Benefits and Restrictions of Robotics in General and Thoracic Surgery

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Original paper

SUMMARY
In clinical surgical practice, robots are used in all almost specialties, including neurosurgery, cardiovascular surgery, orthopedics, general surgery, urology and the gynecology. Most robotic operations emanate from cardiovascular and urological surgery, while there seems to be continuous improvement to the robot techniques in other areas as well. This review paper discusses the applications of robotic systems in general and thoracic surgeries. The benefits and restrictions related to the use of robots in comparison with the traditional approaches are also discussed. Special reference is made regarding the operation length and hospitalization time using the robot technique in comparison with the traditional methods. Cholecystectomies, treatment of gastroesophageal reflux disease and esophageal achalasia, bariatric surgeries, colon operations and thymectomies are only some of the general and thoracic surgical procedures that can be performed with the support of robot technologies. According to the review the effectiveness of robotics in the above procedures has been proved in many clinical trials describing successful outcomes. The currently available systems are mainly based in visual three-dimensional feedback. The restrictions of the robotic surgeries are based to the fact that surgeons, usually use their hands during the operations. The lack of haptic sense is considered to be the one of the most important disadvantages of modern systems. All conclusions concerning surgical robotics should always take into account that it is a relatively recent technology which has not been utilised adequately which has not yet become a common part of the everyday surgical practice.

Key words: robotic surgeries, telesurgery, general surgery, thoracic surgery, robots

1. INTRODUCTION

The term telemedicine refers to the combined use of telecommunications and informatics for the provision of healthcare services and education/counseling from distance. Telemedicine uses e-messages to transfer medical data from one site to another. These messages can be biosignals, laboratory test results, 2D and 3D images, electronic health record data etc. The above mentioned data may be transmitted alongside with audio and video. The data transfer can be synchronous or asynchronous and may be transmitted through a telephone line, the internet, an organization's intranet or a satellite connection. The first telemedicine applications appeared in the 70s and were used for counseling and provision of instructions to ships, in the case of an emergency event. The appearance of the first computer systems and the evolution of communication technologies during the 80s and 90s contributed to the rapid development of telemedicine applications (1), such as telediagnosis, tele-consultation, teleactinology, telecardiology and telecare.

Telesurgery is a field of telemedicine with rapid development in the recent years. Actually the physicians' interest to visually review the internal organs has existed since the ancient time. The first described endoscopy was by Hippocrates who made reference to a rectal speculum (2). The term telesurgery refers to the surgeon supported by robot systems being at his service during the surgical operation. Techniques supporting laparoscopic operations and the provision of support, consultation and education, are major applications of great impact. The development and utilization of robot systems, such as the Zeus and da Vinci system within the clinical environment makes it possible to perform surgical operations from distance. Apart from the demand in modern telecommunication services, there is the need for the appropriate software and hardware in order to achieve the simulation of the actual surgery site. For this reason, virtual reality technologies are being used.

The first distance assisted surgical operations have been performed in 1999 in Singapore, in connection with John Hopkins Hospital (Baltimore, USA). Other similar operations followed up during the next years. This has been achieved with the use of a teleconsultation platform with real time audio and video support and the distance control of a AESOP 1000TS robot arm. The application has been supported by

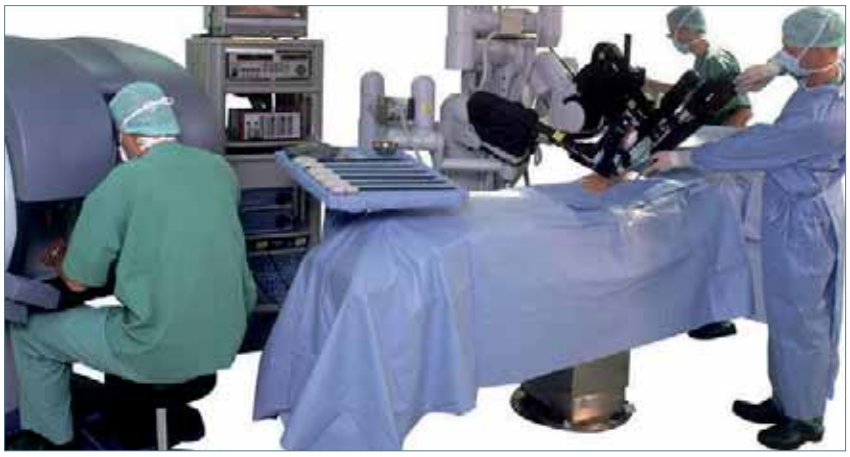

Image 1. Use of da Vinci robot system during an operation

three ISDN lines (baud rate 384 Kbps/sec), while the control of the robot arm was enabled through a second analog line. The surgical operations included successful resections and the distance between the J. Hopkins and the client hospitals varied between 7200 and 17600 km. The lag time was within the acceptable limits in the above procedures but too long for a purely distance operated procedure (3). In the year 2001 the tele collaboration system Socrates, has been used together with the robot surgical system Zeus for the first purely telesurgical operation. An amended version of the above system, namely Zeus TS, has been used in an over Atlantic cholecystectomy by Dr. Jacques Marescaux on a 68 old female patient. The robot system and the patient were located in Strasburg, France while the surgeon and the control panel were 7000 Km away, in New York, USA.

In the case of very long distances, the signal needs a few milliseconds to be transmitted and this is a very crucial issue to be taken into account. Even the use of geosynchronous satellites appears to have a delay time of 1.5 sec. Marescaux and Gagner estimated that a safe surgical procedure from distance should have a delay time no longer than 300 milliseconds. (4) An optical ATM connection has been used due to the high speed (10Mb/s) and the service quality, in a cholecystectomy has been performed with success. This surgical operation is known as Lindbergh operation (5). Finally, in the year 2003 the first tele robot supported operation has been performed in Canada between two hospitals 400 km away from each other.

1.1. Robots

According to the Robotics Institute of the Carnegie Mellon University, USA, a robot is a reprogrammable controller of multiple functions that has been specifically designed to move objects, tools and devices through programmable movements in order to fulfill various activities. The principle of robot technology is the digital control (method of reprogramming tools-machines) and telechirics (the use of mechanical arms to perform physical hand activities) (6), (7). The mechanical part of a robot includes their arms. Based on the activity that the robot system has been designed for, the robot may include one or more arms. Each arm is made of the following parts:

- Base: fixed onto the robot and attached with connectors and joints which are connected with the action tool.
- Connectors: solid, metal parts which keep together the arm of the robot system.
- Joints: mechanisms that allow the relative movement between two connectors.
- Motors: used to move the joints and sensors for the control of the location and speed of joints.
- Action tool: it is a specifically designed tool located onto the arm of the robot system.

Each moving joint adds one degree of freedom (DF) to the robot. In order to describe the position of a solid object in space we need to define six variables, three for its location and three for its orientation. Therefore each robot system should have at least 6 DFs. The human arm is estimated to have approximately 7 DFs (8).

1.2. The surgical robot

According to the theory, if a robot is built upon suitable software, it has the ability to perform a surgical operation. The surgical robot is a computer controlled device that has been programmed to perform precise movements of surgical tools, thus supporting the surgeon to perform complex operations. It is important to stress that the surgical robots cannot perform operations solely be themselves and function in dependence with the surgeon, serving as their "mechanical extensions". There is a master-slave relationship between robot systems and the surgeon. Each master-slave system consists of two parts, namely the console-master of the surgeon and his robot arms-slaves. The console is the interconnection between the surgeon with the robot system. The computer is placed between the patient and surgeon, providing valuable information. Through digital analysis, the robotic system provides precise three dimensional imaging to the surgeon. The commands of the surgeon with the use of controls are interpreted into precise digital signals to the surgical arms-slaves (9).

1.3. Robotics in Medical Practice

Minimally invasive surgery (MIS) has been introduced 25 years ago, aiming to support medical operations with minimal trauma and shortest possible recovery time. This method was based on microcameras attached onto devices called endoscopes or laparoscopes which go through small

Image 2. Robotic Cholecystectomy

holes of 1 cm throughout the patient's body with the aid of a monitor. The success was so great that a new specialization started to exist, namely the laparoscopic surgery. It has been the first time that the control of the surgical field has been taken over by the person who controls the system. In clinical surgical practice, robots are used in all almost specialties, including neurosurgery, cardiovascular surgery, orthopaedics, general surgery, urology and the gynecology. Most robotic operations emanate from cardiovascular and urological surgery.

2. SCOPE AND METHODS

This review paper discusses the applications of robotic systems in general and thoracic surgeries. The benefits and restrictions related to the use of robots in comparison with the traditional approaches are also discussed. Special reference is made regarding the operation length and hospitalization time using the robot technique in comparison with the traditional methods.

An extended literature research has been made using Medline. The research identified those review papers and clinical trials which describe operations that have been performed using robot technologies and refer to the field of general and thoracic surgery. The presentation of the clinical trials pinpoint to the benefits and restrictions of the robot techniques, while a comparison is made with traditional methods, as far as specific indicators are concerned. These indicators include the time duration of the surgery, the post-operation hospitalization length and the rate of successful operations while in some cases reference is made regarding the in-surgery complications.

3. APPLICATIONS IN GENERAL AND THORACIC SURGERY

The application of robotics in general and thoracic surgery and more specifically in the gastrointerine system is relatively new. Up to now, robotic systems have been used in laparoscopic cholecystectomies, in operations for the treatment of gastroesophageal reflux disease and esophageal achalasia, in surgeries for the pathological obesity, in colon and rectum operations, as well as in the case of spleen and pancreas surgeries. The field of thoracic surgery finally describes robotic operations in the lungs and the thymus.

3.1. Cholecystectomy

The first robot supported cholecystectomy was performed by Himpens in March 1997 with the aid of the MONA system, precursor of robotic da Vinci system, and was completed in 82 minutes. Cadière performed 48 cholecystectomies, using the da Vinci system. The mean operation time length was 70 minutes. In 4 cases the disease has been the acute cholecystitis, while in one case blood transfusion was performed during the operation. The mean number of hospitalisation days was 2. The use of the robotic system provided improved motor skill, superior ergonomy and increased mobility of the tools, while the time needed for the operation and the hospitalisation were found to be within the acceptable limits. Marescaux and his team performed 25 cholecystectomies in 2001 using the system Zeus, including 20 symptomatic cases of cholelithiasis, 4 acute cases and one case with polyps. The clinical outcomes of the interventions were satisfactory, while in one only case there was the need to perform an open surgical operation. In September 2001, following experiments in pigs, Marescaux and his team performed the first transatlantic robotics cholecystectomy lasting 54 minutes, known as operation Lindbergh (10).

3.2. Treatment of gastroesophageal reflux disease

The surgical techniques that are used for the treatment of the **gastroesophageal reflux disease** are two, namely tholoplasty Nissen, or tholoplasty 360O. The surgeons make 4-5 small 5 mm holes throughout the skin without muscular cut (11).

The first robot supported Nissen operations were performed by Cadière in 1999. Cadière performed 10 such robotic operations using the MONA system and 11 operations using the classic laparoscopic method. The mean duration of the robot supported operations was considerably longer than that of the conventional laparoscopic methods (76 and 52 minutes respectively), while the mean hospitalisation days was similar in the two cases. Despite the fact that the robotics method was proved to be a feasible and safe technique, it did not show significant advantages against the laparoscopic technique. Due to the narrow gastric space and the curved gastric morphology during the operation there have not been performed enough robotics operations for the treatment of gastroesophageal reflux disease, either with tholoplasty Nissen or with any other technique. Based on the results of these clinical trials the robotic tholoplasty Nissen gives similar patient outcomes with the conventional technique, but it is a more precise and slower operational procedure. The mortality rates in all cases were null (12).

3.3. Treatment of the Esophageal Achalasia

Esophageal Achalasia is a disorder which is related with the mobility of the esophagus. The cause is usually unknown. The esophagus is unable to perform its peristaltic movement and the lower part of the esophagi clamp does not open sufficiently when

food goes through, being in constant convulsion. The disease is frequent in the ages between 30-60 years in one out of 100.000 patients and its symptoms are dysphagia, diverticula and weight loss. The laparoscopic surgical treatment of the esophageal achalasia is called myotomy Heller and in certain cases is performed alongside with laparoscopic tholoplasty Dor (180[O]) or Toupet (270[O]). Small surgical incisions (5 mm) allow the endoscope and the surgical tools to enter the abdomen. Then, a small incision in the muscular tissue of the oesophagus is made and, if needed, the operation is followed up by a plastic surgery of the oesophagus (11).

According to a report published in 2004 in Chicago by Jacobsen et al. (13) on the performance of 35 robotic Heller myotomies, there have been absolutely no cases of esophageal perforation, an achievement related with fact the detailed three-dimensional view of the muscular system of esophagus and the wide range of movements of the specialized EndoWrist tools of the da Vinci system. The mean duration of the robot supported myotomies was considerably smaller when compared with that of the conventional laparoscopic operations (10).

Bariatric Surgery

While the problem of obesity has received epidemic dimensions in the western world, there has been a considerable increase in the number of patients going through bariatric surgical operations, in order to lose weight. Nowadays, bariatric surgery for the treatment of pathological obesity constitutes an autonomous surgical sector with many possibilities and prospects. The higher portion of these operations is being performed with conventional laparoscopic techniques, while only recently some of them are performed with the support of robotic technology. These include the technique of silastic gastric ring (LAP-Band), the gastric bypass Roux-en-Y (gastric bypass) and oblong gastrectomy (sleeve gastrectomy).

Silastic gastric ring

The gastric ring surgery is one of the most popular operations for the treatment of pathological obesity. In the upper part of the stomach and near the esophagus, a silastic ring is placed, which drastically limits the quantity of food that passes through the stomach. The ring is connected with a drum that is implanted onto the abdomen. The method is performed either with the laparoscopic technique or with robotic method (14). The importance of the robotic da Vinci system in bariatric surgeries has been proved through a series of operations, specifically in the case of gastric ring or gastric bypass operations. The mortality rates in all cases were null (12).

Gastric bypass Roux-en-Y

Of all operations for the treatment of pathological obesity, the gastric bypass Roux-en-Y is the mostly applied technique. A small part of the stomach is directly connected with the intestine, so the food passes through a long way across the gastrointerine route (14).

The laparoscopic operation can also be performed with the robotic method with similar surgical duration in comparison with the conventional technique and also with minimal risk of morbidity or mortality. The robotic method constitutes an alternative technique for the achievement of gastrostomy and the anastomosis offering important advantages to the bariatric surgeon. The three-dimensional depiction of the surgical field and the additional degrees of freedom allow the surgeon to perform better and more precise surgical sutures, which the method considerably decreases the chances of gastrointerine leakage. The hospitalisation length remains the same, regardless of the followed technique.

Data from gastric bypass Roux-en-Y operations performed within a five-year-period, showed that the robotic method, was even more precise than the conventional surgical technique, showing important advantages. The data concerned 605 cases of patients. 356 of them followed the conventional laparoscopic technique while 249 patients were treated with the robotic method (15).

Vertical Sleeve gastrectomy

Sleeve gastrectomy is an operation for the treatment of obesity that has started to be used recently. It is the removal of a large part of the stomach without however disturbing substantially the normal operation of digestion and absorption of nutritious components. With this technique the 85% of stomach is removed vertically, while the remaining part of the stomach is rejoined. This is an operation also performed with the support of robotic surgery with the help of four to five small (1 cm) incisions (14).

3.4. Robot Supported Colon Operations

Many operations have been performed in the colon and the rectum using robotic systems. Some of these operations include right and left colon extraction, sigmoid colon extraction, orchidopexy, low anterior extraction and total colon extraction. Nevertheless, despite the advanced technical characteristics of the da Vinci system, most reports on robotic colon surgeries do not demonstrate any important advantages of against the traditional laparoscopic technique.

Since Weber and his team announced the two first colectomies with the help of the robotic system da Vinci in March 2001, colostomy operations with the support of robotics have been increased. Clinical studies have shown the feasibility and the safety of robotic colectomies not only for the treatment of non-malignant but also in malignant colon diseases. The comparison of 18 cases of right and 10 left semi-colectomy with the support of robotics with 50 cases of right and 73 cases of left laparoscopic semi-colectomy, suggests that the robotic colon surgeries is a feasible and safe method but requires a longer time for the operation to complete (16).

Delaney et. al also found similar to the previous study results (17). Similarly, another study indicated that the clinical results of the robotic and laparoscopic colectomies were similar, while the robotic operations required considerably longer time in the case of the right colectomy. The longer time duration of the robotic techniques was attributed, to the endosomatic anastomosis. Nevertheless, there is no proof that the particular anastomosis is a better method in colectomy operations in comparison with the exterior anastomosis (18).

According to the above mentioned reports, the robotics colectomy is proved to be a feasible and safe method, but it is not related with better clinical outcomes despite the fact that the robotic system da Vinci is a technological step towards compared to the classic laparoscopic tools. For this reason, the relation between the technological virtues of da Vinci and anatomic characteristics during the colectomy should be taken into account. The large surgical field during the operation limits that advantages offered by the three-dimensional view that supports the robotic system (eg x10 zoom, stability). The surgeon has a good view of the surgical field, even when utilising the x2 enlargement that the classic laparoscopic technique offers, while a well-trained assistant can handle the laparoscopic camera.

In addition, the easy and suitable draught of the traditional laparoscopic tools compensates for the advantages of the two added degrees of freedom of robotic system during the colectomy operation, due to the large size of the surgical field which is not limited by any bone structures (eg the basin). The robotic surgery is in general, feasible and safe method for colectomy operations. Up until now however, it does not seem to be related with better clinical outcomes when compared with the open or conventional laparoscopic method. There are yet much needed technological developments to be utilised, such as the haptic feedback and the designing of special tools for suitable for pulling out the redundant colon. Moreover, the improvement of in exterior freedom of the robotic arm is also expected to be a technically improve colon operations, while collisions between the arms of system usually happens because the extraction of the redundant colon requires an external (out-of-body) movement of the robotic arm (19).

3.5. Thymectomy

Myasthenia gravis is rare disease that causes disorder of the normal neuromuscular synapsis and is characterized by progressive and rapid loss of muscular force during repeated or continuous efforts. Since 1941, when Blalock and his colleagues reported the outcomes of the first thymectomy on patients with serious myasthenia, this method has acquired an important role in the treatment of the particular disease. A number of techniques can be used for the removal of the thyme, namely the traditional thymectomy through the breastbone, thymectomy through the nape, the thoracoscopic approach with the aid of a moving image and, more recently, the robotic supported thymectomy with the surgical da Vinci system.

Regarding the last mentioned method, there already exist certain few studies that confirm the safety and effectiveness of the technique. Rea et. al (20) describe 33 cases of patients, 24 women and 9 men with (mean age=41 years), who were treated with robotic thoracoscopic thymectomy for heavy myasthenia without thymoma. The operations were performed between April 2002 and October 2004 in Italy. A left-side approach was adopted during the operations, via 3 small incisions because this provided better eye contact with the surgical field and decreased the chances of accidentally injuring the phrenic neuron. The mean time duration of the operations was 120 minutes and they were all successful without the appearance of any complications. Only two patients (6%) presented post surgical complications. The mean hospitalisation length was 2.6 days. The evaluation of the first 24 patients, after a mean post surgical period of 23.8 months, showed that 4 of them (16.7%) were cured and 18 of them (75%) were found to show clinical improvement.

3.6. Other Operations

Only a few cases of surgical operations with the support of robotic systems, in the spleen, the pancreas, the esophagus and the intestine have been reported, while the added value of the use of robots in hepatic operations is under consideration. The first application of robotic surgery in the pancreas concerned the removal of a neuroendocrinic tumor with the help of da Vinci system and was performed by Melvin in 2003 (21).

In another case, 8 patients went through a duodeno-pancreatic extraction. During these operations, hepato- and gastro- jejunoileal stomies were internally performed manually (with the surgeon's hand). The lack of haptic feedback technologies restrict, at least for now, the use of robotics in complex pancreatic operations. Such surgical process is also the operation Whipple, in which the use of surgeon's hand is absolutely essential (22). In splinectomy operations, the da Vinci system helps the surgeon determine the vessel structure and sketch out the spleen area while the precision of the surgical EndoWrist tools facilitates the exposure of spleen vessels. In 2003, however, Talamini et al. reported 2 ammendments in open surgical methods that they had to make due to the difficulties that met in 7 cases of robotics operation, proposing that spleen extractions should not be performed by robotics surgeries.

In another series of spleen extraction in 2005 that were performed by Bodner's team in 7 patients, using da Vinci the system,

there were observed no complications during the operation and no alteration in the predefined procedure was needed. The team concludes that robotics extraction of the spleen with the da Vinci system is technically feasible and safe, while it constitutes an alternative of the conventional laparoscopic method. Nevertheless, the team underlines that a restriction of this robotic system is the lack of compatible devices. For this reason, the surgical control of the suture of the splenic gate should be performed with the use of conventional devices (10).

Liver robotic surgery methods are yet under development and for this reason there are not many reports that support the effectiveness of such techniques. A series of left partial extractions were performed in the liver of 3 patients in the year 2007 in Seoul, and the process showed that the particular technique is also feasible and safe for patients with small malignant tumors and non-malignant hepatic diseases. The first of these cases concerned a hepatocytic carcinoma (HCC), the second patient was diagnosed with colon cancer with liver metastasis, while the third case concerned the existence of endohepatic stones. The above three operations were successful and the patients recovered without any complications. The hospitalisation length was smaller than the corresponding conventional methods, while the patients started eating normally (from mouth) early. Nevertheless, the first patient developed hepatocytic cancer three months after the operation (23).

4. DISCUSSION

The surgical robots constitute an integral piece of medical sciences. Commercial systems are already available many years now, and their clinical value has already been under scientific evaluation with the help of clinical trials. As an example, the control possibilities and the multiple degrees of freedom offered by the da Vinci system increase the virtuosity and limit the hand tremor of the surgeon, while the improved and detailed visualization of the surgical field allows the implementation of micro inosculations. In various cases, modern robotic systems decrease the length of hospitalization time and the above fact is related with positive outcomes for the patients but also economic gain for hospitals.

There is a view considering robotic systems as part of the information systems, having the ability to support technologies that are developed and already in use within the surgical hall. An example of the above is the merging of images from the various examinations (ie topography) with the image of the surgical field for the most effective guidance of the surgeon towards the identification of pathology and the performance of accurate incisions. This data can equally be used for the implementation of pre-operational trials in complex operations. The nature of robotic systems also supports the possibility for advisory services from experts and the guidance of operations from distance, while it provides opportunities for the training and evaluation of new surgeons via simulation.

Telesurgery is the next step of surgical robotics and despite various restrictions it appears to have great potential. One should, however recognise that telesurgery is just one aspect of telemedicine, and that all other applications, when combined together contribute to the improvement of medical care. Since the telecommunications technology makes rapid progress and the relative costs have significantly decreased, it is expected that telemedicine, including telesurgical applications should have an important impact in future.

Despite the fact that the effectiveness of robotics in surgical systems has been proved, it is important to recognize a number of issues related with the high cost of purchase and maintenance as well as with the bulkiness and weight within the surgical room (eg da Vinci system). Additional issues that should be considered is the adaptation within the new robotic reality, the training of the medical and nursing staff and the acceptance of the new technology both by surgeons and the patients. All conclusions concerning surgical robotics should always take into account that it is a relatively recent technology which has not been utilised enough and has not yet become common part of the everyday surgical practice. No conclusions can be made on the long term results of the use of robot systems and on the ultimate form the technology will be finally incorporated in most hospitals (24).

Robot systems are expected to keep improving and their evolution will help face the limitations described in this paper. Aim of the researchers is to develop robot systems that will allow the surgeons to feel and to have control of the tissues in a "natural" way during the operations. The currently available systems are based mainly in visual feedback. Magnified three-dimensional models guide the surgeons indicating them the diseased tissues, so that the amount of force that needs to be applied by the robot system can be controlled. Surgeons, however, usually use their hands during the operations and their actions are based on the information the touch of the tissues offers to them. The lack of haptic sense is considered to be the one of the most important disadvantages of modern systems. Even though there are many sensors and methods of control that offer haptic feedback, there are various issues that have to be resolved, namely the cost, the complexity and their compatibility with the robotic systems and the human tissues (25).

The familiarization of surgeons with the new technology is another important aspect. Some of them face robotics in surgery with reserve. This reaction is normal and expected, due to the fact that surgical education has remained unchanged for more than

one century. Even though many young surgeons seem to be interested in the application of robotic systems, very few institutions offer the required education and training. The integration of surgical robotics in the curriculum is not only expected to reduce the learning curve of new surgeons but it is should also lead to important changes in the way young surgeons improve their surgical skills, with the support of virtual environments.

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