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Robotic systems in cardiovascular surgery

Emprego de sistemas robóticos na cirurgia cardiovascular*

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" Our future in surgery lies not in blood and guts, but in bits and bytes!"
Colonel Richard Satava

Abstract

The development of robotic systems for surgery started in the 1980s, motivated by the US army's requirement of surgical procedures in combat areas with the surgeon in a distant place (telepresence). But the first human application of robotic surgery occurred in a robotic surgery, years later.

Cardiac surgeons were attracted by the robotic techniques due to the potential reduction in the invasive character of the procedures. This results in reduced trauma, fast recovery and low cost of surgery. Robotic systems were developed, allowing totally thoracoscopic cardiac surgery for myocardial revascularization and multi-site pacemaker implant in selected cases. Support systems for videothoracoscopic also exist and may give support to internal thoracic artery harvesting, mitral valve reconstruction correction of congenital heart defects. We have used the AESOP® system, with HERMES® voice control, to harvest the internal thoracic arteries, trans-thoracic implantation of left ventricular electrodes and to correct congenital heart defects.

In spite of scientific enthusiasm relating to robotic surgery, there is no clear evidence of superiority of this technique if compared to conventional procedures in terms of results. The same is true with the cost of the procedures as even if a single robotic surgery is less expensive, the initial investment for a complete robotic system (console, video control, instruments) can only be compensated with many procedures. But there is no doubt that robotic surgery will have a place in the future of surgery, providing telepresence of the surgeon, allowing teaching and training and performing less invasive surgical procedures.

Descriptors: **Robotics. Cardiac surgical procedures, methods. Surgical procedures, minimally invasive.**

Resumo

O desenvolvimento de sistemas robóticos para cirurgia teve início na década de 80, por solicitação do exército norte-americano, que antevia a possibilidade de realizar operações em teatros de guerra, distantes do local onde estava o cirurgião. Entretanto, o primeiro uso em humanos só ocorreu anos mais tarde, numa ressecção transuretral de hiperplasia benigna de próstata.

Cirurgiões cardíacos foram logo atraídos pela técnica robótica devido a possível aplicação com reduzido caráter invasivo; esperava-se menor trauma cirúrgico e redução da dor, morbidade, tempo de internação e custo do procedimento. Atualmente, de forma restrita e em casos selecionados, robôs

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são usados para revascularização do miocárdio e implante de marcapasso em cirurgias cardíacas totalmente endoscópicas; podendo também constituir apoio visual na retirada de artéria torácica interna, reconstrução valvar mitral e correção de defeitos congênitos. Utilizando o robô auxiliar AESOP® para controle do videotoracoscópio, com controle vocal por meio do sistema HERMES®, temos realizado dissecção da artéria torácica interna, implante de eletrodo ventricular esquerdo e abordagem de defeitos congênitos na cirurgia de correção.

Apesar do entusiasmo científico inicial com a cirurgia robótica, ainda não existe evidência clara de superioridade desta técnica em relação à operação convencional, em termos de resultado. Isto se aplica também ao custo, pois o investimento inicial na aquisição de sistema cirúrgico completo (console, controle de vídeo, instrumental) provavelmente é compensado após muitos procedimentos e longo intervalo. Mas é certo que a cirurgia robótica terá um lugar no futuro, possibilitando aprendizagem, telepresença e realização de procedimentos pouco invasivos, embora complexos.

Descritores: **Robótica. Procedimentos cirúrgicos cardíacos, métodos. Procedimentos cirúrgicos minimamente invasivos.**

INTRODUCTION

A robot is defined as "a reprogrammable multifunctional manipulator made to move materials, tools or specialist instruments by means of programmed movements to perform varying tasks", according to the Robot Institute of America.

The initial concept of robotics in surgery involved the idea of performing an operation at a distance to the surgeon. This possibility attracted the North-American Military, who began to develop robots aiming at performing surgeries in combat zones by remote control [1]. Also for aerospace medicine, this concept seemed applicable.

Following the development of the initial prototypes, the first utilization of robots in surgery occurred with a transurethral resection for benign prostatic hyperplasia [2]. But the development of initial projects was directed to the area of neurosurgery as early as the 1980s when an industrial robot was used to hold the instruments in a stereostatic biopsy [3].

During the same period, in the area of general surgery, videolaparoscopy progressed, enabling several abdominal surgeries to be performed with diminutive incisions, contributing to a reduction in the cost of the procedure and a faster recovery of the patient [4].

According to this trend, the motivation to use robotic systems in surgery became the invasiveness of the procedure, a result of less surgical injury and a reduction in the pain and morbidity related to the surgery, from the period of hospitalization and the cost of the procedure [5]. However, the initial motivation, telepresence of the surgeon, was not forgotten in the more modern and complex systems.

The aim of this work is to present a review of current aspects of robotic surgery, to show the experience of the authors and to forecast the evolution of correlated techniques.

Surgical robotic systems

The surgical robotic system is defined as "a computer controlled manipulator with artificial sensors that can be reprogrammed to move and position surgical instruments aiming at performing surgical tasks" [3].

Surgically useful robots can be classified in several forms [2,6]. The most practical of these is to divide them in two categories: passive and active.

A 'passive' robot would be used to correctly position a fixed instrument and then be turned off, with the surgeon inserting the other instruments thereafter. There are at least three robots in this category available today: AESOP, Fips endoarm and Endoassist [4,7-10]. They are particularly useful in surgeries that depend more on the production of imaging, such as laparoscopic procedures, as the image generated by them is more stable than those generated by human assistants, because of the firm hold of the endoscope by the robot [11].

An active robot, on the other hand, is capable of moving the instruments utilized in the surgery, accurately transmitting the movement of the hands, filtering and eliminating the natural shaking and increasing surgical precision. [12]. The surgeon manipulates an electronic hand that captures his movements, controlling the robot, in a concept called master-slave [12,13]. This is also referred to as telemanipulating, as it permits the remote control of the instrument by the surgeon. The ZEUS (Computer motion, Goleta, California, USA) [14] and da Vinci (Intuitive Surgical, Sunnyvale, California, USA) systems are examples of this type of robot, with the da Vinci model probably more utilized in 'total' robotic surgeries. SUNG & GILL [15] have already performed a comparative study of these two systems in an experimental laparoscopic porcine model. They demonstrated that both were effective, but the da Vinci presented a shorter learning curve, a shorter time to perform the procedures and a more intuitive control.

The current operating systems represent the combination of a visual device, for control of the movement of the video camera and a motor device to control the surgical instruments. The support of the endoscope, capable of moving the camera according to the needs and orders of the surgeon, usually is complemented by a verbal control system of equipment in the surgical room, which permits the surgeon not only the visual control of the procedure, but also how to determine the function of some equipment such as the electric scalpel, to position the surgical table or focus the illumination. The endoscopic system, or 'passive' robot, frequently utilized in isolation in laparoscopic and thoracoscopic procedures, is compulsory in more complex telesurgery, as it assists the visual function. Figure 1 illustrates the AESOP model used by the authors.

Fig. 1 - The AESOP system (utilized by the authors)

The motor device is composed of a master unit located at a distance from the patient in which the surgeon manipulates the instruments and a slave unit, that enables 'telepresence' within the surgical field to manipulate instruments. In heart surgery two mechanical arms are used that control the instruments inserted by means of transthoracic trocars. Figure 2 illustrates the Zeus system and Figure 3 the da Vinci system.

ROBOTIC SURGERY

The concept of robotic surgery, considering the videothoracoscopic technique in particular, is approaching the current proposals of surgery, in which procedures with reduced operative trauma and quick recovery of the patient are performed [16].

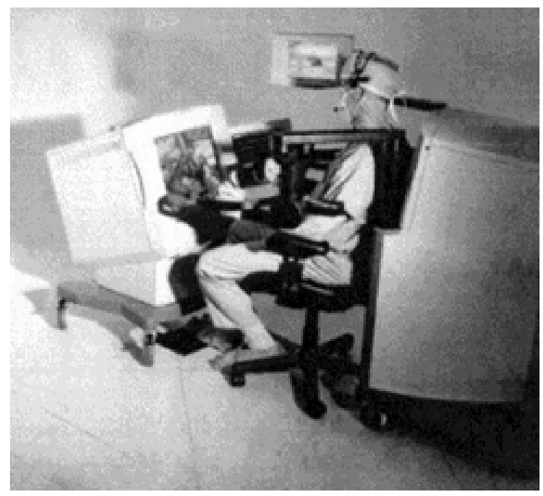

Fig. 2 - The Zeus system

Fig. 3 - The da Vinci system

This brings lower postoperative morbidity and has a direct influence on the individual cost of the procedure, which theoretically will be reduced. How much time will be necessary to compensate for the elevated initial investment, especially when considering the cost of complex surgical systems is not known.

The advantages cited are common to endoscopic systems. The specific attraction of robotic surgery over conventional endoscopic surgery [17,18] makes a more widespread indication of the technique possible, especially in thoracic surgery. The compatible procedures are summarized in Table 1. A great number of these advantages can be summarized in the concept of visual transparency, that is, the correct mapping between what the surgeon sees and does and how his movements are transmitted from the console to the surgical field.

Applications in cardiovascular surgery

Traditionally, coronary artery bypass grafting and valve

Table 1. Comparison of the limitations of the endoscopic techniques in relation to robotic surgery (Mohr et al., 2001 [18])

Function	Conventional endoscopic instruments	Telemanipulators
Degree of freedom	4	6
Shake filtration	No	Yes
Rate of movement transmission	1:1	1:1 to 5:1 (adjustable)
Alignment hand-eye	Poor	Natural
Effect of the lever	Reverse movement	Is not effective
Force transmission	Great/abnormal/non-linear (depends on the length of the instrument)	Programmable
Ergonometry (for the surgeon)	unfavorable	Favorable
Image	Bidimensional	3-dimensional

replacement surgeries have been achieved using sternotomy, an approach that allows access to all the cardiac structures and great vessels [18]. Cardiopulmonary bypass (CPB), combined with myocardial protection using cardioplegia, for a long time was considered as an adjunct necessary to heart surgery, providing a surgical field without movement or bleeding. The appearance of the evolution of interventionalist procedures for myocardial revascularization gave an alternative therapy free of surgical trauma, without anesthesia and with the possibility of the rapid recovery of the patient, challenging the surgical approach. Consequently, techniques of off-pump CABG were developed and also performed through mini-thoracotomies providing excellent results. Simultaneously, the development of equipment that permitted CPB with the thorax closed by the Heartport Company brought more solid support to the application of endoscopic techniques in heart surgery.

In a simplified form, the current utilization of robots in coronary surgery can be split at two levels [17]:

1 – Control of the robotic camera (by means of telemanipulation) for dissection of the arterial graft (usually the internal mammary artery), which is followed by distal anastomosis through mini-thoracotomy coincident to the place of the procedure.

2 – Total endoscopic coronary artery bypass grafting (TECABG): The harvesting and preparation of the arterial graft, the preparation of the coronary vessel to be anastomosed, the control of the procedure and the anastomoses are all performed by the surgeon by means of remote control at the console.

Dissection of the internal mammary artery with telemanipulators has already been proven [19]. The utilization of this method, in a revascularization surgery with mini-thoracotomy, reduces the pain in the postoperative period, probably because of less traction of the rib cage. In two different studies, utilizing the da Vinci system reported by MOHR et al. [18] and by FALK et al. [20], on average 64 ± 64 minutes and 61 ± 27 minutes were required for the dissection of the artery, but this time was reduce to 25 to 40 minutes, respectively, in the last cases of the series. Both demonstrated a mean functioning after anastomosis of greater than 95%.

The first series of cases in which TECABG was performed was presented in 1999 by LOULMET et al. [21], who presented results of the revascularization surgery of the anterior descending artery in four patients utilizing the Intuitive Surgical System. In spite of previous training in animals and corpses and previously performing more simple procedures, technical difficulties appeared during the procedures, with surgeries being completed in the totally endoscopic manner in two of the cases and in the others a mini-thoracotomy was necessary. The procedures were long, requiring 78 ± 12 minutes for dissection of the internal mammary artery, 25 ± 8 minutes to prepare the appendix of the artery and 18 and 32 minutes for anastomosis. A catheterism demonstrated patency of the graft and six months after the patients are free of symptoms. In relation to the possible advantages of the technique, one of the patients who underwent TECABG did not require analgesia in the postoperative period. However, for reasons of safety, as this is a new technique, there was no difference in the time of hospitalization when compared to conventional surgeries.

The most significant experiences with TECABG were reported by MOHR et al. [18] and DOGAN et al. [22], with 27 and 45 cases, respectively. Both demonstrated that this approach is possible and safe for selected patients. WIMMER-GREINECKER et al. [23] demonstrated a conversion rate to open surgery of 22% at the start of their experience, which was reduced to 5% in the last 30 patients (total conversion rate 10 cases, with seven converted to mini-thoracotomies and three to sternotomies), with a total surgery time of 61 ± 5 minutes. The 22 patients who underwent catheterism presented patency of the graft and six months after, all the patients in the series were free of symptoms.

MOHR et al. [18] presented, in a total of 148 procedures performed with robotic surgery including 27 cases of TECABG. In five of these (18.5%), it was necessary to convert the surgery to a more invasive form (mini-thoracotomy in four and sternotomy in one). There were no deaths and all the patients were released after catheterism proving the grafts were patent and functioning well. The time necessary to perform the procedure ranged from 3.5 to 8 hours, with a significant learning curve.

The techniques described in this study have the limitation of utilizing CPB using the Heartport system. Even though this system, created by a group in Stamford University is efficacious, it does not eliminate the deleterious effects inherent to CPB, such as systemic inflammatory response, the release of microbubbles, myocardial depression and the scaring problems caused by hypothermia [24,25]. In the patients of MOHR et al. [18] attempts of off-pump TECABG were made in eight, but only in four the attempts were successful. The authors attributed this limitation to the technical difficulty of the procedure in itself, which required a second robotic console to make surgical assistance available and the lack of endoscopic stabilizers that could be correctly adapted to robotic instrumentation.

Analyzing these experiences and others [18,22,26-28], a significant increase in the surgical time, the surgical team, general anesthesia, CPB time and cost with equipment was identified, but this seems to be compensated in some way by a shorted time of hospitalization and in the ICU, a reduced level of pain in the postoperative period and a better esthetic result. It is evident that the results tend to improve as the team gains experience [26], in such a way that you can predict future results harmonious with the theoretical advantages and the initial enthusiasm. Some more sweeping clinical trials are already under way trying to confirm these expectations [27,29].

Robotic systems have also been used in the area of cardiovascular surgery for mitral valve remodeling [30], the correction of interatrial septum defects [31-33] and the implantation of epimyocardial electrodes for left ventricular pacing [34,35]. In the near future, not only other conventional heart surgeries will be added to this list, but also molecular biology techniques such as stem cell transplantation and the injection of angiogenesis promoting factors.

Experience of the authors

Aiming at acquiring experience in robotic surgery, we utilized the robot assistance of AESOP (COMPUTER MOTION, USA), a piece of equipment that is incorporated in the Zeus system, for control of videothoracoscopy. The procedures that have been performed with this technique are CABG, to harvest the internal mammary artery (Nesralla I.A. and colleagues, Heart Institute, RGS, Porto Alegre, 2001) and an unprecedented work with the implantation of left ventricle epimyocardial electrodes for multiple site heart stimulation with a multi-chamber pacemaker [36].

Other applications of robotics in medicine (Table 2)

It was thought that the ability to transport the surgical practice and technique from one place to another at distance (other hospital, combat area, space station, underdeveloped country) could expand the application of robots in surgery and increase the number of interventions. Although some procedures have been performed remotely, there is no defined manner for this type of procedure due to the limitations of cost, transmission delay and medical and legal issues. In the foreseeable future, telepresence will probably be limited to telemonitoring and not remote manipulation [37].

It will be permissible for the surgeon to teach or guide the performance of an advanced technique at a distant site utilizing teleobservation and monitoring in real time. Robotic systems allow diverse surgeons share an experience during an operation by means of the internet.

Other applications of robotics include assistance to the surgeon (mechanical or visual), improving the ability, interlinking the systems in networks and varying therapeutic possibilities guided by imaging.

The surgical ability can be improved by placing a microprocessor between the surgeon's hand and the point of the surgical instrument. This enables microscale (superhuman) tasks to be performed, which would not be possible without the intervention of the computer, favoring interventions in the most varied areas of microsurgery.

There is also a potential application in respect to the techniques of non-visual imaging, including 3-dimensional reconstruction and modeling starting from information of images obtained in computed tomography, magnetic resonance and ultrasound. This allows the real time acquisition of pathological characteristics, the creation of special models and the application of percutaneous therapies by remote control.

Robotic systems enable diverse surgeons share an experience during an operation by means of the internet. It is possible to predict the availability of surgical training programs in the near future which will need to be completed by residents (and surgeons under training); and these systems will have a function analogous to the flight

Table 2. Technology development and forecast: Robotics and Computer assistance in surgery (Mack, 2001 [37])

Task	Function	Forecast
Surgical Assistant	Voice-Activated Endoscopic Holder / Positioning	Becoming Routine
Dexterity Entrancement Motion Scaling Tremor Filtration Force Feedback	Facilitate precision endoscopic procedures	D1 1000 Procedures now preformed, 50% are cardiac and 50% are laparoscopic
Operation room systems networking	Surgeon Control of or via voice activation, touch screen	Rapid Integration of operating room systems in near future
Telepresence Surgery Remote Surgery	Surgeon at remote site from patient using broadband transmission or internet	No clear path to clinical application
Telemonitoring	Proctoring from a remote site	Demonstrated to have potential for new educational paradigm
Information Entrancement 3-Dimensional Modeling and reconstruction image referencing guidance	Real – time Data Acquisition and non-visual imaging	3-Dimensional Reconstruction of Computed Tomography, magnetic resonance imaging and Ultrasonography with surgical Overlays to Facilitate Percutaneous Therapy
Virtual Stillness (Motion Stabilization)	"Gate" Time Visualization and Surgical Instruments to Heart Motion to Create Illusion of Stillness	Facilitate Endoscopy "Beating Heart" Surgery
Virtual Simulators	Flight simulators for surgery	About to become realistic and Affordable
Information Entrancement Sensory Feedback	Action in response to Non-visual Feedback	Potential for integrated "smart" local delivery at drug/energy Based on tissue-level feedback
Microelectronic Mechanical Systems	Miniature Autonomous Robots	Remote Diagnosis and delivery Via Body Lumina

simulation programs used by airplane pilots.

Limitations of robotic surgery

Apart from the initial investment (about 1 million dollars for complete robotic surgery systems), it is necessary to stress that the indications of robotic surgery, in particular in the cardiovascular area, are very specific and encompass a restricted number of procedures. In Brazil, as in all of Latin America, the cost of an operational robotic system can not be justified by financial return, even if it is frequently used over a long period; thus, it is possible that its use for some time will be restricted to only a few centers, where research and professional formation are important. But, if the systems are improved, the cost is reduced and the experience of training centers can be adequately transmitted, it is possible that the technique will be divulged and become more widely available.

The endoscopic approach presents specific challenges:

1 – Loss of the degree of freedom, a limitation imposed on the performance of a task by the confined space and by the reduced motricity of instruments; robots and other techniques of automation and compensation should reduce this limitation.

2 – The 3-dimensional imaging is lost on a television screen. The current solutions to compensate this restriction include digital amplification, shading to create the illusion of the 3rd dimension and presentation of high-resolution imaging. The creation of a 3-dimensional image has been limited by the loss of resolution associated with filtering systems and the size of the systems of visualization necessary to produce perception at depth, but even so with systems, such as da Vinci, 3-dimensional vision goggles are included.

3 – Difficulty to adapt the endoscopic techniques to reconstructive procedures, such as CABG surgery; as the excising or ablative procedures are more easily performed by thoracoscopic techniques [37].

The employment of telemanipulators still requires high velocity connections either by telephone or satellite [38]. The effect of the delay between the order given by the surgeon (master) and the corresponding movement of the robot (slave) [39] has already been studied. These authors concluded that a distance between master and slave of more than 700 meters implicates more errors in the manipulation of the robot. Currently, there is a general consensus that the acceptable time delay for the execution of an order should be the time relative to a distance of less than 300 meters [2,38,39].

CONCLUSIONS

Despite of the initial scientific enthusiasm of robotic surgery, it has already been five years since its first application in cardiovascular surgery and today there is still no clear evidence of its superiority in terms of results, when compared with those obtained by available conventional methods, with the exception of the esthetic aspect [40]. Thus, there is doubt whether robotic technology has failed to reach its expectations or if we are going through a natural progression for a better future in cardiac surgery [17].

But it is evident that endoscopic beating-heart CABG surgery requires perfection and development of techniques, before it can be widely used. It is equally uncertain if robotic surgery will be established using the same technology, principles and proposals as currently considered. We know that the introduction of any technology in medicine brings with it questionable initial results, inadequate safety for the patients and a higher cost of the procedures. The progression of robotic heart surgery has theoretical basis and growing technical support, but it is limited by the difficulties of experience with the technique due to the restricted indications (few patients are candidates) and the availability of other therapeutic options with well known outcomes. However, both for the survival of heart surgery as a specialty and for the benefit of the patients, the investment in robotic surgery and in other techniques capable of reducing the invasive character of the procedures is valid and should be encouraged. It is evident that intervention based on catheters conquered a very important place in the treatment of coronary disease and that cardiologists and patients have opted for less invasive methods of treatment [17,41], even though patients submitted to surgery present with lower rates of recurrence of angina and reoperations. Robotic surgery could represent a new attraction for direct myocardial revascularization.

It can not be forgotten that, within the visible future, the role of the surgeon will be preponderant in taking medical decisions, operating robotic systems and conduct the procedure in a way to provide the proposed surgical correction. Thus, the hand of the surgeon will continue to be the most important tool of a surgeon, independent of the interface that is interposed between him and the patient.

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