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9 Robotic surgery in otolaryngology

9.1 Introduction

This chapter is about surgical robots and their applications in otolaryngology. Surgical robots are different from the robots widely used in the industrial applications. Industrial robots are programmed for performing some technological manipulations and production operations, which after programming are being done automatically and repetitively for many fabricated products. Such scheme of robot use is illustrated in Fig. 9.1.

However, such scheme was not proper for the use of the robots in surgery. In industrial applications, the task is easier. Every fabricated element is identical; therefore, the sequence of operations performed by robot for every fabricated element can be the same. The sequence of actions performed by robot can be programmed once and executed many times. In surgery, the situation is different. Every human body is different, and every lesion is different. It means that for every operation, robot should be programmed separately. It is very inconvenient. Therefore, during the surgical use, robot is controlled by the surgeon. The structure of such control system is presented in Fig. 9.2. The work of the surgeon is easier and more comfortable than during traditional surgery because instead of standing at the operating table, they can sit comfortably by a special control console. Moreover, the computer that controls the movements of surgical instruments inserted into the patient's body through the robot's arms can perform very precise movements related to the operation. The ratio between the surgeon's hand movement on the manipulator in the robot control console and the movement of the surgical tool controlled inside the patient's body can be 1:10, which allows obtaining unattainable precision in the cutting and sewing of the operated tissues. The computer can also completely eliminate these surgeon movements, which can have a detrimental effect on the outcome of the operation, for example, hand tremor or accidental excessive movement that may lead to damage to adjacent organs. The surgeon can see the surgical field and every movement of surgical instruments because the robot has TV cameras and special illuminators on one of the arms inserted into the patient body, and the console is equipped with a vision system presenting images from the inside of the patient's body stereoscopically and (if necessary) enlarged (up to 30 times). One of the illuminators is a laser-emitting monochromatic light that allows you to notice the course of blood vessels inside the operated organ.

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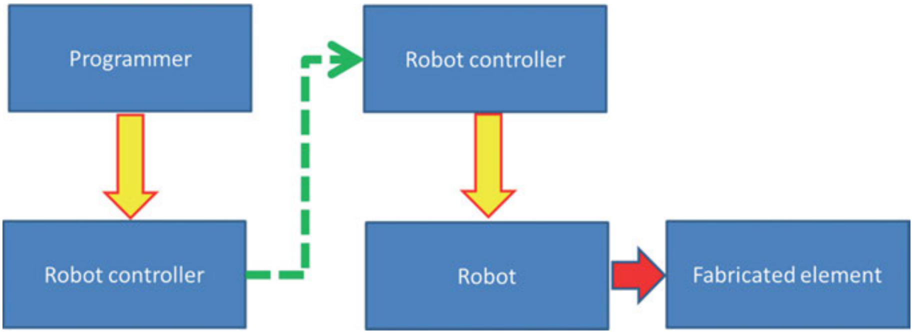

Fig. 9.1: Scheme of typical industrial robot use. Source: own elaboration.

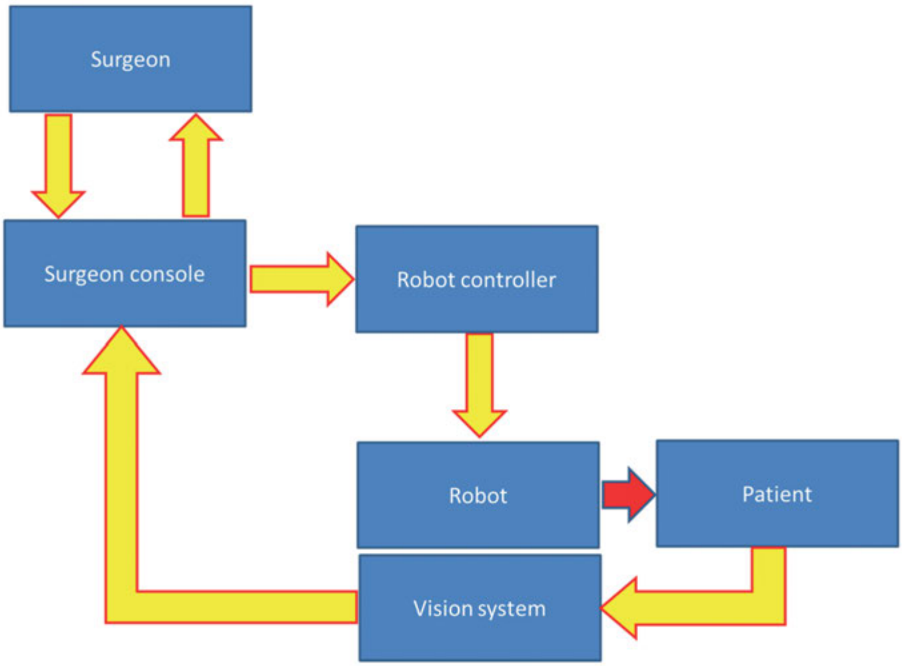

Fig. 9.2: Scheme of typical surgical robot. Source: own elaboration.

Finally, it can be concluded that the surgical robot does not present such a level of automation of the activities performed that is achievable using industrial robots. It is actually an intelligent manipulator, not a robot in the full sense of the word. However, the use of this tool is very purposeful because it guarantees better results from the patient's point of view (the surgical procedure is less invasive and can be more precisely carried out) and for the surgeon (more comfortable work).

9.2 General remarks

The first use of robot during a surgical operation probably occurred on March 12, 1984, at the UBC Hospital in Vancouver. The robot (named *Arthrobot*) was used in an orthopedic surgical procedure [1]. After this success, over 60 arthroscopic surgical procedures were performed in the same hospital in the following year. In 1985, an industrial robot, the Unimation Puma 200, was used to navigate a needle for a brain biopsy under CT guidance during a neurological procedure [2]. A robotic system for commercial use was first developed in 1995. The history of robotic surgery, the description of the structure and functions of surgical robots, and the detailed descriptions of the methodology of robotic surgery in urological applications were presented in book [3]. The removal of a cancerous prostate has been a popular robot-assisted treatment, but there are numerous other applications. In general, robot-assisted surgery can be used for heart surgery, thoracic, gastrointestinal, gynecological, orthopedic surgery, and many others. Examples of the use of robotic surgery systems in heart surgery are described by Mayer et al. [4]. Robots are used for three heart surgery types: atrial septal defect repair, mitral valve repair, and coronary artery bypass. The robotic heart surgery is part of more general area of robotic thoracic surgery, described by Melfi et al. [5].

Also, a very broad area of robotic surgery applications is connected with gastrointestinal surgery [6] as well the robotic surgery in gynecology [7]. However, these interventions will not be considered in this chapter of the book.

The first surgical robots were invented also for telesurgery, with an intention to operate astronauts in the orbit or soldiers wounded on remote battlefields [8]. In fact, remote robotic surgery has actually never been performed in space for astronauts. The number of robot teleoperations in military applications is not known because of military secrecy. Therefore, the first (and famous) official teleoperation using surgical robot was conducted on September 7, 2001. This operation was conducted through the Atlantic Ocean and was named Operation Lindbergh after Charles Lindbergh's pioneering transatlantic flight. The surgeon (Jacques Marescaux) was in New York and the patient was in Strasbourg. Computer Motion's *Zeus* robot was used, and the performed teleoperation was a cholecystectomy. The scheme of this pioneering operation is presented in Fig. 9.3.

9.3 Robotic surgery in head and neck—advantages and disadvantages

The main problem, considered in this chapter, is the application of surgical robots in head and neck surgery. The general overview of this problem was presented by Garg et al. [9]. The most widely used robotic system in otolaryngology is the da Vinci Surgical Robot (Intuitive Surgical Inc., Sunnyvale, CA, USA), and the majority of the surgical procedures are performed via the oral cavity (transoral robotic surgery [TORS]).

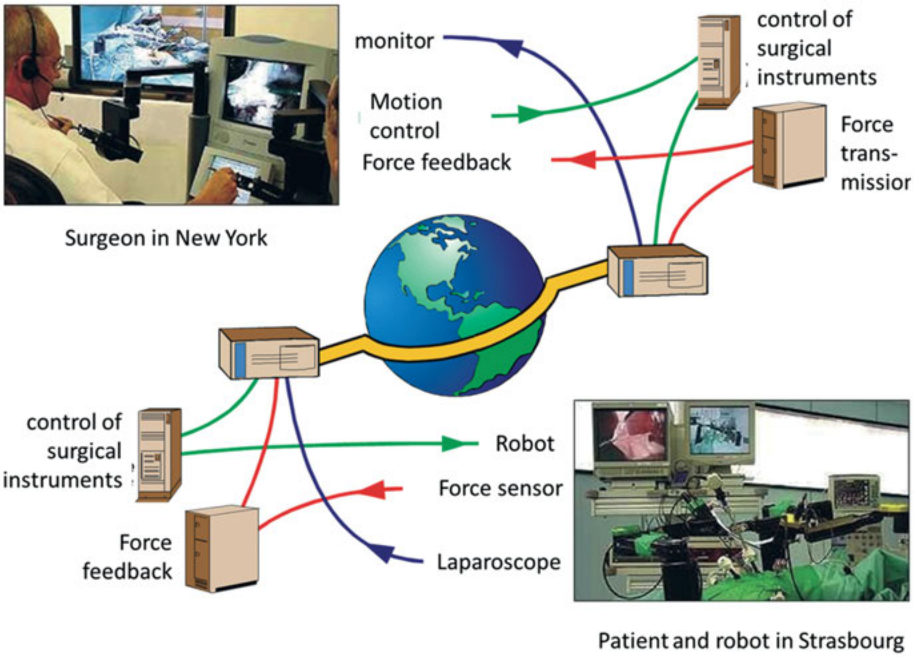

Fig. 9.3: Remote surgery with the robot use. Source: own elaboration.

The system has been approved by the Food and Drug Administration for head and neck surgery in 2009.

The da Vinci system includes three components [3, 10]:

(1) a surgical cart with a robotic manipulator and three arms (one for a camera and two for other instruments; the instruments have several degrees of freedom to mimic the movements of the human wrist) (Fig. 9.4)
(2) a vision cart that provides visualization (two cameras in one endoscope)
(3) a surgeon's console with a three-dimensional stereoscopic viewer (Fig. 9.5)

Robot-assisted surgery can be particularly useful in the head and neck region for several reasons [11]:

(1) Robotic surgery allows for minimally invasive procedures. In open approaches, the incision needs to be wide enough to ensure direct visualization of the surgical field. Endoscopic approaches (including those applied for robotic surgery) require only minimal "keyhole" incisions to introduce the camera and the surgical devices. For intranasal and intraoral procedures, the endoscopes are introduced through natural openings and may not require any additional tissue damage to provide adequate visualization. The reduction of the surgical incision size is extremely important on the head and neck, where the scars are usually

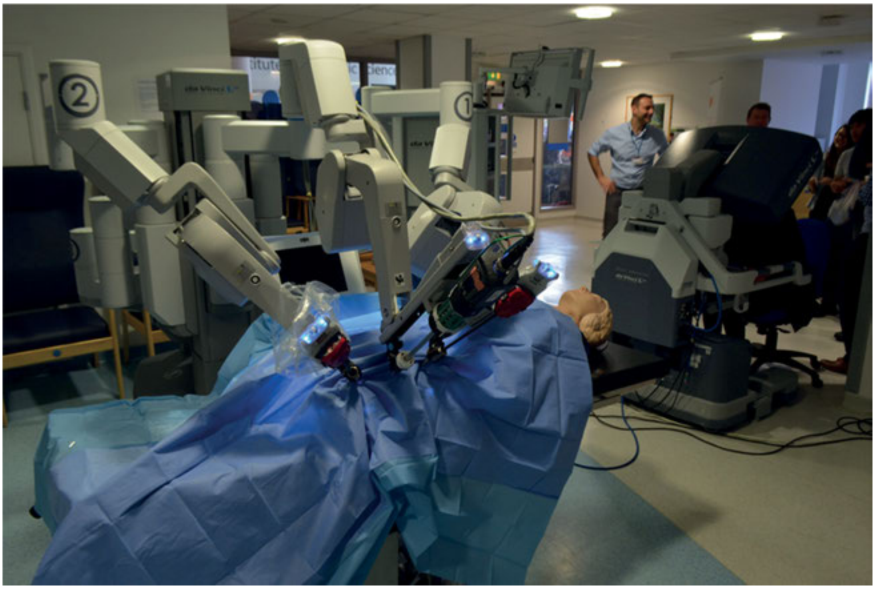

Fig. 9.4: da Vinci surgical cart. Source: https://upload.wikimedia.org/wikipedia/commons/2/23/Cmglee_Cambridge_Science_Festival_2015_da_Vinci.jpg. This file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license.

Fig. 9.5: Surgeon console in the da Vinci robot system https://upload.wikimedia.org/wikipedia/commons/6/68/Cmglee_Cambridge_Science_Festival_2015_da_Vinci_console.jpg. This file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license.

readily visible. Open surgical procedures, especially on the face, frequently cause scarring that may be hardly acceptable for the patient.

(2) The anatomy of the head and neck is very complex, and many vital structures are located very close to one another. In classic approaches (without angled endoscopes and instruments), it is sometimes difficult or even impossible to avoid damage to the nerves or blood vessels or other structures that "stand in the way." It is not uncommon that gaining access to the pathology can cause more damage than the procedure itself [12]. This problem can be (literally) circumvented if robotic surgery is applied. One of the most important advantages of TORS is the fact that even extensive procedures can be completed without the necessity to perform mandibulotomy (incision of the mandible) that is often necessary in open procedures. Minimally invasive procedures ensure better functional results and improved quality of life.

(3) The head and neck surgeon frequently has to operate in confined spaces, and microsurgery constitutes an important part of everyday otolaryngological practice. Three-dimensional visualization with sufficient magnification provided by the robotic system helps the surgeon to precisely maneuver the instruments in microscale. Moreover, the system eliminates the tremor of the surgeon's hand. As the instruments are not directly handheld, large movements of the surgeon's hand can be translated into much smaller and more precise movements in the surgical field ("motion scaling") [12].

(4) Surgical approaches to the head and neck are frequently uncomfortable for the surgeon. For example, during endonasal or transoral procedures, the surgeon often needs to bend over the lying patient and remain in a forced position to introduce the instruments and endoscopes at the required angles. The hands holding the endoscope and other instruments are not supported. Therefore, prolonged operations may cause fatigue and reduce the quality of the surgeon's performance. In robotic surgery, the remote workstation allows for a comfortable and ergonomic position (seated position with supported forearms and head).

(5) Currently, endoscopic surgery is the gold standard for many procedures in otolaryngology. Endoscopic surgery has several drawbacks compared with robotic surgery. In endoscopic procedures, one hand has to hold the endoscope, which leaves only one hand free to manipulate the tissues. Besides, the endoscopic visualization lacks the third dimension that is frequently crucial for adequate assessment of the surgical field. The surgical robots provide both bimanual manipulation and three-dimensional visualization.

(6) Many surgical procedures in the head and neck are optimally performed with surgical lasers. The robotic systems allow for better maneuverability of the laser tip and improve the visualization of the area of resection. Traditionally, the laser has to be used in the line of sight. The robotic arms allow for working at different angles or even "around corners" [13].

However, the application of the da Vinci system has also several disadvantages:
(1) One of the most important factors limiting the access to surgical robots in many countries is the high price of their installation and maintenance. Therefore, the cost-effectiveness of these devices is frequently questioned. Besides, the equipment needs a lot of space in the operating room—a requirement that may not be fulfilled in many hospitals.
(2) Robotic surgery requires special training of the surgeon and assistant personnel. Some surgeons are unwilling to learn a new skill, which requires time and effort. However, the robotic system allows the trainee to be supervised by an experienced colleague at another console or to use a virtual training environment. The learning curve for surgeons already trained in transoral surgery was shown to be short [14].
(3) The setup of the system and the exposure of the surgical field are time consuming and prolong the time of operation, especially if the personnel is still learning how to operate the system [15].
(4) The surgeon has to rely only on the visual feedback without tactic or haptic sensation. After classic training, the surgeon is accustomed to use the sense of touch to examine the tissues or adjust the force applied with the instruments. To operate a robotic system, one needs to change these habits.
(5) The access to the surgical field provided by the robotic system can turn out to be suboptimal in certain patients. Patients with mandibular deformities or trismus may require conversion from an transoral approach to open procedures [16].
(6) The robot is too bulky to be used for some endonasal or otologic procedures [17].

Some of the limitations of the da Vinci robot were addressed in the next robotic system (FLEX Robotic System) designed and manufactured by Medrobotics Inc. (Raynham, MA). It provides high flexibility and maneuverability, and its smaller size makes it easier to fit in most operative rooms. The access of both the camera and the instruments to the surgical site is nonlinear. The surgeon can easily maneuver around anatomical structures, which makes the system very well suited for transoral procedures. The FLEX system can also provide some haptic feedback [18].

9.4 Applications of the da Vinci system for head and neck surgery

The da Vinci system was first applied in the head and neck region by Haus in animal models in 2003 [19]. Its first application in a human patient was a transoral excision of a vallecular cyst performed by McLeod and Melder in 2005 [20]. This pioneer operation was also preceded by studies in porcine and cadaveric models because the da Vinci system was originally designed for much wider surgical fields (abdomen and thorax) and adjusting its setup for airway surgery proved to be challenging [21].

In the same year, Hockstein, Nolan, O'Malley and Woo tested the de da Vinci robot on an airway mannequin to define the optimal method of exposure for microlaryngeal surgery. Traditionally, endolaryngeal procedures are performed via a laryngoscope. Its narrow closed tube does not provide enough space to introduce the large robotic arms and ensure an adequate range of their movements. The authors concluded that the best access was provided by a mouth gag with cheek retractors, a tongue blade and a 30-degree endoscope [21]. Later, the same authors tested the setup described above on a cadaver and proved that the exposure was sufficient to perform several endolaryngeal and pharyngeal surgical procedures. They also observed that the wristed instruments (with tips that can bend at required angles) allowed for manipulations that would be much more difficult or even impossible with traditional rigid instruments introduced via a laryngoscope. This feature of the da Vinci robot was found very promising because it could facilitate endoscopic management of lesions that would otherwise require open procedures [22]. Further experiments were conducted by Weinstein, O'Malley, and Hockstein in canine models [23, 24].

9.5 Transoral robotic operations

The most common use of medical robots in head and neck surgery is connected with TORS. In 2006, the preclinical studies were followed by transoral robotic excisions of T1-T2 tongue base malignant tumors in three human patients. It was possible to perform complete *en bloc* resections, whereas the transoral laser surgery usually requires piecemeal or cutting through tumor resection. There were no complications and adverse events. The authors claim that robotic excision was less technically challenging than endoscopic laser procedures. They also observed that TORS offered better options for hemostasis than endoscopic surgery [25].

In 2007, the robotic technology for TORS was successfully coupled with CO_2 laser technology [26].

In subsequent years, the scope of robotic surgery expanded even further. TORS was used for supraglottic partial laryngectomy [27], radical tonsillectomy for previously untreated invasive squamous cell carcinoma of the tonsillar region [28], and oropharyngeal carcinoma, including advanced T4 tumors [29, 30] in much larger groups of patients. Disease control, survival, and safety were similar to standard treatments, and the number of patients that required a gastrostomy after oropharyngeal cancer excision was even lower than for standard nonsurgical therapies.

TORS was shown to have the benefit of shorter hospital stay and fewer postoperative complications when compared with open approaches [31]. A recent analysis of over 2,000 TORS patients compared with over 6,000 nonrobotic surgery patients operated for early stage oropharyngeal cancer in the United States showed that the advantages of robotic surgery were lower likelihood of postsurgical positive margins and subsequent need for adjuvant chemoradiotherapy [32].

More and more challenging transoral robotic procedures are still being developed. Recently, even a total transoral laryngectomy was shown to be feasible; however, it seems to be reasonable primarily in these rare cases when concurrent neck dissection is not necessary [33–36].

9.6 The FLEX system

The application of the FLEX robotic system for transoral surgery was first tested on human cadavers in 2012 [37]. The endolarynx was easily visualized without laryngeal suspension. Subsequently, the robot's efficacy was shown in several endolaryngeal, laryngopharyngeal, and oropharyngeal procedures [38]. In 2014, FLEX received the CE approval and was used for the first surgeries in human patients [39]. The robot was used for transoral surgery for oropharyngeal tumors [40]. The use of the considered robot for first 40 operations was described by Mattheis et al. [41]. This robot was also used in the United States [42]. It was evaluated as easy to setup, precise, and safe.

9.7 Conclusion

The examples of successful applications of two different types (da Vinci and FLEX) of surgical robots for head and neck surgery show that robotic surgery can be used, and should be used, in otolaryngology. Currently, the limit is the very high price of a surgical robot, which means that only very rich hospitals can afford this type of technical support for doctors. However, one can hope that the numerous advantages of surgery using robots (described in the Introduction) will lead to a wider use of this method of performing surgical operations, and also in the field of laryngology.

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