161, rue Ada, 34392 Montpellier cedex 05, France*
[b] *Service d'ORL, hôpital Gui-de-Chauliac, centre hospitalier universitaire de Montpellier, 80, avenue Augustin-Fliche, 34000 Montpellier, France*

KEYWORDS
Robotics;
Skull base;
Paranasal sinuses;
Surgery

Summary
Objective: There has been a considerable growth in the indications of endonasal surgery that now include malignant tumours of the nasal fossae and anterior and middle cranial fossa. However, new limitations have also been identified, such as bleeding and cerebrospinal fluid leak, as well as the need to use several instruments simultaneously. Can robotics provide solutions to these problems?
Method: Review of the literature based on the three main databases: Medline, Pubmed and Cochrane.
Results: Ten publications were identified. Some authors have developed surgical approaches to the skull base using the da Vinci® robot, while others have designed specific robots.
Conclusion: None of the currently available solutions appears to be completely suitable. The da Vinci® robot is very cumbersome and can only be used in the middle cranial fossa via complex and relatively invasive routes. The other robots are laboratory prototypes. We are currently developing an innovative, compact, ergonomic and safe dedicated endoscope holder.

Introduction

The robots used in head and neck surgery are either commercial robots (exclusively the Intuitive Surgical da Vinci® robot), or laboratory prototypes. Several teams have published promising results with the use of the da Vinci® robot in head and neck surgery [1], but no results have been published for prototype robots. In contrast, the da Vinci® robot is not used in otological surgery, while several prototypes have been tested over recent years in France, particularly by Prof. Sterkers, and in the rest of the world [2—6].

Endonasal surgery was developed in the 1970s by the Austrian surgeons Stammberger and Messerklinger [7] for the treatment of chronic sinusitis refractory to medical treatment. In 1985, Dr David Kennedy (trained by these two surgeons) was the first author to describe Functional Endoscopic Sinus Surgery (FESS). This new technique constituted a revolution in this field, by transforming extensive non-functional surgery into minimally invasive surgery designed to restore functional and physiological ventilation of the sinuses. Improvement in operative techniques,

---

* Corresponding author. Tel.: +33 06 83 87 73 00.
E-mail address: v.trevillot@gmail.com (V. Trévillot).

http://dx.doi.org/10.1016/j.anorl.2012.03.010

reconstruction techniques and equipment subsequently allowed extensions of the operative indications, first to benign tumours and now to malignant tumours invading the skull base. However, these extensive resections are limited by new complications (bleeding and cerebrospinal fluid leak) requiring the use of several tools simultaneously (endoscope, suction, grasping forceps, coagulation). Castelnuovo et al. [8] (otorhinolaryngologist in Varese, Italy) and Nicolaï (Neurosurgeon in Varese, Italy) consequently published several papers describing a technique called ''Four-hand surgery'' allowing extensive skull base resections by a team of two surgeons using several instruments introduced via the two nostrils. This technique demonstrates the possibility of working with more than two instruments in the nose, but it is poorly reproducible, not very ergonomic and requires two experienced senior surgeons.

We believe that robotics can provide the surgeon with an ''additional hand'' and we therefore conducted a review of the literature to see whether other teams are working on this subject, the problems encountered and the solutions provided.

Method

The review of the literature was performed on the Pubmed, Medline and Cochrane databases and robotic and otorhinolaryngology specialist journals using the following key words: ''skull base robotics'', ''sinonasal robotics'', ''functional endoscopic sinonasal surgery and robotics'' and ''ENT [and] robotics'' at Montpellier university hospital and in the Laboratoire d'Informatique, de Robotique et de Micro-électronique de Montpellier (LIRMM) (Montpellier Computers, Robotics and Micro-electronics laboratory). No selection criteria were used and all articles concerning this subject were therefore reviewed. However, as navigation, simulation and augmented reality are not considered to be robotic techniques, articles concerning these aspects were not included in this analysis.

Results

Endonasal surgery and the da Vinci® robot

In 2007, Hanna et al. [9] described a surgical approach to the anterior cranial fossa using the da Vinci® robot on four frozen cadavres via bilateral superior vestibular incisions. Osteotomies of the anterior wall of the maxillary sinuses in canine fossae were then performed. Two bilateral middle meatotomies were performed from the interior of the sinus to the nasal fossa to allow introduction of two instruments. After resection of the posterior part of the septum, the 5 mm diameter 3D camera was introduced via one of the nostrils:

- advantages: this approach provides access to the posterior ethmoid, sphenoid, sella turcica, suprasellar and parasellar regions and the cribriform plate. Skull base reconstruction can be performed with the robot. The two-hand approach, the absence of tremor and the magnified vision facilitate surgery;
- disadvantages: this approach remains extremely invasive and does not provide access to the anterior ethmoid or middle meatus.


16/2/2008 2:41

Figure 1 C-TORS technique: surgical incision posterior to the submaxillary glands.

O'Malley and Weinstein [10], in 2007, described a skull base approach using the da Vinci® robot: cervical transoral robotic surgery (C-TORS) on one cadavre and one dog: incision along the posterior margin of the 2 submaxillary glands and ''blind'' placement of blunt trocars directed superiorly, medially and along the anterior border of the cervical spine. Instruments were then introduced with their extremities in the oropharynx. The 3D camera was introduced transorally:

- advantages: according to the authors, this technique allows resections in the sellar, suprasellar and parasellar regions with good visualization of the anterior skull base (Fig. 1);
- disadvantages: this technique is extremely invasive and requires blind introduction of trocars.

Lee et al. [11], in 2010, described an entirely transoral approach on seven cadavres: the camera and instruments were introduced transorally. Two red rubber catheters were then introduced via the nostrils and brought out through the mouth to retract the soft palate (Fig. 2):


16/2/2008 2:46

Figure 2 Transoral approach.

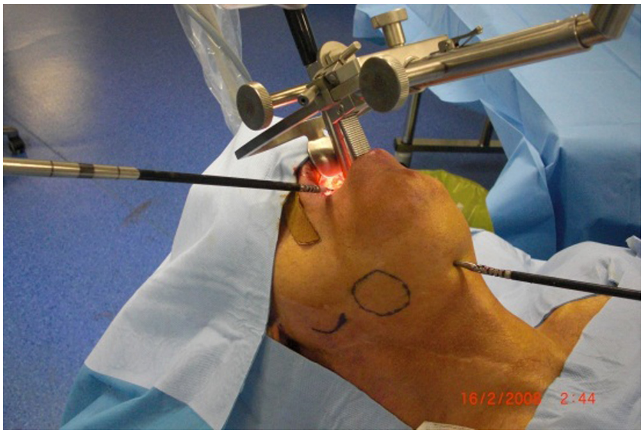


Figure 3 Suprahyoid approach.

- advantages: this is the only minimally invasive approach allowing the use of the da Vinci® robot in middle cranial fossa surgery;
- disadvantages: this technique does not provide access to the middle and anterior parts of the anterior cranial fossa.

McCool et al. [12], in 2010, described a midline suprahyoid approach to the infratemporal fossa using the da Vinci® robot: one of the two instruments was introduced via a midline suprahyoid incision into the vallecula and then into the oropharynx and nasopharynx. The other instrument and the camera were introduced transorally:

- advantages: this approach provides good access to the infratemporal fossa by visualizing and preserving all critical structures (V3 branch of the trigeminal nerve, XI, XII, internal carotid artery and internal jugular vein) (Fig. 3);
- disadvantage: this approach is invasive.

Endonasal surgery and experimental robots

Endonasal surgery requires the surgeon to hold the endoscope with one hand, leaving the surgeon with only one hand to manipulate the various instruments: suction, forceps, stripper. One solution consists of working with an assistant surgeon to perform four-hand surgery [8]. Briner et al. [13] also demonstrated that the operating time was significantly longer (by an average of 21%) with two-hand surgery compared to the four-hand technique.

Several teams of surgical robotic engineers then decided to design an instrument (endoscope or other instrument) holder robot. Table 1 lists the robots dedicated to endonasal surgery.

In 2004, Nimski et al. [14] adapted a robot initially designed for neurosurgery (ventriculostomies) to endoscopic transsphenoidal skull base surgery (Table 1). This was the first endoscope holder to be used in endonasal surgery:

- advantages: it allows the use of a standard endoscope and ensures very precise movements;
- disadvantages: this robot is much too cumbersome to be used routinely in endonasal surgery. The maximum forces that can be applied, much too high for endonasal surgery (250 Newton), increase the risk of complications.

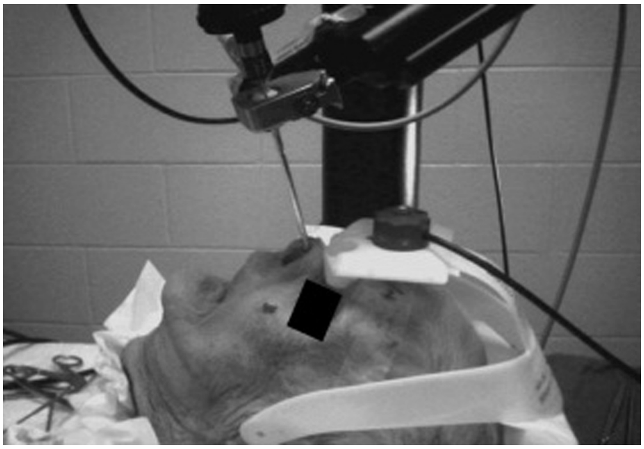

[redacted]

Figure 4 AESOP robot and its endonasal application.

Figure 5 Neuroptik T 30*.

In 2005, Nathan's team then transformed the AESOP endoscope positioner (which is no longer marketed) initially designed for laparoscopy, by changing the endoscope grip system [15] and tested it on 10 cadavres (Fig. 4) (Table 1):

- advantages: this robot provides good access to the sphenoid, allowing a transseptal approach to the pituitary. It can memorize certain positions so that the endoscope can be automatically returned to these positions and has a satisfactory level of precision;
- disadvantages: the large working space occupied by the robot and its high cost prevents its use in routine surgery.

In 2005, Wurm et al. [16] developed an entirely automatic robot dedicated to pituitary surgery: the ''A 73'' (Table 1):

- advantages: it is a small calibre, multifunction, single instrument and its precision are the major advantages of this robot (Fig. 5). Tasks are automated (definition of the trajectory on preoperative imaging). A remote-control unit has also been added to allow the surgeon to correct a trajectory or complete an insufficient resection;

Table 1 Summary robot table devoted to the endonasal surgery.

	Nimski	Nathan	Wurm	Strauss	Xia	Eichhorn
Robot name	Evolution 1	AESOP	A-73	None	None	Tx40
Year of development	2004	2005	2005	2007	2008	2011
Mechanical structure	Parallel M-800, Physik instrument PI, Waldbronn, Germany	7 degrees of freedom arm	Arm RV1A (MitsubishiElectric) 6 degrees of freedom	Arm PA10-6c, (Mitsubishi) 6 degrees of freedom	Neuromate Robot (Renishaw Mayfiels, U)	Arm
Type of instrument	Endoscope	Endoscope	Neuroptik T30* (endoscope, drill and operating channels)	Endoscope	Drill or endoscope	Endoscope
Instrument diameter	4 mm	3 mm	5 mm	4 mm	Variable	4 mm
Set-up time	30 minutes	Several minutes	Long	Less than 20 minutes	Long	Unknown
Work space occupied	Major	Major	Major	Major	Major	Major
Precision of repetition	20 μm	50 μm	20 μm	850 μm	1 mm	Unknown
Type of control interface	Joystick	Voice-controlled	Joystick	Joystick	Co-manipulation	Joystick and automatic tracking
Safety	Satisfactory	Satisfactory	Satisfactory	Satisfactory	Satisfactory	Satisfactory
Specific characteristics	Maximum workspace: $160 \times 60 \times 100$ mm Three different speeds: 0.5, 1, 2 mm/s Maximum force: 250 N	Integrated navigation system	Length 226 mm, Visual field: 105° Four channels: one for the scope, one for the drill and two for suction/irrigation Speed: 2100 mm/s Integrated navigation	Integrated navigation system	Integrated navigation system It defines the work space into three zones A forbidden zone limits A boundary zone A safe zone	Automatic washing of the endoscope lens

Figure 6 Cadavre sphenoidotomy using the Neuroptik T 30*.

- disadvantages: it cannot be used for any operations other than sphenoidotomy (Fig. 6) and its large dimensions limit its use.

In 2007, Strauss et al. [17] developed a prototype endoscope holder dedicated to endonasal surgery and tested it during 49 total ethmoidectomy procedures (Table 1):

- advantages: it is the only robot that can be used to perform total ethmoidectomy and that provides access to the anterior skull base;
- disadvantages: its large dimensions.

In 2008, Xia et al. [18] created an effector robot able to open the sphenoid, cooperatively with the surgeon, to provide access to the skull base while avoiding dangerous zones (Table 1). This robot was tested on five cadavres:

- advantages: co-manipulation system. With this type of robot, the operator and the robot share control of the instruments (endoscope, forceps, drill). Three types of zones are defined on preoperative imaging: forbidden, boundary and safe. After entering these data into the robot, the robot induces an increasingly strong resistance close to forbidden structures in order to prevent access to these structures;
- disadvantages: inaccuracy of about one millimetre due to an initial placement error, calibration error, and robot kinematic error.

In 2011, Eichhorn and Bootz [19] published an article describing robot-assisted endoscopy dedicated to endonasal surgery (Table 1):

- advantages: the robot was designed to automatically maintain the extremity of the instrument in the centre of the visual field (visual servoing) and is equipped with an automatic lens cleaning system. The dimensions of this robot are perfectly adapted to endonasal surgery;
- disadvantages: the robot dimensions limit the surgeon's range of movement.

The collective work [20] written by the main French authors in this field provides a very comprehensive overview of surgical robotics with, in particular, presentation of the main applications and the methodological and technological tools used to design, control and interact with robotic systems. The advantages, limitations and risks related to these systems are discussed.

Discussion

No robot is used routinely at the present time for endoscopic sinus and skull base surgery. Many teams (essentially North American) are studying new approaches providing access to the skull base with the da Vinci® robot, but none of these solutions can be used in living subjects due to their invasive nature and the lack of improvement of the medical service provided. Other preclinical research teams, mainly German and North American, i.e. working on the development of robots, but none of the proposed robots are completely satisfactory and cannot be used routinely. For a robot to be accepted in the operating room, it must first of all be useful: automation of the task must save time for the surgeon and/or enhance the surgeon's capacities. It must then be reliable, which implies a good knowledge of the environment in which it is used (its work space) and the characteristics of the interactions between the instruments that it holds and the tissues. Probably the most eagerly awaited function is force feedback, which is not yet available on any of the commercial robots. Ergonomy, i.e. the ease with which the surgeon can perform the procedure and the rapidity of the learning curve, are also essential aspects. Finally the robot dimensions must be as small as possible to avoid restricting the surgeon's range of movement and to facilitate installation of the robot in the operating room.

Two of the most common obstacles to the use of robotics in the operating room are: the poor knowledge of robotic engineers concerning operative techniques, which is accentuated by the surgeons' difficulty to express their needs; the limitations of current robots, especially in terms of dimensions, integration of active perception (vision, force) in their controls and the man/machine interface. To overcome the first obstacle, surgeons must collaborate with surgical robot laboratories to describe their difficulties and their needs, to provide their anatomical knowledge and sometimes to participate in basic research such as the study of the physical properties of tissues with which the robot is in contact. To overcome the second obstacle, the robotic engineers must design innovative robotic mechanical architectures (possibly by using new materials) adapted to dedicated operative procedures, by miniaturizing the components (especially the motor and force transducers) and by imagining interfaces adapted to the safety and ergonomy requirements of the surgical environment.

We believe that robot-assisted endoscopic sinus and anterior skull base surgery is a useful technique, as it is both time-saving [21] and enhances the surgeon's capacities. Over the last year, we have therefore been working on the development of a dedicated robot, for which we have established strict specifications in terms of dimensions, ergonomy and safety. We are currently collecting the necessary data

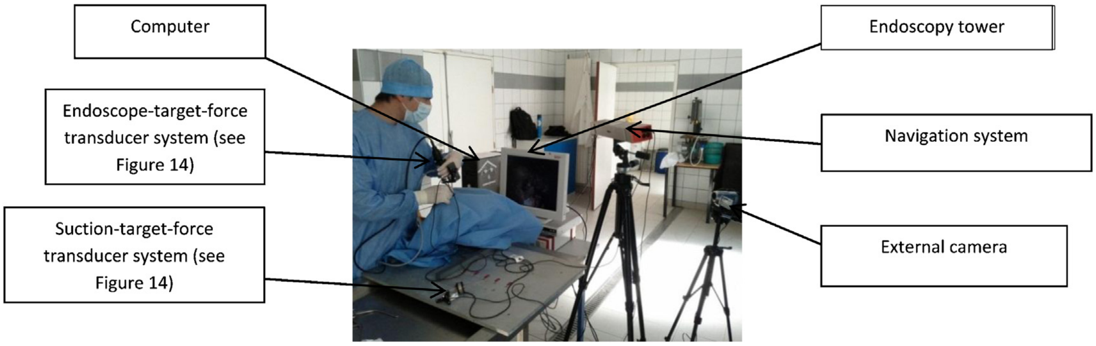


Figure 7 Material and installation for the analysis of the operative procedure.

to define the robot dimensions. We have developed an experimental protocol and we have performed 13 total ethmoidectomies with sacrifice of the internal carotid artery, optic nerve, lamina papyracea and skull base. The material used consists of force transducers, a navigation system, and frozen cadavre heads in which ''preoperative'' CT scanning was performed (Fig. 7). The objectives are as follows:

- measurement of the physical properties of the environment: measurement of the various resistance capacities of the structures of the nasal fossae or adjacent structures (in order to define the forces beyond which the robot could induce a complication);
- characterization of the procedure as it is performed at the present time:
  - measurement of the angular range of motion,
  - measurement of the angular velocities, measurement of the forces and couple exerted on the endoscope,
  - measurement of the depth of penetration of the endoscope in the nostril;
- determination of a fixed point in order to guide the choice of kinematic structure.

Conclusion

We believe that robotics can help to extend the indications of endoscopic sinus and middle and anterior skull base surgery. However, the complicated access prevents the use of the da Vinci® robot in this application in living subjects, and the main problems with the prototypes described in the literature concern their large dimensions in the work space. We are currently working on miniaturization of a prototype and development of a more intuitive interface. Our approach is based on analysis of endonasal surgical procedures and evaluation of the various robot designs able to reproduce these procedures, while complying with the constraints of size, ergonomy and safety.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

References

[1] Arora A, Cunningham A, Chawdhary G, et al. Clinical applications of telerobotic ENT-head and neck surgery. Int J Surg 2011;9:277—84 [cité 2011 juin 15].

[2] Nguyen Y, Miroir M, Vellin JF, et al. Minimally invasive computer-assisted approach for cochlear implantation: a human temporal bone study [Internet]. Surg Innov 2011 [cité 2011 juin 14. Available from: http://www.ncbi.nlm.nih.gov/pubmed/21502203].

[3] Majdani O, Schurzig D, Hussong A, et al. Force measurement of insertion of cochlear implant electrode arrays in vitro: comparison of surgeon to automated insertion tool. Acta Otolaryngol 2010;130:31—6 [cité 2011 juin 14].

[4] Schurzig D, Webster RJ, 3rd, et al. Force of cochlear implant electrode insertion performed by a robotic insertion tool: comparison of traditional versus Advance Off-Stylet techniques. Otol Neurotol 2010;31:1207—10 [cité 2011 juin 14].

[5] Hussong A, Rau T, Eilers H, et al. Conception and design of an automated insertion tool for cochlear implants. Conf Proc IEEE Eng Med Biol Soc 2008;2008:5593—6 [cité 2011 juin 14].

[6] Coulson CJ, Taylor RP, Reid AP, et al. An autonomous surgical robot for drilling a cochleostomy: preliminary porcine trial. Clin Otolaryngol 2008;33:343—7 [cité 2011 juin 14].

[7] Frèche CH, Fontanel JP, Peynegre R. La polypose naso sinusienne. Rapport de la société française d'ORL et de chirurgie cervico-faciale. Paris: L'européenne d'édition; 2000. p. 311.

[8] Castelnuovo P, Dallan I, Battaglia P, et al. Endoscopic endonasal skull base surgery: past, present and future. Eur Arch Otorhinolaryngol 2010;267:649—63.

[9] Hanna EY, Holsinger C, DeMonte F, et al. Robotic endoscopic surgery of the skull base: a novel surgical approach. Arch Otolaryngol Head Neck Surg 2007;133:1209—14.

[10] O'Malley BW, Weinstein GS. Robotic anterior and midline skull base surgery: preclinical investigations. Int J Radiat Oncol Biol Phys 2007;69:S125—8.

[11] Lee JYK, O'Malley BW, Newman JG, et al. Transoral robotic surgery of the skull base: a cadaver and feasibility study. ORL J Otorhinolaryngol Relat Spec 2010;72:181—7.

[12] McCool RR, Warren FM, Wiggins RH, et al. Robotic surgery of the infratemporal fossa utilizing novel suprahyoid port. Laryngoscope 2010;120:1738—43.

[13] Briner HR, Simmen D, Jones N. Endoscopic sinus surgery: advantages of the bimanual technique. Am J Rhinol 2005;19:269—73 [cité 2011 avr 20].

[14] Nimsky C, Rachinger J, Iro H, et al. Adaptation of a hexapod-based robotic system for extended endoscope-assisted

transsphenoidal skull base surgery. Minim Invasive Neurosurg 2004;47:41—6.

[15] Nathan C-AO, Chakradeo V, Malhotra K, et al. The voice-controlled robotic assist scope holder AESOP for the endoscopic approach to the sella. Skull Base 2006;16:123—31.

[16] Wurm J, Bumm K, Steinhart H, et al. Development of an active robot system for multi-modal paranasal sinus surgery. HNO 2005;53:446—54.

[17] Strauss G, Hofer M, Kehrt S, et al. Manipulator assisted endoscope guidance in functional endoscopic sinus surgery: proof of concept. HNO 2007;55:177—84.

[18] Xia T, Baird C, Jallo G, et al. An integrated system for planning, navigation and robotic assistance for skull base surgery. Int J Med Robot 2008;4:321—30.

[19] Eichhorn KWG, Bootz F. Clinical requirements and possible applications of robot assisted endoscopy in skull base and sinus surgery. Acta Neurochir Suppl 2011;109:237—40 [cité 2011 janv 19].

[20] Troccaz J, Dombre E. Medical robotics. ISTE Ltd and John Wiley & Sons Inc; 2012.

[21] Briner HR, Simmen D, Jones N. Endoscopic sinus surgery: advantages of the bimanual technique. Am J Rhinol 2005;19:269—73 [cité 2011 juill 30].