Robotic surgery: a review

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Minimally invasive techniques have revolutionized surgery by reducing surgical trauma and therefore hospital stay and subsequently cost. There are limitations, however. Robot-assisted surgery endeavours to minimize these technical hindrances and so allow better, more precise surgical practise while still minimizing surgical trauma.

Even though endoscopic surgery has progressed greatly in the last 20 years there are limitations. These include two-dimensional views, reduced degrees of freedom, little or no tactile feedback and ergonomically difficult positions for the surgeon. Such problems undoubtedly affect surgical precision. This has lead to interest in robotic master–slave systems (where the surgeon is the master, i.e. the operator, and the robot is the slave). Such devices have been under trial over the last 10 years. They offer many benefits, which have arisen as a result of new technology in lenses, cameras and computer software. These advantages are two-fold, first for the patient and second for the surgeon (*Table 1*).

Many surgical specialties have embraced the progression of robot-assisted techniques including general surgery, cardiothoracic surgery, urology, orthopaedics, ear nose and throat surgery and paediatric surgery. There is also evidence in animal models (Aiono et al, 2002) for progression in other specialties such as neurosurgery. Specialties which use microsurgical techniques will particularly benefit in the future. Examples are shown in *Table 2*.

Owing to the nature of minimally invasive surgery being used to access body cavities the two areas where robot-assisted systems have been evaluated extensively are the chest and abdomen.

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CARDIOTHORACIC SURGERY WITH COMPUTER-ENHANCED SYSTEMS

At present, there is no consensus even between cardiac surgeons involved in the development of the field as to the exact definition of minimally invasive cardiothoracic surgery (MICS). Some consider a definition to be the avoidance of cardiopulmonary bypass (CPB), others the downsizing of the full sternotomy incision and others the type of visualization used as either direct or video-assisted. Robotically-assisted technique such as totally endoscopic coronary artery bypass (TECAB) on a beating heart combines all the above mentioned categories

TABLE 1. Advantages of robot-assisted surgery for the patient and the surgeon

Advantages for the patient	Smaller incisions
	Decreased postoperative pain
	Shorter length of stay in hospital
	Reduced blood loss
	Reduced tissue trauma and inflammatory response to surgery
	Improved cosmetic result
	Faster return to work
Advantages for the surgeon	Better visualization (higher magnification)
	Hand tremor is eliminated allowing greater precision
	The 'robotic wrist' is more flexible than the human wrist, improving manoeuvring around organs and vessels
	Large external movements of the surgical hands can be scaled and transformed to limited internal movements of the 'robotic hands' extending the surgical ability to perform complex technical tasks in limited space
	The surgeon is able to work with less stress under an ergonomic environment and able to achieve higher levels of concentration
	The computer can compensate for the beating movement of the heart making it unnecessary to stop the heart during surgery
	Less need for assistants

and can be considered as one of the latest advances in MICS. Surgeons are trying to expand the initial minimally invasive concept of minimal access through limited incision towards a totally endoscopic access with a 1 cm incision performed remotely preserving the integrity of the chest (*Figure 1*).

Despite numerous attempts over the last decade, epicardial and intracardiac surgery with manual endoscopes has been proven technically impossible. During the last 3 years, more 'intelligent' instruments have been developed with higher precision, improved dexterity and intuitive remote handling allowing endoscopic reconstructive microsurgery to be performed (Cadiere et al, 2001; Marescaux et al, 2001; Goto et al, 2003). The reasons that cardiothoracic procedures are more difficult to perform completely endoscopically are:

1. There is fixed and limited space between the heart and chest wall that cannot be expanded with carbon dioxide (CO_2) insufflation (limited exposure).
2. It is technically very demanding to perform reliable microvascular suturing which is required for the most common tasks in cardiac surgery (coronary anastomosis, mitral valve repair or replacement).

TABLE 2.
Examples of robot-assisted procedures in various surgical specialties

Speciality	Robot-assisted procedure
General	Cholecystectomy
	Fundoplication
	Adrenalectomy
	Splenectomy
	Intestinal anastomosis
	Heller myotomy
Cardiothoracic	Coronary artery bypass grafting
	Mitral valve repair
	Patent ductus arteriosus, atrial septal defect closure
	Ablation for atrial fibrillation
	Biventricular pacemaker placement
	Mediastinal tumours
	Thymectomy
	Excision of enteral cyst
	Lung resection for cancer
	Excision of benign lung tumours
	Enucleation for tuberculoma
	Stiching of bullae
	Pericardial window
	Excision of pleural tumours
	Oesophageal resection
	Oesophageal tumours and cysts
	Oesophageal diverticulum
	Achalasia
	Gastro-oesophageal reflux
	Sympathectomy
Orthopaedics	Anterior cruciate ligament and posterior cruciate ligament repair and/or replacement
	Internal hip fixation
Neurosurgery	Navigation
	Tumour removal
Urology	Radical prostatectomy
	Pyeloplasty
Ear nose and throat	Stapedotomy
Gynaecology	Tubal reanastomosis

TYPE OF OPERATIONS PERFORMED ROBOTICALLY-ASSISTED IN CARDIOTHORACIC SURGERY

Robotic assistance increases the technical precision (accuracy of less than 5 µm) of the surgical human hands (accuracy of 10 µm) and offers three-dimensional visualization, improved magnification, filtering of tremor and down-scaling of movement. It has enabled cardiothoracic surgeons to perform different types of procedures including: coronary surgery, mitral valve surgery, congenital heart diseases, arrhythmia surgery, biventricular pacemaker placement, oesophageal surgery, lung cancer surgery, and surgical management of pericardial and mediastinal diseases (Mack, 2001; Reuthebuch et al, 2002; Torracca et al, 2002).

In order to carry out intracardiac procedures (closure of atrial septal defects, mitral valve repair) CPB is required. In MICS percutaneous

Figure 1. Example of postoperative scarring following totally endoscopic coronary artery bypass surgery.

cardiopulmonary support with the Heartport endo system (Heartport, Redwood City, CA, USA) can be used (the femoral artery for arterial access and the femoral vein for venous return) (Galloway et al, 1998).

ROBOTIC SYSTEMS USED IN CARDIOTHORACIC SURGERY

Two systems that enable robotic minimally invasive coronary surgery are the Da Vinci telemanipulation system (Intuitive Surgical, Mountain View, CA, USA) and the Zeus robotic system (Computer Motion, Santa Barbara, CA, USA). Advantages of the Da Vinci system are the three-dimensional visualization and the robotic wrist providing articulated motion with a full 7° of freedom inside the chest cavity. This feature is technically more advantageous in performing endoscopic left internal thoracic artery harvesting, complex mitral valve repair and coronary anastomoses. Also the time required to perform these tasks is less in comparison to the Zeus system. Disadvantages of the Da Vinci system in comparison to the Zeus system are the fact that the instrument arms have a larger diameter and in general the system is more bulky, limiting the space for assistants in the operating theatre (Sung and Gill, 2001).

CURRENT STATUS OF CORONARY REVASCULARIZATION

In a very short period robotic techniques have been established in coronary surgery. The first coronary artery bypass procedure in a closed chest was performed in 1998 by Loulmet and Carpentier (Loulmet et al, 1999).

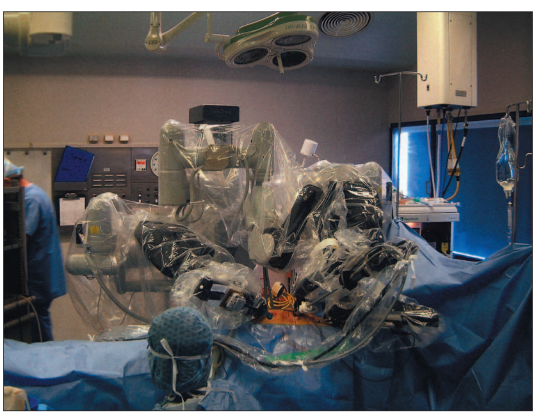
The first seven TECAB procedures in a beating heart with the Da Vinci System in UK were performed during the last year in St Mary's Hospital, London (*Figure 2*) (Casula et al, 2003).

The surgical technique for coronary revascularization involves: double lumen intubation, draping and positioning of the patient supine with 20–30° elevation of the left hemithorax, positioning of the camera port in the fifth space (anterior axillary line) and insufflation of CO_2. Following this the camera is inserted and two more ports for instrumentation are required in the third and sixth intercostal space anteriorly to the camera entry site. In cases where bilateral internal thoracic arteries need to be harvested the right thoracic artery is harvested first using the 0° endoscope and then, changing to a 30° endoscope, the left internal thoracic artery can be harvested. Following the division of the pericardium identification of the coronary targets can be performed. Another port is required for the insertion of the epicardial stabilizer in order to immobilize the coronary targets and to perform the coronary anastomosis with or without CPB (*Figure 3*).

Indications for robotic coronary revascularization procedures are not clearly defined. Robotic coronary revascularization has been applied in selected elective patients without significant enlargement of the left ventricle, without left ventricular dysfunction and without intramyocardial coronary vessels. Other relative contraindications are anatomically small intrathoracic space or morbid obesity.

The robotic harvesting of the left internal thoracic artery (*Figure 4*) is a well-established procedure and can be part of:

Figure 2. Da Vinci system robot.



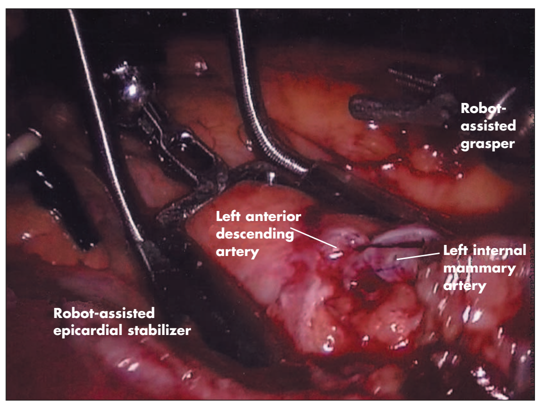


Figure 3. Robotic epicardial stabilizer in situ during left internal mammary artery to left anterior descending artery anastomosis.

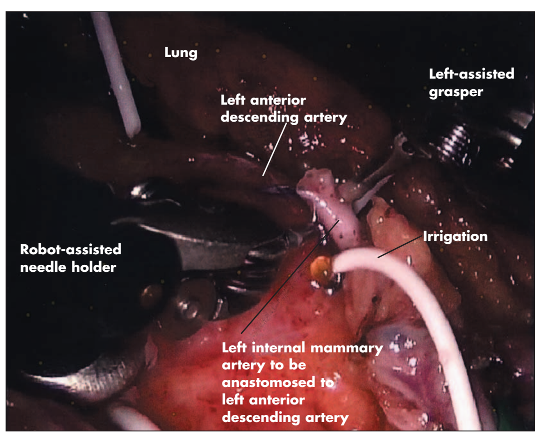


Figure 4. Endoscopic robotic left internal mammary artery harvesting before anastomosis with left anterior descending artery.

1. TECAB for single vessel disease on the beating heart (left internal thoracic artery to left anterior descending coronary artery) or with the use of CPB
2. A minimally invasive direct coronary artery bypass procedure through a small anterior thoracotomy without spreading the ribs (atraumatic coronary artery bypass) or conventionally by spreading the ribs
3. TECAB for multivessel disease with the assistance of CPB.

Coronary anastomoses performed robotically on the human beating heart have been performed, anastomosing the left internal thoracic artery on the left anterior descending territory. In Dresden the Da Vinci system has been used for harvesting bilateral internal thoracic arteries in combination with left anterior thoracotomy and CPB (Dresden technique) for multivessel coronary artery bypass grafting (Cichon et al, 2000). This approach is attractive for diabetic patients where harvesting of bilateral internal thoracic arteries is associated with significant risk of sternotomy wound-related complications. Studies on the arrested heart evaluating the quality of the coronary anastomosis (patency, intactness, alignment, intimal tears, dehiscence) and time required for the procedure have shown that by using telemanipulation systems an anastomosis performed endoscopically can be comparable to ones performed conventionally (Falk et al, 1999).

CURRENT STATUS OF ROBOTIC MITRAL VALVE SURGERY

Several reports have shown that the aim of a totally endoscopic mitral valve procedure has not yet been achieved and a small right thoracotomy and manual opening of the left atrium are required (Felger et al, 2001). Despite the fact that robotic systems have been implemented in association with development of modified surgical instruments and equipment (Chitwood knot pusher, aortic endoclamps, new design rib retractors to facilitate exposure), currently the operation on the mitral valve cannot be completely endoscopic. Also the use of Heartport endo system for closed chest CPB support and intraoperative monitoring of the middle cerebral artery flow by transcranial Doppler to detect potential migration of the endoclamp in order to avoid neurological complications are mandatory.

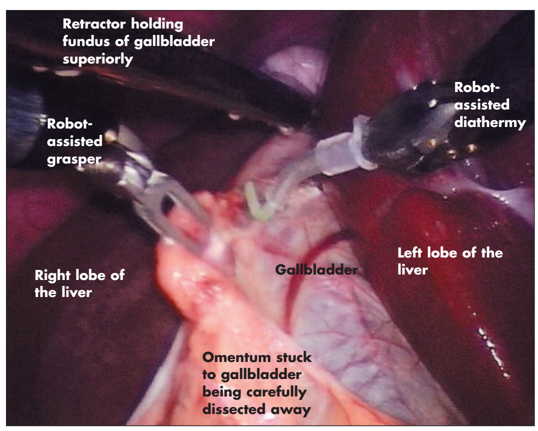
Preliminary clinical results are satisfactory and comparable to conventional techniques performing quadrangular resection, prosthetic ring implantation and edge-to-edge repair (Chitwood et al, 2001). The technique has been applied even in complex cases (re-do operations or patients with previous implantation of biological tricuspid mitral valves).

The current international experience with robotic heart surgery is mostly anecdotal, retrospective, and non-controlled. The efficacy and cost effectiveness of robotic cardiothoracic procedures has not yet been evaluated (Damiano et al, 2001). Results of rigorous prospective randomized studies in the United States under Food and Drug Administration-approved protocols are in progress. The use of robotic telemanipulation technology for heart surgery is restricted in the United States to patients enrolled in clinical studies in a few elite centres. The best operation should have priority over the approach. Quality should never be compromised to minimize hospital cost, improve cosmesis or lessen temporary discomfort.

GENERAL SURGERY WITH COMPUTER-ENHANCED SYSTEMS

The range of gastrointestinal procedures where robot systems have been tested is wide and includes adrenalectomy, cholecystectomy (*Figures 5* and *6*), fundoplication (*Figure 7*), splenectomy, intestinal anastomosis and oesophageal surgery. The technical feasibility of such procedures remains unquestioned – the authors were not able to find studies where the procedures had failed both for animal studies and those in clinical trials but Cadiere et al (2001) showed no obvious benefit at present. A second study by Marescaux et al (2001), although concluding that there are no benefits at present, recognized the potential for advantages in the future especially when interfaced ‘with other forms of digitised data, such as pre- or intra-operative imaging studies, or be (sic) trans-

Figure 5. Mobilization of the gallbladder during robotic laparoscopic cholecystectomy.



mitted over a distance'. The majority of texts reviewed were very optimistic about the potential gain from the use of robotic systems, even suggesting reduction of potential complications because of the three-dimensional view and better magnification (Melvin et al, 2001).

Work has taken place to ascertain the usefulness of a robotic camera device and it has been found that robotic camera systems offer more stability and control (Aiono et al, 2002) than a human system. They also found that operating times were less with the robot-assisted camera. However, Merola et al (2002) concluded that 'the use of a voice-controlled robotic camera holder does not alter the length of the operative procedure, the patient's length of stay, or post-operative morbidity', but that, subjectively, the surgeons had a sense that there was 'less smudging, fogging, and inadvertent movements of the laparoscope when it is controlled by a robotic system'. Both studies discuss the fact that systems would remove the need for a human camera assistant, especially when used with a voice-controlled system. This would allow procedures to be performed by a surgeon and a nurse and thus be more cost effective (Nieburh and Born, 2000).

Other studies have found comparable techniques easier with the robot system rather than with the manual system (Wykypiel et al, 2003). Basic laparoscopic manoeuvres such as tying, clipping and suturing have been compared (Lomanto et al, 2001) showing that, robotically, they were 'as accurate and as fast as manoeuvres made without robotics'.

Several different systems have been used in the studies detailed above and thus the comparison is not standardized. However, it is important to note that whichever system was used the results seem to be favourable as the basic principles of the systems are the same. The authors were not able to find many examples of robotic surgery for smaller procedures such as herniorraphy. Expertise in such fields would undoubtedly aid day case surgery as well.

At present the majority of trials using robotic systems concentrate on elective cases; however, trials have been carried out to estimate the feasibility of carrying out robotic surgery in emergency settings such as for trauma (Lomanto et al, 2001). Bowersox et al (1998) concluded, from animal models, that such procedures were possible and that complex manipulations were possible in the trauma setting, but that there was a considerable increase in the time taken for the robotic procedures. The study was carried out in 1998 and as the systems are more advanced and the operators are now more experienced, surely the robotic master–slave applications have a place in the emergency setting too. Further work in this field would also have huge implications for remote surgery.

IMPLICATIONS OF THE USE OF ROBOT-ENHANCED SYSTEMS

The potential impact of robotic technology in the future of surgery is to expand the concept of minimally invasive robot-assisted systems beyond its current role which means:

- Difficult minimally invasive operations can be performed more easily
- Minimally invasive operations performed rarely can be transformed to routine operations
- New surgical procedures are possible
- The role and efficiency of other devices is increased (anastomotic devices for proximal or distal anastomoses, for example)
- The type of surgical training required with the application of surgical stimulation techniques and telementoring can change, providing more objective ways of reviewing surgical training
- The relationship between trainer and trainee will change, as will methods of evaluation of surgical performance

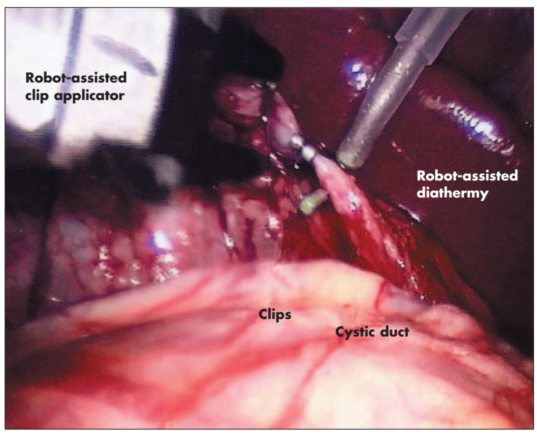


Figure 6. Placement of clips on cystic duct before its division in robotic laparoscopic cholecystectomy.

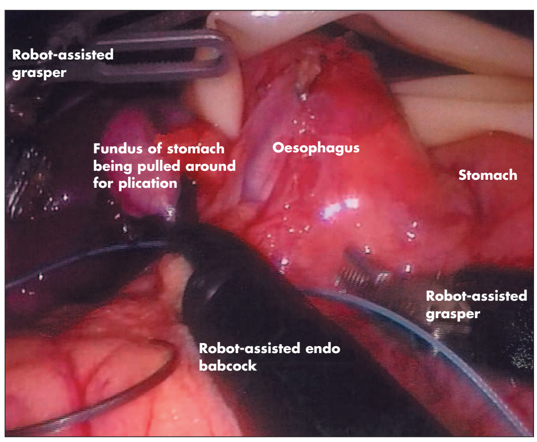


Figure 7. Wrapping the fundus of the stomach around the posterior aspect of the oesophagus, before plication in robotic Nissen's fundoplication.

- The method by which patients are referred for surgery might change.

There are, however, a few disadvantages of computer-enhanced operations.

- Increased cost
- Increased operating time and set up of the system
- Socioeconomic implications
- Significant risk of conversion to conventional techniques
- Prolonged learning curve
- Multiple repositioning of the arms can cause trauma
- Haemostasis
- Collision of the robotic arms in extreme positions.

DISCUSSION

Robotic systems seem to have huge advantages, but their efficacy, precision, complication rate and reliability have all been questioned (Buckingham and Buckingham, 1995). All these pertinent factors have been evaluated favourably in various clinical trials (Chitwood et al, 2001; Horgan and Vanuno, 2001). Other studies have started to compare the different systems on the market looking at ease of using the system, speed of procedures and learning curves of the operators (Sung and Gill, 2001). Such favourable studies ensure a promising future for the robotic systems and their manufacturers and operators, but they are not flawless. Currently the systems consist of hugely expensive, large machines and most surgeons are not familiar with their use although if technology continues to improve at the current rate all these factors will be rectifiable. The procedures at present are also lengthy, which also has implications for anaesthesia.

There are further implications which apply to the medical system in general. These include training, consent and insurance policies.

TABLE 3.
Technical changes that would improve cardiothoracic robot-assisted operations

New instruments for robotic systems need to be designed to facilitate specific tasks especially in thoracic surgery
Need for new generation endoscopic stabilizers and endoscopic apical suction to facilitate multi-vessel coronary artery bypass grafting on the beating heart
New generation of robotic systems with less bulky arms – ‘miniaturism’
Automated instrument tracking and image-guided triangulation using position markers at the tip of the instrument may improve orientation
Sensors on the tips of the instruments providing tactile and force feedback will improve the manipulation of tissue and thin sutures
Need for versatile multitask effectors could eliminate the need for instrument changes
Implementation of harmonic scalpel for harvesting the internal thoracic artery could overcome problems with electrocautery (smoke, heat, bleeding from side branches)
Virtual immobilization of the heart can facilitate work on the beating heart
New generation of endoscopic devices for automatic stapling or suturing will reduce the time required for these tasks

Implications for surgical training

Robotic systems offer an exciting prospect for the future of surgical skills and education. Simulators and virtual training may allow the objective measurement of surgical dexterity and continuing evaluation of surgical skills would also be possible. Curricula have been developed for the training of robotic surgery and have been successfully applied to surgical trainees (Chitwood et al, 2001). Trainees would also be able to watch their own procedures and be potentially debriefed enabling constructive criticism and further progression in methodology.

Implications for consent

It is important for the surgeon to explain exactly what the procedure entails. Many patients are under the impression that the robot actually performs the operation. The understanding of the master–slave systems must be conveyed to the patient. As with any minimally invasive technique, the possibility of the procedure being converted must be discussed. Currently robot-assisted cases are not routine and thus patients are selected for these procedures – this should also be explained to the patient. It would also be beneficial for any department undertaking robotic surgery to make such information available to their general patient population to facilitate general understanding of the current position of robot surgery.

Implications for insurance

The increased cost and the fact that this is such a new development in surgery has huge implications for insurance policies. Once robot techniques are common place, it will be interesting to see where their insurance rating lies.

WHAT DOES THE FUTURE HOLD?

Smaller, more cost-effective machines would undoubtedly change the surgical outlook for the population in general. More trained operators would be needed to operate the increasing number of machines. Smaller technology and instrumentation would also empower neonatal and fetal surgeons and vastly improve the work in cardiothoracic surgical cases (*Table 3*). The possibility of image-based navigation systems would facilitate further meticulous dissection and eventually allow surgeons to rehearse on patient-specific virtual models before the actual case, perhaps even in a holographic setting (Gorman et al, 2000).

The above discussion has been confined to the use of large-scale robot technologies. With technology getting smaller and faster the possibility of robots on a microscopic or even cellular level may even be considered. Such 'nanobots' are not a science fiction fantasy but are many years away from widespread surgical use. Potential pitfalls may include adequate control and programming, energy supplies, navigation and life span.

Progressive, forward-thinking individuals and continuing evolution of technology have created exciting possibilities for the developments in robotic surgery for the future, which will continue to change minimally invasive surgical practise with closely monitored clinical trials. **HM**

Conflict of interest: none.

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KEY POINTS

- Robot-assisted surgery is now taking place on selected patients in certain centres in the UK.
- Its benefits are to reduce the technical problems currently experienced by laparoscopic surgeons, while maintaining reduced surgical trauma and short hospital stay times for patients.
- Major procedures such as one vessel coronary artery bypass surgery are being performed completely with the robot-assisted systems.
- There are further implications to the routine use of such new technology, especially for surgical training, the development of a new anaesthetic speciality, consent for surgery and patient insurance policies.
- There is continuing interest in the development of new instruments and technology that will further aid robot-assisted procedures to be performed more easily.
- As techniques and technology improves the current expense of the procedures will be reduced.
- The future for minimally invasive surgery continues not only with robot-assisted systems but also with nanotechnology that will lead to a further new surgical speciality.