

# Pearls and Pitfalls: Lessons Learned in Endoscopic Robotic Surgery— The da Vinci™ Experience

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## ABSTRACT

The da Vinci™ telemanipulation system (Intuitive Surgical, Mountain View, CA) is a computer-enhanced instrumentation system that has helped to overcome some of the limitations of traditional endoscopic instruments. As of May 2001, a total of 1,250 endoscopic cardiac procedures have been performed using the da Vinci system. With the use of wristed instruments and a new generation of endoscopic stabilizers, total endoscopic coronary artery bypass grafting on the beating heart has been achieved in 56 cases. Mitral valve repair and closure of atrial septal defects have been performed successfully through 1 cm incisions in 140 patients. The development of adjunct technologies as well as integration of image-based navigation systems may help to expand the use of computer-enhanced instrumentation systems in the near future.

## MATERIALS AND METHODS

### *The da Vinci Telemanipulation system*

The use of computer-enhanced telemanipulation systems has helped to overcome the limitations of conventional endoscopic instruments and has promoted endoscopic cardiac surgery. The da Vinci™ telemanipulation system (Intuitive Surgical, Mountain View, CA) is a dexterous, computer-enhanced system that consists of a surgeon's console and cart-mounted manipulators [Falk 1999a, Falk 1999b, Guthart 2000]. The console houses the display system, the master handles, the user interface, and the electronic controller that allows for motion scaling, indexing, and tremor filtering of involuntary motions. The master handles act both as high resolution input devices, reading the position, orientation and grip commands from the surgeon, and as haptic displays, transmitting forces and torques to the surgeon in response to various measured and synthetic force cues. However, due to the lack of force-sensors at the tip of the instruments, no real haptic feedback is provided. The master handles are gravity-compensated to minimize fatigue of the operator. The image

of the surgical site is transmitted to the surgeon through a high-resolution stereo display. The system projects the image of the surgical site atop the surgeon's hands (via mirrored overlay optics), while the controller transforms the spatial motion of the tools into the camera frame of reference. Hereby the system constantly restores hand-eye coordination.

The patient side-cart consists of "slave" manipulators, the camera manipulator, the endoscope, and exchangeable instruments (end-effectors) with six degrees' freedom of motion by means of a wrist mechanism at the tip of the instruments. An automated instrument recognition system allows for easy exchange of instruments. Setup of the patient-side system takes approximately fifteen minutes, but emergency removal of the manipulator from the patient can be performed in seconds. The system has been cleared by the FDA for laparoscopic and thoracoscopic procedures and has received CE mark approval.

### *Clinical Experience*

#### *Coronary Artery Bypass Surgery*

The da Vinci system has been evaluated in a series of experimental studies that demonstrated the feasibility of endoscopic bypass grafting [Falk 1999c, Falk 1999d]. After its clinical introduction in 1998, the system was mainly used for thoracoscopic internal thoracic artery (ITA) take-down followed by a MIDCAB procedure. After an initial learning curve that was observed in all centers using this technology, harvest times for the ITA are now in the range of 25 to 40 minutes for both the left and right ITA. The technique of robotic-assisted ITA harvest has been described in detail elsewhere [Falk 2000a]. In brief, patients are placed in a supine position with the left chest slightly elevated and the left arm lowered. The left lung is deflated and a 30°-angled scope is inserted at the fourth intercostal space (ICS). Continuous CO<sub>2</sub> insufflation is applied to create space and enhance exposure. Although insufflation pressures up to 12 mm Hg are in general well tolerated, hemodynamic studies have demonstrated an increase in right ventricular filling pressures, resulting in a decreased intrathoracic blood volume index and right ventricular ejection fraction. As a result, cardiac index and mean arterial pressure (MAP) decreased despite a compensatory increase in heart rate [Falk 2000b]. The instrument ports are created in the third and sixth ICSs. The ITA is usually dissected as a pedicle from the first rib to the sixth ICS using low energy cautery. Due to the wristed instruments, skeletonization is also possible. As of May 2001, 1,137 cases

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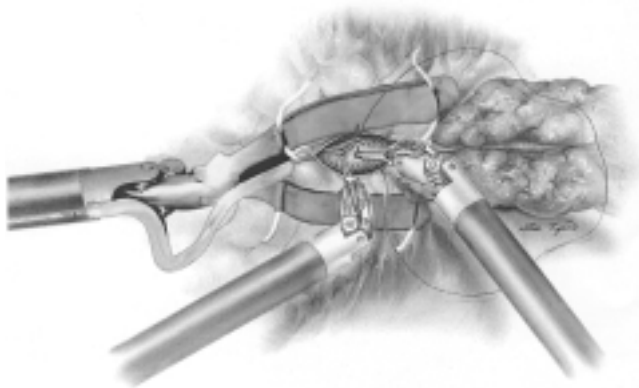


Figure 1. Close-up of an endoscopic coronary artery bypass graft anastomosis performed on the beating heart using an endoscopic stabilizer. Note that silastic bands are anchored in cleats at the stabilizer pads. Suturing is facilitated by the use of wristed instruments.

of robotic-assisted ITA take-downs have been reported in a company-based registry.

The first successful total endoscopic coronary artery bypass graft procedure (TECAB) was reported by Loulmet [Loulmet 1999]. Following ITA take-down, a pericardial window is created and the LAD is identified. After full heparinization and temporary ITA occlusion, femoro-femoral bypass is initiated using the Port-Access<sup>®</sup> system (Heart Port, Inc., Redwood City, CA) for closed-chest cardiopulmonary bypass and antegrade cardioplegic cardiac arrest. The anastomosis is then performed in a running fashion on the arrested heart through the same ports. As of May 2001, 109 TECAB cases have been reported. The majority ( $n = 103$ ) were single-vessel revascularizations of the ITA to the LAD [Mohr 1999, Mohr (in press)]. In a number of patients, the right ITA was used to graft the right coronary artery (RCA). In six cases, successful double-vessel TECAB has been reported [Kappert (in press)]. In a different approach, both ITAs are harvested endoscopically followed by a multivessel revascularization on the arrested heart through a left parasternal minithoracotomy in the second interspace (Dresden technique) [Cichon 2000].

The development of endoscopic coronary artery bypass grafting on the beating heart required the development of endoscopic stabilizers and methods for temporary vascular occlusion. With the use of a Nitinol-based, self-expanding endoscopic stabilizer, complete endoscopic bypass grafting was first achieved in a canine model [Falk 1999e]. More advanced stabilizers have recently been developed by Intuitive Surgical and Computer Motion. These stabilizers allow free articulation of the pads and thus provide easier placement. Complete TECAB procedures on the beating heart have been first reported by our group using an endoscopic stabilizer that was inserted through a subxyphoidal port (Figure 1, ©) [Falk 2000b]. At present, 56 cases have been reported in the registry, mostly single-vessel revascularizations (53 cases). The conversion rate (elective conversion to a MIDCAB procedure) with this approach is high (>50%), and

LAD occlusion times exceed those reported for MIDCAB procedures. Among the difficulties are excessive epicardial fat, pericardial adhesions, left ventricular (LV) dilatation, determination of optimal anastomotic site, excessive target vessel calcification, inadequate stabilizer positioning, and back-bleeding from septal branches.

#### Mitral Valve Surgery

In May 1998, a prototype of the da Vinci system was first used to perform part of a mitral valve repair [Carpentier 1998]. Since then, successful mitral valve repair has been performed with all critical steps of the repair procedure being carried out intracorporeally [Falk 1999f].

After femoro-femoral bypass is initiated, a small minithoracotomy is made in the right fourth intercostal space, the pericardium is opened manually, and traction sutures are placed to enhance exposure. After aortic clamping using the Port-Access system or a transthoracic clamp (Chitwood clamp), the left atrium is opened and the valve exposed using the Heartport left atrial retractor (Heartport, Inc., Redwood City, CA). Mitral valve repair, including ring implantation, is then performed remotely from the surgical console. After the repair is completed, the left atrium is closed manually using standard endoscopic instruments. As of May 2001, 107 mitral valves have been successfully repaired endoscopically using the da Vinci system.

Inability to achieve sufficient endoscopic exposure of the mitral valve is currently the limiting obstacle for closed-chest mitral valve repair. In order to provide endoscopic access to the mitral valve, an internal intra-atrial retraction/expansion device (inflatable balloon or self-expanding stent) needs to be developed. Recently, Lange reported the first complete, closed-chest mitral valve repair using the da Vinci telemanipulation system (Lange R, personal communication). Exposure of the valve was achieved by attaching the roof of the left atrium to the chest using patch-enforced stay sutures.

## DISCUSSION

The da Vinci telemanipulation system is intended to provide the operator with dexterity in confined spaces. In this context, end-effectors with six degrees' freedom of motion seem to be superior to instrumentation systems with a lesser range of motion. Intelligent man-machine interfaces and multi-level servo controls allow precise tissue handling despite the lack of fine tactile feedback. Current 3D vision technology provides enough optical resolution to visualize and manipulate small structures such as coronary arteries [Falk (in press)]. From the data presented here, it can be concluded that the use of the da Vinci telemanipulation system is safe, provided the user has a low threshold for conversion. Operating times exceed those for comparable open procedures, and only a few types of operations are currently performed with the system (single-vessel bypass grafting of the LAD, occasionally double-vessel grafting, mitral valve repair, and some atrial septal defect (ASD) closures). While some of the limitations that complicate endoscopic cardiac surgery are patient-related (limited space, chest shape), others are related

Table 1. Computer enhanced coronary artery bypass grafting using the da Vinci system

Author	System	Procedure	N	Procedure time	Conversion rate	Initial Patency	Patency at Follow-up
Mohr [10]	2	LITA-Take-down / MIDCAB	81	2.4,5h	2/81	96,3%	
Falk, Mohr [7,10]	2	TECAB	27	3,5-8h	5/27 (18,5%)	100% (22/22) 3-6d	95,4% (21/22) 3 months
Kappert [11]	2	LITA-Take-down / MIDCAB	60	137±60 min			
Kappert [11]	2	TECAB	10	260±92 min			

Patency rates as demonstrated by angiography system 1: da Vinci Intuitive Surgical), LITA = left internal thoracic artery, MIDCAB = minimally invasive direct coronary artery bypass, TECAB = total endoscopic coronary artery bypass.

to the target organ, the beating heart. Optimal access and exposure of epicardial and intracardiac structures remains a difficult challenge despite the improved technology. Other difficulties arise from design constraints inherent in the architecture of the telemanipulation system.

The ideal design for a telemanipulation system to be used in a cardiac surgical suite has yet to be determined. The use of wristed instruments has been the key to the clinical success of the present system. By increasing the intracorporeal dexterity of the instruments compared to standard endoscopic instruments, replication of manual surgical skills in an endoscopic environment is greatly facilitated. Although the increased dexterity comes at the price of larger instrument diameter, this has not been a critical issue except in the case of pediatric surgery. Despite the benefit of additional degrees of freedom, some procedural steps force the operator to extreme instrument positions where a degree of freedom might be lost (singularity). Various wrist design modifications may help to overcome this problem in the future.

The manipulators of the da Vinci are cart-mounted. This design provides maximum stability but forces the operator always to use the same triangle for port-location, with the camera being placed in the center between the left and right instruments. This potentially decreases the flexibility for choosing port locations. In addition, motion of the patient relative to the manipulator (tilting the table or moving the patient on the table) is not possible with the instruments inserted.

The directions for development in endoscopic coronary artery bypass grafting are currently twofold: (1) performance of multi-vessel revascularization on the arrested heart using a percutaneous cardiopulmonary bypass system, and (2) standardization of endoscopic beating heart bypass grafting. For multi-vessel revascularization, devices for exposure of the back wall of the heart need to be developed. Alternatively, different access routes may be explored. To help identify coronary pathology and to define the ideal location for an anastomosis in the absence of tactile feedback, intraoperative endoscopic ultrasound may be useful [Falk 2000c]. Multi-detector CT scanning has proven to be beneficial for preoperative planning and the assessment of coronary anatomy.

## CONCLUSION

With refinements in telemanipulator technology and the development of adjunct devices to enhance exposure, the technique of computer-enhanced endoscopic cardiac surgery

will further evolve and may prove beneficial for selected patients. Smaller and more flexible modular robotic arms will be developed, and new control algorithms will eventually allow one operator to control multiple arms. Sensorized instruments that use strain gauge sensors to measure forces could enhance haptic feedback. 3D-HDTV systems will provide even better optical resolution in the near future. The application of multi-modal 3D imaging and computational modeling of the range of motion of the robotic arms in an individual patient data-set may improve preoperative planning of the procedure [Chiu 2000]. Furthermore, the telemanipulation system may have potential as an educational tool, as it permits the introduction of the “driving school” concept into cardiac surgical training by linking two consoles. Endoscopic cardiac surgical simulation programs are currently being developed that will advance future educational efforts.

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