Medical robots in cardiac surgery

Roboty medyczne w kardiochirurgii

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Streszczenie

Chirurgia jest związana ze złożonym postępowaniem wymagającym dokładnej kontroli pozycji i siły w czasie operacji. Artykuł stanowi krótki przegląd możliwości aplikacyjnych robotów w zakresie kardiochirurgii. Współczesna historia robotyki medycznej w chirurgii została utworzona przez amerykańskie telemanipulatory da Vinci i Zeus, ale rozwija się następne pokolenie chirurgicznych robotów. Fundacja Rozwoju Kardiochirurgii (FCSD) realizuje konsekwentnie projekt polskiego robota Robin Heart oraz innowacyjnych, mechatronicznych narzędzi. Potencjalny obszar stosowania robotów w kardiochirurgii obejmuje dziś takie procedury, jak: operacje naprawcze zastawek serca, serca i naczyń oraz rewaskularyzację laserową. Autor rozważa również możliwość zastosowania robota do wszczepiania i serwisowania sztucznych narządów układu sercowo-naczyniowego.
Słowa kluczowe: chirurgia, kardiochirurgia, roboty medyczne, narzędzia chirurgiczne, sztuczne narządy.

Abstract

Surgery is a complex procedure requiring precise control of position and force. A review of application of robots in cardiac surgery has been performed. Contemporary history of medical robotics in surgery has been created by the da Vinci and Zeus systems, but the next generation of surgical robots is developing. The Foundation of Cardiac Surgery Development (FCSD) is implementing the project of the Polish robot named Robin Heart and mechatronic tools. The potential applications of robotics in cardiac surgery include: valve replacement and repair, ventricular restraint jacket, transmyocardial laser revascularization, ventricular septal defect, patent ductus arteriosus, and coarctation. The possibility of robot application for heart prostheses implantation and service is considered.
Key words: surgery, cardiac surgery, medical robots, surgical tools, artificial organs.

Introduction

Surgery is a complex procedure requiring precise control of position and force. The robot is intended to keep the surgeon in the most comfortable, dexterous and ergonomic position. The main task of the robot (Master-Slave teleoperator) is reliable mapping of surgeon hand movements (setting of position/velocity/acceleration of other physical quantities) onto the movements of the tool arm, through calculation of control signals for its motors.

Cardiosurgical robots have been produced by two, currently merged, companies, Computer Motion® (Computer Motion Inc. of Goleta, Calif., CM) produced ZEUS and AESOP robots, and Intuitive Surgical® (Intuitive Surgical, Mountain View, Calif., IS) produced da Vinci (DV), first used in European clinics [2-6]. The world's first mechanical surgeon's assistant – the voice-controlled endoscope positioner AESOP 1000 (Auto Endoscopic System for Optimal Positioning) – was introduced by the firm CM in 1994. Currently IS's primary focus remains the *da Vinci* Surgical System. Today approximately 400 *da Vinci* Systems have been installed worldwide, and its application has been described in thousands of scientific publications and presentations. To date, tens of thousands of procedures, including general, urological, gynaecological, thoracoscopic and thoracoscopically-assisted cardiotomy procedures have been performed using the *da Vinci* Surgical System [1].

Contemporary history of medical robotics in surgery has been created by the *da Vinci* and Zeus systems, but in several laboratories and universities the next generation of surgical robots is waiting to cross from the laboratory to the surgery. The Foundation of Cardiac Surgery Development (FCSD) is implementing the project of a Polish robot useful for cardiac surgery. The multidisciplinary team has prepared families of robot prototypes named Robin Heart and mechatronic tools [7]. 3D modelling using a virtual reality technology based on EON Reality software was carried out

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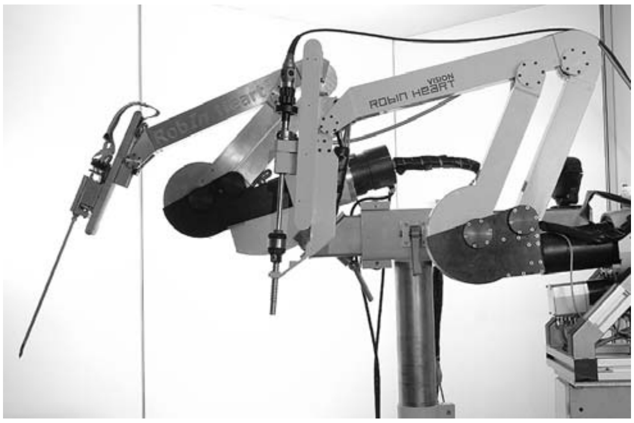

B

C

Fig. 1A-C. Robin Heart *in vitro* expreriments
A – Robin Heart & Robin Heart vision; B – the telemanipulation study; C – the Pig Heart robotically assisted surgery

in FCSD [8] to plan a complete system scene of the clinical operating room, including Robin Heart, and was used to demonstrate the procedures in figures in this article. This advanced training station can be used to plan a future realistic surgery process (surgeon test) or can be used to simulate a natural robot behaviour (robot test).

Robin Heart

Several models and prototypes of Polish **Robin Heart** robots for use in cardiac surgery have been created between 2000 and 2007. Now test results of these arms are the basis for work on the new tele-manipulator systems including the modification of both the mechanical and control part with special focus on development of its safety system. Presented test results of both mechanical and electronic parts of Robin Heart tele-manipulator systems show significant progress both in their dimensions and weight as well as improvement of characterizing the test parameters.

The Robin Heart manipulator has a very good and relatively large working space, in which the surgeon can select a small subspace with very good isotropic kinematic properties for manipulating objects with good position accuracy. This arm is based on the spherical structure, using parallelograms for constructing a constant point mechanism. Accuracy and reliability tests were performed for several types of driving systems for this mechanism. The system was verified both functionally and technically by means of innovative testing methods for precise external robotic arm trajectory registration (testing stand based on several digital cameras or using gyroscopic and accelerometer sensors for vibration analysis). Standard technical evaluation allowed estimation of the value of positioning resolution equal to 0.1 [mm].

The current state of the Polish Robin Heart family (the first European cardio-robot) is represented by eight years of experience in cardiac surgery robot development that started from basic studies. Our first prototype Robin Heart 1 – a surgery tool telemanipulator – and the latest robot, Robin Heart Vision – a robotic arm for endoscopic, visual channel holding – are original Master-Slave tele-manipulators equipped with a user interface tool, control system and arm with surgery tool (Fig. 1). The original surgical console prototype Robin Heart Shell has been constructed. We are also working on innovative surgical tools "for hand and for robot" – the project Robin Heart Uni Tools System. This mechatronic device will be used as robot arm equipment or as an endoscopic tool manually manipulated directly by the surgeon's hand. For education the Robin Heart DuoTeacher is under investigation.

We plan the first animal test of our robot for the end of 2008; the first clinical application of endocamera arm

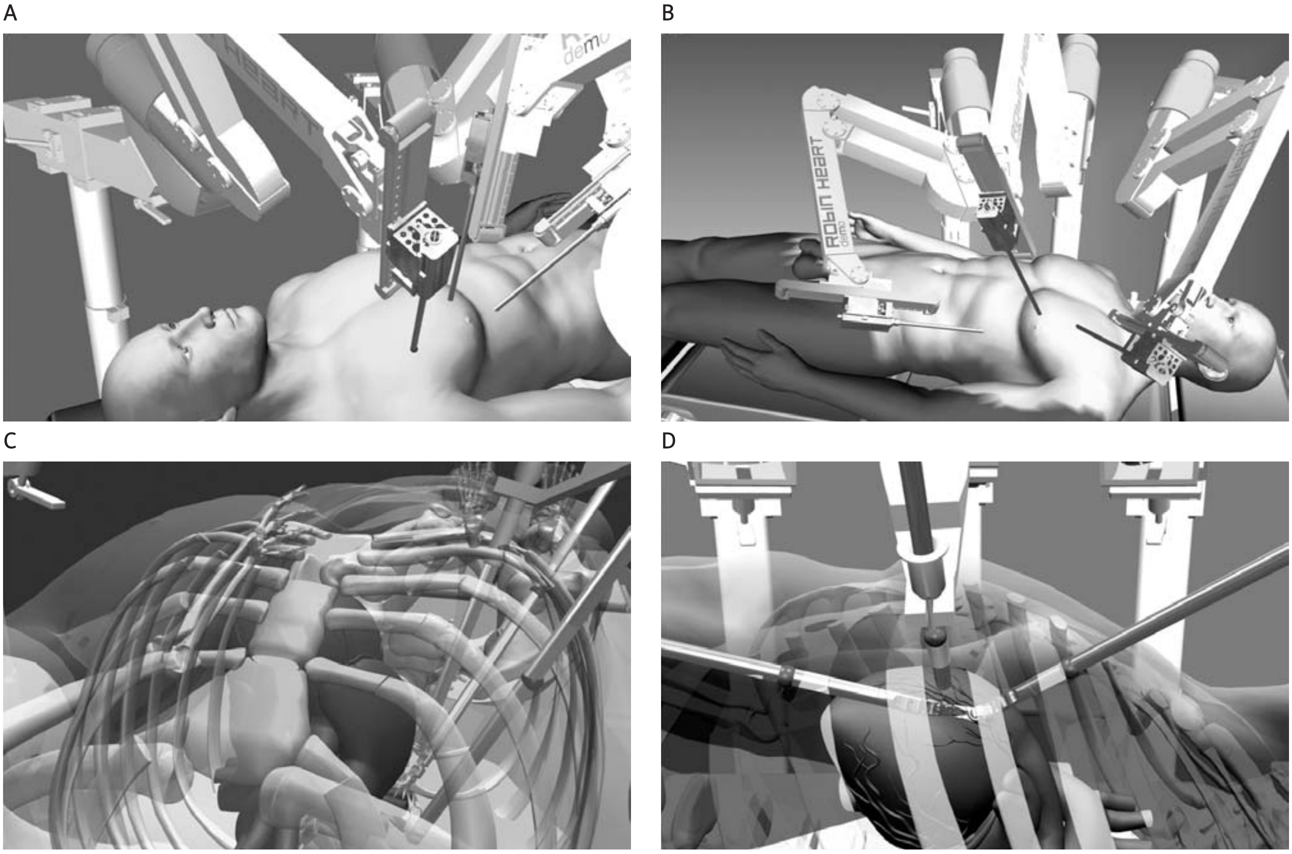

Fig. 2. The Virtual Operating Room investigation surgery planning. A-D. Mitral valve reconstruction planning

Robin Heart Vision, robotically controlled in 2009; the first operation performed by Robin Heart in 2010. Robin Heart Vision robotic assistance has enabled a solo surgery approach – the procedure completed without the need for an additional assistant. We have already got to know the complex secret of the word “innovation”. We are heading for setting in motion the production of medical robots in Poland, based on the Robin Heart project. The period of financial support for the Robin Heart Service venture by the programme of Common Initiative EQUAL – European Social Fund (ESF) is just coming to the end. I hope that this first Polish industrial plant will convert into a company which will service the mass production of Polish Robin Heart medical robots.

Our systems are equipped with a parallel-developed surgery advisory system (Robin Expert) (Fig. 2, 3), created on the basis of our long-term experience of using the simulation methods as a decision-making support for surgeons. Virtual reality (3D) software has been used for presentation of results of using the Robin Heart in the operating room, and for operation planning: the optimisation of port location and choreography of the robot arm. All these activities are carried out toward the goal of a system more amenable for the surgeon, as well as safer for the patient. In the near future, after preparation of specialized tools, the operation of ventricular assist device implantation by means of Robin Heart is planned. Based on Robin Heart project development, currently our team is working on the system AORobAS – Artificial Organs Robotically Assisted Surgery for artificial organ implantation, service, repair, exchange, and removal.

Present medicine is developing in considerable measure thanks to the use of the newest achievements of sciences as well as introduction of new methods, techniques and technologies. The future is open for innovation which is needed for the physicians and their patients, especially in the operating room.

Robot applications in cardiac surgery

In 1998 the group led by Carpentier [2, 4] performed the first robotic cardiac surgical operations, which included an atrial septal defect closure and several mitral valve repairs, and [1] also described the world’s first two successful totally endoscopic coronary operations. Mohr and Falk performed additional mitral operations and next the first robotic coronary using da Vinci (IS) prototypes anastomosis, through an open incision [3, 6]. Reichenspurner’s group [5] performed videoscopic ITA harvest with subsequent anastomosis to the left anterior descending coronary artery using a ZEUS robot (CM), which incorporated a voice-activated AESOP. The surgeons added a minithoracotomy for “safety”, but each anastomosis was done by the robotic method [9]. In 2005, a total of 2984 cardiac procedures were performed worldwide using the da Vinci system. This includes totally endoscopic coronary artery bypass grafting (TECAB), mitral valve repair (MVR) procedures, ASD closure and cardiac tissue ablation for atrial fibrillation [10]. The estimated number of robotic procedures, from heart bypass surgeries to kidney transplants and hysterectomies, performed in 2005 was 36, 600; in 2006 more than 70, 000 procedures. In general, patients were excluded if they could not tolerate single-lung ventilation or peripheral cardiopulmonary bypass, or otherwise were considered poor candidates for a thoracoscopic approach [11].

"Solo surgery"

The procedure completed without the need for an additional assistant is called "solo surgery." Robotic assistance has enabled a solo surgery approach [12]: a robotic endoscope positioning system that can be controlled by hand, foot or voice. The robot system EndoAssist (Armstrong Healthcare Ltd) is co-ordinated by the surgeon's head movements.

The most popular, over 130 000 applications, was the voice-controlled robotic arm AESOP, providing a stable and precise video image with excellent exposure of all valvular and subvalvular structures, heart and vessels [1].

Coronary revascularization, TECAB

Total endoscopic coronary artery bypass grafting (TECAB) means the robotic assisted procedure is applied to graft the left internal mammary artery (IMA) to the left anterior descending coronary artery (LAD) without opening the chest. Since its introduction in the 1960s, coronary artery bypass grafting (CABG) has become one of the most common surgical procedures, with more than 500,000 performed annually [13]. This is the reason for which development of TECAB was so important for the strategy of surgery robot development.

The patients are intubated with a double-lumen endotracheal tube, allowing single right lung ventilation. The patient stays in a supine position with 30-degree left chest elevation and the left arm placed along the body below the mid-axillary line. A larger chest is desirable since it allows a larger triangle for port placement, which helps to minimize the risk of collisions. In women large breasts may alter port placement [14].

The robot's arms were replaced within the left side of the chest and according to Loulmet's study [15]:

- the camera port (4th intercostal space (ICS)) had to be placed to visualize the entire length of the LIMA to be dissected; via this port insufflations with carbon dioxide created a 5-mm Hg intrapleural pressure.
- the right instrument port (3rd ICS or 4th ICS at the anterior axillary line AAL) allowed the middle third of the LAD and both extremities of the LIMA to be reached
- the left instrument port (6th ICS or 7th ICS at AAL) allowed the middle third of the LAD and both extremities of the LIMA to be reached.

A

B

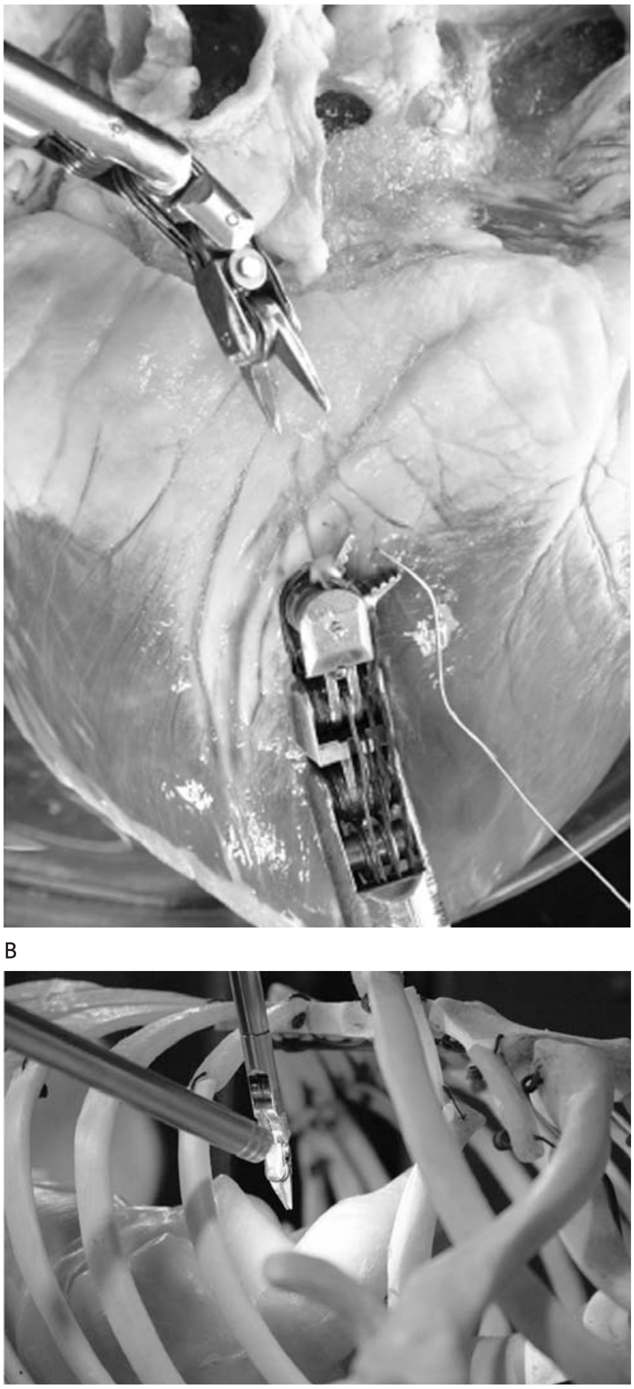

Fig. 3. The real (A) and virtual (B) experiments comparison

The previously postulated rule of creating a triangle-like port arrangement in the left chest of the patient is not always reliable to ensure adequate patient safety throughout the case. During ITA harvesting Falk [14] noted that it is very important to maintain a high (about 10 mm Hg) enough intrathoracic pressure so as to provide as much working space between the anterior chest wall and the mediastinum as possible.

After internal mammary artery takedown, preparation of the internal mammary arteries is performed either inside the chest of the patient, for TECAB, or under direct sight, with the pedicle being pulled through the chest incision, for REDTCAB or MIDCAB [16]. In MIDCAB, access to the heart is achieved via a 4- to 6-cm left lateral chest incision in the 4th ICS. During the REDTCAB procedure, LIMA or BIMA dissection is followed by percutaneous venous cannulation of the right femoral vein, direct aortic cannulation via a 6- to 8-cm minithoracotomy in the 2nd ICS of the left chest. The TECAB patients were operated on while on the pump using an endovascular bypass system (Heartport) or TECAB on a beating heart. For off-pump technique, an additional 1-cm subxiphoid port is placed for the introduction of an endoscopic stabilizing device [16]. Occasionally this procedure is combined with percutaneous coronary intervention of right-sided and/or posterior vessels with drug-eluting stents, in what has been termed a 'hybrid coronary revascularization' [17, 18].

Mitral valve reconstruction

The history of clinical robot application started with mitral valve (1998 Paris, Lipzing) reconstruction. Minimally-invasive procedures for mitral valve repair or replacement include endoscopic video-assisted approaches and robotically assisted procedures.

The mitral valve lies in the sagittal plane in the body and thus a right chest approach yields an outstanding, clear, *en face* view of the entire mitral valve. Chordal reconstruction is greatly aided by robotic 3D visualization [18]. All patients with isolated degenerative mitral valve disease are now considered for robotic mitral valve repair. Patients with severely calcified mitral annuli are not suitable candidates. De-calcification methods will require further instrument development [19]. Patients are anaesthetized and positioned with the right chest elevated to 30° and with the right arm tucked by the side. Single left lung ventilation is performed to facilitate pericardial, aortic, and cardiac exposure. A 4-cm long inframammary incision is used and the chest is entered through the 4th intercostal space (ICS).

After valve inspection, positions for robot arm port incisions are determined [19]:

- the right trocar is placed in the 5th or 6th ICS posterolaterally to the incision and parallel to the right inferior pulmonary vein.
- the left trocar is generally placed 6 cm cephalad and medial to the right trocar, insuring internal clearance between arms to avoid both external and internal conflicts. Optimal robotic arm convergence avoids left atrial wall tearing during instrument manipulations.
- the 3D endoscope (30° angulation) is placed through the medial portion of the minithoracotomy.

Major requirements for an ideal valve operation relate to access, dexterity, visualization, and perfusion. Chitwood reported that the device has functioned optimally in 98% of operations and in the others the back-up operation was a videoscopic repair through the same incision. The technical learning curve seems to be about 50 mitral repair operations [20].

Aortic valve surgery

Folliguet et al. [21] reported initial experience with aortic valve replacement using robotic da Vinci assistance. One or two ports and a 5-cm intercostal incision in the right chest were used for access. A 4–5-cm anterior incision was made in the right 3rd ICS or 4th ICS; the exact location was determined according to a preoperative gated CT scan. A 30° angled camera was placed through the anterior aspect of the incision. Two ports were placed, one in the 2nd ICS mid-axillary and one in the 5th ICS or 4th ICS. The da Vinci system was used to excise the valve and to place 12 suture stitches on the annulus, and to close the aortotomy. This early experience of combining robotic assistance and a mini-thoracotomy is a first step toward total endoscopic aortic valve replacement.

Atrial septal defect (ASD)

In 2001, the Columbia robotic cardiac surgery conducted by Argenziano's team performed the first robotically-assisted atrial septal defect (ASD) repair, without a chest incision of any kind. Argenziano reported [22] that after establishment of selective left lung ventilation, a port incision was made in the 4th ICS, in the mid-clavicular line, and an endoscopic trocar was placed into the pleural space. The endoscopic camera was inserted and after pleural adhesions were ruled out, the pleural space was insufflated with carbon dioxide to a maximum pressure of 8 mm Hg. Two additional 8-mm port incisions were made in the 3rd ICS and 6th ICS, in the AAL. The da Vinci Surgical Cart was positioned at the operating table, and the left and right robotic arms inserted into the pleural space. A fourth port incision (15 mm) was made in the 5th ICS, in the posterior axillary line, for use as a service entrance. By avoiding thoracotomy incisions and rib spreading, this procedure results in minimal pain and postoperative recovery time.

Paediatric application

Technology for minimally invasive approaches to congenital heart disease is a rapidly evolving field. Ohye et al. [23] report a novel approach to combining two of the newer technologies available to treat a paediatric patient with an ASD and a vascular ring: the da Vinci assisted division of the vascular ring, joined with an Amplatzer closure of the ASD.

The Le Bret study [24] demonstrates that endoscopic patent ductus arteriosus PDA closure with robotically assisted instrumentation (ZEUS) is technically feasible in children, even in low-weight babies. He concluded that the robotic approach for PAD interruption in children appears more complicated, demanding, and time-consuming and presently has no particular advantage over the regular technique. This difference is not due to specific surgical difficulties but rather to the technical complexity of the robot placement. For PDA closure, the voice-controlled robotic arm is positioned on the foot side on the left rail, and instrument positioners are installed on the head side on the left rail and the foot side on the right rail. The videoscope is attached to the AESOP arm, the two first 60° angled hooks for lung retraction are held by the assistant, the third hook is connected to the left arm of the robot, and the electrocautery hook is held by the right arm of the robot.

Robotic LV lead placement

Cardiac resynchronization therapy for severe left ventricular dysfunction has gained widespread acceptance. In scenarios where the left ventricular lead cannot be successfully percutaneously implanted, perhaps 5-10%, the LV lead needs to be surgically placed on the high lateral LV wall [18]. The technique of robotically assisted LV epicardial lead placement via the posterior approach was developed in an attempt to perform a minimally invasive rescue procedure for resynchronization therapy CRT after failed coronary sinus CS placement [25].

Patients were positioned in the full posterolateral thoracotomy position and the da Vinci robotic surgical system was used for all portions of the operation. A camera port was placed in the 7th ICS in the posterior axillary line. The left and right arms were positioned in the 9th ICS and 5th ICS. A 10-mm working port was inserted posterior to the camera port and was used for the introduction of the lead and sutures as necessary. The authors conclude [25]: in summary, robotically assisted LV epicardial lead implantation is a safe, reliable, fast, and effective technique for CRT in all patients.

Intracardiac tumour resection

Woo et al. [26] described the robotic minimally invasive resection of a 1-cm mobile mass on the edge of the aortic valve noncoronary leaflet. Although relatively uncommon, robotic resection of intracardiac tumours, left atrial myxoma and aortic valve papillary fibroelastoma has been reported.

Atrial fibrillation ablation

The radiofrequency ablation technique uses a high energy pulse emitted from the tip of a catheter threaded through blood vessels into the heart to destroy a small area of heart muscle cells, in order to prevent them from conducting nerve signals that trigger fibrillation. The device may use a computer to control a magnetic field that robotically moves the catheter tip or X-rays to track the location of the target and the catheter tip. Robotic catheter navigation with a magnet-tipped catheter directed by large, computer-directed magnets can provide more precise catheter control as compared to manual catheter manipulation. There are currently two robotic systems designed for use in the electrophysiology lab (from Stereotaxis, St. Louis, Missouri, and Hansen Medical, Mountain View, California). However, robotic systems are expensive to purchase and install, and it is as yet unclear whether the clinical benefits will justify this extra expense [27].

Surgical electrical isolation of the pulmonary veins is commonly performed during concomitant mitral valve and other cardiac surgery and has been approached with robotics as well. Robotics have been utilized to provided visualization and guidance of an ablating catheter around the posterior left atrium to form a box lesion around all four pulmonary veins [18]. Reade et al. presented [28] a technique that combines robotic mitral valve repairs (MVP) (through a 4-cm right minithoracotomy) with left atrial fibrillation ablation. A Flex-10 microwave catheter is passed around the pulmonary veins, and after weaning from cardiopulmonary bypass, peripulmonary vein microwave ablations are performed. After cardioplegic arrest, the da Vinci system is used to manipulate the catheter to create endocardial lesions around the left atrial appendage. When the left atrial appendage is closed, the MVP is performed robotically. They concluded that robotic microwave ablation during robotic MVP is a safe, effective way to resolve atrial fibrillation. These methods offer a promising prelude to the combined totally endoscopic treatment of atrial arrhythmias and mitral insufficiency.

Transmyocardial laser revascularization

Laser transmyocardial revascularization is an emerging therapy for intractable angina stemming from diffuse, small-vessel coronary disease not amenable to percutaneous coronary intervention or coronary bypass grafting. Presently, this therapy is delivered through a median sternotomy or left thoracotomy. It is possible to combine the advantages of a dexterous robotic surgical platform with a flexible fibreoptic laser to develop a minimally invasive approach to transmyocardial revascularization. Brunsting LA [29] described in 2006 the first use of totally endoscopic, off-pump, robot-assisted transmyocardial laser revascularization in a 58-year-old man with refractory rest angina who had undergone two prior coronary bypass operations. Preoperative testing revealed reversible ischaemia of the left ventricular apex with diffuse coronary atherosclerotic disease not suitable for further treatment by conventional techniques. During surgery a fibreoptic laser delivery system was manipulated using the da Vinci robotic system to create 25 transmural channels in the left ventricular myocardium. Postoperative recovery was rapid and uneventful, with complete relief of anginal symptoms at 30 days.

Conclusions

Endoscopic microsurgery is difficult to perform with standard hand held instruments but so far robotically assisted surgery has not solved all the problems. Among surgical procedures assisted by a robot, only part of heart procedures are made using a robot, such as mammary artery harvests. For instance Jacobs et al. reported [10] that the conversion rate in overall patients was about 30% but decreased over time to nearly 10% [30]. Since the introduction of beating heart TECAB, only approximately 400 patients have undergone the procedure worldwide. Despite a successful and promising beginning with IMA-takedown

(1784 from 2984 procedures in 2005) and accomplishing some TECAB cases on pump, the technique has not been widely accepted by surgeons. The number of MVR increased from 450 cases in 2004, to over 600 in 2005, to 850 in the first ten months of 2006 (reported in a company-based registry). The lack of rapid improvement and the time-consuming procedure led to frustration and many centres did not proceed [10].

Currently we can see that the strategy of the IS firm is transformation of the da Vinci robotic system field of application from heart to prostate.

The company has made continuous progress in increasing the percentage of prostatectomies, for which it was approved in May 2001. That year it was used in less than 1 percent of all prostatectomies, in 2005 more than 20 percent [30].

The most crucial limitations today remain related to the [31]:
- new tools,
- stabilization procedure,
- suture technique,
- preoperative planning and intraoperative navigation.

The surgeon needs assistance of the next robot arm during operations mainly for stabilization of the heart (beating heart bypass grafting) or another tissue. Several trials of using two da Vinci consoles have tested the advantages of such a system. As the answer, IS prepared the da Vinci S model with four arms. Devices providing an “inside equipment store” for the surgeon are also needed. A self-sufficient Cargo Module was developed as a transportation and depot device by the Dresden group. With the Assist Module the surgical equipment, tissue and vessels can be positioned on a desired place in the operating field. This module provides the surgeon an “assistant” inside the closed chest.

Further technological developments in suture technique are much needed: a computerized stabilization platform, and innovative sutureless anastomosis techniques, based either on magnetic devices such as the Ventrica system or on TM expandable stents such as those of Saint Jude Medical [31].

Based on pre-operation cardiac surgery simulations the optimisation of cardiac surgery procedures can be established. The development of simulation methods is required for a better approach to reality.

Falk reported the successful application of preoperative planning bypass procedure [32]. He concluded that more complete understanding of the surgical decision process is required to better formalize the planning algorithms.

Searching for new application fields is very important, for example reliable evaluation for which procedure the robotic supported surgery is the optimal solution.

The potential applications of robotics in cardiac surgery [18] include:
- Aortic valve replacement (standard or percutaneous technology),
- Tricuspid valve repair,
- Ventricular restraint jacket,
- Descending thoracic aortic surgery (alternative to endovascular stent in non-candidates or using stent technology in patients with arterial access limitations),
- Transmyocardial laser revascularization,
- Ventricular septal defect, patent ductus arteriosus, coarctation,
- Intramyocardial delivery platform for biological agents such as stem cells, molecular therapeutics, genetic vectors.

And we can add two more:
- Ventricular assist device implantation (particularly miniaturized axial flow pumps) [33, 34],
- AOROBAS – Artificial Organs Robotically Assisted Surgery [35].

The FCSD future plans include carrying out robotically assisted less invasive procedures to implant pumps and valves and mini-invasive service of temporarily applied artificial organs (AOROBAS project). In our team the first work on the assumptions for a heart pump and valve special for the robot and MIS application is being done and special tools of the robot are being constructed.

Efficiency and development of the field of robot usage requires assessment of the optimal cardiac robot application range, building the strategy of their use, simulation of the operation results, creating a knowledge base supporting the robot arm navigation and cardiac surgeon decision making, and studying image processing methods for optimal robot arm navigation

Education and training influence the achievement of success.

A further point is cost-effectiveness. The investment and maintenance costs still represent the major problem of the da Vinci robot working in about 300 hospitals worldwide. Due to the high cost of robotically assisted procedures one of the pioneering centres in Dresden discontinued da Vinci usage in cardiosurgery practice (R. Cichoń’s communication during the Medical Robotics 2006 Conference in Zabrze, Dec. 2006).

The da Vinci robotic surgical instruments have a fixed usage life of 10 procedures per instrument. An average operation uses up $1, 500 in consumable tools. Da Vinci lists for $1.3 million, and an IS economist estimates that high-volume hospitals will spend another $525, 000 per year for service contracts and parts for the three units [36]. But Morgan et al. [37] concluded that robotic technology did not significantly increase total hospital cost for ASD closure or MVr (including amortization cost it was increased by about $4, 000). Furthermore, other benefits, such as improvement in postoperative quality of life and more expeditious return to work, may make a robotic approach cost-effective.

To make robotically-assisted surgery more widely acceptable the operation has to be easier and more attractive for the end user, i.e. the surgeon (new tools, pre-planning, advisory system), and less expensive for the hospital owner. It seems attainable in the near future – if only monopolistic and conservative tendencies of commercial firms will not prevail over the above spirit of inventiveness and spontaneous interest which we can observe in many scientific and academic centres in Europe.

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