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Minimally-Invasive Surgery of Mitral Valve. State of the Art

Daniel Pereda and Elena Sandoval

Abstract

Minimally-invasive mitral valve surgery has been in development during the last thirty years and now allows to perform mitral and tricuspid interventions, coronary bypass surgery, repair of congenital heart defects and more. Current state-of-the-art technology and clinical knowledge make possible to offer this approach in expert centers to a growing number of patients, who benefit from its advantages. Minimally-invasive mitral surgery is becoming the best option to repair que mitral valve and patients are able to recover better and faster than after conventional surgery without compromising quality of the repair. With the aid of high-definition 3D visualization and specifically designed instruments, including robotic telemanipulation, thoracoscopic and robotic surgery performed this way require only small incisions in the right chest. In the present chapter we will expose the current state of this field, going into detail regarding patient selection and operative techniques, and also reviewing the requirements for building a successful program.

Keywords: Mitral valve, endoscopic, robotic, minimally-invasive

1. Introduction

Modern minimally-invasive mitral surgery started in the mid 90's with the arrival of technical improvements in peripheral cannulation for cardiopulmonary bypass, vacuum-assisted drainage and specifically-designed long-shafted instruments, that allowed surgeons to safely perform mitral interventions through small anterolateral thoracotomies using thoracoscopic visualization [1].

Another major step forward in this field was the development of endoaortic balloon occlusion devices that, introduced through the femoral artery and positioned in the ascending aorta, allowed to occlude the aorta and to administer antegrade cardioplegia to arrest the heart. The safe and effective utilization of this device required close coordination between the anesthesiologist, the perfusionist and the surgeon, together with continuous monitorization of its correct position by transesophageal echocardiography and avoid its migration during the case, with the risks of injuring the aortic valve (proximal migration) or the occlusion of the head vessels in the aortic arch (distal migration). There were also risks of embolization of atherosclerotic debris and even of aortic dissection, making the selection of adequate candidates for the procedure of paramount importance. Another strategy that evolved to simplify the operation consisted in cross-clamping the aorta using specifically designed transthoracic vascular clamps. These can be rigid or articulated and are introduced either from the working port or using a separate incision in the chest, allowing an external occlusion of the aorta as in conventional surgery. This

strategy reduces the complexity and costs of the procedure and avoids the risks involved with the use of the endoaortic balloon.

Two more percutaneous tools have been developed to facilitate minimally-invasive operations, both designed to be inserted by the anesthesiologist through the right jugular vein, the “endovent”: a suction catheter introduced in the pulmonary artery to reduce the blood return from the pulmonary veins into the left atrium during surgery, and the “endoplegia”: a catheter placed inside the coronary sinus to administer retrograde cardioplegia throughout the case.

Further refinements and technological developments included specifically-designed instruments, the introduction of high-definition videothoracoscopy and, more recently, 3D visualization. All these advancements facilitate the performance of this complex procedures and try to mitigate the learning curve involved. Despite these refinements, thoracoscopic mitral repair has not been widely adopted by the cardiac surgery community, and difficult procedures such as complex repairs, reoperations, combined ablation and multivalvular procedures are mostly performed in few, high-volume centers.

Robotic surgery was developed in the late 90's and the first mitral repair and mitral replacement with the da Vinci system (Intuitive Surgical, CA, USA) were performed in Europe by Carpentier [2] and Mohr [3] in 1998 and in the USA by Chitwood [4] in 2000, respectively.

Robotic mitral surgery has slowly expanded worldwide and it is currently the preferred surgical approach for mitral repair in many programs. The only robotic platform in clinical use for cardiac surgery is the DaVinci system (Intuitive Surgical, CA, USA), which is currently in its 4th generation with the X and the Xi systems. These two systems are capable to perform cardiac surgery and provide some advantages with respect to previous models. However, many groups still rely on the previous generation, the Si, which is particularly useful for coronary revascularization since it has dedicated instruments such as the coronary endo-stabilizer, that are not provided for the newest generation.

Robotic technology allows the surgeon to regain much of the dexterity lost by the use of long-shafted instruments and provides superb high-definition 3D visualization with up to 10x magnification. This technology provides unparalleled precision inside the chest and a range of movement even wider than that of the human hand [5]. Another great advantage of robotic telemanipulation in the field of mitral surgery comes with the use of a third robotic arm equipped with the dynamic atrial retractor. This instrument provides outstanding exposure of the valve that adapts to every patient's particular anatomy and is controlled with the same precision and dexterity as the rest of surgical instruments. As exposure and visualization of the valve and subvalvular apparatus is better, all repair techniques can be robotically performed, including the most complex ones such as papillary muscle repositioning or the sliding leaflet plasty. Reported results in experienced centers show excellent results, both in repair rate and postoperative complications. Robotic mitral surgery has demonstrated shorter intensive care unit (ICU) and hospital length of stay, better quality of life postoperatively and better cosmesis, as compared to conventional surgery [6, 7].

In this chapter, we will review in detail all the key points of current state-of-the-art minimally invasive mitral surgery, both thoracoscopic and robotic, from the indications and the evaluation of candidates to a step-by-step walkthrough of both techniques.

2. Preoperative evaluation

All patients should undergo a high-quality comprehensive transthoracic or transesophageal echocardiographic evaluation to have a good understanding of their

particular valve disease before the operation. Echocardiography also provides valuable clues to avoid technique-related complications such as systolic anterior motion (SAM) and helps in the selection of the most adequate type and size of annuloplasty prosthesis.

Proper patient selection is crucial to avoid postoperative complications. Minimally-invasive surgery is more difficult in morbidly obese patients and in those with small thoracic cavities. Other anatomical issues that affect port placement or may limit the movements of the robotic arms include: scoliosis, pectus excavatum, phrenic nerve palsy and intrathoracic herniation of abdominal viscera. History of prior thoracic surgery, radiation or thoracic trauma should be ruled out preoperatively and may contraindicate a thoracoscopic or robotic surgery [8–10].

The need for peripheral cannulation for cardiopulmonary bypass mandates a thorough evaluation of the vascular system and an adequate size of the femoral vessels. A detailed physical examination and preoperative thoracic, abdominal and pelvic computed tomography angiograms are essential to ensure a safe operation. Evaluation of the venous system for signs of thrombosis or occlusion (interrupted inferior vena cava, presence of cava filters or extrinsic compression) is also achieved with these examinations. Patients with cardiovascular risk factors should undergo a preoperative coronary angiogram (with coronary catheterization or computed tomography angiography) to rule out ischemic heart disease.

Minimally-invasive surgery requires single-lung ventilation at different moments during the operation. Single-lung ventilation causes hypoxia and hypercarbia and increased pulmonary artery pressure. Patients with chronic pulmonary disease or pulmonary hypertension should undergo further testing to determine if they can tolerate this safely. Single-lung ventilation can be reduced or even avoided at the expense of longer cardiopulmonary bypass duration, so a tailored risk–benefit evaluation should be performed for these patients [11].

2.1 Indications and contraindications

Minimally-invasive mitral surgery follows the same indications that apply to conventional surgery, as described in the current guidelines published by the major European and American scientific societies of cardiac surgery and cardiology [12, 13].

Minimally-invasive surgery has some contraindications, detailed below [8–10]:

- Coronary artery disease requiring revascularization.
- Severe peripheral vascular disease or aneurysms of the descending thoracic or abdominal aorta.
- Prior right chest surgery.
- Severe chest wall deformities.
- Ascending aorta dilatation >45 mm or calcification.
- Moderate to severe aortic stenosis or regurgitation.
- Severe calcification of the mitral annulus.
- Severe pulmonary dysfunction or pulmonary hypertension.

All the prior situations described would difficult basic steps for a minimally invasive surgery and deem the operation unsafe. However, certain aspects of the technique, such as peripheral cannulation or cardioplegia administration, can be modified in order to adapt to some of these situations and still be able to offer a minimally invasive approach.

3. Fundamentals of minimally-invasive mitral surgery

Both thoracoscopic and robotic approaches to repair the mitral valve share a basic common set of techniques, skills, tools, anesthetic management and mitral repair techniques. These include the use of retrograde peripheral perfusion, similar options for myocardial protection, working with thoracic ports, thoracoscopic visualization instead of direct vision, and the use of specifically designed surgical instruments.

In addition to these intraoperative and more technical aspects, both approaches also share a similar philosophy in terms of patient selection and postoperative management to assure a successful outcome and an improved postoperative recovery, with a faster return to normal activities after surgery.

3.1 Mitral repair techniques used in minimally-invasive surgery

We follow the same basic principles of mitral repair regardless of the approach used, conventional or minimally-invasive, as established by Carpentier over 30 years ago [14]. This can be summarized in these principles:

1. Preservation or restoration of normal leaflet mobility.
2. Creation of a good coaptation between the anterior and the posterior leaflet along the entire coaptation line.
3. Remodeling and stabilization of the mitral annulus using an annuloplasty band or ring.

To achieve a successful mitral repair program, it is mandatory to clearly understand both the vast array of mitral pathology and to master a large armamentarium of techniques to address every specific case. A comprehensive understanding of mitral pathology is imperative to follow a structured analysis, as proposed by Carpentier, clearly distinguishing between etiology, lesions and dysfunctions. Etiology is the cause of the valvular problem (e.g., fibroelastic deficiency, infective endocarditis, ischemic heart disease), lesions are the results of the disease (e.g., chordal rupture, leaflet perforation, annular calcification) and the dysfunction is the result of the lesions (e.g., leaflet prolapse, restricted leaflet closure) (**Figure 1**). This may appear simple, but it is not uncommon to see these three concepts mixed up when evaluating echocardiography reports, discussing with other surgeons and cardiology colleagues and reading the medical literature. Following this approach to mitral disease, we are able to follow a systematic methodology to describe the problem and solve it.

Most of the techniques described and used in open surgery to repair the mitral valve can also be used successfully in minimally-invasive surgery, both thoracoscopic and robotic, but some adaptations must be implemented to facilitate its use in these approaches.

Figure 1.
A shows a two-chamber view of the preoperative transesophageal echocardiography where a flail anterior leaflet due to chordal rupture can be seen. B shows an intraoperative view of the anterior mitral leaflet of the same patient during robotic mitral repair, confirming the preoperative echocardiographic findings.

3.1.1 Triangular and quadrangular resections

Triangular resections are ideal to treat a localized prolapse of the posterior leaflet, when the prolapsing segment involves only one scallop without affecting the complete length of its free edge. This technique is very well suited for thoracoscopic and robotic surgery. The resection is triangular in shape with its base at the free edge and extending towards the annulus up to 2/3 to 3/4 of the leaflet height. Ideally, the edges of the resection should be convex towards each other and care must be taken not to resect too much of the free edge, to avoid producing a “curtain effect” upon re-approximation. Reconstruction of the leaflet can be accomplished with interrupted or running sutures. If the latter is preferred, the surgeon must avoid a purse-string effect that could impair leaflet mobility. We prefer to use a double running technique using 4/0 polypropylene sutures. Some surgeons prefer using 5/0 sutures, but we only use them when the leaflets are very thin (**Figure 2**).

Quadrangular resections are preferred when large portions of the posterior leaflet are prolapsing with great excess of tissue. In this technique the resection is extended all the way to the posterior annulus in a rectangular or trapezoidal shape. In order to avoid excessive tension upon reapproximation, the posterior annulus is plicated using interrupted, pledgeted 2/0 braided sutures. This maneuver excludes a portion of the dilated annulus from the final repaired valve, increasing the amount of annular remodeling. In complex cases, where a very large portion of the posterior must be resected, the “sliding plasty” technique allows reconstruction without the need for excessive annular plication. In this technique the base of posterior leaflet on both ends of the resection are detached from the annulus and advanced centrally during reattachment.

3.1.2 Chordal replacement

Neochordal implantation using polytetrafluoroethylene (PTFE) sutures has gained great popularity in the treatment of mitral prolapse, particularly on the anterior leaflet. There are some reasons for the enthusiastic adoption of this technique, particularly in minimally-invasive approaches:

- **Simplicity:** is a simple way to treat complex problems.
- **Availability:** neochords can be easily constructed in any number and length to accommodate any particular anatomy.

- **Reversibility:** in case of a suboptimal result, it is easy to remove the neochord and replace it with another at any moment during the operation. In contrast, once a resection is performed, this cannot be undone.
- **Precision:** adjusting the length of the chords allows the optimization of coaptation, this can be performed during water test to simulate systolic closure. In cases of very redundant leaflets, applying more restriction on the posterior leaflet by shortening the neochords can prevent SAM.
- **Reproducibility and good long-term durability:** using a standardized technique, mitral repair with this approach has proven extremely effective and durable.

Neochords are constructed using 4/0 PTFE sutures that are anchored in the tip of the papillary muscle and the free edge of the prolapsing leaflet (**Figure 2**). Our technique of choice consists in passing both ends of the suture with a PTFE pledget through the tip of the target papillary muscle head. We do not tie the suture down in the papillary muscle to allow both ends of the suture to automatically adjust their length, so that tension is equally distributed among them. Then, both chords are passed twice around the free edge of the prolapsing segment in a “figure-of-eight” fashion and chordal length is adjusted visually, taking into account the distance to annular plane, the length of the normal chords on both sides of the prolapsing segment and the excess of leaflet tissue. The valve is then tested using saline to fill the ventricle and the final length adjustments are made to optimize the depth of

Figure 2.
Displays different steps of a minimally-invasive mitral repair: A shows the placement of the transthoracic aortic clamp in the ascending aorta through the transverse sinus with the aid of three robotic arms. B represents the initial surgical valve analysis, showing a posterior leaflet prolapse of its central scallop. C shows the surgical exposition of the posteromedial papillary muscle during the implantation of a PTFE neochord. D shows the final aspect of a repaired valve after the annuloplasty has been performed using a flexible band implanted using continuous sutures.

coaptation and the position of the closure line. Once the desired result is achieved, the chords are tied on the atrial side of the leaflet to secure the resulting length.

3.1.3 Mitral annuloplasty

As discussed earlier, we implant an annuloplasty ring in nearly all repairs. The choice of the ring depends on the etiology and the dysfunction of the patient. We favor flexible bands for cases with mitral prolapse and complete rigid rings for functional regurgitation and whenever significant leaflet tethering is present. Sizing of the ring follows a standardized method, taking into account the intertrigonal distance and most importantly, the surface area of the anterior leaflet. A small under or oversizing from this initial measurement can be added to accommodate the repair according to some particular features of the case such as the perceived risk of SAM, very significant excess of tissue on the leaflets and leaflet tethering due to ventricular dilatation.

Annuloplasty rings can be implanted using interrupted or running sutures. For complete rings and bands implanted thoracoscopically or through median sternotomy, we favor the interrupted suturing technique using 2-0 braided sutures. On robotic cases, we prefer to use the running suturing technique with monofilament sutures (barbed polybutester or PTFE) instead, due to the significant gain in time and the simplicity it provides while working with the bedside surgeon during the implant. This running suturing technique is facilitated by the greater dexterity of the robotic system and the main drawback is that it may be more difficult to judge the distribution of sutures along the annulus and the band, particularly in cases with very dilated annulus requiring significant annular remodeling (**Figure 2**).

4. Operative technique

4.1 Common steps for robotic and thoracoscopic surgery: patient preparation and cardiopulmonary bypass

After induction of anesthesia, the patient is intubated and a transesophageal echocardiography (TEE) probe is positioned. Intubation can be performed either with a double-lumen endotracheal tube or with a single lumen tube and a bronchial occluder with a balloon. The patient is positioned in supine, as close as possible to the right side of the surgical table, the right chest is slightly elevated placing a blanket roll along the right hemithorax and the right arm is allowed to fall below the right chest to expose the lateral chest and the axilla. Care must be taken to protect the arm to avoid neural injuries due to compression against the structure of the table.

Cardiopulmonary bypass (CPB) is commonly instituted with cannulation of the right common femoral vessels, using a small 3 cm incision to expose both vessels (**Figure 3**). Dissection is kept to a minimum to avoid damage to the surrounding neural structures and to decrease the risk of seroma formation after surgery. Only the anterior wall of the vessels is exposed, and two 5/0 polypropylene purse-strings are placed in a rectangular fashion following the long axis of both vessels. After heparinization, the femoral vein is cannulated using the Seldinger technique and a guidewire is advanced under TEE guidance into the superior vena cava. Then the puncture site is sequentially enlarged using dilators and finally a 25F multiperforated venous cannula is, under TEE guidance, introduced and placed with its tips 3 to 5 cm inside the superior vena cava (SVC). After securing the

Figure 3.
Shows the right common femoral artery and vein cannulated for cardiopulmonary bypass.

venous cannula to the skin with stay sutures, arterial cannulation is performed following the same technique described, using TEE to verify the position of the guidewire in the descending aorta. The diameter of the vessel is the sole determinant of the size chosen for the arterial cannula and typically ranges from 15F to 19F. We never oversize the arterial cannula and prefer to use a 6-8 mm Dacron side-graft if in doubt. In rare cases when we have to use a cannula that completely occludes the lumen (as in obese patients with poor femoral arteries) and the planned procedure is long, we place a distal perfusion line to prevent limb ischemia and a postoperative compartment syndrome. For this purpose, we use a 6F introducer connected to the arterial line through a side port.

Using this technique, we do not need routine cannulation of the jugular vein for mitral surgery, but it is crucial to always use vacuum-assisted drainage in the venous line and to make sure the venous cannula is correctly positioned inside the superior vena cava to avoid its occlusion by the Chitwood clamp when the atrial retractor is placed in the left atrium and pulled anteriorly to expose the valve.

4.2 Endoscopic surgery

4.2.1 Port placement and initial steps

Under left-lung ventilation the working port is created in the 4th intercostal space performing a 3-4 cm incision around the level of the anterior axillary line and a soft-tissue retractor (Alexis XSI, Applied Medical, CA) is placed to prevent inadvertently introducing fatty tissue or debris in the cardiac chambers during the introduction of surgical instruments, sutures or valvular prostheses. Then, a 5 mm trocar is placed in the third intercostal space along the anterior axillary line and CO₂ is continuously insufflated (4 L/min) throughout the entire operation, to create an intrathoracic CO₂ environment that reduces the risk of air embolism after releasing the aortic clamp. This trocar is used to introduce a 5 mm 30-degree videothoracoscopic HD camera to guide the procedure and the camera is held by an articulated arm placed in the right side of the head piece of the surgical table (**Figure 4**). An 11 mm trocar is placed in the 6th intercostal space, mid-axillary line. We use this second trocar to exteriorize retraction sutures (placed in the diaphragm and in the lower portion of the pericardium) and to introduce the left atrial vent line. After the

Figure 4.
Presents the final set-up of an endoscopic surgery. A shows the surgical field with all the ports during a mitral repair through a periareolar incision. In this image the surgeon is using two long-shafted instruments through the working port and the assistant is moving the left atrial retractor to improve exposure. B shows the thoracoscopic camera held in position by an articulated arm. C show how the transthoracic clamp is inserted below the camera trocar.

procedure is completed, a 28F chest tube will be passed through this trocar and left in the pleural space. If diaphragmatic retraction is needed (>75% of cases), a pledgeted “2/0” PTFE suture is placed and tied in the central tendon, taking great care not to damage the liver during this maneuver. The traction suture is

exteriorized through the 11 mm trocar and tension is applied to improve exposure. Then, the pericardium completely opened in its lateral aspect with a longitudinal incision performed at least 3 cm anterior to the phrenic nerve. Two PTFE stay sutures are placed near the cranial and caudal ends of the posterior edge of the pericardium and exteriorized using the 11 mm trocar for the caudal suture and a transthoracic puncture just cranial and posterior to the working port, in the mid axillary line.

After opening the pericardium and placing the stay sutures in the diaphragm and the pericardium, the aortic cross-clamp is inserted through a 5mm incision in the 3rd intercostal space mid-axillary line (**Figure 4**). A curved Chitwood clamp is advanced inside the pericardium and placed across the ascending aorta, with its lower jaw placed inside the transverse sinus under thoracoscopic vision and using blunt instruments (typically a thoracoscopic suction cannula) to push the aorta anteriorly. Once the aortic clamp is in place, a pledgeted purse string is placed in the ascending aorta and a long cardioplegic needle is inserted through the working port under thoracoscopic vision. At this point, cardiopulmonary bypass is initiated and, upon reaching full systemic flow, the ventilator is disconnected and the aorta is cross-clamped.

Our technique for myocardial protection consists on antegrade administration of cold blood cardioplegia (Buckberg's technique) after cross-clamping the aorta and repeated every 20 minutes thereafter. During cardioplegia infusion, the left atrium is opened just below the interatrial septum and the left atrial vent is introduced and placed in the left pulmonary veins to maintain a bloodless surgical field. The size of the left atrial retractor blade is selected at this moment and the stem of the retractor is placed under thoracoscopic control, typically through the 5th intercostal space along the midclavicular line. The retractor is then assembled inside the thorax and placed inside the left atrium. Retraction is then applied to achieve an adequate exposure of the mitral valve. The atrial retractor is held in place using a second articulated arm placed on the left side of the table.

4.2.2 Completion of the operation

After achieving the mitral repair or replacement, the left atriotomy is closed. Our preference for this is to use monofilament sutures (barbed polybutester or PTFE) using two sutures secured at both ends of the atriotomy and sutured towards the center. While finishing this step, the left atrial vent line is removed so blood is allowed to start filling the left cardiac chambers to begin de-airing. After closing the atriotomy, suction is applied in the root vent line and both lungs are manually inflated to remove as much air as possible from the heart and pulmonary veins before releasing the aortic cross-clamp. To further assist this process, the venous line can be intermittently clamped to allow blood to fill the right heart and the lungs and push air out from the heart. After completing de-airing, the aortic clamp is released and the heart is reperfused. We do not put pacing wires routinely after isolated mitral repair in patients without previous rhythm abnormalities; if they are required, they can be placed in the right atrial wall and/or on the right ventricular wall. After normal rhythm is restored, and preliminary echocardiographic evaluation of valvular and ventricular function is satisfactory, the patient is weaned from cardiopulmonary bypass in the usual fashion. Our preference is to remove the aortic root vent after echocardiographic evaluation of the result is completed under a short period of full-flow cardiopulmonary bypass, to facilitate the removal of the cannula and the repair of the entry site with low aortic pressure and reduced pulsatility. After this is completed satisfactorily, the patient is weaned from cardiopulmonary bypass and decannulated, and protamine is given. All ports

are removed under thoracoscopic control to avoid any port site bleeding, and pericardial (19F Blake drain) and pleural (28F curved chest tube) draining tubes are implanted using the port incisions. The pericardium is loosely approximated with two or three interrupted sutures to avoid the low risk of cardiac herniation and facilitate reoperation, should future procedures be needed.

After cannulas are removed from the femoral vessels, the purse strings are tied and both cannulation sites are reinforced with 5/0 polypropylene sutures. After hemostasis is accomplished all incisions are closed in the usual fashion and the patient is usually extubated in the operating room immediately after the operation is completed.

4.3 Robotic surgery

Most of the preparations and initial steps of the operation are the same as described before in detail for the endoscopic surgical procedure. In short, the patient is positioned in supine with mild right chest elevation, on demand single-lung mechanical ventilation is prepared and cardiopulmonary bypass is established using the right femoral vessels.

The placement of the trocars for the robotic arms starts with the introduction of an 8 mm trocar in the 4th intercostal space between the mid clavicular and the anterior axillary lines using blunt dissection; this will serve as the camera port. After insertion, the camera port is connected to a CO₂ line to create a controlled pneumothorax using a pressure limit of 7-10 mmHg. The scope is inserted in the trocar and the right pleural space inspected for adhesions. Under thoracoscopic visualization, 3 angiocaths are inserted at the 4th, 6th and 7th intercostal spaces in the posterior axillary line; these will be used to exteriorize the traction sutures placed on the diaphragm and the pericardium. It is important to keep these catheters occluded to avoid losing CO₂ during this phase. Then, the right arm trocar is inserted in the 6th intercostal space, approximately 2 cm posterior to the camera port. Thereafter, the left arm trocar is inserted in the 2nd or 3rd intercostal space at the same level as the

Figure 5.
This picture shows a patient set-up for a robotic mitral repair. Markings in the chest reveal the surgical landmarks used for port placement and the anticipated location of the four arms of the robot. The location of the working port (WP) is also shown, and the mid-axillary line (MAL) is drawn to help in the placement of the retraction sutures for the diaphragm and the pericardium.

camera port. Finally, the trocar for the atrial retractor is inserted in the 6th intercostal space just medial to the mid clavicular line, avoiding injuring the internal thoracic artery. All trocars are inserted under direct vision using the scope. Once all trocars are in place, a 2-3 cm thoracotomy is performed around 3 cm lateral to the camera port, in the same intercostal space, to serve as the working port. After achieving proper hemostasis, a soft tissue retractor is applied leaving a suction catheter outside, that will be used as a left atrial vent during the operation (**Figure 5**).

Once all thoracic steps are completed, heparin can be administered and the femoral vessels are cannulated as described earlier in detail. Once both cannulas are secured and connected to the CPB circuit, the DaVinci system can be docked to the patient. It is extremely important to connect the trocars in the direction they will move to avoid potential conflicts between the robotic arms. The camera port is connected to arm number 2 and, under endoscopic visualization, instruments are placed in arms 1 and 4 and introduced inside the thorax for the console surgeon control (**Figure 6**). At this stage CPB can be started, although in some patients with

Figure 6. Final view of the operating room during a robotic mitral repair. A shows the operative field with all four robotic arms connected to the trocars. B shows the working port and bed side surgeon preparing to place the transthoracic clamp. C is a general view of the robotic operating room to demonstrate the location of the surgical assistants, the perfusion team, the anesthesia team and the three components of the robotic system: The patient cart (the robot itself), the vision cart and the surgeon console in the back of the room.

excellent anatomy the pericardium can be opened and the diaphragm retracted before starting CPB. For diaphragmatic and pericardial retraction, we normally use a 2/0 PTFE sutures as described in the thoracoscopic procedure. These sutures exit the chest through the angiocaths placed at the beginning of the operation.

The atrial retractor is inserted under direct vision on the robotic arm number 3, and used to separate the aorta from the SVC to expose the transverse sinus. Placement of the transthoracic aortic clamp and cardioplegia administration are performed as described for the endoscopic procedure. The left atrium is incised to expose the mitral valve using the dynamic left atrial retractor (**Figure 2**).

Once the mitral repair or replacement is completed, the left atrium is closed using two running sutures from both ends of the incision as described for the endoscopic procedure. After proper deairing the cross-clamp is removed and the patient is weaned from CPB as described earlier. At this point, the 3rd arm is removed and the trocar is used to insert a 19F Blake drainage inside the pericardium, which is approximated with two sutures. The remaining trocars are removed and checked for bleeding using the camera, and a 24F curved chest tube is inserted in the pleural space using the right arm trocar incision.

5. Results

The primary goal of minimally-invasive mitral repair is, as in open surgery, to achieve a successful and durable valve repair. Despite its perceived technical complexity, experienced centers have reported excellent repair results with 95% freedom from mitral regurgitation at 5 years, even in complex mitral pathology [15–18].

In addition to a durable result, minimally-invasive mitral surgery aims for a faster recovery and higher patient satisfaction as incisions are smaller. Recent series reported higher quality of life and earlier return to work in minimally invasive surgery [16]. Furthermore, several publications have shown that despite longer CPB and aortic-clamp times, minimally invasive surgery is associated with a very low complication rate, reduced blood loss and shorter ICU and in-hospital length of stay [17, 19].

6. Starting a new program

The most successful centers in minimally-invasive mitral surgery are usually high-volume referral centers with vast experience in mitral repair when they started their programs. Minimally invasive surgery, and even more robotic surgery, require developing new skills such as peripheral cannulation, intra-aortic occlusion and the use of thoracoscopic vision and long-shafted instruments. It is not only the surgeon, but the whole operating team (anesthesiologists, perfusionists, Operating room nurses, etc.) that has to learn to use new tools and adapt to new surgical techniques [20].

Based on our own experience, there is an increase in complexity for the whole team when transitioning from open to thoracoscopic surgery, which is even steeper when going further from there to robotic surgery. For this reason, we consider that it is mandatory for the whole surgical team to undergo specific in-depth training in thoracoscopic and robotic cardiac surgery as basic first-step before starting a successful program, either endoscopic or robotic. Training must include the acquisition of the required theoretical knowledge and the progressive achievement of the technical skills required. For the latter, the first step is practicing on simulators and dry lab training. After this step is accomplished, the team can move to higher fidelity wet labs, and training in live, large animal and/or human cadaveric models.

After this basic training the members of the surgical team should do repeated case observation work in experienced large volume institutions and during the first phases of their experience have the aid of expert proctors that can provide the required support to ensure safety for the patient and a profitable learning experience to the team [21].

The best way to establish a successful program is to avoid overlapping learning curves. Results are better during the initial phases if a robotic program is started by teams with wide experience in mitral repair and there is a strict patient selection protocol. As programs grow in experience, there is a tendency to extend the indication to more complex patients. Surgeons should pay close attention to their results in order to detect any changes on the appearance of complications while extending their inclusion criteria and adjust them accordingly [22, 23].

7. Latest developments and percutaneous devices

Following the expansion of transcatheter devices to treat aortic stenosis, several developments have appeared to repair or replace the mitral valve. The most extended one in the repair group is the MitraClip (Abbott Laboratories. IL, USA), which resembles an edge-to-edge repair. It requires venous access and a transeptal puncture. To date, more than 100000 implants have been performed, mostly on selected patients with secondary mitral regurgitation [24]. More recently, another device using the same concept has been introduced, the Pascal repair system (Edwards Lifesciences. CA, USA) [25].

New transapical devices are trying to resemble mitral repair using neochords, such as the Harpoon (Edwards Lifesciences. CA, USA) [26] and the Neochord (Neochord INC. MN, USA) [27] devices, which allow the transapical insertion of neochords on the beating heart under TEE guidance. Both of them require a left mini-thoracotomy and can be used without CPB.

The Cardioband (Edwards Lifesciences. CA, USA) percutaneously delivers an annuloplasty band using a transseptal access. It is anchored with several screws into the mitral annulus and then cinches the valve under TEE guidance.

In the field of percutaneous mitral replacement, the Tendyne bioprosthetic mitral valve system (Abbott Medical Inc. IL, USA) accumulates the larger clinical experience. It is a fully retrievable and repositionable device that is implanted using an off-pump transapical approach.

These and other developments [28, 29] will undoubtedly continue in the future and will reshape the landscape of options to treat the mitral valve for the benefit of patients.

Conflict of interests

The authors declare no conflict of interests.

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