IZOBRAŽEVANJE/EDUCATION

Robots and Medicine – Shaping and Defining the Future of Surgery, Endovascular Surgery, Electrophysiology and Interventional Radiology

Roboti in medicina - oblikovanje in opredelitev prihodnosti kirurgije, endovaskularne kirurgije, elektrofiziologije in interventne radiologije

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Abstract

The article is discussing the development of robotic surgery from its beginnings to the present. Introducing the early stages of development thinking on the use of robots in medicine, special emphasis is devoted to the latest knowledge in the creation of flexible robots. Described are the advantages and disadvantages of robotic surgery in different applications and also look to the future: where it will and can be implemented. A special emphasis is put toward robotic learning, simulations, and in this respect also the question how to develop new skills. is potentially answered.

Izvleček

Članek obravnava razvoj robotske kirurgije od njenih začetkov pa do danes. Uvodoma so predstavljene zgodnje faze razvoja uporabe robotov v medicini, poseben poudarek pa je na najnovejših dognanjih pri izdelavi fleksibilnih robotov. Opisane so prednosti in slabosti robotske kirurgije pri različnih namenih uporabe kot tudi pogled v prihodnost: kje se lahko in se bo uporabljala. Posebna pozornost je namenjena robotskemu učenju in simulacijam, s tem v zvezi pa se tudi že ponuja dogovor na vprašanje, kako razvijati nove sposobnosti.

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Ključne besede:
robotska kirurgija, fleksibilna robotika, elektrofiziologija, žilna kirurgija, posegi na srcu in ožilju

Key words:
robotic surgery, flexible robotics, electrophysiology, vascular surgery, cardiovascular interventions

Introduction

All the people dwelling in the world today are caught in between two realities: living in the past gives us memories but our dreams are focused on the future. In our memories as well as dreams, a not so marginal place may be occupied by a specific idea of a perfect machine, of a robot, which will take an important part in human society. Not all of us, however, are aware that this is already happening because in our generalized idea, robots are in reality anthropomorphic beings, much like Mr. Daneel Oliwaw, sculptured by Issac Asimov.[1] Looking around us, we live among robots, they are a part of our lives much more than can be seen with the naked eye – and also very dependent on how we define a robot. A cellular phone, a car, even an elevator – they are all specific robots, doing specific tasks, not available to human being, or so to speak, humans were not designed for those tasks.

We are in a constant conflict with our idea of an ideal robot, a perfect machine, and a reality, that at the end of the day, robots are imperfect machines because they are designed by imperfect beings, humans. Despite this fact, if you ask a patient if he/she should choose a robot before a doctor, the answer goes almost always in the robotic direction. This is not strange, however. What is strange is the lack of interest and dedica-

Citirajte kot/Cite as:
Zdrav Vestn 2011;
80: 614–31

Prispelo: 20. jun. 2011,
Sprejeto: 1. jul. 2011

tion of doctors to use this technology on a regular and routine basis.

This hesitation is best described by the chasm in the technology adoption life cycle,[2] which can be defined as a part of the so-called high-tech marketing illusion. This gap between innovators and early adopters on one side and early and late majority followed by laggards on the other is the empty space of present "robotic" day. It is not a question of money or financing for robotic medicine, it is a profound lack of understanding for both: the abyss of human imperfection combined with ignorance of its intellectual potential.

And it is true, that man is always reacting in a similar way proving that the law of increasing degree of ideality is the central law of evolution of technology.[3] Reaction to a new thing, including robotics and especially in medicine is simple: on one side we have understanding, implementation and evaluation, on the other destruction, disposal and ignorance.

It is the people who strive to advance humanity by crossing the chasm who are to be rewarded for what we have today: electricity, airplanes, a flag on the moon, beta-blockers, pacemakers and organ transplants.

Evolution of robotic instrumentation in surgery

The concept of *robotics* has evolved significantly over time and its use has had a large impact on many fields, including manufacturing, services, exploration and medicine. In some areas, robots simply help humans avoid doing tasks that are considered either unpleasant or harmful to them. In some other areas, robots serve as a cheaper and more reliable alternative to human labor. Yet, in particular fields, robots enhance our ability to carry out difficult tasks with a high level of precision and accuracy that is simply beyond the limits of manual manipulation.

What is a robot?

The Robot Institute of America sets a definition of what a robot is: "A reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks." While this definition broadly captures the concept of robotics, it fails to define the requirements for the interface between a robot and a human being. The so-called *autonomous* robotics removes the human factor from the equation once the robot is programmed and set to do its assigned tasks by interacting with its environment. A robotic device, however, does not have to be autonomous, and may continuously be intervened by a human factor, as in a surgical robot. In this context, robotics does not remove the human factor. It serves as an operant that removes the human factor from the immediate field of operation, translates manual manipulations to enhanced robotic movements, and introduces other degrees of freedom.

A brief history of robotics:

In 322 B.C., the Greek philosopher Aristotle wrote, "If every tool, when ordered, or even of its own accord, could do the work that befits it... then there would be no need either of apprentices for the master workers or of slaves for the lords," suggesting the possibility of robotics and insinuating how nice it would be to have a few robots around.

In 1942, Isaac Asimov used the word *robotics* for the first time in the short story Runaround and described "robotherapist," which served as a communication liaison device between man and machine. In 1956, George C. Devol who was a successful inventor and entrepreneur met with the engineer Joseph F. Engelberger and formulated the initial concepts for the first commercially purposed robot. Norman Schafler of Condec Corporation in Danbury provided the first seed investment to this duo, and hence the first commercial company to make robots called 'Unimation' (universal automation) was founded. Their first robot was called the "Unimate," and Engelberger became known as the "father of modern robotics."

General Motors purchased the first Unimate and purposed it for heated die-casting machines. Unimates were also utilized for spot welding on auto bodies. Unimate was to complete tasks that would be considered otherwise unsafe and difficult for humans to perform. The integration robotics into General Motors manufacturing process was quite successful and sparked the so-called *robotic industrial revolution*. Unimates worked reliably, saved money on labor, and allowed humans to avoid doing tasks that were considered particularly undesirable. In Japan, the first industrial robot was introduced in 1967. It was called Versatron and developed by American Machine and Foundary (AMF). Soon after, Kawasaki licensed the hydraulic robot designs from Unimation and began large volume production in Japan. From that time onwards, Japan has rapidly become the global leader in the design, development and distribution of robots of all types (particularly industrial). While Europe did eventually outperformed Japan in the number of industrial robotic applications, no single country comes close to Japan in the number of robotic installations. According to the International Federation of Robotics, Japan (approximately the size of California) has 60 % of the world's "working robots" and installed three times the number of industrial robots than did the U.S. and Germany in 2001 (28,369 vs. 10,824 and 12,524 , respectively). Germany, which is also a very industrialized country, installed 12,524 robots in the same year.[7]

Robotics in surgery

SRI telepresence surgical system

The United States Department of Defense had long been interested in making frontline access to surgical care more readily and immediately available to injured soldiers. During George H. W. Bush's administration, the National Aeronautics and Space Administration (NASA) Ames Research Center began to fund proposals aimed at developing remote medical capabilities.[4] Michael McGreevey and Stephen Ellis began to lead a team of researchers who investigated 19,861 computer-generated scenarios that could be perceived on head-mounted displays (HMDs).[5] An important member of this team was Scott Fisher who added 3D audio and developed the concept of "telepresence." This was the notion that "one person could be projected with the immersive experience of another (real or imaginary)." Meanwhile, Joseph Rosen, a plastic surgeon from Stanford, began to collaborate with Philip Green from Stanford Research Institute (SRI) to develop dexterity-enhancing robotic tools for telemanipulation.[6] These two teams would eventually collaborate, combining the "virtual reality" systems of NASA for an immersive experience with the dexterity enhancing robotics of SRI, and together Joe Rosen and Scott Fisher developed the fundamentals of telepresence surgery. The missing piece of the telepresence system was filled by a computer scientist named Jaron Lanier who had developed the notion of the "data gloves," which would digitally track the operator's hand motions and reproduce them at remote robotic instruments.[7]

With all these pieces put together, the initial robotic system conceived that the surgeon would be in a helmeted immersive sight/sound environment wired electronically to "data gloves" that would telemanipulate the end-effectors, which were substantially similar to open surgical instruments. However, many of these designed features were still unworkable from an engineering standpoint. The HMD had to be replaced with monitors and the data gloves replaced with joystick controllers at the surgeon's console.[7]

In 1989, serendipitously, the team involved with the telepresence project attended the meeting of the Society of American Gastrointestinal Endoscopic Surgeons (SAGES) in Atlanta, where Jacques Perrisat of Bordeaux presented on the technique of laparoscopic cholecystectomy. Upon their return, the team began thinking about applying the concepts of telepresence and telemanipulation to laparoscopic surgery. Their efforts made it possible to perform a bowel anastomosis using the telepresence surgery system. This robotic operation was presented to the Association of Military Surgeons of the United States in 1992 by Colonel Richard Satava who was involved with the project.[7]

As a result of this demonstration, Satava became the program manager for Advance Biomedical Technologies, funded by Defense Advanced Research Projects Agency (DARPA), to aid funding of technologically advanced projects. With adequate financial support available for the project, by 1995, the prototype of the robotic system was mounted into an armored vehicle (the Bradley 557A) that could "virtually" take the surgeon to the front lines and immediately render surgical care to the wounded. This system was called MEDFAST (Medical Forward Area Surgical Team).[8]

The prospects for this technology were actually beginning to look quite intriguing to SRI, at first for allowing expert surgeons to perform elective surgery on patients in rural locations, and potentially later for minimally invasive surgery where the "remote" surgery actually took place inside a patient using three specially-designed thin laparoscopic tools, while the surgeon's hands remained outside. Two of the tools would function as the surgeon's remote hands wielding various surgical tools within the patient, and the third would be the laparoscope itself (the cameras and lights).

PUMA for trans-urethral prostatectomy – 1988

In 1988, trans-urethral resection of the prostate were performed successfully with a unimate PUMA at Imperial College, London.[9] Further improvements to PUMA led to the advent of SARP (Surgeon Assistant Robot for Prostatectomy). This technology utilized a motorized version of the manual frame used in the previous robot. SARP was successfully applied in a live case in 1991, in Shaftesbury Hospital, Institute of Urology, London, UK. This case was perhaps the world's first reported robotic prostate surgery. The next generation of SARP was called PROBOT (robot for prostatectomies).[10]

ARTEMIS – 1990s

The ARTEMIS system (Advanced Robotic Telemanipulator for Minimally Invasive Surgery), was developed in Germany by Schurr and colleagues.[11] While this was a functionally successful robotic system that achieved six degrees of freedom, the project was ultimately terminated due to lack of funding.

HERMES and AESOP – 1993

In 1993, a faculty member at the University of California, Santa Barbara, Yulyn Wang, Ph.D., developed software for robotic control of motion and founded a company called Computer Motion. Wang developed a robotic camera arm called Automated Endoscopic System for Optimal Positioning (AESOP). He then became highly interested in complete robotic surgery and obtained funding to develop a modular robotic system to be integrated with AESOP. HERMES was the integrated operating room control system that allowed the complete integration of Computer Motion's robotic system.[12] In 2001, a device combining both the AESOP and HERMES was developed by Computer Motion, the ZEUS robotic system. This was a master-slave device that allowed the surgeon to be positioned at a console and control a separate robotic slave device.

da Vinci Surgical System (1995-present)

In 1995, Frederic H. Moll, M.D. (a successful medical device entrepreneur), Rob Younge (an engineer) and John Freund (an MBA from Harvard) became interested in the potential of the telepresence work from SRI.[13] By that time, laparoscopic techniques were widely and successfully used for almost 95 % of gall bladder surgeries and a few OB/GYN procedures, but for very little else. One significant problem for surgeons was that the external surgical movements in a typical laparoscopic procedure had to be done with "reverse" geometry relative to the procedure actually being performed in the body.[14] In addition, unwanted "tremor" could also be magnified by the surgical instruments, and

Table 1: Advantages and disadvantages of conventional laparoscopic surgery versus robot-assisted surgery.[18]

	Conventional Laparoscopic Surgery	Robot-assisted Surgery
Advantages	Well-developed technology Affordable and ubiquitous Proven efficacy	3-D visualization Improved dexterity Seven degrees of freedom Elimination of fulcrum effect Elimination of physiologic tremors Ability to scale motions Micro-anastomoses possible Tele-surgery possible Ergonomic position
Disadvantages	Loss of touch sensation Loss of 3-D visualization Compromised dexterity Limited degrees of motion The fulcrum effect Amplification of physiologic tremors	Very expensive High start-up cost May require extra staff to operate New technology Unproven benefit in many areas

there was a constrained range of motion and maneuverability inside the body cavity along with lack of depth perception, all of which affected the dexterity and confidence of the surgeon. As one of the recognized visionaries in the world of minimally invasive surgery, Fred knew that solving these problems, or at least minimizing them, would be a key to the future development of these surgical techniques.

Based on this vision, these three entrepreneurs founded a start-up company called Intuitive Surgical to build the first true surgical robot for laparoscopic surgery.[15] The *da Vinci* robotic system comprised three main components:

1. a master-slave software-driven system that provided control of seven-degree-of-freedom robotic instruments,
2. a three-dimensional immersive vision system, and
3. a sensor-based safety monitoring system to continuously reassess the device's performance to maximize patient safety.

The first prototype was tested in March 1997. By April 15, 1997 the first robotic surgery was performed by Jacques Himpens and Guy Cardiere of Brussels, Belgium: a robotic cholecystectomy.[16] The first 200-patient trial was completed on cholecystectomy and Nissen fundoplications leading to Food and Drug Administration (FDA) approval of this robotic system in July 2000 . In December 2002, the FDA also approved the use of the next generation *da Vinci* System with the addition of a fourth robotic arm to the tower.[7]

Intuitive Surgical set out to extend the benefits of minimally invasive surgery to the broadest possible range. Since the first *da Vinci* System shipment, Intuitive Surgical has expanded its installed base to more than 1,500 hospital sites, while sustaining growth in excess of 25 % annually.[17]

Advantages of *da Vinci* assisted surgery

The advantages of these systems are many because they overcome many of the obstacles of laparoscopic surgery (Table 1). They increase dexterity, restore proper hand-eye coordination and an ergonomic position, and improve visualization (Table 2). In addition, these systems make surgeries that were technically difficult or unfeasible previously, now possible.

The robotic systems enhance dexterity in multiple ways. Increased degrees of freedom built into the end-effectors greatly enhance the operator's ability to manipulate instruments and hence the tissues. The system can scale movements so that large movements of the control grips can be transformed into micromotions inside the patient. The robotic system eliminates the fulcrum effect, making manipulation of instruments more intuitive. Furthermore, this system comprises hardware and software filters that

Table 2: Advantages and disadvantages of robot-assisted surgery versus conventional surgery[17]

Human strengths	Human limitations	Robot strengths	Robot limitations
Strong hand-eye coordination	Limited dexterity outside natural scale	Good geometric accuracy	No judgment
Dexterous	Prone to tremor and fatigue	Stable and untiring	Unable to use qualitative information
Flexible and adaptable	Limited geometric accuracy	Scale motion	Expensive
Can integrate extensive and diverse information	Limited ability to use quantitative information	Can use diverse sensors in control	Technology in flux
Rudimentary haptic abilities	Limited sterility	May be sterilized	More studies needed
Able to use qualitative information	Susceptible to radiation and infection	Resistant to radiation and infection	
Good judgment			

compensate for hand tremors on the end-effectors.[19]

With the surgeon sitting comfortably at an ergonomically designed remote station, operator strain is minimized. The operator no longer needs to twist and turn in awkward positions to move the instruments and visualize the monitor.

The robotic system also restores proper hand-eye coordination. In addition, the enhanced vision afforded by these systems is quite remarkable. The 3-dimensional view with depth perception is a marked improvement over the conventional laparoscopic camera views. Also, the surgeon is able to directly control a stable visual field with increased magnification and maneuverability. All of these features help to create images with increased resolution that, combined with the increased degrees of freedom and enhanced dexterity, greatly enhance the surgeon's ability to identify and dissect anatomic structures as well as to construct microanastomoses.[17]

Given these technical advantages, the *da Vinci* Surgical System improves minimally invasive surgery in three fundamental ways:[16]

1. *da Vinci* Surgery simplifies many existing minimally invasive procedures,
2. *da Vinci* Surgery makes difficult operations routine,
3. *da Vinci* makes new minimally invasive surgical procedures possible.

By improving surgical capabilities, Intuitive's products have also shown to improve clinical outcomes in different areas. Patients may experience the following benefits (specific to the referenced procedures):

- Excellent cancer control, where indicated[20]
- Less blood loss and transfusions
- Shortened hospital stay[21]
- Less pain[20]
- Low risk of infection, complications[19]
- Fast recovery and return to normal activities[22]
- Small incisions for less scarring[23]

Disadvantages of *da Vinci* assisted surgery

There are several disadvantages to the robotic system. The robotic system occupies a large space in the already crowded operating rooms and robotic arms, though improved significantly in design, are still cumbersome.[24] Miniaturizing the robotic arms and instruments may address the problems associated with their current size. At the same time, many centers simply adopt larger operating suites with multiple booms and wall mountings to accommodate the extra space requirements of robotic surgical systems. The cost of these robots and larger operating suites make them an especially expensive technology.[17]

Another disadvantage of robotic systems is a lack of compatible instruments and equipment. The lack of certain instruments increases reliance on tableside assistants to perform part of the surgery.[25] New technologies, however, will likely be developed to address these shortcomings.

Importantly, robotic surgery is still a new technology and its uses and efficacy have not yet been well established in many areas. Many procedures will also have to be redesigned to optimize the use of robotic arms and increase efficiency.[17]

Most of the disadvantages identified will be remedied with time and improvements in technology.

Evolution of robotic cardiovascular surgery

Valve Procedures

During the past decade, the advent of robotic instrumentation system, advances in closed-chest cardiopulmonary bypass (CPB) and myocardial protection, and improved intra-cardiac visualization, have enabled a shift toward a more minimally invasive endoscopic cardiac surgery.

Conventional cardiac valve operations have been performed through a median sternotomy, which provides generous surgical exposure and allows ample access to all cardiac structures and proximal great vessels. Today, it is possible to perform complex reconstructive mitral valve operations through small incisions using a robotic interface. So far, surgical results have been promising. Innovations in computer-assisted tele-manipulation cardiovascular surgery occurred rapidly in the mid 1990s. By 1998, Carpentier and colleagues[26] had performed the first truly endoscopic mitral valve repair using an early prototype of the *da Vinci* Surgical System. In 2000, Kypson and colleagues performed the first complete mitral valve repair in North America using the *da Vinci* system.[27] In that operation, a large P2 trapezoidal resection was done with the defect closed using multiple interrupted sutures, followed by implantation of an annuloplasty band. Mehmanesh and colleagues were the first to perform a totally endoscopic mitral valve repair using only 1-cm ports and the *da Vinci* system.[28] Although most surgeons still use a 4-cm incision for assistant access, robotic technology has progressed to a point where totally endoscopic mitral procedures are the routine operation of choice for patients having isolated mitral valve pathology.[29]

Coronary Artery Bypass Grafting

Less invasive coronary artery surgery techniques aim at combining the advantages of CABG and interventional cardiology techniques. Minimizing the incision and the deleterious effects of cardiopulmonary bypass (CPB) has always been the main impetus for cardiac surgeons to pursue less invasive strategies. The ultimate goal of minimally invasive coronary revascularization has always been to perform totally endoscopic CABG without CPB on the beating heart.[30] As an intermediary step, cardiac surgeons opted for the completion of CABG through three 1-cm ports with the heart arrested during the anastomosis. Attempts with this technique were confronted with problems of limited visualization and increased technical difficulties when using standard endosurgery instruments with limited range of motion.[31]

In endoscopic surgery, looking at a monitor and using conventional endoinstruments, the operator loses his visual perception of depth and the natural hand-eye coordination. In terms of motion, the classic endoinstruments have only 5 degrees of freedom. Moreover, the hand of the surgeon and the tip of the instruments move in opposite directions. These limitations have restricted the use of endosurgery techniques to mainly excisional procedures.

The development of the *da Vinci* system's "master-slave robotics," incorporating not only robotic assisted visualization but also robotic assisted instrumentation, provided surgeons with an unprecedented opportunity to finally carry out cardiac surgery endoscopically. The system's kinematic (or joint movements) structure allows the surgeon to use his traditional open surgery techniques at the console ("master"), which are simultaneously reproduced using endosurgery movements by the instruments (slaves) at the surgical site with 7 degrees of freedom. In other words, the system acts as

Figure 1: Flexible robotic arm for 3D catheter control

a translator of open surgery techniques into endosurgery techniques with set-up joints brought as close to the tissue as possible.[32]

In regards to LITA harvesting, the system's high magnification allows dissection of a very thin vascular pedicle without injuring the intercostal muscles or the periosteum of the costal cartilages. Three-dimensional vision provides a much better perception than 2-dimensional visualization as far as spatial orientation of the vessels and the instruments are concerned. The "mechanical wrist" allowed for a full range of motion of the tip of the instruments, which facilitated the dissection in remote areas such as the proximal and distal extremities of the LITA pedicle.

The capability of the system is also fully appreciated during the completion of the anastomosis. The distal articulation of the instruments allows perpendicular suture needle positioning to the arterial tissue in all cases. Image magnification allows observation of important details that cannot be seen in open surgery, such as microclots or microdroplets of fat present in the anastomotic site. Three-dimensional vision also allows perfect control of the needle trajectory during suturing.

While the first generation of the *da Vinci* robots addressed many of the challenges that cardiac surgeons faced in performing endoscopic bypass grafting, still there were design challenges that limited its use in totally endoscopic off-pump coronary artery bypass grafting such as lack of tactile feedback, lack of traction and countertraction, difficult exposition of coronary target sites, limited endothoracic space and suboptimal epicardial stabilization, and a limited visual field within the chest.[33]

The first step toward beating heart multivessel TECAB was independent of the evolution of the robotics technology and was made possible by the elimination of the heart–lung machine and the access trauma of a sternotomy from conventional CABG, the so-called MIDCAB technique. This paradigm shift, away from conventional coronary artery bypass grafting with the heart–lung machine, was stimulated by reports in 2001 of decreased risks-adjusted morbidity and mortality and improved outcomes associated with off-pump coronary artery bypass grafting from large multi-institutional studies of the Veterans Administration[34] and The Society of Thoracic Surgeons database.[35] Improved outcomes were confirmed by hundreds of peer-reviewed studies and

Table 3: Current Applications of rigid robotic surgery[17]

Orthopedic surgery	Neurosurgery	Gynecologic surgery	Cardiothoracic surgery	Urology	General surgery
Total hip-arthroplasty; femur preparation	Complement image-guided surgery	Tubal re-anastomosis	Mammary artery harvest	Radical prostatectomy	Cholecystectomy
Total hip arthroplasty; acetabular cup placement	Radiosurgery	Hysterectomies	CABG	Ureter repair	Nissen fundoplication
Knee surgery		Ovary resection	Mitral valve repair	Nephrectomy	Heller myotomy
Spine surgery					Gastric bypass
					Adrenalectomy
					Bowel resection
					Esophagectomy

were reported by Reston and colleagues in a meta-analysis.[36]

As the MIDCAB and TECAB procedures evolved, the *da Vinci* system evolved to further enable these procedures and address many of the previous limitations of the system.

- The robotic arms were improved to make the procedures less sensitive to perfect placement of the thoracic instrument ports. The size of the robotic arms was reduced, allowing them to be placed in a wider range of positions around the patient's body. Greater flexibility in access to the patient's chest resulted in an ability to reach more coronary vessels through the same access points.
- A fourth robotic arm was added to the system in addition to the two existing surgical instrument control arms and the endoscopic camera control arm. The fourth arm was selectively controlled by the surgeon to "assist" in the procedures by stabilizing or retracting tissue.
- A new suction-enhanced beating heart instrument was added for stabilizing and retracting cardiac tissue. The new instrument provided secure and stable access to the coronary vessels on a beating heart during the surgical anastomosis.

With these advancements, one out of three patients was becoming eligible for a true beating- heart TECAB, and the conversion rate to a MIDCAB procedure (originally at about 30 %) slowly began to decline with improved operative technique.[37]

Despite all these accomplishments and advancements, the dream of robotically-enhanced multi-vessel TECAB has not yet been fully realized. There have only been sporadic cases where multi-vessel TECAB has been attempted, and the technique of endoscopic bilateral IMA (BIMA) grafting can be performed on very few patients.[36] However, both the robotic technology and the operative technique are evolving towards the right direction to make this dream a reality.

Benefits of robotic cardiac surgery to patients

In general, minimally invasive heart surgery offers patients several advantages compared to open-chest procedures, including:

- **Faster return to normal activities.** Rather than waiting several weeks to heal, patients can return to work or other activities much more quickly—usually within three weeks.
- **Shorter hospital stay.** Time spent in the hospital can sometimes be reduced by as much at 50 percent, compared to open procedures.
- **No splitting of the breastbone.** Keeping the breastbone (sternum) intact reduces the chance for post-surgical complications and infection.

Figure 2: Hansen Medical's Sensei® system

- **Smaller incisions.** Depending upon the case, the operation may be performed through four to five dime-size incisions, or through a 2- to 5-inch incision at the side of the chest. Traditional open-heart procedures require a longer incision down the center of the chest.
- **Quicker resolution of pain.** Decreased damage to tissue and muscle results in pain that does not last as long as after a sternal incision. Tylenol or aspirin are often enough to manage pain after hospital discharge.
- **Elimination of the heart-lung bypass machine, in most cases.** Avoiding the bypass machine decreases the risks for neurological complications and stroke.
- **Minimal blood loss and less need for transfusion.**
- **Little scarring.** Instead of a long chest scar, only a few tiny scars or a short, 2- to 5-inch scar remains.

Evolution of Robotic Thoracic Surgery

There are relatively few publications on non-cardiac robotic chest surgery, and even fewer detailing the preparation and planning necessary for an efficient robotic procedure. Moreover, the number of cases performed at any single institution has been insufficient to achieve adequate experience. Cardiac and respiratory movement presents technical challenges for detailed work that are not present in other endoscopic surgical procedures. Kernstine provides a good overview of some of the thoracic procedures performed with robotic assistance to this date.[38] Some of the procedures that may lend themselves well to robotics include Nissen Fundoplication,[39] esophageal myotomy (or Heller) procedure,[40] resection of esophageal masses,[41,42] esophagectomy (mainly for neoplasia),[43] RATE (Robotically-Assisted Transhiatal Total Esophagectomy) procedure,[44] thymectomy,[45] removal of anterior and posterior mediastinal masses,[46,47] and video-assisted lobectomies.[48] Case reports describing these procedures have demonsrated that robotic chest surgery may be performed safely and a number of institutions are actively leveraging the technology in pursuit of better patient outcomes. As confidence in the instruments and techniques improves, we expect that more and varied procedures will be performed.

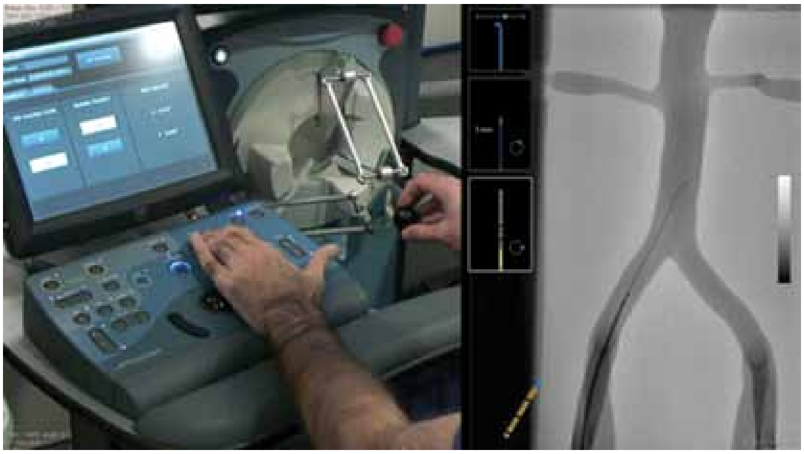

Figure 3: Magellan™ vascular system

Applications of rigid robotic assisted surgery

To date, surgeons have performed robotic procedures in various areas (Table 3).

Flexible Robotics

Hansen Medical Flexible Robotic Catheter System – Sensei™

As the success of the *da Vinci* system became apparent, the founders of Intuitive Surgical, led by Fred Moll, set out to revolutionize the field of medical robotics once again, this time focusing on developing flexible robotics technology as opposed to rigid robotics. This was the vision behind founding Hansen Medical in 2002.

Hansen Medical's technology would overcome the limitations of manual technique by facilitating accurate positioning, manipulation, and stable control of catheter and catheter-based technologies during electrophysiology (EP) procedures. The system provided Instinctive Motion™ control and navigation of flexible catheters, resulting in enhanced access, stability, and control in complex interventional procedures. The key to this realization is the company's proprietary Instinctive Motion™ technology that accurately and responsively translates the physician's hand movements at the motion controller to the robotically controlled steerable catheter in the patient's anatomy. This unique combination of technology and ergonomics helps physicians to establish a new standard of care by enabling a new class of percutaneous procedures using advanced electromechanical technology.

In 2007, Sensei® Robotic Catheter System & Artisan™ Control Catheter were cleared by the FDA and received CE Marks. Since then, more than 100 installments have taken place worldwide, and the system is used to perform catheter ablation procedures mostly in patients suffering from medication refractory atrial fibrillation and/or flutter. Improved navigation, maneuverability (Figure 1), and catheter stability has shown to offer distinct clinical benefits for both operators and patients.

Sensei® X Robotic Catheter System

The Sensei® X Robotic Catheter System (Figure 2) combines advanced levels of 3D catheter control and 3D visualization to bring physicians accuracy and stability during catheter-based electrophysiology procedures. By translating hand motions at the workstation to the control catheter inside the patient's heart, the Sensei X System's proprietary instinctive motion control technology empowers accurate and deliberate catheter placement.

Artisan Extend™ Control Catheter

The Artisan Extend™ Control Catheter is designed to work in harmony with the Sensei® X Robotic Catheter System by providing advanced navigational capabilities and the flexibility required to reach difficult-to-access cardiac anatomy while maintaining stability during complex cardiac arrhythmia procedures.

CoHesion™ 3D Visualization

The CoHesion 3D Visualization Module combines the accuracy of 3D catheter control with the visual guidance of 3D electroanatomical mapping, a synergistic technology combination that realizes the full potential of instinctive motion.

IntelliSense® Fine Force Technology® Interface

IntelliSense® technology measures fine forces on the working catheter—an important advance because evidence suggests a link between force and map quality.[49] IntelliSense includes a tactile vibration feature that provides immediate feedback on

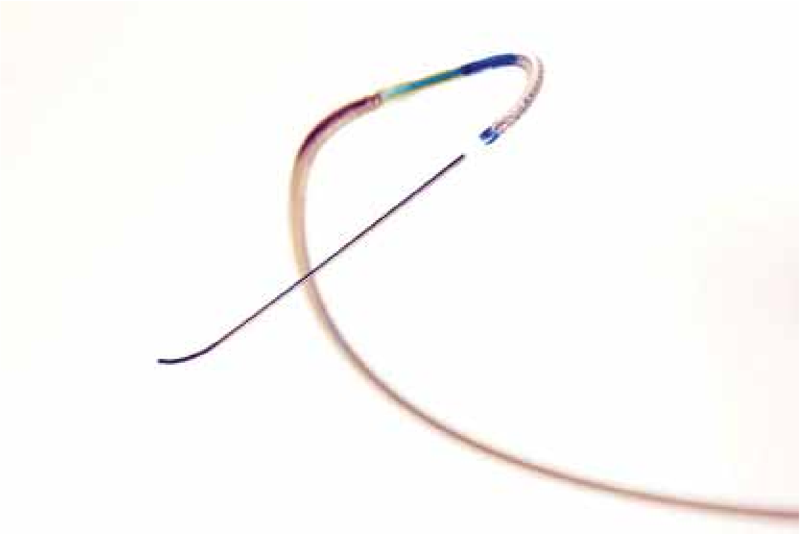

Figure 4: Vascular catheter used in Magellan™ vascular system.

IntelliSense's proximal force measurement—so the user sees a visual measurement of force and feels it through vibration of the Instinctive Motion Controller (IMC). IntelliSense utilizes advanced processing to ignore frictional drag forces and discern small force variation so the operator gets constant, reliable feedback delivered in a clear and instinctive tactile and visual format.

Hansen Medical Flexible Robotic System – Magellan™

Although open surgery remains the gold standard, endovascular techniques and devices have improved dramatically over the last several years, thereby making endovascular therapies the preferred option of treatment for numerous interventionalists. However, endovascular treatments are not without challenges. Endoluminal navigation is plagued by several elements, namely the limitation of range of motion provided by the available pre-shaped catheters as well as embolization and wall injuries provoked by those same catheters. Endoluminal therapies today rely on a series of wall and catheter interactions in order to allow a therapeutic device such as a stent or angioplasty balloon to reach its target vessel. This is not without consequence as our group has recently shown that navigation in the thoracic aorta and in particular the aortic arch leads to significant cerebral embolization.[50] Therefore a mode of navigation is proposed, which minimizes embolic potential, namely off-the-wall, or center lumen navigation.

As mentioned, Hansen Medical made accurate 3-dimensional remote control of an endovascular catheter possible by developing Artisan™ Catheter and Sensei™ Robotic System. Although EP is the only application area for which this technology has so far been approved, its clinical utility for endovascular intervention was quickly demonstrated in some of the off-label uses. For example, the group from Methodist Hospital in Houston performed pulmonary artery stenting in a patient who could otherwise not be managed with standard catheterization techniques.[51] Feasibility has also been demonstrated clinically in such spaces as endovascular repair of infra-renal aortic aneurysm,[52] and Valderrabano and colleagues at The Methodist Hospital in Houston, Texas, have in the EP lab performed robotically assisted valve repairs (unpublished data). These applications only scratch the surface of potential usages for flexible robotics.

Extending the benefits of flexible robotics technology to endovascular interventions, in 2008, Hansen Medical set out to create the first robotic vascular catheter platform to facilitate vessel navigation, selective angiogram generation, robotic guidewire control, and therapeutic device placement and delivery. The new vascular system, called Magellan®, is designed and engineered to meet the needs of vascular surgeons, interventional cardiologists and interventional radiologists, and extends the current Hansen Sensei® architectural advancements in robotic catheter manipulation, catheter design, robotic capabilities, instinctive control, and data visualization.

By offering a stable, steerable catheter tip, and a remote catheter control interface that enables instinctive driving, this new vascular system offers a myriad of potential benefits that may (1) allow clinicians to perform procedures less invasively, (2) reduce radiation exposure to patient and physician, (3) and reduce the likelihood of failure, complications, and prolonged procedure times. Targeted endovascular procedures cover procedures performed in the arterial and venous vasculatures and include interventions involving the abdominal and thoracic aortic grafting as well as access and stenting of branches of the aorta and arterial system including the coronary and carotid arteries and the iliac, femoral, popliteal, renal and mesenteric vessels.

One of the major limitations of using the EP system for endovascular interventions was the dimension of the currently approved Artisan™ catheter, which stands in direct contrast to that of the new Magellan™ vascular system (Figure 3). The Artisan™ is significantly larger than the vascular catheter, as the outer lumen of the sheath on the vascular system actually corresponds to a 7Fr. equivalent standard sheath. Although, both systems are built on the same basic concept—a leading catheter that telescopes within a flexible sheath—the differences are not so subtle when one is familiar with them. Due to the smaller diameter, some of the stability of the Vascular Robotic Catheter sheath is sacrificed in order to make it significantly more flexible. A further difference is that the Artisan™ sheath can only flex to one side, whereas the vascular sheath has the same degrees of freedom on all sides, as does the leading catheter (Figure 4). As a result, the operator can safely access more difficult branch vessels such as mesenteric, renal or carotids, with the vascular catheter, even though some groups had already demonstrated improved cannulation times in silicone models even with the Artisan™ catheter. In addition, it has been shown in an animal model that the vascular robotic catheter not only enables the operator to perform these maneuvers efficiently but also safely (publication pending in Journal of Endovascular Therapy, April 2011). This small experience demonstrated that vessel injury in the renal, superior mesenteric and iliofemoral arteries was significantly less than in corresponding manual catheterization cases, which was demonstrated by both gross and histological examination.

This efficacy of navigation has also been corroborated clinically as part of a first-in-man study in Ljubljana, Slovenia, where in 2010 we treated a total of 20 legs with the vascular robotic system, successfully performing interventions on the iliofemoral arterial segment (Fugure 5). The goal was to navigate the system across the aortic bifurcation and into the contralateral femoral artery, which was achieved in all patients. This speaks in great part to the strength of the robotic system.

Evolution Continues

As described, the evolution of robotic instrumentation in surgery has been both fascinating and remarkable over the past few decades. Today, both rigid robotic systems such as Intutitive Surgical's *da Vinci* system as well as flexible robotic systems such as those developed by Hansen Medical are becoming standard parts of hospital settings and help physicians perform complex procedures with more confidence. Of course, patient outcomes still need to be scrutinized fully in order to identify which procedures unequivocally benefit from robotic assistance. Advances in imaging, information technology, and decision-making support tools have also complemented the evolution of robotics. The reason one may find it difficult to distinguish where surgeon's manipulations end and where the robotic instrumentation takes over is that surgeon and robot are part of a continuum and only together form a complete system that may help patients achieve better outcomes.

Future of Robotic Instrumentation in Surgery

Robotic surgery still has a long way to go and perhaps some of the most compelling application areas are yet to be discovered. Many obstacles and disadvantages will be resolved in time and undoubtedly many other questions and opportunity areas will arise. Aside from some of the well-known technical questions and challenges, we need to answer questions such as malpractice liability, credentialing, training requirements, and interstate licensing for tele-surgeons, to name just a few.

Figure 5: Magellan™ vascular system mounted to imaging system.

Overcoming mechanical constraints

The current size of rigid instruments, intrathoracic instrument collisions, and extrathoracic "elbow" conflicts still can limit dexterity. Similarly, flexible robotic instruments such as Hansen Medical's robotic catheters do not yet offer complete range of sizes typically required for interventional procedures. As smaller instruments are developed, these restraints may be resolved and newer applications such as microsurgery in the eye or the ear or endovascular interventions in neurovasculature may be attempted.

Technically, much remains to be done before robotic surgery's full potential can be realized. Although these systems have greatly improved dexterity or catheter control, they have yet to develop the full potential in instrumentation or to incorporate the full range of localization and sensory input. In addition, more standard mechanical tools and more energy directed tools need to be developed.

Long-distance surgery

The nature of robotic systems also makes the possibility of long-distance intraoperative consultation or guidance possible and it may provide new opportunities for teaching and assessment of new surgeons through mentoring and simulation.

Robotic surgery advancing diagnostics

Some authors also believe that robotic surgery can be extended into the realm of advanced diagnostic testing with the development and use of ultrasonography, near infrared, and confocal microscopy equipment.[53]

Simulation

The robotic system may serve as both a pre-procedural planning as well as an educational tool. Surgical vision and training systems will help us model most procedures through immersive technology. Over the past decade, we have seen a burgeoning use of preoperative (computed tomography or magnetic resonance) and intraoperative video image fusion to better guide the surgeon in dissection and identifying pathology.[54] Indeed, a "flight simulator" concept is emerging where surgeons may be able to practice and perform the operation without a patient.[55] Future systems might enable a surgeon to program the surgery and merely supervise as the robot performs most of the tasks.

In 2004, the Food and Drug Administration (FDA) suggested that simulation should be an integral part of the training of interventionalists who wish to perform carotid artery stenting (CAS) procedures.[56] Advances in simulator technology now allow the individual interventionalist to upload and incorporate patient-specific Digital Imaging and Communications in Medicine (DICOM) imagery data (computed tomography (CT) and magnetic resonance imaging (MRI)) into the simulation software, so that the surgeons or interventionalists can rehearse and plan the procedure on the real patient's anatomy, prior to performing the intervention on the patient.[57,58]

One such simulation platform is developed by Simbionix USA Corporation (Cleveland, OH, USA). The Simbionix PROcedure™ rehearsal studio software is used to create the 3D reconstruction and the AngioMentor™ Express simulator may be used to conduct the patient-specific simulation . The simulator includes a haptic device, simulation computer, two LCD screens and controls for table movement, contrast medium injection, fluoroscopic C-arm positioning, cine-loop recording, road mapping, balloon inflation and stent deployment. The haptics unit is designed to be the virtual patient with a simulated introducer in the groin, and allows the user to insert and manipulate guidewires, embolic protection devices (EPDs), catheters, balloons and stents.[59]

Willaert et al. evaluated the utility of this simulator on a carotid artery stenting (CAS) procedure.[60] Thirty-three endovascular physicians with varying degrees of CAS experience participated: inexperienced (5–20 CAS procedures; n = 11), moderately (21–50 CAS procedures; n = 7) or highly experienced (> 50 CAS procedures; n = 15). Investigators noted that the simulation had a significant influence on the behavior of interventionalists performing a difficult CAS, especially on the selection of catheters and (guiding) sheaths to access the common carotid artery as well as the optimal fluoroscopy angles. Moreover, they noticed that inexperienced interventionalists often altered their approach to stenting and balloon dilation based on the simulation. The rehearsal also provided an excellent opportunity for the participants to assess the complexity of the case. As a result, 20 % of the participants indicated that they would likely benefit from having a more experienced interventional team than they had initially planned. At the same time, highly experienced group of practitioners noted the same preference, even though prior to the rehearsal they had had generally indicated that they required a less experienced team. This change reflects the observation that even experienced interventionalists can underestimate the complexity of specific cases based solely on a preoperative review of standard two-dimensional (2D) and 3D CTA images.[58] This phenomenon is also documented by surgeons performing other complex procedures.[61,62]

Integrating Hansen Medical's Magellan™ Robotic Vascular Catheter Platform with simulators such as the one developed by Simbionix brings us a step closer to performing true patient-specific rehearsals before the operation. By incorporating fiber optic shape sensing and localization (FOS-SL) technology into robotic catheters, a rehearsed procedure could be implemented in-vivo with catheter location and shapes registered intra-operatively with pre-operative 3D reconstructions. While full integration and registration are key requirements for making this vision possible, 3D models should either forecast device-vasculature interactions before the actual operation begins or adjust robotic movements real-time based on intra-operative imaging. While we still have to make significant advancements before this vision is fully realized, the path towards such capabilities that can offer true patient safety and outcome benefits is now clear.

Informatic Surgery

The advent of surgical robotics, in combination with other technologies, introduces the possibility of a new data-driven paradigm, which Lang and Sutherland call *Informatic Surgery*:

> "The performance of surgery using multiple inputs and outputs, to and from the surgeon, and hence from and to the subject of surgery (i.e., the patient), in such a manner that the inputs and outputs are interpreted and modulated by a central computer system."[63]

Informatic surgery extends the concept of surgical simulation. Whereas robotic-assisted surgery requires all interactions between surgeon and patient to be mediated by computer, the motions and forces of surgery can be digitized, recorded, and recreated . Hence, future surgeons will be instructed on how to manipulate tissue in quantified forces and guided maneuvers. Unwanted and errant surgical behaviors are identified and discouraged, while wanted and effective surgical techniques are reinforced. This approach will significantly advance surgical education and reduce the learning curve associated with new surgical techniques. Hence, informatic surgery may potentially enable us to formally study, objectively teach, and uniformly standardize surgical techniques to the extent possible. Tissue manipulation data, generated during surgery, will be applied to both quality assurance and the creation of increasingly realistic surgical simulation.[63]

While necessary, surgical robotics is by no means sufficient for the realization of informatic surgery. The operating room contains a dynamic data set of boundless complexity, which the surgeon has to process and manipulate. The digital replication of, and immersion within, this data set by means of a multisensory human–machine interface defines the surgical algorithm. The field of haptics is determining how touch can be reproduced and binocular optics can effect 3D visualization in high definition. We need to be able to recreate the entire spectrum of sensory information (sight, touch, and sound) before we can achieve optimal integration of robotics into the operating room.[63]

Leveraging multi-modality imaging data sets enhances informatic surgery beyond the natural human sensorium. Imaging advances that would allow better visualization of anatomic structures, specific identification of neoplastic cells at the molecular level, and information about function within organ microenvironments will further enable surgeon's capabilities.[63]

Overall, informatic surgery is an extension of robotic surgery and its realization is dependent on our ability to generate, collect, and utilize surgical data. As Lang and Sutherland aptly describe:

> …The master-slave organization of most surgical robotics platforms serves to couple the accuracy of robotics to the decision-making capacity of the human surgeon. Imaging modalities and sensory replication will continue to advance, illuminating that which is invisible to the naked eye and making felt that which eludes the fingertips. This expanse of data will be mated to precision unavailable to even the most dexterous. The works of the grand masters of surgery will be recorded, and a replicable gold standard created. With each using its unique strengths, human and machine will combine to improve surgery.[64]

Final Remarks

The future of robotics in surgery is limited only by imagination and cost. We must continue to critically evaluate robotic technology in this new era. We must be careful because indices of operative safety, speed of recovery, level of discomfort, procedural cost, and long-term operative quality have yet to be defined. Traditional valve operations or carotid endarterectomy, for example, still enjoy long-term success with ever-decreasing morbidity and mortality and remain our gold standard. We must remember that we are seeking the safest and most efficacious operation at the lowest cost. Although we have so far been successful, we should be careful to choose the right path for the remainder of this exciting journey.

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