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A REVIEW OF ROBOTIC SURGERY EVOLUTION, CURRENT APPLICATIONS AND FUTURE PROSPECTS

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Abstract

The aim of this paper is to review the background of robotic surgery, the existing technology associated with this field, the main robotic surgical procedures, the training methods, the financial aspect of using these systems and future prospects for robotic-assisted surgery. Given the fact that robotic surgery has a history of only 30 years, the surgical possibilities are not researched to their full extent. The most appreciated feature of the robotic system is considered to be the high mobility and wide array of movement allowing access to do surgery on tissues inaccessible to classical approaches. With regards to the downside of this technique, it's almost unanimous accepted that it's cost related. To write this article over 60 literature sources about the history and development of surgical robots also concerning case studies, animal and human trials and their results obtained throughout the past few years were reviewed. Numerous trials that analyze new surgical applications are undergoing and although the system has been mainly used for soft tissue small interventions, its limits are yet to be determined.

Keywords*: animal model, da Vinci system, minimally invasive, robotic surgery.*

INTRODUCTION

Robotic surgery represents the newest and the most controversial type of minimally invasive surgery.

Although the first notions of robotic systems were mentioned for the first time centuries ago, robots were introduced to most fields like manufacturing, space exploration, research, transportation, in the past couple of decades, being just a matter of time for them to be designed for surgical purposes.

The development of new technology, at such a fast pace, brings new attributes to robotic systems and combined with the training of more and more surgeons in these techniques, it permanently modifies the existing data on advantages, disadvantages and possible uses of robotic surgery.

This review intends to offer complex and detailed data on the current situation of robotic surgery, analyzing multiple literature sources. Information about the background and beginning of robotic surgery, about the robotic systems available on the market, the training methods and about the procedures performed with this technology will be presented in this paper.

To write this article over 60 literature sources were reviewed. The papers were selected using specific criteria, using the following guiding points:

- Articles have to be published between 2000 and 2018;
- Articles have to be published as full papers;
- Particular keywords were used for each chapter of the review;
- Articles should have at least 15 references;
- Articles have to be written in English;
- Articles have to published from different medical settings;
- Their content had to be relevant to the subjects approached in this review.

All articles published before 2000, that only had an abstract presentation, that had less than 15 references, with no English translation and that had an irrelevant content were eliminated from reviewing. Over 200 articles were analyzed but only 62 met the criteria.

Robotic surgery is becoming more and more popular amongst the minimally invasive surgical centers, numerous hospitals already using this system or being in the process of implementing such protocols.

Due to its rising medical popularity both amongst doctors and patients, a paper that gathers the most recent data on this subject was thought necessary. Being a new field that develops at such a fast pace, the need for meta-analysis is high, idea supported by the fact that one of the most mentioned drawbacks of adopting this system is the poor literature on this subject associated with the lack of feedback.

History and evolution of robotic surgery

The use of robotics in surgery is first mentioned in 1985, which makes the history of this field only 33 years long. “Robota” is a Czech word used to describe forced labor and it was used to define artificial people almost a century ago. Although terms like “robotics” and “robots” are first used associated with science fiction literature and movies, these words were taken over by the scientific departments of several research fields, robots being designed for multiple purposes. Surgical robots have an impressive history, with multiple events and historical premieres during a short amount of time (Fig. 1). Da Vinci envisions a humanoid model over 500 years ago, for which he uses several mechanical details. His work on this human-shaped mechanical model inspires the Intuitive Surgical company to name their product the “da Vinci robot”, which is currently high-end surgical robotic technology.

Imagined at first to be used in out of reach areas such as outer space, deep underwater or to be used around dangerous materials and substances, the robots were reinvented once the microelectronics and digital imagining have developed at an increasing pace, making robotics suitable for the surgical field. The da Vinci robot is the most used surgical robot, due to its multiple functions and characteristics (Lanfranco et al., 2004).

The telesurgical system was intended for different purposes, in the beginning, gradually being adapted to the popular system that it is today. This technology drew attention to it from the start. In 1972 NASA was considering telepresence surgery as a solution to provide surgical support to astronauts. At that point in time, the technical development couldn’t allow this project to be implemented. The telesurgery concept was further developed and made tangible the remote manipulation of scopes and different types of instruments. The Defense Advanced Research Projects Administration (DARPA) also shown interest in this technology, as was seen as a viable option to perform surgery on soldiers in areas that surgeons can’t have immediate access. Several years later, this system was developed for commercial use, bringing it into minimally invasive centers around the world.

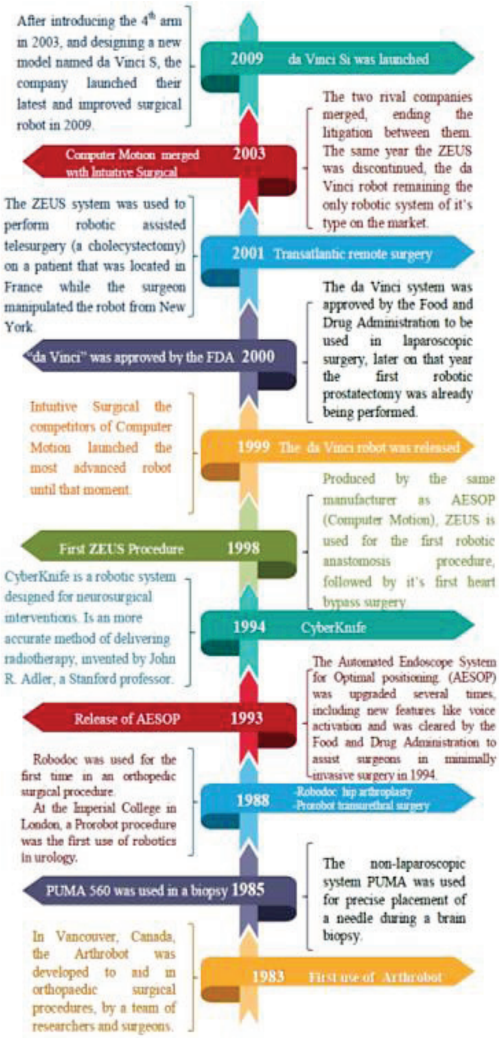

Figure. 1. The timeline of surgical robots development

The Intuitive Surgical Corporation launches the da Vinci robot in 1999 as groundbreaking medical technology, although the ZEUS robot, that was built on a similar concept, was already in use but with fewer characteristics (Shah et al., 2014).

The main robotic systems

Robotic surgery can be divided into 3 types, considering the surgeon's implication during the procedure:

- supervisory controlled: robotic arms execute the procedure following a predetermined program;
- telesurgical: remote surgery is conducted by the robotic arms manipulated from a distance by a specialized surgeon;
- shared-control: the surgeon performs the procedure using robotic arms as an aid, due to their characteristics of accurately manipulating the instruments.

Most medical robots were designed for a certain purpose, to be used in a certain type of procedure or for a specific medical field like neurosurgery, urology, gynecology, but every device is envisioned to extend the human skills, to compensate for surgeon errors, but not to replace the doctor's role in medical procedures.

Another way to classify the robotic systems is by their procedural role:

- passive role;
- restricted role;
- active role.

The current tendency is to use robots with active role that move more of the responsibility on the machines, decreasing this way the load that was supported by the surgeons.

The main robotic systems used until present day are the following:

- *Cyberknife* is an autonomous device that accurately positions and delivers radiation therapy to a tumor, guided by preloaded CT images correlated with real-time x-ray images.
- *Aesop* is a robotic system with voice control, that manipulates an endoscope. It has a restricted role because it's used only for visual support.
- *Robodoc* is a robot used in orthopedic procedures, specifically designed for hip replacement. This system is used for a certain part of this complex procedure, its role being bone drilling.
- *Acrobot* is another example of the use of robotics in orthopedic surgery. It has a similar role to Robodoc but it's used in the total knee arthroplasty procedure.
- *NeuroMate* is one of the first medical robots used in surgery, being also a system guided by preoperative images, that has as the main characteristic the ability to precisely position instruments, eliminating the human hand error.
- *ZEUS* is a robot used in laparoscopic and thoracoscopic surgical procedures. It has three robotic arms, one of them being strictly used for the endoscope, being an AESOP arm with voice control, while the other two are used to manipulate surgical laparoscopic instruments. The voice commands refer to the position of the endoscope, asking it to move vertically or horizontally until the command "stop" is given. This system had added a flexible wrist device. The telesurgical technology used here was improved and replaced by the one utilized in the da Vinci robot.
- *Da Vinci robot* is the most recent and complex robotic system and with its recent updates has become the most desirable technology for more and more minimally invasive surgical centers (Camarillo et al., 2004).

Given the wide array of possible procedures, correlated with all its features, often when robotic surgery is the subject of a debate, the use of the da Vinci robot is implied. This is why explaining how medical robots work will be made on this particular one.

Unlike all its predecessors, da Vinci it's the first that was approved by the FDA to be used in general laparoscopic surgery.

It is a teleoperated system, which implies that the surgeon manipulates instruments and scopes attached to the robotic arms, from a console placed at a distance from the actual surgical field (Freeman and Towle, 2015).

This technology is not intended to be autonomous, but to act as an extension of human capabilities, the surgeon being the one to control every movement of the instruments. Because of this particularity, these systems are often called "master-slave manipulators".

During the brief history of this technology, only ZEUS and da Vinci systems were approved to assist in surgery and nowadays only the latter is still produced, making it the sole robotic device of its type (Morris, 2005).
The da Vinci system has three main components:

- the surgeon's console;
- the patient-side cart;
- the visual tower.

The surgeon's console (Fig. 2) is the interface between the surgeon and the robot and has multiple functions such as:

- The console viewer offers HD images of the surgical site, with the possibility of magnification up to ten times;
- The master controllers are also called fingertip controllers, being manipulated by the surgeon's hands. The motion scaling feature is one of the most appreciated characteristics allowing the adjustment of hand-to-instrument movement ratios. Another great feature associated with the master manipulators is the hand tremor filter which removes any unwanted movement (Bodner et al., 2004);
- The footswitch panel is used to perform other tasks such as switching between instruments or adjusting the light;
- Numerous ergonomic settings are designed to offer the surgeon comfort during surgery;
- After the latest upgrades, the newer da Vinci robot offers the dual console feature, a technical innovation that allows collaboration between surgeons, being also a great training asset.

A widely cited disadvantage of robotic systems is the absence of tactile feedback (Wottawa et al., 2015).
The patient side cart represents the main robotic component with four active arms. Endowrist instruments can be attached to the robotic arms that control them (Fig. 3). Changing the instruments require the help of a medical professional. A wide selection of instruments is available such as:

- energy instruments used for coagulation, cutting or dissection;
- grasping instruments;
- needle drivers that have a cutting blade integrated;
- retracting instruments;
- suction and irrigation probes;
- clip appliers, probe graspers and other specific instruments.

When replaced the instruments are automatically recognized and their type and function is displayed. The endowrist instruments are defined by their micro-articulation near the active tip, that gives them 7 degrees of freedom, that being the greatest possible motion around a joint, making these arms able to reach around, beyond and behind. Some studies were done on the endowrist particularly, approaching aspects like suture damage, grasping (Hirano et al., 2010; Teoh et al., 2017). The force applied can be set from the computer to deliver as much needed for the task at hand. In addition to the active instruments, a lightweight 3D HD camera is introduced inside the body for vision setup.
The vision cart stores components of the visual system and monitors that allow the team to watch the intervention. The new system has the TilePro feature that is a multi-image display that can show on screen simultaneous images of the surgical field and two other video sources like ultrasound or EKG (www.intuitivesurgical.com, 2018).

Figure 2. Da Vinci console


Figure 3. Da Vinci patient-side cart

Robotic surgery applications

Being performed on live animals just for experimental or training purposes at the moment, robotic surgery is still a field that exclusively defines human medicine (Gastrich et al., 2011).

Over the past 20 years, numerous articles were published mentioning the use of robotic surgery as an alternative to laparoscopic or open surgery or even as a unique, groundbreaking treatment, but the lack of sufficient data makes it impossible, at this moment, to establish its real utility (Al-Naami et al., 2013; Alemzadeh et al., 2016; Singh, 2011).

After reviewing the literature on robotic surgery applications, it can be said that the most frequent procedures belong to the following fields:

- Neurological surgery;
- Urological surgery;
- Gynecological surgery;
- Cardiothoracic surgery;
- Gastrointestinal surgery;
- General surgery.

In a short period of time, robotic interventions have been executed in numerous surgical fields, rapidly becoming a possibility for almost every medical specialty. The most cited procedures which can be performed with the assist of a robotic system are urological and gynecological.

Robotic surgery is an option for a significant number of urological procedures but its great success and groundbreaking techniques, that made the da Vinci system so popular, apply to the prostate followed by the kidneys and bladder (Yates et al., 2011).

The prostatectomy performed on patients diagnosed with prostate cancer is the most discussed procedure of its type (Orvieto and Patel, 2009). While there are a large number of studies that report the advantages of this method and implicitly the superiority of robot-assisted radical prostatectomy (RARP) when compared with the laparoscopic radical prostatectomy (LRP), other reviews conclude that the literature is limited and that the methodological quality is low, questioning the validity of the results that declare the robotic procedure superior to the laparoscopic one (Boggie et al., 2014; Box and Ahlering, 2008; Kang et al., 2010). Although the procedure's costs are high, the robotic radical prostatectomy tends to become the golden standard in treating patients with prostate cancer. Robots assist in oncological surgeries of the kidneys and bladder with a better outcome than in classical procedures. The most common robotic procedures done on kidneys are the partial nephrectomy and pyeloplasty, while for the bladder the method of choice for a patient with cancer is the robotic-assisted radical cystectomy (Benway et al., 2009; Bozzini et al., 2016; Dal Moro, 2017; Hubert et al., 2003; Kingo et al., 2016). Other urological interventions are performed such as ureteral reconstruction (Brandao et al., 2016).

The first cardiac surgery performed with a robotic system was in 1999 and since then the most challenging surgical interventions are being performed using the da Vinci system (Kim et al., 2018; Poffo et al., 2013).

The major types of robotic heart surgeries:

- Coronary artery bypass;
- Mitral valve repair or replacement;
- Tricuspid valve repair;
- Atrial septal defect repair;
- Patent foramen ovale repair;
- Removal of cardiac tumors.

Other thoracic procedures are experimentally done, such as robot-assisted pulmonary lobectomy (Lococo et al., 2014).

Regarding general surgery, complicated and demanding procedures such as pancreatectomy, Whipple surgery, liver resection for transplant have been done especially in the last 10 years (Baek and Kim, 2014; Lomanto, 2001; Panaro et al., 2011; Rashid et al., 2015; Tselios, 2013).

Robotic surgery in gynecology is growing at a fast pace, being used in the present to treat oncological pathologies and also fibroids, endometriosis, pelvic prolapse (Scandola et al., 2011).

In the fields of neurosurgery and orthopedics specially designed robots, with limited and precise functions are used, the da Vinci system, which can be used only for soft tissues, not being one of them (Beasley, 2012).

Training methods

One of the most challenging aspects of implementing a robotic surgical center is training the surgeons. Being such a new specialization few regulations and training protocols exist (Brinkman et al., 2016; Hung et al., 2013). Most published articles and reviews state that a step by step training program should be applied.

A surgeon that participates in robotic surgery training has to follow several phases, such as:

- A didactic phase;
- Inanimate laboratory;
- Cadaveric laboratory;
- Animal laboratory;
- Operative observation and operating under supervision (Chitwood et al., 2001).

The first step of the learning process is gaining theoretical knowledge. The trainee needs to learn about the robot's functions, its uses and the possible technical problems that can occur during surgery. This step includes also learning how to properly position the patient, followed by correct port placement, both being of the utmost importance in assuring access to target organs. Online courses are available on basic robotic surgery concepts, offering information on robotic components and troubleshooting.

The second step in robotic surgery training is the so-called inanimate laboratory or skills laboratory. This part can include several training methods depending on the curriculum in place. Training exercises from the basic movement of the robotic arms to more complex procedures can be performed during this lab, but they are mainly used for learning how to control the instruments, adjust the camera and familiarize with the system.

Also designed for gaining hands-on skills, the virtual reality (VR) simulators are a great, cost-efficient learning tool. Currently, five VR simulators are available for robotic training:

- Robotic Surgical Simulator (RoSS);
- dV-Trainer;
- SEP Robot;
- Da Vinci Skills Simulator (Culligan et al., 2014);
- Robotex mentor (Schreuder et al., 2011).

These simulators have been upgraded over the years, offering now the possibility of learning specific procedures not only basic skills. The trainee watches a video of a specific intervention being performed while the robotic arms move accordingly with the surgical steps. After registering all the movements, the trainee can try and reproduce them (Bric et al., 2014; Hammound et al., 2008; Hart and Karthigasu, 2007; Liu and Curet, 2015; Beyer-Berjot and Aggarwal, 2013).

Apart from using synthetic dummies or inorganic models, surgeons can be trained using wet labs. The training material used for the wet labs is represented by animal or human cadavers, animal tissues and organs or live animal models. These models can be used for procedural training, enabling the surgeon to practice in the most realistic conditions. Cadaveric models are an excellent material to practice dissection, excision and other basic techniques, while the live animal models allow in addition, vascular control which can only be learned during wet labs. Laboratories that use live animal models are more expensive, harder to schedule and in some countries raise ethical or religion-related problems (Sridhar et al., 2017). Although dogs, sheep and other live animal models have been used, the most chosen animal model for surgical training sessions is the pig. Swine are considered a great model due to their similarities with human anatomy and physiology (Ganpule et al., 2015; Joseph et al., 2008). Surgeons should enroll to live animal labs as the last step of their training or near the ending of their learning curve (Fig. 4).

After gaining practical skills, the next step for a surgeon is observing live cases, starting with videos and continuing in the operating room. To finish their training and start performing robotic surgery, the trainee needs to be under direct supervision of an expert, a proctor at first and then a mentor, the latter allowing the trainee more opportunities to operate (Santok et al., 2016). Mentoring can be made easier by the mentoring console, which is a dual console with two modes: "swap" and "nudge", that allow the surgeons to operate simultaneously or to shift the control from one surgeon to another. There are studies that bring arguments in favor of surgeons undergoing laparoscopic training before learning robotic techniques (Abaza, 2009).

An important aspect of the training is the "learning curve", which represents the number of surgical procedures performed before a doctor has an acceptable surgical outcome, analyzing parameters such as blood loss, complication rate and the conversion rate to open surgery (Hanly et al., 2004; Heemskerk et al., 2007; Hassan et al., 2015; Hayn et al., 2010; Lenihan et al., 2008). The learning curve for hysterectomies in considered 50 cases and for RARP is 40 cases.

A form of evaluation is also required to assess the technical skills of surgical trainees. Several methods are in the process of implementation at the moment, but often the Objective Structured Assessment of Technical Skills (OSATS) is used as a global rating scale (Niitsu et al., 2012).

More and more medical centers with training facilities, approved to teach residents and fellows, try to include robotic surgery into their programs, creating curriculum levels and regulations.

Figure 4. Training session for robotic surgery using a swine model.

Financial aspects

The greatest problem that medical centers face when considering to introduce a robotic system to their hospitals, is the cost. Robotic surgery is expensive due to the cost of equipment, maintenance and repair fees, due to the cost of additional surgical training and of an increased operating room setup time (Hussain et al., 2014). The da Vinci Surgical System, used for soft tissues surgery, being the main surgical robot, has costs per unit that range from 1 to 2.5 million dollars (Barbash and Glied, 2010). To this amount are added maintenance costs of over 100.000 $ per year. Every surgery depending on its complexity and duration brings additional costs of 2.000$ to 4.000$, which includes drapes and replacement tools. A cost analysis was made in Turkey and concluded that money can be saved if the time used in the preparation stage is shortened. In this study, the time before the actual intervention started, was divided into three intervals: first ending when the anesthesia was ready, the second one when the drapes were secured and the last one ended after the ports were introduced. All of these steps can be realized faster by properly trained professionals, reducing the costs (Zeybek et al., 2014).

This being the financial situation associated with robotic surgery, a cost-effectiveness analysis has to be done, weighing the potential benefits, such as lower complication rate, reduced hospital stay, smaller incision and disadvantages represented by the increased costs. There are not enough studies published to conclude if the robotic surgery procedures are superior to the laparoscopic ones and it can’t be said if the increased costs bring real medical advantages (Davies, 2014).

Many authors consider that in the future, with increasing the competition between the robot manufacturers and with more trained surgeons being able to perform robotic surgery, the costs will be reduced. Another aspect of the prohibitive prices is the monopoly that the manufacturer of da Vinci robot has over the production of robotic parts. In the future, when this technology will lose its patent protection, cheaper components will be produced by other companies, robots becoming more affordable and accessible even for veterinary medicine (Mayhew, 2014).

Future of robotic surgery

With a short history of under 30 years, robotic surgical systems represent cutting-edge technology, being the most advanced surgical equipment on the market. Although they have numerous advantages, these systems can be further improved and redesigned, steadily evolving.

For now, telesurgery is possible only with the surgeon being in the proximity of the patient, but it is envisioned that wireless commands will be developed and the distance between the surgeon and the patient can significantly grow.

The da Vinci system is used with manually switching the instruments, but manufacturing an automated system will save time and will remove the need for an assistant to do this job. Another way to improve this system is integrating voice command that can control several functions, making the system even more automated. Surgeons suggest that robotic systems should have integrated diagnostic testing equipment like ultrasonography or small microscopes. In the following years, the surgical robots are expected to become smaller, with more sensors, better cameras, with new and revolutionary instruments. Besides the technical improvements and novelties envisioned for this systems, the surgical efficiency is expected to increase due to shorter operative time, once the surgeons gain more experience.

Surgical robots may change direction from being multifunction, proper for every procedure system to smaller, simpler, more task focused devices.

Robotic surgery faces some challenges concerning ethical and legal aspects, that have to be addressed in the future, such as:

- If a technical problem occurs during surgery it goes under malpractice liability or the blame goes to the technical team or manufacturer?
- If the robotic surgery offers a marginal benefit is it ethical to impose a financial burden on medical systems or the patients (Kumar Pal et al., 2011)?
- If telesurgery will become possible for longer distances, the regulation of which country will apply when surgery is performed, when the surgeon and the patient are in different countries?
- Should some training requirements be set in place?

Although robotic systems were build to address the limitations of laparoscopic surgery, they will push the boundaries of medicine by further extending human abilities, but not being able to take over for human surgeons in the near future.

CONCLUSIONS

Robotic surgery is described among minimally invasive techniques as revolutionary, with several advantages associated, such as reduced blood loss, less postoperative pain, shorter hospital stays, smaller incisions that bring cosmetic benefits. Besides the benefits brought to patients, robotic surgery seems to overcome the limitation of laparoscopic surgery, making it possible to reach areas inaccessible to conventional laparoscopic instruments, offering a 3D magnification of the surgical site, instruments that have articulation with 7 degrees of freedom and a specially designed console that brings a more comfortable setting to the surgeon. Having all these characteristics and improving surgical precision and dexterity, robotic surgery may seem a perfect choice, but numerous questions about this system remain to be answered.

Longer operative times and the expensive equipment make the cost of a robotic surgical intervention go higher than for a similar procedure performed laparoscopically. Almost every study to date highlights the need for more randomized studies to be conducted, in different settings to determine if the benefit of using a robotic system overcomes the cost of its implementation. Studies need to be run to evaluate the true benefits of robotic surgery, to demonstrate its superiority over laparoscopic procedures or to confirm their similar results.

It is suggested that nowadays some medical centers embraced robotic surgery to keep their status as a cutting-edge facility, because of its popularity, the apparently reduced morbidity, its potential use for groundbreaking procedures and the ability to conduct experimental studies with this technology. Although the cost slows the expanding of robotic systems, a couple thousand robots are used all over the world and with more studies started every day and a prediction of a diminished cost in the future, the reluctance that most surgeons and patients manifest will fade.

This field also faces challenges about vague regulations, about the fact that few residency centers offer robotic surgery training and that a small number of training facilities exist. These facilities need a second system to be used exclusively for training which implies huge additional costs.

Robotic surgery will be further improved, new instruments and accessories will be developed and it will become an important part of the history of minimally invasive surgery once it will be settled when and for what type of procedure it will be best used, once all the questions about its efficacy, safety, cost-effectiveness and training requirements will be answered.

It is considered that will become an interest for veterinary surgery as well, as soon as it becomes more affordable and more applications become available. This prediction is supported by the fact that veterinarians already collaborate with human medicine specialists in training sessions that use live animals.

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