Keynote Lecture Series

# Complications and their management in robotic mitral valve surgery from the surgical assistant's perspective

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Robotic mitral valve (MV) repair is an alternative approach to traditional MV repair via median sternotomy. There is a rich history of innovation embedded within robotic MV surgery. Since the inaugural robotic MV repair performed in May 1998 by Carpentier, progressive techniques and expanding indications have given surgeons the opportunity to offer an increasing number of their patients access to robotic MV surgery. This, coupled with less cynicism surrounding robotic and minimally invasive surgery, has stimulated robotic cardiac surgery program development and the number of robotic MV procedures performed annually. Utilizing the robotic technology in MV surgery is far from the standard of care and must be approached modestly by only well trained and experienced cardiothoracic surgeons and teams. Advanced surgical techniques provide numerous opportunities for complications and adverse outcomes. It is essential for the entire robotic cardiac surgery team to be aware of the additional risks during each step of the procedure. The fundamental principle of robotic MV repair is to avoid complications with anticipation. No surgery is without risk, and unfortunately, some of those risks are unavoidable. If a complication does occur, it is essential the surgeon and robotic team understand their roles and how to triage the event. This keynote lecture will outline each phase of the robotic MV repair surgery before, during and after the patient cart is docked to the patient. Within each phase we will identify potential complications and their management.

**Keywords:** Robotic surgery; minimally invasive surgery; mitral valve (MV); complications

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## Introduction

Innovations in cardiothoracic surgery and surgical robotics generated the opportunity for the two to merge and produce an alternative to the traditional median sternotomy approach. Intuitive Surgical originated as a start-up company in 1995. After acquiring tele-presence surgical technology from Stanford Research Institute, Intuitive Surgical started developing the da Vinci Surgical System (1). Subsequent acquisitions by Intuitive Surgical aided in the development of their first surgical robotic system, da Vinci. To date, Intuitive Surgical have developed five robotic surgical systems: da Vinci, da Vinci S, da Vinci Si, da Vinci Xi and da Vinci X.

Robotic assisted minimally invasive mitral valve (MV) surgery is an innovative technique highly experience surgeons utilize in lieu of an invasive median sternotomy. Robotic assisted MV repair has been widely adopted since the first case was performed by Dr. Carpentier and Dr. Mohr in 1998. The first MV repair was performed using a prototype of the da Vinci system, prior to the first generation da Vinci receiving Food and Drug Administration approval for intra-cardiac use in 2002 (2). Robotic MV surgery has since evolved in both the technology used and the surgical approach. To date, three

 

**Table 1** Absolute and relative contraindications to robotic mitral valve repair and replacement

| Absolute | Relative |
|---|---|
| Prior right thoracotomy | Previous sternotomy |
| Severe pulmonary dysfunction | Moderate pulmonary dysfunction |
| Myocardial infarction or ischemia <30 days | Asymptomatic CAD (treated) |
| Coronary artery disease—requiring CABG | Coronary artery disease—requiring PCI |
| Severe generalized vascular disease | Limited peripheral vascular disease |
| Symptomatic CVD or stroke <30 days | Asymptomatic CVD |
| Poor right ventricular dysfunction | Poor left ventricular function (EF <30%) |
| Pulmonary hypertension (fixed >60 torr) | Pulmonary hypertension (variable >60 torr) |
| Significant aortic stenosis or insufficiency | Mild to moderate aortic stenosis or insufficiency |
| Severe annular calcification (repairs) | Moderate annular calcification |
| Severe liver dysfunction | |
| Significant bleeding disorders | |

Chitwood (2). CABG, coronary artery bypass grafting; CVD, cerebrovascular disease; EF, ejection fraction; CAD, coronary artery disease; PCI, percutaneous coronary intervention.

surgical approaches for robotic MV repair have been described: classic robotic MV repair, lateral endoscopic approach with robotics (LEAR) and complete endoscopic approach (3). This keynote lecture focuses on the classic robotic MV repair approach.

The robotic assisted approach to MV repair creates favorable intraoperative and postoperative advantages for patients. Benefits of minimally invasive cardiac surgery include less pain, less blood loss, decreased hospital length of stay, improved cosmesis and quicker return to normal activity (4). Conversely, robotic assisted MV repair is more challenging from a technical standpoint and introduces risks at each step of the procedure. The cardiothoracic surgeon and every member of the robotic surgery team must be aware of risks associated with robotic MV repair and be prepared for the complications they may encounter.

## Preoperative considerations

Risk prevention in robotic MV surgery begins before the patient enters the operating room (OR). First, creating a well-trained and dedicated robotic surgery team is essential. This team consists of the cardiothoracic surgeon, anesthesiologist, bedside assistant, perfusionist, circulating nurse and surgical technician. Each robotic MV surgery should be performed with only these individuals. The cardiothoracic surgeon must be experienced and proficient in minimally invasive non-robotic MV surgery. It is recommended the cardiothoracic surgeon completes a fellowship in minimally invasive surgery and attends Intuitive Surgical's practical training lab. Repetition increases familiarity; therefore, the dedicated robotic cardiac surgery team must practice "dry-runs" of robotic assisted MV repair at a structured cadence.

Patient selection is one of the most essential steps in robotic assisted MV repair and a predictor of potential intraoperative and postoperative complication. Although indications for robotic assisted MV surgery have expanded since its adoption, careful patient selection will reduce complications and adverse outcomes. Absolute and relative contraindications to robotic MV surgery are described by Dr. Chitwood (*Table 1*). Patient selection is a process that should involve a multidisciplinary team to ensure favorable outcomes.

## Phases of surgery

Cardiothoracic surgeons must anticipate prolonged cardiopulmonary bypass (CPB), aortic cross clamp and intraoperative times during robotic cardiac surgery due to the increased number of steps compared to traditional median sternotomy (5). *Figure 1* outlines the phases of

 

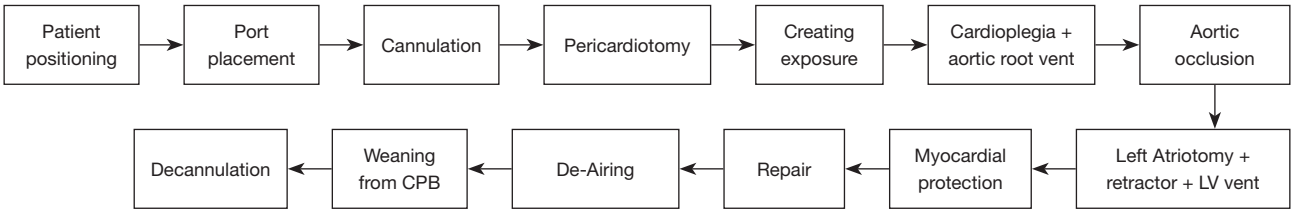


**Figure 1** Phases of robotic surgery. CPB, cardiopulmonary bypass; LV, left ventricle.

a robotic MV repair. It is important to understand the phases of robotic surgery and anticipate when and how complications may occur.

## Patient positioning

After establishing intravenous access, arterial catheter(s), intubation, central venous catheter (CVC), Foley catheter, Swan-Ganz catheter if indicated and transesophageal echocardiogram (TEE), attention will be focused on positioning of the patient. Positioning for the classic robotic MV repair will have subtle nuances from site-to-site. The following steps are taken to ensure optimal functionality with the da Vinci Xi patient cart and safety to the patient. Defibrillator pads on right scapula and left anterolateral chest wall. Bovie grounding pads should be placed on bilateral buttocks unless surgical implant is present. Patient is moved to align right flank with the right edge of the operative table; 500 mL saline bag wrapped in a bed sheet to serve as a "bump" is placed under the right scapula, anterior to the heater-cooler blanket. This allows the chest to elevate approximately thirty degrees and the right shoulder to drop posteriorly to prevent collision with the robotic left arm. Wrist restraint is placed on patient's right wrist and passed under patient and secured to the left side of operative table. Left upper extremity is tucked in normal fashion using multiple foam or gel pads to protect critical structures. Right upper extremity will be suspended off the right side of operative table. Both upper extremities are positioned in a dependent position, avoiding abduction, external rotation and shoulder displacement. Hips and lower extremities are placed in anatomic position, ensuring no rotation of the hips and five degrees of flexion at the patient's knees. Feet are protected with foam and secured to the operative table to prevent shifting during the operation. Positioning of the patient must be done meticulously to avoid injury to peripheral nerves, brachial plexus and cervical spine. If a heater-cooler blanket is used, avoid direct contact with the patient's skin to avoid a burn injury. Applying Tegaderm or film dressing over defibrillator and bovie pads will prevent pooling of surgical prep solution, avoiding risk of surgical fire and ensuring proper contact with the patient. Unique to robotic mitral valve (MV) surgery, when applicable, the patient's right axilla must be shaved, as it is oftentimes in the surgical field to accommodate the cross-clamp port. In addition to the right axilla, the entire anterior surface of the patient's chest and lower extremities should be prepped into the surgical field in the event of emergent conversion to sternotomy.

## Port placement

Placing surgical ports in the correct intercostal spaces reduces the risk of complication and overall difficulty of the operation. Preoperative imaging is essential to understanding the patient's anatomy and planning of port location. Posteroanterior and lateral chest X-ray provides intrathoracic measurements ensuring patient's anatomy is amenable to acceptable working area. Three-dimensional computed tomography with angiography (CTA) of the chest allows the surgeon to visualize the patient's cardiac anatomy in relation to the rib spaces. Additionally, surgeons can create digital ports to determine the correct location for placement during surgery. Non-contrast computed tomography (CT) of the chest is still beneficial for preoperative assessment if contrast is contraindicated or to limit radiation exposure to the patient. Incorrect placement of ports may lead to iatrogenic injury to critical anatomy, external robotic arm collision, increased case complexity and even inability to complete the operation minimally invasively with the assistance of the robot.

Mini-right thoracotomy, or working port, is performed on all cases at our institution and established prior to port placement. Surgical ports should always be placed under direct visualization with the assistance of the robotic endoscope or laparoscopic tower. When utilizing a mini thoracotomy, the surgeon may use intrathoracic finger palpation to guide port placement. This practice will

 

reduce the risk of injury to intercostal vessels, right internal thoracic artery (ITA), or puncture of critical anatomy. If intercostal bleeding is encountered, hemostasis must be achieved before proceeding onto the next step. Hemostasis is achieved with cautery, surgical clip, oversewing stitch or manual compression. Cauterization should be performed intrathoracic to avoid delayed wound healing, infection and to ensure proper cosmesis. A high rising diaphragm may cause visual obstruction. Retraction of the diaphragm can be achieved with retraction stitch. Using a pledgeted stitch is recommended to prevent laceration of the diaphragm. Control any diaphragmatic bleeding with additional pledgeted stitches. At the end of the operation, the diaphragmatic retraction stitch should be tied on itself rather than removed to avoid postoperative bleeding. If Endo Close device is used, intercostal bleeding may occur. The area should be inspected after each use, and hemostasis achieved at that time. If diaphragmatic retraction stitch is not desired or the patient has a large AP diameter, use of a 15-cm robotic trocar for the right robotic arm will exclude the diaphragm completely.

### Cannulation: internal jugular vein

Robotic assisted MV repair requires peripheral bicaval cannulation. Superior vena cava (SVC) cannulation is commonly achieved via right internal jugular vein. Facilities must establish roles for this process to avoid contamination and iatrogenic injury. A two-operator approach is best practice. The SVC cannula may be placed in the ipsilateral side as the CVC. To avoid complications with SVC cannula insertion, it is important to maintain a sterile field and communicate efficiently. During all percutaneous cannulations, the surgeon must have complete visualization of needles, wires and cannulas with ultrasound and TEE imaging. Inadvertent carotid artery puncture during placement is rare but may occur. If this scenario occurs, the provider should not remove the needle due to limited control with manual compression. The injury should be inspected with ultrasound. Vascular surgery should evaluate, and dependent on the extent of the injury, an angiogram, covered stent, or cutdown with repair may be necessary. The SVC cannula should be inserted using the Seldinger technique in a controlled and methodical manner. Its position may be adjusted by TEE guidance or via the working port with direct palpation prior to initiating CPB. Excessive blood loss and exsanguination is avoided with SVC cannula occlusion using two tubing clamps and appropriate communication between operators. The right ventricle (RV) is at risk of perforation during SVC and inferior vena cava (IVC) cannulation by the guidewire or cannula. To avoid this, the operator must have clear visualization with TEE when inserting the guidewire and positioning the cannula. If the RV is perforated, management depends on the extent of the injury. If the perforation is small, from the guidewire, the operator may choose to monitor and evaluate prior to closing. If the perforation is sizeable, and the patient is not on CPB, it will be extremely difficult to repair minimally invasively. The operator will be required to convert to sternotomy for open repair.

### Cannulation: femoral vessels

Ilio-femoral vessels are routinely accessed for IVC cannulation and retrograde arterial cannulation. Thorough review of the patient's history to identify presence of atherosclerotic disease, active wound infections and a recent coronary angiogram must be performed. If peripheral vascular disease (PVD) is suspected, preoperative evaluation of the lower extremities with CTA is preferred. In the event the patient does have severe PVD, consider contralateral femoral artery or alternate access. Assessment of the aortic arch and descending thoracic aorta with intraoperative TEE is to be performed prior to commitment to retrograde arterial cannulation via the femoral artery. Retrograde arterial perfusion increases risk of embolic stroke and retrograde aortic dissection (2). If significant atherosclerotic disease or mobile plaque is present in the ascending or descending thoracic aorta, alternate access or sternotomy approach must be considered. Any recent history of a coronary angiogram performed with femoral artery for access is noted.

Coronary angiogram may cause fibrosis, scarring or narrowing of the femoral artery used for access. If femoral access coronary angiogram occurred >30 days from operative date, the ipsilateral artery is appropriate for use at our institution. If coronary angiogram occurred <30 days from operative date, the contralateral femoral artery or alternative access is considered. However, if the femoral artery diameter is generous, ipsilateral femoral access is not an absolute contraindication at our institution. Femoral arteries with a minimal luminal diameter of <7 mm are considered poor candidates for cannulation, and alternate access must be considered (6). Femoral access in the presence of active wound infection is an absolute

 

contraindication at our institution and should be prepped out of the operative field.

Percutaneous and traditional cut-down access to femoral vessels have been previously described. Intraoperative ultrasound is recommended regardless of approach to identify common femoral artery, superior to profunda femoris artery. Cut-down technique is preferred at Northwell Health, and is the technique recommended for patients with recent percutaneous intervention such as recent cardiac catheterization or prior percutaneous closure device and intervention. Cut-down technique gives the surgeon more control and access to repair the femoral vessels if required. Complications to consider with the cut-down technique typically occur post-operatively and include seroma, hematoma, delayed healing, lymphatic fistula and wound infection. These complications are avoided with the percutaneous approach, however the risk of limb ischemia, pseudoaneurysm and other vascular complications increase. Limb ischemia may be prevented or treated with placement of a distal perfusion cannula. Distal perfusion cannula is recommended for suspected lengthy CPB time, a small common femoral artery or abrupt change in near-infrared spectroscopy monitors (NIRS). If using NIRS, relative changes from the patient's baseline $rSO_2$ are more useful predictors of limb ischemia than the absolute values of $rSO_2$ (7). If limb ischemia is of concern while exercising percutaneous cannulation, femoral cut-down is recommended for inspection. Compartment syndrome is a sequala of acute and prolonged limb ischemia. If compartment syndrome is suspected or identified, immediate release via fasciotomy is recommended. Vascular surgery should be consulted intraoperatively for assessment of muscle viability. Limb ischemia must be avoided in every robotic mitral operation. Limb ischemia and subsequent fasciotomy are absolute catastrophes in a minimally invasive operation and eclipse any benefit the patient would receive from a robotic MV approach.

Complications resulting from IVC cannula insertion can be avoided with diligent TEE guidance and communication between surgeon and anesthesiologist. Whether inserting by cut-down or percutaneous techniques, cannulation is performed by Seldinger technique over a wire. If not performed methodically, the guidewire may perforate the right atrium (RA) or create a patent foramen ovale (PFO). Injury to the RA can be repaired primarily via mini-right thoracotomy. If PFO is created, it can be repaired primarily while on CPB. After successful cannulation, both arterial and venous cannulas must be secured in place. We recommend suturing the cannulas to the patient with 2-0 silk suture. After initiation of successful CPB, the arterial and venous cannulas should be covered with blue towels to avoid disruption and migration during the operation. The bedside assistant must routinely inspect the position of the arterial and venous cannulas throughout the duration of the operation. Any concern must be communicated immediately to the surgeon.

### Cannulation: axillary

Axillary cannulation is recommended in patients with an atheromatous aorta, severe PVD, morbid obesity or active groin infection. Axillary cannulation will provide antegrade arterial perfusion, decreasing the risk of embolic cerebrovascular accident (CVA) in patients with aortic arch or descending thoracic aortic atherosclerosis. Left axillary access should be reserved for patients with a history of right axillary surgery or vascular access as the right axillary artery is closer to the operative field (8). Injury to the brachial plexus may occur during axillary cut-down, therefore dissection must be precise, and stress produced by retractors should be limited. The axillary artery is extremely thin and fragile and must be handled and manipulated delicately. Commonly, an 8mm Dacron graft is sewn end-to-side to the axillary artery. The surgeon and first assistant must anticipate this to prevent dissection of the artery and limb ischemia. If this occurs or is suspected, selective peripheral angiogram needs to be performed and injury repaired to restore perfusion. The operation may need to be aborted if the injury is extensive requiring vascular surgery intervention. Vessel loops should be utilized to establish distal and proximal control and vessel clamps readily available prior to arteriotomy to prevent exsanguination.

### Pericardiotomy

Significant and redundant pericardial adipose pad or residual thymus should be excised prior to pericardiotomy to improve visualization. The adipose pad and thymus are quite vascular. Achieve hemostasis of adipose tissue, thymus or thymic vein upon entry. Bleeding must be controlled when encountered to prevent unnecessary blood transfusion and obstruction of the operative field. Hemostasis can be achieved using robotic EndoWrist cautery, handheld bovie or surgical clips.

Phrenic nerve injury is a known complication of robotic

 

MV repair. Phrenic nerve must always be identified prior to performing pericardiotomy. Pericardiotomy is performed anterior to the phrenic nerve, maintaining generous distance away from the nerve. Pericardiotomy is less complicated once the patient is on CPB, however an experienced surgeon may choose to perform pericardiotomy prior to CPB to decrease time on bypass. Pericardial retraction sutures will be utilized, so a substantial distance from the nerve is preferred to limit the tension applied to it throughout the operation.

Cautery on or near the heart may cause ventricular fibrillation and other dysrhythmias. To avoid this, use the left arm EndoWrist instrument to securely retract the pericardium laterally as the pericardiotomy is performed. If the patient experiences a dysrhythmia, discontinue any use of robotic energy and treat the underlying issue. Placement of defibrillator pads appropriately during patient positioning is essential for this reason.

### Creating exposure

After pericardiotomy is complete and pericardial retraction sutures are placed, exposure necessary for the operation is obtained. Every patient's anatomy is unique and different planes will need to be developed. Dissection around the aorta is necessary if using an aortic cross clamp. Injury to the aorta may occur when developing a plane in the transverse sinus or when extending the pericardiotomy superiorly. If the injury is not substantial, it may be controlled with compression and repaired minimally invasively. If the injury is significant, CPB needs to be established as rapidly as possible. Conversion to sternotomy may be required. Each facility and robotic team must have protocols to follow in the event of aortic injury or conversion. These scenarios must be familiar to all individuals participating in robotic MV surgery and practiced frequently.

The pulmonary artery (PA) may anatomically take a more caudal course in some patients and be at risk for injury when developing planes. This may be controlled with manual compression using the EndoWrist instruments and primary repair. If the injury is more extensive it may require rapid initiation of CPB or conversion to sternotomy.

The bedside assistant must be conscious of all trocars once they are docked to the patient cart. Port placement can be tight in patients with small body habitus. It is essential that the bedside assistant is conscious of all surrounding instruments and ports to reduce robotic arm one induced injury. The bedside assistant must be aware of intrathoracic conflicts and collisions as well. The aortic cross clamp is at risk of collision with robotic arm one inside and outside the chest cavity. Proper port placement, targeting and docking of the da Vinci Xi should prevent external robotic arm collisions. After docking is complete, flex joints and then assess patient clearance to ensure proper spacing between joints, arms and the patient. Unlike earlier generations of the da Vinci robot, the Xi is engineered to create a safer working environment.

### Cardioplegia and aortic root vent

Placement of cardioplegia and aortic root vent cannulas is not necessary when aortic occlusion is achieved with an endoballoon. The central lumen of the endoballoon is utilized for cardioplegia delivery and as the aortic root vent. When a transthoracic aortic occlusion clamp is used, additional aortic root vent and cardioplegia cannula is required. This can be challenging when inserting through a stab incision through the second or third intercostal space in the mid-clavicular line. An extended aortic root vent cannula is used for precise insertion directly through the assist port. To avoid aortic hematoma, bruising and bleeding, aortic root vent stay sutures are placed prior to heparinization. Two 2-0 pledgeted Ethibond sutures are placed to secure the cannula during the operation. The aortic root vent should be placed in the ascending aorta, leaving appropriate room for the transthoracic cross clamp. All peri-aortic adipose tissue and redundant tissue in proximity to the root vent insertion site should be excised to ensure the cannula will remain secure throughout the procedure. At Northwell Health, after achieving activated clotting time (ACT) of >450 seconds, the perfusionist is asked to lower the systemic blood pressure, and the bedside assistant carefully places the aortic root vent. The console surgeon helps guide the bedside assistant with right and left robotic arms. This technique decreases the risk of inadequate penetration of ascending aorta which can result in bleeding, requiring additional pledgeted repair sutures, or even acute aortic dissection. To reduce the number of accessories extending out of the working port, the aortic root vent is secured with a snare and short tourniquet tubing. Three large surgical clips are placed at the distal aspect of the tourniquet to secure its position, and the tourniquet is tucked into the chest, parallel with the SVC and posterior to where the transthoracic aortic cross clamp will be positioned. The bedside assistant must ensure proper

 

de-airing technique is performed when connecting the aortic root cannula to the bifurcated cardioplegia cannula adapter. This step is critical to prevent air embolism which could result in a transient ischemic attack (TIA) or CVA. The provider performing this step must be confident in the steps of de-airing and communicate clearly with the perfusionist.

### Aortic occlusion: aortic cross clamp

Aortic occlusion during robotic MV surgery is achieved by either transthoracic aortic cross clamp or endoballoon aortic occlusion. At our institution, we use either the Cygnet-Flexible clamp or the Chitwood-DeBakey transthoracic clamp. The Cygnet-Flexible clamp is passed through the assist port for application and tucked away from the field and covered with a blue towel. The Chitwood-DeBakey clamp is inserted through an additional incision in the chest wall. Bates describes that when using the Chitwood-DeBakey clamp, it is important to insert the clamp through the second or third intercostal space, mid-to-posterior axillary line (9). To avoid conflict with the left instrument arm, it must be passed closely in front of the SVC at the pericardial junction (9). Caution must be exercised to ensure the upper jaw of the clamp is within the pericardial sac and does not include the pericardial edge.

Aortic cross clamping in robotic cardiac surgery should only be performed by the surgeon or an extremely experienced bedside assistant. This phase of the operation contains potential complications the robotic team must anticipate. Use of the Chitwood-DeBakey clamp requires an additional incision in the chest and puncture of the thoracic cavity. After creating the tunnel, inspect the site with the endoscope to evaluate bleeding. If bleeding is present, it should be controlled prior to inserting the cross clamp. If the chest wall incision for the Chitwood-DeBakey clamp is created too anterior, there is risk for conflict with the left instrument arm which could be catastrophic. Forceful collision could cause aortic rupture, dissection or bruising, and release or migration of the cross clamp. Degree of aortic rupture depends on location and extent. If significant, the operation will be abandoned, the patient will be rapidly placed on CPB, and then converted to sternotomy to repair aortic injury. If aortic dissection is suspected, evaluation of ascending aorta, aortic arch and descending thoracic aorta is performed with TEE by anesthesia. If aortic dissection is confirmed, the operation will be aborted, and dissection managed per dissection type guidelines. Retrograde aortic perfusion is contraindicated in presence of acute aortic dissection as well as establishing alternate access for antegrade aortic perfusion to continue MV surgery. If cross clamp is forcefully displaced causing aortic hematoma or bruising, adventitia should be released by the surgeon and cross clamp repositioned in correct position. Proper positioning of the clamp will prevent these scenarios. The bedside assistant must be conscious of the cross clamp throughout the entirety of the case to avoid collision as well.

Creating exposure is an essential step when utilizing transthoracic aortic cross clamp. The surgeon must develop planes that allow adequate room for the clamp jaws to pass. Failure to complete this step may result in clamping of the PA or left atrial appendage (LAA). Prior to aortic occlusion with the transthoracic aortic clamp, the right PA and LAA must be visualized and freed from the clamp jaws (9). If using the Chitwood-DeBakey clamp, visualize its location in relation to the SVC after aortic occlusion to ensure there is no obstruction which would create insufficient venous drainage. To reduce risk of TIA or CVA, limit number of aortic occlusions with transthoracic cross clamp. Single cross clamping is best practice.

### Aortic occlusion: endoballoon aortic occlusion

Aortic occlusion with endoballoon should be reserved for experienced surgeons with considerable robotic MV experience. Synergy with qualified anesthesiologist is crucial to successful positioning of the endoballoon. This method of aortic occlusion adds complexity to the operation. Difficulty passing the guidewire retrograde across the aortic arch and repetitive cannulation of the great vessels with the guidewire can be troubling. If this occurs, options may include advancing the endoballoon into the descending aorta, pulling the guidewire back and reinserting it again. Additionally, exchanging the guidewire for a multipurpose or JR4 catheter may be beneficial. When endoballoon aortic occlusion is anticipated, the patient will require bilateral radial artery catheters prior to initiation of the operation. Migration of the endoballoon may occur during the operation, which can be identified by discrepancies in radial artery pressure readings. Distal migration of endoballoon will obstruct the origin of the innominate artery resulting in systemic hypotension (4). Proximal migration of the endoballoon has been reported and will obscure the operative field especially near the left fibrous trigone (10).

 

Additional methods have been described to confirm the endoballoon is in the correct position. Inflating the endoballoon with a solution of 0.03% indocyanine green (ICG) in 5% albumin while activating the near-infrared laser on the robotic endoscope fluoresces the endoballoon, allowing it to be visualized as a green band around the aortic wall (11). This technique can be utilized to intermittently confirm position of endoballoon and ensure it has not migrated.

Iatrogenic endoballoon rupture is quite problematic and may occur due to overinflation or puncture. During MV repair, if sub-valvular neochords are used, it is recommended they are placed first and that annuloplasty suture placement start at P1 progressing up to mid-A2 segment as endoballoon rupture may occur with deep suturing in this zone (12).

Iatrogenic aortic dissection resulting from endoballoon aortic occlusion is rare but has been reported. Caution must be exercised in patients with atherosclerotic disease and when utilizing retrograde arterial perfusion in ipsilateral extremity as endoballoon device. When the endoballoon catheter occupies part of the arterial cannula lumen, high jet pressures are created at the exit of the cannula, increasing the risk of retrograde aortic dissection (13). To prevent this, all members of the team must monitor perfusion pressures from that femoral artery cannula. If the patient becomes significantly hypertensive, pharmacotherapy must be used to normalize perfusion pressures. If unsuccessful, the team may try adjusting the trajectory of the femoral cannula or placing an additional retrograde arterial perfusion cannula in the contralateral femoral artery to split arterial perfusion bilaterally (13). Retrograde aortic dissection is a catastrophic complication of this operation. If this occurs, the extent of the dissection must be evaluated by TEE. If there is evidence of malperfusion or rupture, the dissection needs immediate repair by open surgical or endovascular approach. If the dissection is limited, the procedure should be aborted, the patient resuscitated and monitored in the ICU.

TIA and CVA are potential complications of endoballoon aortic occlusion. The endoballoon is typically inserted via left femoral artery. As insertion and positioning occurs over a wire using the Seldinger technique, wire manipulation must be limited to prevent emboli from an atheromatous aorta. As endoballoon is passed retrograde through the descending thoracic aorta, across the aortic arch and into the ascending aorta, anesthesia must use narrow windows on TEE to alert the surgeon of any identifiable atherosclerotic plaque and calcifications. Limit contact with the intima and unnecessary inflation to prevent micro emboli.

### Left atriotomy

Robotic MV exposure is most frequently achieved by left atriotomy through the interatrial groove. The primary incision should be slightly posterior to the interatrial groove. Extension of the atriotomy should be performed inferiorly onto the posterior wall of the left atrium (LA). If the atriotomy is extended superiorly behind the SVC, it will be challenging to close at the conclusion of the operation. The bedside assistant must frequently use suction to keep the operative field free of potential emboli that could cause postoperative TIA/CVA. LA lift retractor is placed in robotic arm three. When exposing the MV, the LA may tear if excessive force is generated anteriorly by the LA lift retractor. This will result in challenging closure at the end of the case.

### Left atrial lift retractor

The LA lift retractor is placed through the robotic third arm port. The port is placed in the fourth or fifth intercostal space, medial to the midclavicular line (4). This port must always be placed under direct visualization. The right ITA is located 2–3 cm lateral to the midline of the sternum. To avoid injury to the ITA, the surgeon should palpate where they intend to place the robotic third arm while visualizing with the robotic endoscope. If the ITA is injured, hemostasis must be achieved. This is performed with surgical clips or suture ligation.

The atrioventricular (AV) septum can be injured by the LA lift retractor when creating exposure of the MV. The distal tips of the LA lift retractor need to be inspected to ensure they do not include the AV septum. If there is injury to the AV septum, it is either identified after removal of the LA lift retractor or when the MV is assessed by the anesthesiologist. Prevent this complication by minimizing tension with the LA lift retractor. Attempt to repair small injuries with primary closure using pledgeted mattress sutures. Larger defects and persistent small injuries will need patch repair.

Excessive anterior tension on the LA by the LA lift retractor may distort or compress the RV. If the LA lift retractor is not relaxed during administration of cardioplegia, the right coronary anatomy may be obstructed

 

and not receive essential myocardial protection. This will result in RV dysfunction when weaning from CPB. The LA lift retractor must always be relaxed when running cardioplegia to ensure adequate distribution and protection. The LA lift retractor also becomes useful at the end of the procedure in providing exposure. The surgeon can retract the RA with the LA lift retractor to expose to the LA suture line. Additionally, if a temporary pacing wire is desired or required, the LA lift retractor can be utilized to lift up the pericardium for placement onto the RV.

### Left ventricular vent

To avoid additional clutter through the working port, the left ventricle (LV) vent may be passed through an additional stab incision. This should be created posterior and slightly superior to the working port. LV perforation is not recognized until after MV repair is complete, aortic occlusion is released and anesthesia is evaluating the competency of the MV. Techniques to prevent this from occurring include using a smaller diameter soft floppy catheter and crossing the MV with the vent under direct visualization after left atriotomy with the robotic arms. Oftentimes, traditional LV vent is not used in robotic MV surgery. Rather, a basket sucker is placed in the LA to clear the operative field while removing the risk of LV perforation. LV perforation by LV vent is identified by surgeon due to excessive bright red blood in the pericardium. Repair of the defect is unlikely from a minimally invasive approach and conversion to sternotomy is required.

### Myocardial protection

It is difficult to utilize myocardial temperature probes due to limited visualization of the RV and essentially no visualization of the LV. Similarly, topical hypothermia with ice is not practical via mini-thoracotomy, and not possible in totally endoscopic surgery. If complex repair is anticipated, systemic hypothermia should be considered. When delivering cardioplegia, it is important to understand infusion and root pressures to ensure the transthoracic cross clamp or endoballoon have not migrated. Typically, and at our institution, del Nido is the cardioplegia solution of choice in robotic MV surgery. It is favorable for this operation given it prolongs myocardial protection and regularly requires only one dose per operation. Communication with anesthesia during cardioplegia delivery is critical. It is important to ensure adequate venous drainage to maintain myocardial temperature and protection. In the event of RV distension, redosing of cardioplegia is essential.

### MV repair

The surgeon and bedside assistant must work as a team during the MV repair due to intricate movements, suture management and knot tying to perform the best repair the first time to limit CPB time. Suture management may become overwhelming for the bedside assistant, so a suture guide can be helpful. There are nuances to every repair depending on the pathology, individual surgeon technique and surgeon preferences. If neo-chords are required, it is recommended they are placed prior to annular sutures. Once neo-chords are placed distally in the papillary muscle, the remaining suture can be passed to the surgeon to be stored in the LV until annular sutures are placed to limit traffic in the working port. To further decrease demand on the bedside assistant, the annuloplasty ring may be passed to the surgeon to be sewn in with running technique rather than interrupted annular stitches with parachuting technique. After annular sutures are properly placed through the annuloplasty ring, they will be secured with either Cor-Knot or traditional tying with assistance of the knot pusher. The bedside assistant and surgical tech must be competent with the knot pusher to avoid loose knots or untying of the knots. If this occurs, it will require additional annular stitches which increase CPB time.

Visualization is improved when utilizing the robotic endoscope with 3DHD vision. Awareness of sinoatrial and AV node location in relation to the MV annulus during suture placement is important to avoid conduction injury. Similarly, the surgeon needs to exercise caution when placing annuloplasty sutures near the P1 scallop, especially in left dominant circumflex systems. Left circumflex injury will be identified when weaning from CPB and new wall motion abnormalities are identified on TEE assessment and inferior ST changes are observed on the electrocardiogram (ECG). To manage this, the surgeon may elect to go back on CPB and replace the annular sutures near the P1 scallop. Other management options include supporting the patient with inotropic pharmacotherapy, intra-aortic balloon pump (IABP), extracorporeal membrane oxygenation (ECMO) or direct transfer to cardiac catheterization lab for coronary angiogram. If there is partial obstruction or kinking of the circumflex, percutaneous coronary intervention (PCI) may be possible. If there is complete occlusion, the patient

 

**Table 2** Echocardiographic risk factors for SAM

| Metric | Parameter |
|---|---|
| Aortomitral angle | (A) <120° |
| End-diastolic-diameter | EDD <4.5 cm |
| Posterior leaflet length | PL ≥1.5 cm |
| Anterior leaflet length | AL ≥2.5 cm |
| Basal septum | BS ≥1.5 cm |
| Coaptation-septum distance | CS ≥2.5 cm |

Denti *et al.* (14). SAM, systolic anterior motion.

will require coronary bypass to the circumflex artery. If the coronary angiogram identifies there is spasm, direct injection of nitroglycerine may improve the patient's condition.

If decalcification of the LA wall is required during the MV repair, the surgeon may experience a posterior LA injury. This occurs due to overzealous removal of calcium from the LA wall. Significant bleeding after removal of aortic occlusion will be experienced. Management of this includes returning onto CPB, re-arresting the heart and repairing the injury from inside the LA. Repair from outside of the heart is not recommended.

AV groove disruption is identified when aortic occlusion is released and bright red blood floods the operative field when attempting to wean from CPB. AV groove disruption can occur from overzealous removal of calcium from the posterior annulus of the MV or implanting too large of a prosthesis during MV replacement. The deep annular sutures will tear and separate. This is a significant complication and requires returning onto CPB, re-arresting and converting to sternotomy for repair. Left atriotomy will need to be reopened to explant the prosthesis. These defects are quite complicated to repair and often require a large patch of autologous or bovine pericardium.

If new aortic insufficiency is identified by the anesthesiologist when separating from CPB, it could be iatrogenic from a suture placed during the MV repair. This needs to be inspected so the patient needs to be placed back onto CPB, the heart re-arrested and the left atriotomy re-entered to inspect the annular sutures. Attention should be paid to the anterior trigone as it may have been damaged or fixed the aortic cusp.

Finally, iatrogenic LV perforation can occur by the bedside assistant when they are evaluating the MV repair with saline injection. If a power suction-irrigator is used with an extended rigid tip, the bedside assistant needs to be conscious as to how deep into the LV they are inserting the tip. As the bedside assistant cannot see into the LV well, they need to be careful when evaluating the valve.

### Systolic anterior motion (SAM)

SAM reportedly occurs in 4–10% of MV repairs or reconstructions irrespective of technique (14). This complication is cumbersome as it is pernicious and can worsen as the geometry of the LV remodels. Denti *et al.* describes TEE parameters (*Table 2*) that increase the risk of SAM in patients undergoing MV surgery (14).

Numerous techniques have been described to prevent and repair SAM depending on the patient's presenting geometry and pathology. At Northwell, Dr. Patel favors use of a large annuloplasty ring with long posterior leaflet, reduction of P2 height with short neo-chords, and avoidance of large quad-resection and slide-folding-plasty. If mitral regurgitation is greater than mild and left ventricular outflow tract (LVOT) gradient is greater than 50 mmHg, Dr. Patel recommends upsizing the annuloplasty ring, shortening the neo-chords, and as a last resort, the Alfieri stitch.

### De-airing: air embolism prevention and treatment

Air embolism is a potential complication in MV surgery regardless of the surgical approach. Robotic MV repair limits the surgeon from performing some of the traditional deairing techniques that require manipulation of the heart. Carbon dioxide ($CO_2$) should flood the operative field during the operation. To ensure it is functioning, submerge the tubing in saline prior to connecting it to the port. All members of the team assisting with critical portions of the surgery need to understand their roles and responsibilities during cannulation, weaning from CPB and decannulation to avoid air embolism.

De-airing techniques vary from institution to institution. Considerations made at Northwell include turning off LV vent and turning root vent on low when closing the left atriotomy, decreasing drainage while allowing the heart to fill with root vent on, left lung ventilation and placing the patient in steep Trendelenburg position. Of note, if the patient is still docked to the robot, unless the OR is equipped with a Trumpf table and integrated table motion, Trendelenburg positioning is

 

contraindicated.

Air in the venous circulation can be managed by perfusionists until the etiology is corrected. Air in the arterial circulation is a severe problem and needs quick attention. If it enters the coronary vasculature, the heart will fibrillate. If still cannulated, go back onto CPB while defibrillating the heart. Turn all vents on high and ask perfusion to increase systemic pressures. To decrease risk of cerebral air embolism, anesthesia should thoroughly inspect the heart with TEE before the LV vent and aortic root vent are removed.

### Weaning from CPB

If having difficulty weaning from CPB, first consider whether the heart has been given enough time to recover. Be conscious of patient temperature and ensure they are normothermic. Double lung ventilation is preferred when weaning from CPB, so ensure the right lung is not isolated to prevent desaturation. If contractility is the culprit, place a temporary pacing wire or add an inotropic agent. Anesthesia should perform complete TEE evaluation of the heart to rule out any new wall motion abnormality, dissection, shunt or dysfunctional valve. Systemic pressure should be driven up by perfusion with background vasopressors or inotropic agents from anesthesia. If substantial waiting and management does not improve the patient's condition, IABP, ECMO or LV/RV support devices should be considered. Decision should be made to either transport directly to the cardiac catheterization lab for diagnostic coronary angiogram versus converting to sternotomy for further inspection and possible coronary artery bypass grafting as a last resort if RV or LV dysfunction is identified.

### Failed repair

TEE assessment of the MV repair must be done intraoperatively prior to decannulation. Unsuccessful repair is an unfortunate complication and presents challenging decisions for the surgeon with significant consequences. All decisions are multifactorial and must be made with confidence as a third repair or replacement is calamitous for the patient.

## Postoperative bleeding

The 3DHD robotic endoscope or a traditional laparoscopic endoscope should be used at the end of the case to inspect all areas accessed or manipulated during the procedure, while on single lung ventilation. The surgeon must be conscious of the oxygen saturation when on single lung ventilation during intrathoracic inspection for hemostasis. Single lung ventilation shortly after separating from CPB may cause hemodynamic compromise, so intrathoracic assessment and hemostasis must be efficient. Port sites are common sources of bleeding and oftentimes difficult to control. The surgeon must be persistent and confirm hemostasis with direct visualization before closure. At our institution, if there is persistent port site bleeding despite cautery and manual compression, the port site incision is extended. The etiology of the bleeding is identified and corrected with cautery, oversewing stitch or hemoclip. Rarely, hemostatic agents are used, however may be appropriate if bleeding cannot be controlled with routine techniques.

Chest tubes should be placed as per comfort level of the surgeon. At Northwell, our standard practice is one 28Fr right angle chest tube in the diaphragmatic gutter, one 32-Fr or 28-Fr straight chest tube positioned laterally to the apex, and oftentimes one 19 Fr Blake in the pericardial edge. Correct positioning of the chest tube(s) is essential. If unable to place the chest tube in the desired location, the endoscope may be used to guide it to the correct position. Location of each chest tube should be passed to critical care staff during handoff in the cardiothoracic intensive care unit (CTICU). Immediate postoperative portable chest X-ray should be performed in the CTICU.

If postoperative bleeding occurs and is not manageable in the CTICU, return to the OR is required. Evacuation of the hemothorax and hemostasis should be attempted through the primary incision unless the patient is severely unstable. Resuscitate with volume, blood transfusion and inotropic agents as per the patient's condition. When re-exploring the operative field, irrigate and inspect all areas from the primary operation.

## Unilateral pulmonary edema (UPE)

UPE is a rare complication succeeding MV surgery performed through the right chest. Although uncommon, it is devastating when encountered. The clinical presentation occurs minutes to hours after weaning from a prolonged CPB (15). The patient will display profound hypoxia from increased shunting, hypercapnia, pulmonary hypertension

 

and hemodynamic instability requiring significant support from vasopressors and inotropic agents (15). Treatment efforts such as ECMO support or inhaled nitric oxide are often futile, as there is rapid progression to multiorgan failure. Short CPB times, avoidance of barotrauma, limited blood product transfusion and minimizing lung deflation times can reduce the risk of UPE (2).

## da Vinci Xi complications

The da Vinci Xi surgical system has transformed minimally invasive surgery and allows patients to undergo complex operations in a non-traditional approach. The system is only beneficial if used by properly trained surgeons and OR staff. The robotic modality adds complexity, opportunity for iatrogenic injury and increased risk if used inappropriately. The surgeon is separated from the patient during the operation, so the bedside assistant must be an expert in utilizing the robot, troubleshooting and anticipating complications. The surgeon and beside assistant must be articulate with their communication and function synergistically.

After docking the robot, EndoWrist instruments must be inserted under direct visualization to prevent puncture or laceration of critical anatomy. Afterwards, guided tool exchange, confirmed with a blinking green LED, allows the bedside assistant to exchange instruments without direct visualization, returning them to within 3 mm of the original position. If guided tool exchange is lost, identified by a solid blue LED light, the surgeon must find the appropriate port and follow the instrument back to the appropriate working area to prevent injury. Similarly, the surgeon must always keep both EndoWrist instruments in their field of vision while working to prevent injury.

The 3DHD endoscope is quite advanced and does not require calibration, focusing or white balancing. While the surgeon is operating, the endoscope may fog or become obstructed. The surgeon must request a camera clean, and never proceed using one eye, as the touchscreen monitor may be displaying the surgeon's obstructed eye. The bedside assistant must communicate clearly to the surgeon when a camera clean is necessary, or they cannot anticipate the operation.

Recoverable and non-recoverable faults may occur during the operation. The surgeon should practice these scenarios with all members of the robotic team prior to a live operation. Robotic team members must understand their individual roles if a fault were to occur. When a fault occurs, the arms lock, an audible beep is heard, the LEDs turn amber or red and a message will display on the monitor to describe the fault. A recoverable fault does not require a system restart and is identified by amber LEDs. The team should read the error message, correct the issue and click "resume use" on the monitor. A non-recoverable fault does require system restart and is identified by red LEDs. In the event of a non-recoverable fault, the endoscope and all EndoWrist instruments must be left in place, and the system is powered down by pressing the power button. During this time, vision will be temporarily lost. Once the LEDs change from red to amber, the system may be restarted by pressing the power button.

Although rare, the EndoWrist instruments may malfunction. Instrument release keys must be peel packed in every robotic room and staff trained on its location and use. If the EndoWrist instrument malfunctions, the bedside assist must use the instrument release key to remove the instrument. First, the emergency stop button must be pushed if the system is not already in a fault state. The bedside assist will insert the key into the release socket, stabilizing the housing with one hand, and turn the key one quarter turn counterclockwise, following the picture on housing. After the jaws open, remove the instrument in normal fashion. The instrument is now unusable and should be returned to Intuitive Surgical per site protocol. "Resume use" should be clicked on the monitor and operation continued. Complications caused by the robotic system are avoidable by anticipation, practicing emergency drills with the robotic team and competence in the technology by all who support robotic procedures.

## Conclusions

Robotic MV repair provides several benefits to patients compared to traditional median sternotomy if performed by experience and well-trained surgeons and staff. The robotic assisted approach enhances the complexity of the case with several additional steps. Consistent and frequent exposure both intraoperatively and through mock scenarios is essential for successful programs. Additionally, understanding of the many phases of the operation, the complications that have potential to occur at each phase and management of those complications is essential for a successful program (*Table 3*). The fundamental principle of robotic MV surgery at Northwell Health is to avoid complications with anticipation.

 

**Table 3** Robotic mitral valve repair complications and management

| Complication | Management |
|---|---|
| Injury to intercostal artery/vein | Immediate hemostasis with cautery, hemoclips, manual compression, or stitch |
| Injury to right intrathoracic artery | Immediate hemostasis with cautery, hemoclips, manual compression, or stitch |
| Diaphragm laceration | Prophylactic use of pledgeted retraction stitch, oversew with additional pledgeted stitches |
| Carotid artery puncture during CVC insertion | Do not withdrawal needle, assess with ultrasound, consider vascular surgery evaluation, angiogram, covered stent, cut-down and repair |
| Blood loss during right internal jugular SVC cannula insertion | Occlude distal aspect of SVC cannula with two [2] tubing clamps prior to insertion |
| Femoral cannulation site seroma, hematoma, infection, delayed healing | Prophylactically avoid complication with diligent closure of wound in multiple layers. Thorough evaluation of wound post operatively |
| Limb ischemia from femoral artery cannulation | Prophylactic use of distal perfusion cannula. Immediate placement of distal perfusion cannula when ischemia is identified intraoperatively |
| Compartment syndrome | Immediate release via fasciotomy and post-operative vascular surgery evaluation |
| PFO during femoral IVC cannula insertion with guidewire | Primary repair on CPB |
| Injury to right atrium during femoral IVC cannula insertion with guidewire | Primary repair on CPB |
| Iatrogenic injury to axillary artery during cannulation | Abort axillary cannulation. Primary repair, patch angioplasty, selective peripheral angiogram. Vascular surgery intervention if extensive |
| Blood loss during axillary artery cannulation | Control blood loss with vessel loops or vessel clamps |
| Phrenic nerve injury | Preventative: Identify phrenic nerve prior to pericardiotomy. Maintain generous distance with cautery and retraction sutures. Limit tension applied |
| Ventricular fibrillation and dysrhythmia when using cautery creating exposure | Discontinue use of cautery/robotic energy. Treat dysrhythmia per ACLS guidelines |
| Aortic injury (transverse sinus dissection or extending pericardiotomy superiorly) | Dependent upon extent of injury. Compression, primary repair with pledgeted suture, rapid CPB, convert to sternotomy, aortic repair |
| Pulmonary artery injury when creating exposure (when artery takes a more caudal course) | Dependent upon extent of injury. Compression, rapid CPB, convert to sternotomy, primary repair, patch angioplasty |
| Aortic hematoma, bruising, and bleeding during root vent placement | Preventative: placement of aortic root vent stay sutures prior to heparinization, excise all peri-aortic adipose tissue and redundant tissue in proximation of root vent insertion site, communicate to perfusion to lower systemic pressure when placing root vent. To manage, release hematoma, cautery, primary repair with pledgeted stitch |
| Air embolism | On CPB: defibrillate heart, turn all vents on high, increase systemic pressures by perfusionist or pharmacotherapy<br>Off CPB: defibrillate heart, manage per ACLS guidelines, increase systemic pressures with pharmacotherapy |
| Aortic injury (disruption of aortic cross clamp by bedside assist or collision with robotic arm 1) | Evaluation of ascending aorta, aortic arch, and descending thoracic aorta with TEE. If dissection identified, abort operation, convert to sternotomy, repair per dissection type guidelines. If no dissection, manage aortic hematoma or bruising by releasing adventitia and reposition cross clamp |
| Iatrogenic endoballoon rupture | TEE inspection. Rapid extraction. Insertion of new endoballoon device |

**Table 3** (*continued*)

 

**Table 3** (*continued*)

| Complication | Management |
|---|---|
| Iatrogenic aortic dissection from endoballoon aortic occlusion | Inspection with TEE. Abort procedure. Repair dissection per dissection type guidelines |
| Left atrial tear from lift retractor | Primary repair or patch repair at conclusion of case |
| Injury to atrioventricular septum with left atrial lift retractor | Small injury: primary closure with pledgeted mattress sutures<br>Large injury: patch repair |
| LV perforation by LV vent | Convert to sternotomy. Management dependent on extent of injury. Primary repair, pledgeted mattress stitches, hemostatic agents, patch repair |
| Left circumflex artery injury | Re-establish CPB and identify etiology. Options include: replace annular sutures near P1 scallop, inotropic pharmacotherapy, IABP, ECMO, transfer to cardiac catheterization lab for coronary angiogram and PCI, direct injection of nitroglycerine, convert to sternotomy and perform coronary bypass |
| Posterior left atrial injury during decalcification | Re-establish CPB, re-arrest heart, repair injury from inside left atrium |
| Atrioventricular groove disruption | Re-establish CPB, re-arrest heart, convert to sternotomy, reopen left atrium, explant prosthesis, large patch repair with autologous or bovine pericardium |
| Aortic Insufficiency after separation from CPB | Inspect aortic valve with TEE. Re-establish CPB, re-arrest heart, re-enter left atrium and inspect mitral annular sutures. If anterior trigone stitches damage or fix the aortic cusp must be replaced. If unclear etiology under minimally invasive inspection, convert to sternotomy and evaluate via open approach |
| Systolic anterior motion | Re-establish CPB, re-arrest heart, re-enter left atrium, evaluate mitral repair with saline injection, re-repair MV |
| Difficulty weaning from CPB | TEE inspection to identify etiology. Wait and allow heart to recover. Ensure patient's core temperature is normothermic. Placement of temporary pacing wire. Inotropic support. Increase systemic pressure (perfusionist or pharmacotherapy), insertion of IABP, ECMO, RV/LV support device, cardiac catheterization for diagnostic coronary angiogram, convert to sternotomy for further inspection, bail-out coronary bypass |
| Unilateral pulmonary edema | If extubated: intubate and support with mechanical ventilation. ECMO support. Inhaled nitric oxide |

CVC, central venous catheter; SVC, superior vena cava; PFO, patent foramen ovale; IVC, inferior vena cava; LV, left ventricle; CPB, cardiopulmonary bypass; ACLS, Advanced Cardiac Life Support; TEE, transesophageal echocardiogram; IABP, intra-aortic balloon pump; ECMO, extracorporeal membrane oxygenation; PCI, percutaneous coronary intervention; MV, mitral valve; RV, right ventricle.

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## Footnote

*Conflicts of Interest:* The authors have no conflicts of interest to declare.



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