Development of Robotic Enhanced Endoscopic Surgery for the Treatment of Coronary Artery Disease

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Background—The introduction of robotic enhanced surgery demanded stepwise development of performed procedures on the basis of growing experience of the operating team.

Methods and Results—Between May 1999 and January 2001, this new wrist-enhanced instrumentation was used in 201 patients (156 men and 45 women, median age 64±10.5 years, left ventricular ejection fraction 68±12.4%). During the development of robotic enhanced CABG, the patients were divided into 3 groups. Group A (n=156) consisted of patients in whom the robotic system was used to harvesting the left or right internal mammary artery, or both, whereas the anastomoses were performed directly through a small chest incision. In group B (n=37), the harvest of the internal mammary arteries and the coronary anastomoses were performed totally endoscopically. In a third early group C, patient (n=8) were treated with robotic enhanced CABG via a median sternotomy already preoperatively planned, whereas gradual step-by-step application of robotic instrumentation and its feasibility were assessed. The survival rate was 99.4%. One patient (0.6%) died due to pneumonia on postoperative day 16. Conversion rate to median sternotomy was 5%. The left and right internal mammary artery conduits could be successfully harvested in 98% and 100%, respectively. The time of dissection of the left internal mammary artery could be significantly reduced alone by increasing experience. All patients were discharged from the hospital after a mean of 7 days. In 9 patients (4.5%), bleeding required reexploration.

Conclusions—The introduction of this new surgical tool enables the development of new endoscopic procedures. Our results gained during the development of robotic enhanced CABG motivate us to establish a set standard for the totally endoscopic treatment of patients with 1-vessel coronary artery disease. (Circulation. 2001;104[suppl I]:I-102-I-107.)

Key Words: robotics ■ bypass ■ endoscopy ■ surgery ■ arteries

Minimally invasive surgical techniques have been successfully introduced into cardiac surgery during recent years.1–7 Acute and chronic complications associated with median sternotomy and cardiopulmonary bypass can be avoided. A further reduction in chest incisions is possible with the use of endoscopic instrumentation.

A minimization of access in minimally invasive cardiac surgery (MICS) using wrist-enhanced robotic instrumentation is leading to a turning point in the history of MICS as totally endoscopic coronary artery bypass (TECAB) grafting procedures become feasible.8–12

With well-established MICS techniques being enhanced by robotic procedures, a broader scale of patients with coronary artery disease (CAD) becomes eligible for minimally invasive operations, avoiding sternotomy and extracorporeal circulation (ECC). New technical innovations, such as the introduction of endoscopic stabilizers into MICS, enable closed-chest TECAB procedures for CAD via 4 chest incisions of 1 cm on a beating heart and the avoidance of ECC.12

The present report is based on a group of 201 patients in whom new wrist-enhanced computer-based instrumentation (da Vinci; Intuitive Surgical) was used for the gradual development of a concept for the minimally invasive surgical treatment of patients with CAD (Figures 1 and 2). The report focuses on totally endoscopic beating-heart revascularization in patients with 1-vessel CAD.13,14

Methods

Between May 1999 and January 2001, this new wrist-enhanced instrumentation was used in 201 patients (156 men and 45 women, median age 64±10.5 years, left ventricular ejection fraction 68±12.4%). According to application of the da Vinci system, the patients were divided into 3 groups (Figure 2).

In group A, robotic instrumentation was applied as an adjunct tool for left and right internal mammary artery (LIMA and RIMA, respectively) harvesting, followed by the application of existing minimally invasive surgical procedures (n=156), such as minimally invasive direct coronary artery bypass (MIDCAB; n=106) or an extended minimally invasive surgical technique via a 6- to 8-cm left lateral chest incision with the use of ECC, which we refer to as...
robotic enhanced Dresden technique coronary artery bypass (REDT-CAB; n=50). In this group, all anastomoses were performed directly via a small chest incision.

Group B included patients who underwent fully endoscopic procedures (n=37), on or off the pump, so surgery was performed as a closed-chest procedure after either single or bilateral IMA (BIMA) harvesting. This patient group consisted of 37 patients (32 men and 5 women, median age 62±9 years). Initially, this series started with 8 TECAB patients using an endovascular bypass system (Heartport). After the introduction of an endoscopic stabilizer, the latter 29 patients (25 men and 4 women, median age 64±9.8 years) underwent a beating-heart TECAB procedure for either 1- or 2-vessel CAD, avoiding the risks of endovascular bypass. The beating-heart TECAB procedure consists of 2 steps: endoscopic harvesting of the LIMA or RIMA and suturing of the coronary anastomoses with use of the robot.

A total of 26 patients with 1-vessel CAD were revascularized with application of the LIMA to left anterior descending coronary artery (LAD) grafting, and 3 patients with 2-vessel CAD received BIMA grafting on a beating heart.

An initial early series of patients (n=8) were treated with robotic enhanced CABG via a median sternotomy already preoperatively planned, whereas a gradual step-by-step application of robotic instrumentation and its feasibility were assessed (group C).

Figure 1. Development of robotic enhanced endoscopic surgery for treatment of patients with CAD.

![Diagram](image)

**Step 1**
AESCOP application
Endoscopic LIMA harvesting
Limitation: rigid 2D instrumentation

**Step 2**
da Vinci surgical system
Single OR team training (04/1999)
Training on animals, wet lab, cadaver

**Step 3**
Installation of the da Vinci surgical robot into the OR
05/1999
Conventional heart surgery is still possible in OR

**Step 4**
Robotic enhanced CABG via median sternotomy
Endoscopic LIMA harvesting performed with the system (n=8)

**Step 5**
Robotic enhanced minimally invasive cardiac procedures
Endoscopic LIMA and RIMA harvesting

**Step 6**
Development of true endoscopic procedures
Robotic performed anastomoses
on pump

**Step 7**
Introduction of an endoscopic stabilizer
01/2000

**Step 8**
Totally endoscopically Coronary Artery Bypass (n=9)
Endoscopic LIMA and/or RIMA harvesting
Endoscopic anastomoses
on pump

**Step 9**
Totally Endoscopically Coronary Artery Bypass (n=29)
Endoscopic LIMA and/or RIMA harvesting
Endoscopic anastomoses
off pump

**Figure 2.** Concept of treatment of patients with CAD with robotic instrumentation.
Preoperatively, 3.5% of the patients were in Canadian Cardiovascular Society (CCS) stage I, 37.1% were in stage II, 53.5% were in stage III, and 5.9% were in stage IV; 8.2% of the patients were in New York Heart Association (NYHA) functional class I, 42.4% were in class II, 48.8% were in class III, and 0.6% were in class IV.

The patients had a complete follow-up that included a physical examination, 12-lead ECG, and chest radiography on the first and seventh postoperative days. All patients were scheduled for a stress ECG and clinical examination 4 weeks after surgery and for a clinical examination after 3 months. Exclusion criteria were aortic sclerosis, peripheral arterial vascular occlusive disease, decreased left ventricular ejection fraction (<40%), decreased lung function (FEV1 <1.0), obesity (body mass index >35 kg/m²), and intramyocardial LAD course or diffuse coronary artery sclerosis.

Perioperative and postoperative data regarding age, sex, body mass index, left ventricular ejection fraction, left ventricular end-diastolic pressure, duration of surgery, duration of endoscopic internal mammary artery dissection, duration of bypass, vessels affected by coronary sclerosis and anastomoses actually performed, ventilation time, intensive care unit stay, and hospitalization were analyzed.

Anesthetic Considerations

Special anesthetic considerations had to be made to provide safe application of this new technology. The induction of anesthesia is based on the use of induction agents such as methohexital or thiopentone and fentanyl as an opioid. For good relaxation and fast intubation, suxamethonium and vecuronium were used as muscle relaxants.

Anesthesia was maintained as balanced anesthesia with the use of enfurane, fentanyl, and vecuronium. All patients received an endobronchial double-lumen tube or a single-lumen tube with left-sided bronchial blocker, a triple-lumen central catheter in the right internal jugular vein, and a right radial artery catheter. Two temperature probes, a pulse oximetry probe on each hand, and 2 fast patches for defibrillation were positioned accordingly. Because access to the patient during the operation is very limited, right positioning of the double lumen endotracheal tube or bronchial blocker has to be confirmed by bronchoscopy, and positioning of the patient must be done very carefully, ensuring that no pressure injury will occur. Single lung ventilation was necessary to allow adequate exposure of the LIMA and RIMA and the coronary vessels. In addition, CO2 insufflation was used in all patients via the optical port. During single lung ventilation, a high FiO2 was used to avoid hypoxia. A reduced tidal volume and a raised ventilation rate were applied to maintain normocarbia, whereas none of the patients observed so far had episodes of hypoxia or extensive hypercarbia. The use of positive end-expiratory pressure to the right lung is limited only to required cases. Normothermia was maintained with the use of warmed fluids, raised operating room temperature, low fresh gas flows, thermomattresses, and forced-air warming blankets in the induction room.

Hemodynamic instabilities were challenged with volume replacements and sometimes the use of “soft” inotropes to maintain mean arterial pressure at >60 mm Hg. After the operation, all patients were sedated, intubated with a single-lumen tube, and ventilated during transport to the intensive care unit.

The da Vinci Surgical System

The first generation was developed in the United States at the company laboratory (Intuitive Surgical). However, we were already given the opportunity to work with the improved second-generation tool. This new robot had been worked with, and new technical features were added to it.

The basic structure is still composed of a 3-armed executive unit (slave), carrying surgical instrumentation, a computer system with a computer net, and a surgical console (master), allowing remote movement of instrumentation. Furthermore, the computer software was improved, and the instrumentation had evolved into very versatile and delicate equipment.

The present surgical telemanipulator, da Vinci, is now characterized by a high amount of accuracy in positioning, which is supported by brilliant 3-dimensional visualization of the operating environment.

The master/slave philosophy enables intuitive operating and an application of hand-arm movements almost similar to conventional techniques. The computer and computer net system transform these movements onto the surgical instrumentation arms. For instrumentation, a broad array of tools are available.

Motion sensing and a haptic regulatory feedback mechanism allow smooth tissue handling. When counterforces are present at the instrumentation in the operating environment, the regulatory feedback mechanism passes this information onto the master/slave unit. Here, an equivalent force is projected onto the handle of the surgeon’s console so that the surgeon has to act against it. It is this principle that, in addition to enabling an optimal visual perception at the teleconsole, builds the groundwork for “hands-off” surgery with this second-generation robotic tool.

The number of chest incisions consists of the 2 thoracic ports for the surgical instrumentation arms and 1 port for the endoscopic camera. From this, the 3-armed concept of the master/slave unit was derived. To operate totally endoscopically on the beating heart, a special stabilizer requires, however, an additional 1-cm subxiphoid incision.

Surgical Techniques

Endoscopic Internal Mammary Artery Harvesting Technique

LIMA takedown was always performed using the 3-armed da Vinci unit via 3 chest incisions of 1 cm, with a left-sided approach. The patients were intubated with a double-lumen endotracheal tube, allowing single right lung ventilation. The patients were in a supine position with 30-degree left chest elevation and the left arm placed along the body below the midaxillary line. After the onset of single lung ventilation, the camera port was introduced into the fifth intercostal space (ICS) in the anterior axillary line. CO2 insufflation, applying pressures of 5 to 10 mm Hg, was used, and the 3-dimensional endoscope was introduced into the chest cavity for exploration. The robot was then placed to the right side of the patient so that the camera actuator of the robot could be connected to the camera port. The 2 other ports for instrumentation, localized in the third (right arm) and sixth (left arm) ICSs in the medioclavicular line, were then introduced, forming a triangle. Set-up time for the system was a mean of 10 minutes.

For BIMA takedown, the LIMA is first exposed by careful marking of the vessel. Further harvesting of the LIMA is continued after dissection of the RIMA. The right pleural cavity is entered along the body below the midaxillary line. After the onset of single lung ventilation, the camera port was introduced into the fifth intercostal space (ICS) in the anterior axillary line. CO2 insufflation, applying pressures of 5 to 10 mm Hg, was used, and the 3-dimensional endoscope was introduced into the chest cavity for exploration. The robot was then placed to the right side of the patient so that the camera actuator of the robot could be connected to the camera port. The 2 other ports for instrumentation, localized in the third (right arm) and sixth (left arm) ICSs in the medioclavicular line, were then introduced, forming a triangle. Set-up time for the system was a mean of 10 minutes.

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 REDTCA or MDCAB. This completes the preparation for coronary anastomoses.

In MIDCAB, after endoscopic LIMA, and possibly BIMA, harvesting, access to the heart is achieved via a 4- to 6-cm left lateral chest incision in the fourth ICS. A specially designed retractor that allows a stabilizing device to be attached to immobilize the desired area for anastomosis was used. All anastomoses were performed directly on the beating heart.

During the REDTCA 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 second ICS of the left chest, and ECC in combination with cardiopulmonary arrest. In addition to direct LIMA or BIMA grafting, aortocoronary venous bypass grafts can be sewed to the aorta.\textsuperscript{15,16}

**TECAB Technique**

The initial series of 8 TECAB patients were operated while on the pump using an endovascular bypass system (Heartport). Currently, our efforts are aimed toward TECAB on a beating heart, because the patient’s benefit is increased by avoiding ECC.

For this new off-pump technique, an additional 1-cm subxiphoid port is placed for the introduction of an endoscopic stabilizing device. Again, robotically harvested unilateral internal mammary artery or BIMA takedown via 3 chest incisions of 1 cm precedes the technique.

The highly versatile endoscopic stabilizing device consists of 2 branches like common MIDCAB stabilizers. The branches of the stabilizer can be moved from outside. A joint at the heel of the stabilizing device allows precise and stable positioning at the anatomic site. For the attachment of Silastic vessel loops, special cleats are placed onto the branches, ensuring a firm hold for the loops during coronary artery occlusion. An irrigation tube is attached above the heel joint of the endostabilizer and allows clear vision of the anastomosis while the suture is made. After placing the stabilizer onto the LAD, blood flow through this vessel is temporarily interrupted using the loops. After incision of the coronary vessel using the wrist-enhanced instrumentation of the slave unit, the anastomosis is completed on a beating heart using a 7-0 Prolene running suture.

**Results**

The survival rate was 99.4%. All patients left the operating room without inotropic support and in sinus rhythm and without signs of acute myocardial ischemia. One patient (0.6%) died due to pneumonia on postoperative day 16.

Nine patients (4.5%) had to undergo reexploration due to bleeding. In 3 group B patients (8.1%), an explorative second look was performed due to increased postoperative drainage. Bleeding muscle tissue adjacent to the ports was coagulated thoroughly, and hemostasis was regained.

Ten patients (4.9%) underwent a median sternotomy due to bleeding from the right subclavian vein (n=1), ventricular fibrillation (n=1), damage caused to the LIMA (n=4), or pleural adhesions (n=4). The patients were converted to a conventional operation through a median sternotomy.

Delayed wound healing at the site of the chest incision was found only in group A: 5 patients (4.7%) who underwent MIDCAB procedures and 5 patients who underwent REDT-CAB procedures (10%). None of the TECAB patients in group B revealed any signs of delayed wound healing or cosmetic impairment.

All patients in group B were operated on via a 3- or 4-point stab incision. The initial long duration of surgery in this group could be significantly shortened by the application of a beating-heart TECAB procedure due to the development of an endoscopic stabilizer in January 2000. The duration of surgery decreased noticeably from 280±80.2 to 186±58.6 minutes. At the present, a continued decrease in duration is still observed (Figure 3).

A statistical analysis of the anastomoses performed was made between a cohort of patients with hand-sewn, direct anastomoses and patients with robotically assisted ones. Clearly, times were longer with robotically assistance: an average of 30±6.5 minutes for robotically performed anastomoses versus 12±3 minutes for directly hand-sewn MIDCAB anastomoses and 7±1.3 minutes for directly hand-sewn anastomoses on the arrested heart during REDCAB procedures. However, a distinct learning curve for robotically assisted anastomoses was observed (Figure 4).

In the overall series of 201 patients, of the patients with intention-to-treat TECAB, 19 (33.9%) were actually converted to a MIDCAB procedure. This was mainly due to several factors: in 5 patients, LAD identification was not possible endoscopically. Diffuse sclerosis of the LAD (5 patients), difficulties with endoscopic stabilization (3 patients), pleural adhesions (2 patients), intramural LAD course (2 patients), and insufficient occlusion of the LAD (2 patients) were also factors for a conversion to a MIDCAB procedure.

During REDTCAB procedures, the concept of total arterial revascularization was successfully applied using BIMA grafting in 80% of patients. Twenty percent had LIMA grafting and additional aortocoronary venous bypasses performed.

In every group A patient, flow measurement of the grafted conduits was performed. For both cohorts, LIMA and RIMA flow was observed at 18±10.6 and 23±12.5 mL/min, respectively.

The stress ECG performed 4 weeks postoperatively was found in only group A: 5 patients (4.7%) who underwent MIDCAB procedures and 5 patients who underwent REDT-CAB procedures (10%). None of the TECAB patients in group B revealed any signs of delayed wound healing or cosmetic impairment.
and the patients underwent successful percutaneous coronary angioplasty. Reinterventions took place only in the MIDCAB cohort. One patient (0.6%, group B) claimed to have angina 6 weeks postoperatively. Coronary angiography revealed a lesion of the circumflex artery due to progression of CAD, and the patient underwent uneventful PTCA.

Postoperative data did not significantly differ within the 2 groups. The intensive care unit stay was 25.6 ± 18.8 and 24.9 ± 6.4 hours, the ventilation time was 6.5 ± 10.6 and 5.3 ± 0.7 hours, and the hospital stay was 7 ± 1 and 6 ± 1 days for groups A and B, respectively.

Of the patients at the 3-month follow-up, 81% were in CCS stage I, 15.2% were in stage II, and 3.8% were in stage III, and 67.1% were in NYHA functional class I, 29.7% were in class II, and 3.1% were in class III. Midterm follow-up angiography in group B patients is under way to further assess patient outcome.

Conclusions
Like in other fields of surgery, a tendency toward a minimization of access and the performance of endoscopic operations can be noticed. Cardiac surgeons around the world are becoming aware of the minimally invasive potential of computer-enhanced robotic procedures.

With the installation of a computer-based surgical system (Intuitive Surgical) at our institution, we were able to treat patients with CAD by using computer-enhanced, fully endoscopic minimally invasive surgical techniques. We began working with the concept of well-established procedures such as MIDCAB and off-pump coronary artery bypass and started applying them in combination with robotic instrumentation as an adjunct tool. With the demonstrated surgical techniques at hand, an optional new concept for minimally invasive surgical treatment of CAD could be developed.13,14

At the present, our standards for the treatment of patients with 1-vessel CAD is routine off-pump TECAB. Nevertheless, to ensure a well-performed anastomosis and high safety standards for the patient, a decision toward conversion to a MIDCAB procedure has to be made at the time of LAD opening by all means.

The improvement in LIMA dissection using wrist-enhanced endoscopic instruments establishes a significant benefit for patients because there is no significant rib trauma or traction on bone structures. The installed minimally invasive surgical techniques can be significantly improved using robotic instrumentation.

The further technical development of an endoscopic stabilizer led to a beating-heart closed-chest procedure via 4 chest incisions of 1 cm. Functioning like a commonly used stabilizer during off-pump surgery, it differs in that an irrigation tube is connected to the shaft to ensure a clear vision of the operating field. Further technical improvement is continuously being made to improve safe stabilization during closed-chest procedures. In the future, we believe that with improved stabilization, which plays a key role in off-pump closed-chest bypass surgery, more patients will become eligible for closed-chest bypass grafting on the beating heart. The good results obtained through our initial series have to be reproducible on a larger scale, however, because they represent only initial experiences.

Patients with multivessel CAD were operated on using the modified robotic-enhanced Dresden technique.15,16 Endoscopic BIMA dissection using the da Vinci system can be used to avoid median sternotomy via a single-sided approach only, thus reducing the risk of sternal instability and infection or chronic pain.

Proper port placement setup plays an essential role in this endoscopic bypass procedure. The robotic arm placement setup is paramount to reducing the degree of difficulty and ensuring success of the procedure. 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. Modifications have to take place in accordance with the patient’s habitus by moving the ports accordingly (Figure 5). Through experience and intuition, the surgeon will, however, keep this golden rule in mind, create an arrangement that is suitable for ensuring proper instrumentation movement inside and outside the chest with careful evaluation of the patient’s ICSs, rib cage, body mass index, breast size, and tissue rigidity. The ports have to be moved according to these factors to avoid actuator collisions. Changing the robotic instruments still takes time and is dependent on an assistant’s experience with the system. A well-planned sequence of activity can considerably shorten the duration of surgery and thus secure a good result.

At last, our demonstrated preliminary experiences in the field of robotic-enhanced minimally invasive coronary artery surgery are positive for a highly selected patient group and represent only the first steps toward future developments.

References

Figure 5. Three 1-cm skin incisions placed in left chest in third ICS at medioclavicular line for right port, in fifth ICS at anterior axillary line for central optical port, and in sixth ICS at medioclavicular line for left port, forming a triangle whose angle may vary depending on habitus of patient.