Anesthesia for Robotic Thoracic Surgery

2

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Abstract

Minimally invasive surgery involving the thoracic cavity is on the rise. With the introduction of the da Vinci robot system more than 10 years ago, cardiac and thoracic operations have been performed.

The literature on this topic currently includes case reports or series of clinically prospective or retrospective observational reports with the use of robotic systems, involving the thoracic cavity (mediastinal mass resection, lobectomies, esophagectomies, mitral valve surgery, assisted endoscopic coronary artery bypass grafting and atrial septal defect repair).

The basic principles applied to minimally invasive surgery of the chest apply to robotic-assisted thoracic surgery. The combination of patient position management, of one-lung ventilation techniques and surgical manipulations after ventilation and perfusion from dependent and non-dependent or collapsed lung. The preferred method for lung isolation during robotic assisted thoracic surgery is the use of a left-sided double-lumen endotracheal tube because of the greater margin of safety and faster lung collapse. Visualization during robotic thoracic surgery may be enhanced by continuous intrathoracic carbon dioxide insufflation which may increase airway pressures and depress hemodynamic performance.

Patient positioning during robotic thoracic surgery represents a challenge for anesthesiologists each particular case might require specific patient position so the surgeon can gain enough space in the axilla for the robot arms and accessory port/instruments in thoracic surgery. Special attention should be given to avoid unnecessary stretching of the elevated arms because it can damage brachial plexus.

The success of robotic thoracic and cardiac surgery includes skills in lung isolation techniques, fiberoptic bronchoscopy techniques, the use of transesophageal echocardiography (cardiac cases) and clear understanding of the concept of robotic surgery and anesthesia.

Keywords

Anesthesia for robotic cardiac and thoracic surgery • Lung isolation, one lung ventilation with left-sided double-lumen endotracheal tube • Fiberoptic bronchoscopy techniques during robotic thoracic surgery • Carbon dioxide (CO_2) insufflation intrathoracic • Brachial plexus injuries during robotic thoracic surgery • Use of transesophageal echocardiogram in robotic cardiac surgery • Regional anesthesia, paravertebral blocks during robotic cardiac and thoracic surgery

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K. Kernstine (ed.), *Atlas of Robotic Thoracic Surgery*, https://doi.org/10.1007/978-3-319-64508-7_2

2.1 Introduction

Minimally invasive surgery approaches have become increasingly popular in cardiac, thoracic and esophageal surgery. With the introduction of robotic systems more than 10 years ago, particularly the da Vinci® Robot System, cardiac and thoracic operations have been performed with some provocative results and limited defined advantages. This review provides an overview of the anesthetic implications and the use of the robotic system in patients undergoing robotic-assisted surgery through the thoracic cavity, with particular emphasis on the mediastinum, lungs, and esophagus.

2.2 Anesthesia Considerations in Robotic Thoracic Surgery

The basic principles applied to minimally invasive surgery of the chest (i.e. thoracoscopic surgery) apply to robotic-assisted thoracic surgery. The combination of patient position, management of one-lung ventilation (OLV) techniques, and surgical manipulations alter ventilation and perfusion from the dependent and non-dependent or collapsed lung. The preferred method for lung isolation during robotic assisted thoracic surgery is the use of a left-sided double-lumen endotracheal tube (DLT) because of the greater margin of safety and faster lung collapse. Also it provides ready access for bronchoscopic evaluation of the airway during surgical resection. In general, careful attention must be given to airway devices because changes in body position may cause tube migration. OLV anesthetic management is more challenging during robotic thoracic surgery due to the presence of the robot chassis that is stationed over the patient. The patient's airway is also usually located far from the anesthesia field. In some instances access to the airway, if needed, is not the most optimal because of the presence of robotic arms nearby.

Visualization during robotic thoracic surgery may be enhanced by continuous intrathoracic carbon dioxide (CO_2) insufflation, which may increase airway pressures and depress hemodynamic performance. When CO_2 is used, intrathoracic pressures greater than 10–15 mmHg are rarely necessary and may compromise the cardiorespiratory function. Increasing the intrathoracic pressure (i.e. >25 mmHg) can decrease venous return and cardiac compliance; in addition, the dependent lung develops higher airway pressures and ventilation can become difficult. During OLV and the robotic surgical procedure, to maintain oxygen saturation above 95%, the FiO_2 may need to be maintained at 100% and the peak inspiratory pressure should be kept <30 cmH_2O. The rate of ventilation should be adjusted to maintain the $PaCO_2$ at approximately 40 mmHg. Table 2.1 shows the surgical procedures performed in thoracic surgery with the da Vinci® Robotic Surgical System.

Table 2.1 Surgical procedures performed in thoracic surgery with the da Vinci® Robotic Surgical System

• Thymectomy
• Mediastinal mass extirpation
• Fundoplications
• Esophageal dissections
• Esophagectomy
• Pulmonary lobectomy

2.3 Robotic-Assisted Surgery and Anesthesia for Mediastinal Masses

Among the thoracic surgical procedures performed to date with the use of the da Vinci® Robotic Surgical System is the thymectomy [1]. Of the patients scheduled for robotic-assisted thymectomy, some have the diagnosis of myasthenia gravis or the presence of a thymic tumor. For patients with myasthenia gravis, adequate preparation of the patient for surgery includes neurological evaluation to assess the patient's neurological status and optimization of myasthenia; continuation of anticholinesterase therapy, plasmapheresis or immunoglobulin therapy may be indicated [2–4]. Precautions regarding anesthetic management include the proper dosing of muscle relaxants and the potentially dire consequences of a large mediastinal mass on airway obstruction and reduced parenchymal compliance.

Patients undergoing robotic thymectomy require the use of lung isolation devices. The most common device used in the setting is the left-sided DLT. Patient positioning for a thymectomy may require a nearly supine with a 30° angle right or a left lateral decubitus position with the use of a beanbag or role. The padded arm of the elevated side is positioned at the patient's side below the level of the table as far back as possible so the surgeon can gain enough space in the axilla for the robotic arms and accessory ports/instruments. While the robot is in use it is imperative to consider strategies to protect all pressure points and to avoid unnecessary stretching of the elevated arm, because this can cause damage to the brachial plexus. In addition, to avoid lung injury before the instruments are placed into the chest cavity, a complete lung collapse must be achieved throughout the procedure. Once the robot has been docked, the current robotic system does not allow for patient body position changes on the operating room table. An additional concern is that the operating room table is rotated obliquely away from the anesthesiologist's field positioning it relative to the robotic chassis. As a result access to the airway to make adjustments to the DLT during the surgery can be challenging and appropriate planning will allow for a safer procedure. In some cases a bilateral surgical approach may be required. In these cases the operation is performed in two stages, one side then the other, and requires undocking the robot and rotating the table 180° to provide surgical access to the opposite chest wall for the second portion of the operation. The anesthesiologist must be cautious during these changes to avoid dislodging the endotracheal tube and ventilator connection tubing, and to ensure that the lines and continuous pulse oximetry, electrocardiogram monitor wires and blood pressure monitoring lines have enough slack to accommodate changes in position. The anesthesiologist must be aware during these cases that possible injury to the contralateral mediastinal pleura to the first side, especially if CO_2 insufflation is used, as the elevated intrathoracic pressure in the contralateral hemithorax can make ventilation of the contralateral ventilated lung difficult and result in cardiovascular collapse essentially "tension" physiology. Special attention must be given to the elevated arm or head to prevent crushing or abrasive injury from the movement of the robotic arms. A recent case report [5] described a brachial plexus injury in an 18-year-old male after robot-assisted thoracoscopic thymectomy. The authors described that the left upper limb was in slight hyperabduction. It is important to keep in mind that hyperabduction of the elevated arm to provide sufficient surgical space can lead to a neurologic injury. Communication between the surgeon and the anesthesiologist provides a safe robotic procedure, reducing the likelihood for such injuries. The elevated arm should be protected with padding and by using a sling device that allows the arm to rest in a relaxed position. The heat from the robotic videoscope light source can be another cause of potential injury. Direct contact of these devices with surgical drapes and the patient's skin can quickly develop fires and burns, respectively, during the changing of the telescopes and cameras.

The reports of complications occurring during or following a robotic thymectomy are few. Bodner et al. [6] reported their retrospective review of 13 patients who underwent a complete *en bloc* thymectomy with the da Vinci® system showed no intraoperative complications or surgical mortality. Savitt et al. [7] reported on 14 patients robot-assisted complete thymectomies intraoperatively managed with OLT and arterial and central venous pressure catheters. All of the patients were approached from the right side and CO_2 insufflation to a pressure of 10–15 mmHg was used to compress the lung away from the operative area. Again, there were no conversions to thoracotomy or median sternotomy, nor any intraoperative complications or surgical mortality; the median hospital stay was 2 days with a range of 1–4 days. Through a left-sided approach, Rückert et al. [8] reported the largest series of robotic thymectomies, 106, with a zero percent mortality and an overall postoperative morbidity rate of 2%. Thus, in the publications to date, the initial robotic thymectomy experience appears to be safe and offers a minimally invasive opportunity for a complete thymectomy.

2.4 Robotic-Assisted Pulmonary Lobectomy

One of the first thoracic applications of the da Vinci® Robotic system was for lobectomy. Numerous investigators reported a sporadic and inconsistent use of robotics to perform lobectomy. In 2006, Park et al. [9] reported the largest and consistent use of the robot in a series of 30 patients, attempting it in 34. Four of the patients (12%) required conversion to thoracotomy Anderson et al. [10] reported a series of 21 robotic lung resection patients in which the 30-day mortality and conversion rate was 0%. The median operating room time and blood loss was 3.6 h and 100 mL. The complication rate was 27%, and included atrial fibrillation and pneumonia. Gharagozloo [11] reported a series of 100 consecutive robotic-assisted lobectomies for lung cancer and concluded that robotic surgery is feasible for mediastinal, hilar, and pulmonary vascular dissection during video-assisted thoracoscopy lobectomy.

Like the thymectomy, positioning the patient for a robotic lobectomy includes placing the patient over a bean bag or some other position maintaining device and typically flexing the operating table to open the intercostal spaces and swing the hip out of the way. The ipsilateral side arm is slightly extended cephalad and/or anteriorly to gain exposure to the axilla. There must be sufficient space to avoid injury to the arm, chest wall and hip. OLV is utilized. Ideally, the anesthesiologist should have experience in placing a DLT [12]. The left-sided DLT is most commonly used double-lumen system and is positioned with a flexible fiberoptic bronchoscope [13]. The airway, in a few instances, is difficult to place a DLT and, instead, a bronchial blocker [14]. Ideally, the operated lung must be isolated from ventilation to minimize lung motion, optimize visibility and reduce parenchymal bleeding.

The monitoring for lobectomy is the same as described above for the thymectomy. Preparation for a potential thoracotomy is important and may occur at any time. Park [9] in their early experience converted to open thoracotomy in 12% of their patients 75% of them for bleeding. The lateral decubitus position and the 180° rotation away from the anesthesiologist's field present particular challenges in managing the endotracheal tube. The chassis of the robot is often positioned over the patients head leaving a very small area for the anesthesiologist to access the airway. As with the thymectomy, some surgical teams use thoracic cavity 10–15 cmH_2O CO_2 insufflation to gain operative exposure. In some patients, this may present challenges and the anesthesiologist must adjust the pressure as the patient accommodates.

With their greater surgical experience with minimally invasive lobectomy, safety is being demonstrated by Gharagozloo et al. [11] reporting their experience in 100 consecutive robotic lobectomies requiring no emergent thoracotomies. Postoperative analgesia was addressed with the infusion of a local anesthetic (0.5% bupivacaine, 4 mL/h) through catheters placed in an extrapleural tunnel placed from intercostal space 2–8. All patients in this report were extubated in the operating room. Their 30-day mortality was 4.9%, with a median length of stay of 4 days. Postoperative complications included atrial fibrillation in four cases, prolonged air leak in two cases, and pleural effusion requiring drainage in two cases, similar complication and rates to the experience with video thoracoscopic surgery. Although lobectomy can be performed via robot-assisted surgery, the advantages at the present time are not well defined.

2.5 Robotic-Assisted Esophageal Surgery

The esophagus can be removed using a robot in using four basic techniques: chest only, transhiatal, abdomen then chest technique with the anastomosis in the neck and the abdomen then chest technique with the anastomosis in the chest. From a patient management viewpoint, the chest then abdomen or the esophagolymphadenectomy technique presents particular challenges [15, 16]. Basically, there are two phases or stages. Each stage requires a different patient position and the operating room needs to be set up according to the patient's new position. The first part of the operation is the dissection of the esophagus and lymph nodes in the thorax. The patient is positioned on a beanbag on the left lateral decubitus position, and the table is tilted to the right so that the patient is almost in the prone reverse Trendelenburg position. The left upper extremity is hyperextended and placed on a sling device very close to the patient's face to create chest space for the robotic ports/instruments. The operating room table is rotated 100° away from the anesthesia field. This part of the operation requires OLV and CO_2 insufflation to provide visualization of the esophagus. The anesthesiologist should anticipate hemodynamic and respiratory changes during CO_2 insufflation; resection of the contralateral pleura is not infrequently required and the CO_2 leakage into the opposite chest presents hemodynamic and ventilatory challenges.

The second stage of the procedure is the abdominal portion, the dissection of the stomach, and creation of the gastric tube and neck pharyngoesophageal-gastric anastomosis. This part of the procedure is performed with the patient in the supine position and with the operating room table rotated 180° away from the anesthesiologist's field. The patient is supine and the robot is brought in over the patient's head limiting the exposure to the airway and the endotracheal tube. The anesthesiologist should be aware that ventilatory pressures and hemodynamics can change rather acutely once the transhiatally-approached mediastinal pleura is breached. This occurs during the dissection around the gastroesophageal junction, CO_2 can escape into the chest trough the hiatus. In this case, the combination of insufflation, fluid flux and the reverse Trendelenburg body position can have an adverse impact on the hemodynamic status of the patient. Adjustments in fluid management, CO_2 pressure, light pressors and ventilatory pressure adjustments are often simultaneously required.

The initial experience with the da Vinci® system in esophageal surgery involved a patient who had a thoracic esophagectomy with wide celiac axis lymphadenectomy; the case was reported by Kernstine et al. [15] and had promising results. Thereafter, another report using the using the da Vinci® system 6 esophagectomy patients without intraoperative complications [17] was published. The surgical approach in this report was performed from the right side of the chest first. A left-sided DLT was used to selectively collapse the right lung. In a report by Van Hillegersberg et al. [18] 21 consecutive patients with esophageal cancer underwent a robot-assisted thoracoscopic esophagolymphadenectomy, 18 cases were completed thoracoscopically and three required conversion to open procedures (because adhesions or intraoperative hemorrhage). In this case series report, all patients received a left-sided DLT and a thoracic epidural catheter as part of their anesthetic management. Positioning of these patients was in a left lateral decubitus position, and the patient was tilted 45° towards the prone position. Once the robotic thoracoscopic phase was completed, the patient was then placed in supine position and a midline laparotomy was performed. A cervical esophagogastrostomy was performed in the neck for the completion of surgery. Of interest, in this series, pulmonary complications occurred in the first ten cases (60%); the authors surmised were caused primarily by left-sided pneumonia and associated acute respiratory distress syndrome in three patients (33%). These complications were felt related to barotrauma to the left lung (the ventilated, or dependent, lung) attributed to high tidal volumes and high peak inspiratory pressures. In the 11 patients that followed, the same authors modified their ventilatory setting to administer continuous positive airway pressure (CPAP) ventilation, 5 cm H_2O during OLV and pressure-controlled ventilation was used; with this approach the respiratory complication rate was reduced to 32%.

Another study [16] involved 14 patients who underwent esophagectomy using the da Vinci® system in different surgical stages. It showed that for a complete robotic esophagectomy including laparoscopic gastric conduct, the operating room time was an average of 11 h with a console time by the surgeon of 5 h, an estimated average blood loss of 400 ± 300 mL. In this report after the robotic thoracoscopic part of the surgery was accomplished with the patient in the lateral decubitus position, patients were then placed in supine position and reintubated, and the DLT was replaced with a single-lumen endotracheal tube. The technique required that

Table 2.2 Complications of robotic-assisted thoracic surgery

Author	Number of cases	Operation	Intraoperative complications	Postoperative complications
Rea et al. [1]	33	Thymectomy	0	Chylothorax n = 1
				Hemothorax n = 1
Pandey et al. [5]	1	Thymectomy	–	Brachial plexus injury
Bodner et al. [6]	14	Mediastinal mass resection	0	Postoperative hoarseness due to lesion to left laryngeal recurrent nerve
Savitt et al. [7]	15	Mediastinal mass resection	0	Atrial fibrillation n = 1
Rückert et al. [8]	106	Thymectomy	Bleeding n = 1	Phrenic nerve injury n = 1
Park et al. [9]	34	Lobectomy	Conversion to open thoracotomy n = 3	Supraventricular arrhythmia n = 6
			Lack lung isolation n = 1	Bleeding n = 1
				Air leak n = 1
Gharagozloo et al. [11]	100	Lobectomy	0	Atrial fibrillation n = 4
				Air leak n = 2
				Bleeding n = 1
				Pleural effusion n = 2
Van Hillegersberg et al. [18]	21	Esophagectomy	Conversion to open procedure n = 3	Pulmonary complication 60% first 10 cases
				Pulmonary complication 32%, 11 patients
Kernstine et al. [15]	14	Esophagectomy	Conversion to open procedure n = 1	Thoracic duct leak n = 3
				Vocal cord paralysis n = 3
				Atrial fibrillation n = 5

the head be turned upward and to the patient's right, exposing the left neck for the cervical part of the operation. Atrial fibrillation was the more common complication presenting in five out of 14 patients.

Kim et al. [19] studied 21 patients undergoing robotic-assisted esophagectomy. The airway was managed with the use of a Univent® bronchial blocker endotracheal tube to isolate the right lung. Once the trocars were placed CO_2 insufflation was initiated at 8–10 mmHg pressure. Hemodynamic and respiratory parameters showed an increase in central venous pressure and mean pulmonary artery pressure when the patients were in a prone position and they were further elevated during OLV. All variables returned to baseline when the patients were repositioned to the supine position at the end of the thoracic phase. Cardiac index and mean arterial blood pressure were maintained with no significant changes during the procedure. The authors also reported elevation of peak airway pressure and plateau pressure with a decrease in static lung compliance during the pone position with no alterations in PaO_2 or $PaCO_2$. After OLV was initiated, static lung compliance significantly decreased below 50% of baseline. This change also caused a marked increase in peak airway and plateau pressures with a decrease in PaO_2 and an increase in $PaCO_2$.

In the report by Kernstine et al. [15], among the recommendations to improve efficiency in these cases is the "use of an experienced anesthesiologist who can efficiently intubate and manage single-lung ventilation and hemodynamically support of the patient during the procedure." This follows what Nifong and Chitwood [12] have reported in their editorial that a team approach with expertise in these procedures involving nurses, anesthesiologists, and surgeons with an interest in robotic procedures is required. Table 2.2 displays the complications of robotic-assisted thoracic surgery involving the mediastinum, lung, and esophagus.

2.6 Carbon Dioxide Insufflation During Thoracoscopy

Continuous low-flow insufflation of CO_2 has been demonstrated as an aid for surgical exposure during minimally invasive thoracic procedures. It has been used as the only means of providing surgical exposure to the thoracic cavity, or more frequently in conjunction with a DLT or a bronchial blocker. The compression of the lung parenchyma assists in retraction, and it also helps by effacing subpleural lesions [20].

Vassiliades [21] reported the results of a study in 75 patients undergoing minimally invasive coronary artery bypass graft surgery (CABG) and showed that CO_2 insufflation in combination with single-lung ventilation increases central venous pressures and pulmonary artery pressures, while negative effects were seen on systemic blood pressure, cardiac output, and stroke volume at higher pressures. He concluded that single-lung ventilation and CO_2 insufflation enhance the technical ease of thoracoscopic internal mammary harvest, and he suggested that while it is safe in the majority of patients, CO_2 insufflation should be use with caution in hypovolemic patients and patients with poor left ventricular function. Tomescu et al. [22], reported in 24 patients a statistically significant decrease in cardiac index, stroke index, and mean arterial blood pressure however, these changes had minimal clinical relevance. A study by Ohtsuka et al. [23] involving 38 patients undergoing minimally invasive internal mammary harvest found significant increases in mean central venous pressure, pulmonary artery pressure and the pulmonary artery wedge pressure. They also found that on the right side hemithorax, but not on the left side, slight decreases were noted in the mean arterial blood pressure and cardiac index. They concluded that the hemodynamic effect from continuous insufflation of CO_2 at 8–10 mmHg for 30–40 min is mild in both hemithoraces, although the impact is greater on the right. This information was supported by another study [24]. This study involving 20 patients undergoing thoracoscopic sympathectomy and concluded that compared to the left side hemithorax the impact of CO_2 insufflation on the vena cava and the right atrium during right-sided procedures was associated with reduction of venous return and low cardiac index and stroke volume.

The impact of CO_2 insufflation on the respiratory system has also been studied. El-Dawlatly et al. [25] reported a significant pressure-dependent increase in peak airway pressure and a decrease in dynamic lung compliance but no difference in tidal volume or minute ventilation.

Insufflation of CO_2 should only be started after initial thoracoscopic evaluation has ruled out that the port of insufflation has not compromised a vascular structure or the lung parenchyma. Communication between the surgeon, anesthesiologist, and operating room personnel is crucial at this point. Insufflation is ideally started at low pressures of 4–5 mmHg and is gradually increased while monitoring the patient's vital signs. The use of intrathoracic pressure of more than 15 mmHg has not been reported in the literature and should be avoided because it increases the risks of cardiovascular collapse. The anesthesiologist should always be aware of the possibility of gas embolization during these cases. In the case of sudden cardiac collapse, the CO_2 flow should be discontinued immediately. Ventilation during CO_2 insufflation should be titrated to keep adequate oxygenation and a normal PCO_2 and pH. Also, damage to the contralateral pleura may occur resulting in CO_2 flow to the contralateral chest, making ventilation difficult and also causing hemodynamic compromise.

2.7 Anesthesia Considerations in Robotic Cardiac Surgery

Robotic cardiac surgery has been developing over the last 10 years. In the United States as of 2008, approximately 1700 cardiac surgeries are performed robotically, and the number continues to increase [26]. The major advantages of introducing robotic technology in cardiac surgery are to minimize surgical incision by avoiding sternotomy and to minimize postoperative pain and recovery time. Common robotic cardiac cases include mitral valve repair (MVR) [27–29] coronary artery bypass grafting (CABG) [30–32], atrial septal defect (ASD) repair [33–35], and intracardiac tumor resection [36, 37]; robotic arrhythmia surgery and resynchronization have been reported as well [38, 39]. Table 2.3 displays common robotic cardiac surgical cases and outcomes.

Robotic cardiac surgery and anesthesia requires knowledge in thoracic anesthesia and regional anesthesia, also these surgical cases require invasive monitoring including a transesophageal echocardiogram (TEE) and a pulmonary artery catheter. OLV with a lung isolation device is required for robotic cardiac surgery, because the robotic arms enter through either the right or left thorax. Lack of lung collapse will interfere with the procedure or even require conversion of the procedure to sternotomy. The most common devices used for an absolute lung isolation is the left-sided DLT because of its margin of safety. However, specific situations, i.e. difficult airway or mechanical ventilation in the postoperative period (as commonly presented in cardiac surgery), will require the use of a single-lumen endotracheal tube and the use of an independent bronchial blocker [40]. In order to maximize the benefit of robotic, minimally invasive surgery, the anesthesia technique should be modified accordingly.

2.8 Anesthetic Considerations in Robotic Mitral Valve Surgery

Robotic mitral valve surgery requires left OLV, as the right chest is entered through a 4–5 cm right lateral thoracotomy in the fourth intercostal space. On selected patients this robotic surgery is well tolerated and there have been no case reports of conversion [29, 41]. The patient is positioned in a modified lateral decubitus position with the right chest elevated 30–40°. The right arm can be suspended over the patient's forehead. There may be less risk of brachial plexus injury if the arm is positioned at the patient's side, with moderate flexion at the elbow [42]. Because access to the heart is

Table 2.3 Case reports robotic cardiac surgery

	Case reports	N	Surgical time CPB time (min)	ICU stay (h)	LOS (days)	Comments
Robotic mitral valve repair	Tatooles et al. [27]	25	199 ± 43 (140–287)	35.4 ± 18.5	2.68 ± 3.1	n = 21 extubated in the OR
			126 ± 25 (89–186)	(18–72)	(1–16)	n = 8 discharge within 24 h
						n = 2 required MV replacement
	Nifong et al. [28]	112	266 ± 73 (150–463)	36.6 ± 24.7	4.7 ± 3.0	Multicenter phase II FDA study
			168 ± 47 (82–316)	(6–140)	(1–18)	No deaths, strokes, or device-related complications
						No sternotomy conversion
						n = 6 required reoperations replacement and 1repair
	Chitwood et al. [29]	300	Surgical time *NIA* 158 ± 4	32.4 ± 67.3	5.2 ± 4.2	n = 9 were converted to videoscopic assisted minimally invasive approach (da Vinci system malfunction (n = 3), poor surgical exposure (n = 4), external instrument conflicts (n = l), need for MV replacement (n = l))
						n = 16 required reoperation
						1\vo 30-days mortalities and 6 late mortalities
Robotic assisted IMA harvesting	Subramanian et al. [30]	30	444 ± 49	NIA	NIA	Average number of bypass grafts 2.6
			NIA (off-pump CABG)			n = 29 were extubated immediately after surgery
						n = 15 were discharged within 24 h after surgery
						n = 2 required reexploration for bleeding
						n = 2 readmitted to hospital within 30 days (pleural effusion (n = l), wound infection (n = l))
	Srivastava et al. [31]	150	311 ± 11	NIA	3.9 ± 2.9	Bilateral internal mammary artery harvest with da Vinci system
			NIA (off-pump CABG)			Average number of bypass grafts 2.6 ± 0.8
						Bilateral IMA revascularization was completed in 148 (99%) patients
						n = 5 required reexploration for bleeding
AHTECAB	Argenziano et al. [32]	98	353 ± 89 (200–600)	35 ± 37	5.1 ± 3.4	Multicenter trial of IMA harvest and LIMA-LAD with AHTECAB
			117 ± 44 (41–254)			n = l8 were converted to another approach intraoperatively (failed peripheral cannulation for CPB (n = l0), poor visualization of coronary targets (n = 2), dense pleuropericardial adhesions (n = l), damage of the graft (n = 2), inadequate coronary anastomosis (n = 3))

(continued)

Table 2.3 (continued)

	Case reports	N	Surgical time CPB time (min)	ICU stay (h)	LOS (days)	Comments
Robotic ASD repair	Argenziano et al. [33]	17	CPB time 122 (Median)	20 (Median)	4 (Median) (2.5–10)	n = 1 required reoperation for recurrent shunt on POD-5
	Bonaros et al. [34]	17	314 (215–590)	26 (15–150)	8 (5–14)	
			144 (91–239)			
Rumor removal	Murphy et al. [36]	3	CPB time 103 ± 40	NA	4	Totally robotic resection of myxoma.
Arrhythmia and Resynchronization surgery	Jansens et al. [38]	15	150 ± 48	NA	NA	Robotic-enhanced biventricular resynchronization
						Two patients required conversion to a small thoracotomy
	Loulment et al. [39]	1	255	NA	NA	First case report of robotic assisted epicardial pulmonary veins isolation

CPB cardiopulmonary bypass, *ICU* intensive care unit, *LOS* length of stay, *IMA* internal mammary artery, *AHTECAB* arrested heart totally endoscopic robotic coronary artery bypass grafting, *LIMA-LAD* left internal mammary artery to left anterior descending coronary artery, *POD* post operative day

limited during thoracoscopic surgery, external defibrillator patches must be placed on the thoracic cage away from the surgical incision. Of note, when the patient requires external defibrillation, immediate termination of lung isolation might be necessary in order to conduct sufficient electric current through the heart [43]. A TEE is also essential for robotic mitral surgery [44]. Moreover, some rare complications of robotic thoracic surgery, such as aortic dissection and atrial or ventricular perforation, can be identified with TEE. LeVan et al. [45] reported the case of a left atrial appendage perforation during femoral venous cannulation. They immediately converted the procedure to sternotomy after significant pericardial effusion was diagnosed by TEE.

Cardiopulmonary bypass (CPB) is established with femoral arterial inflow and inferior vena cava drainage through femoral venous and superior vena cava through right internal jugular vein cannulation. Aortic cross-clamp and cardiac arrest can be done by either port access or the transthoracic cross-clamp technique. The transthoracic cross-clamp technique has been shown to have fewer complications compared to the port access system [46, 47]. If the patient has had a previous sternotomy, a pacing pulmonary artery catheter should be considered because there may be limited access to the ventricle.

Postoperatively, the patients can be extubated immediately after surgery or at an early postoperative stage during their stay in the surgical intensive care unit. Tatooles et al. [27] reported a successful fast-track postoperative course following a robotic mitral valve surgery. The mean operating time was 199 min, CPB time 126 min, and aortic cross-clamp time 87 min. Twenty-one out of 25 (84%) patients were extubated in the operating room, and the remainder of the patients was extubated within 5 h after surgery. The average length of stay in the hospital was 2.7 days. Despite a high re-admission rate (28%), the author of the study commented that early discharge did not alter postoperative morbidity and that select patients with close follow-up can be safely discharged on their first postoperative day. In a US 11-center trial, the operation time, CPB time, and aortic cross-clamp time ranged from 150 to 463 min, 82 to 316 min, and 60 to 227 min, respectively [28]. Thus, a longer operating time may preclude early postoperative extubation. Some studies have shown that operating time decreases significantly with greater surgeon experience in robotic cardiac surgery [28, 48].

2.9 Robotic-Assisted Endoscopic Coronary Artery Bypass Grafting

Robotic-assisted endoscopic CABG spans a range from robotic-assisted endoscopic internal mammary artery (IMA) harvesting and direct graft anastomosis via thoracotomy to totally endoscopic coronary artery bypass grafting (TECAB), with or without CPB [31, 49]. When TECAB is performed with CPB, the port access system is utilized.

Robotic-assisted endoscopic CABG requires essentially the same anesthetic preparation as robotic MVR except for the side of OLV. Because the robotic arms and endoscope enter from the left thorax, right OLV should be applied to the patient. To facilitate the instruments' entrance, the patients are positioned supine with the left chest elevated 30° and the left arm placed lower than the posterior axillary line [50]. Insufflation of CO_2 is used for effective lung collapse at the pressure of 5–15 mmHg. OLV with insufflation of CO_2 can deteriorate hemodynamics. Immediately after initiation of CO_2 insufflation, the right ventricle is compressed, and venous return is obstructed by artificial tension pneumothorax. To attenuate this acute hemodynamic instability, volume therapy should be necessary before the onset of CO_2 insufflation [51]. Hypercarbia and hypoxia could induce acute pulmonary hypertension and right ventricular failure. In selected groups, patients tolerate OLV with insufflation of CO_2; nevertheless, some cases had to be converted to sternotomy [50, 52].

Subramanian et al. reported successful fast-tracking of 30 patients who underwent off-pump minimally invasive multivessel coronary bypass with robotic-assisted IMA harvesting [30]. Twenty-nine (97%) patients were extubated in the operating room, 15 patients (50%) were discharged within 24 h, and only two patients had a length of stay more than 3 days. There were only two patients who required re-admission within 30 days. There have been some reported failures of completion of these procedures (~13%) [32, 53]. Pleuropericardial adhesions, unstable hemodynamics with OLV, inadequacy of IMA flow, inadvertent injury during IMA harvesting, difficulties with CPB cannulation, poor visualization of target vessel, and inadequacy of the coronary anastomosis might require intraoperative conversion to an open procedure.

2.10 Robotically Assisted Totally Endoscopic Atrial Septal Defect Repair

There are limited reports of ASD repair and intracardiac tumor resection with the use of the robotic da Vinci® Robot System. Torracca et al. [54] reported first six cases of ASD closure using a robotic device. Subsequently, studies [34, 35] reported that the learning curve is steep for the procedure, enhanced postoperative recovery, and improved patient quality-of-life. Intracardiac tumors, including left atrial myxoma and aortic valve papillary fibroelastoma, have been successfully removed with a robotic surgical system [36, 37, 55].

Anesthesia preparation is similar as robotic MVR. Right lung isolation is required because the robotic arms enter through the right hemithorax. Note that continuous vigilance with TEE is needed for potential gas embolism during insufflation with CO_2 because this could cause a stroke due to right-to-left shunt [56].

2.11 Robotic Arrhythmia Surgery and Resynchronization

Cardiac electrophysiological therapy also can be assisted by robotic technology. Robotic assisted surgery for atrial fibrillation with or without CPB has been reported [39, 57]. The choice of DLT for the lung isolation device is recommended when epicardial isolation of the pulmonary veins technique is applied because the robotic arms enter right hemithorax, followed by the left hemithorax.

Robotic-assisted left ventricular epicardial lead implantation for resynchronization therapy merged as rescue technique due to the 10–15% failure rate of left ventricle lead placement via coronary sinus percutaneously [58]. Left lung isolation is required because the robotic arms enter through the left hemithorax. The patient is placed in the right decubitus position, the same position as with a posterolateral thoracotomy position [59]. Notably, those patients who are candidates for this procedure are mostly presented with decompensated heart failure.

2.12 Postoperative Pain Control in Robotic Cardiac Surgery

Postoperative pain management can be accomplished with various regional anesthesia techniques. Although duration of pain control is limited, an intercostal block under direct vision is commonly performed by the surgeon. Also, continuous local anesthetic infusion catheter could be placed at the spaces between the muscle layer and the ribs, as well as the muscle layer and the subcutaneous tissue [31]. A neuraxial block, including thoracic epidural anesthesia (TEA) and spinal anesthesia, has been utilized in cardiac surgery with excellent pain control. An epidural hematoma from systemic heparinization is a potential complication of these techniques [60], though the rate of incidence is extremely low and comparable to non-cardiac surgery. A thoracic paravertebral block is another alternative for post-thoracotomy pain control. Mehta et al. [61] showed that a paravertebral block was comparable to TEA with regard to quality of analgesia after robotic-assisted CABG.

2.13 Complications of Robotic Cardiac Surgery

With selected patients and experienced surgeons, robotic cardiac surgery can be safely performed with comparable or fewer complications than a traditional approach via sternotomy. Chitwood et al. [29] reported the results of robotic MVR of 300 patients with 0.7% 30-day mortality and fewer complications, including strokes (0.7%), transient ischemic attacks (0.7%), myocardial infarctions (1.0%), and reoperations for bleeding (2.3%). Surgeons have identified complications that are more specific or related to robotic cardiac surgery; Table 2.4 displays the complications in robotic cardiac surgery. Aortic dissection caused by femoral arterial or antegrade cardioplegia cannulation is a rare but serious complication [46, 48]. Perforation of the right ventricle by the endopulmonary vent in the port access system [47] is another cannula-related complication. The unique positioning required for robotic system access often presents new

Table 2.4 Robotic cardiac surgery and complications

Complications	Incidence	References
Early postoperative death (<30 days)		
MVR	1–3%	[28, 40, 64]
CABG	0%	[29, 30, 31, 51, 52, 62]
Revision due to lack of completion of procedure		
MVR	0–2.9%	[27, 28, 40, 46, 64]
CABG	1–18%	[30, 31, 51]
Reoperation for bleeding		
MVR	2–6%	[28, 40, 46, 64]
CABG	2–5%	[30, 31, 51]
Complication related to robotic system	Patients	
Aortic/femoral artery dissection	n = 3	[33, 45, 47]
RV perforation	n = 1	[46]
Left atrial appendage perforation	n = 1	[44]
Lower extremity compartment syndrome	n = 1	[32]
Groin lymphocele or infection	n = 4	[26, 31, 61]
Tracheal injury from DLT placement	n = 1	[46]

MVR mitral valve repair, *CABG* coronary artery bypass grafting, *RV* right ventricle, *DLT* double-lumen tube

anesthesia-related complications. There is a report of a tracheal rupture from DLT placement [47] in a patient undergoing robotic surgery. Perioperative blood loss and transfusion rate do not seem to be reduced by robotic approach even though sternotomy is avoided. In a study by Folliguet et al. [62] compared robotic mitral valve repair with conventional sternotomy approach and there were no differences in blood loss and transfusion rate between two groups.

2.14 Summary

Robotic thoracic and cardiac surgeries have evolved, and the technology is still improving at an exponential rate. To achieve success with robotic cardiac and thoracic surgery, including completion of the procedure through minimal access and a fast-track postoperative recovery, anesthesiologists must be skilled in lung isolation techniques, fiberoptic bronchoscopy techniques and transesophageal echocardiography (TEE) and have an understanding of the concept of robotic surgery and anesthesia [63].

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