Minimally invasive mitral valve repair

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Abstract

Minimally invasive mitral valve (MV) repair is being increasingly performed over the last 2 decades due to the constantly growing patient demand, since it offers a shorter recovery, less restriction and faster return to normal physical activities, reduction in pain, and superior cosmetic results. However, such procedures have to be performed through small incisions which limit visualization and the freedom of movement of the surgeon, in contrast to conventional operations that are performed through a sternotomy. Therefore, special long surgical instruments are required, and visualization is usually enhanced with advanced port-access two-dimensional (2D) or three-dimensional (3D) thoracoscopic cameras. This makes performance of a minimally invasive MV repair more challenging for the surgeon and is thereby associated with a steep learning curve. Nonetheless, the vast majority of patients who require MV repair are usually good candidates for this less invasive technique, though adequate patient selection is of utmost importance for success. Concomitant cardiac procedures such as ablation surgery for atrial fibrillation or right-sided interventions such as tricuspid valve surgery, heart tumor resection, and atrial septal defect closure can easily be performed using this approach. Short- and long-term results after minimally invasive MV repair are excellent and comparable with those achieved through a sternotomy approach. There are few drawbacks associated with minimally invasive MV repair such as the high technical demands of working through a constrained space and development of complications associated with peripheral cannulation and seldom unilateral pulmonary edema. Nonetheless, high-volume centers have been able to achieve similar operating times, postoperative complication rates, and mid-/long-term outcomes to those obtained through conventional sternotomy. Up-to-date evidence is needed in order to improve recommendations supporting minimally invasive MV repair. Future innovations should concentrate on decreasing complexity and improving reproducibility of minimally invasive procedures in low-volume centers.

Keywords Minimally invasive mitral valve repair · Two-dimensional · Three-dimensional

Introduction

Minimally invasive MV repair is being performed by an increasing number of surgeons over the last 2 decades. It offers similar efficacy and safety when compared with the conventional median sternotomy approach, especially in high-volume centers, as demonstrated by low perioperative morbidity and mortality rates [1]. Additionally, patient approval is greater due to superior aesthetic results, shorter recovery times, and lesser restriction of physical activities. Nevertheless, minimally invasive MV repair is technically

more difficult and is associated with a steep learning curve. Therefore, adoption rates of minimally invasive operations vary from less than 30% in the USA to approximately 50% in Germany [1]. The current heart valve disease guidelines recommend early surgical intervention even for patients with asymptomatic mitral regurgitation (MR) in centers of experience, where the mortality risk is lower than 1% and the likelihood of repair is greater than 90% [2]. These high standards are also expected of minimally invasive mitral repair procedures, making it a challenging surgical alternative, which requires greater surgical dexterity and experience. This review offers an overview of the most important aspects related to minimally invasive MV repair under direct visualization and/or thoracoscopic assistance. Robotic cardiac surgery is the least invasive technique for minimally invasive surgery, but its technical complexity and special instrumentation require a detailed discussion, which is beyond the scope of this review.

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Brief history

The first attempts at MV repair were about a century ago [3–5]. However, Carpentier's landmark paper entitled "The French Correction" [6] published in 1983 standardized and facilitated reconstructive MV surgery and started the modern era of MV repair. Thereafter, introduction of modified cardiopulmonary bypass (CPB) circuits and techniques as well as the development of special long-shafted surgical instruments allowed the safe and efficacious performance of minimally invasive MV surgery [7, 8]. This led to the emergence of modified less invasive incisions for MV surgery [9–11]. Further development led to the first video endoscopic minimally invasive MV repair through a right mini-thoracotomy, which was performed by Carpentier in 1996 [12] followed by the first completely robotic MV repair using telemanipulation with the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA) in 1998 [13]. Falk et al. introduced the voice-controlled robotic camera in 1998 [14] and subsequently established large-scale thoracoscopic minimally invasive and robotic MV repair programs with excellent results [15, 16].

Definition

The concept of "minimally invasive cardiac surgery" has been traditionally defined as a small chest wall incision, which does not involve a complete sternotomy [17]. Furthermore, minimally invasive MV surgery results in avoidance of any kind of sternotomy, a decrease in blood product utilization, shortening of mechanical ventilation times, reduction of intensive care and hospital stays, and lessening of postoperative pain. There are four levels of invasiveness that exist in minimally invasive cardiac surgery as shown in Table 1 [18, 19].

The most frequently used minimally invasive approach to the MV is the right mini-thoracotomy. Other incisions such as lower mini-sternotomy and parasternal incisions may also be employed. A special set of long-shafted surgical instruments is required to perform these procedures. Port-access 2 D or 3 D thoracoscopic cameras can either be used as video assistance in performing the procedure by direct vision or as the sole source of vision in expediting the procedure without rib-spreading.

Patient selection

Minimally invasive MV surgery can be performed in almost all patients who require isolated MV repair or replacement. Other concomitant procedures such as tricuspid valve surgery, atrial ablation procedures, atrial septal defect closures, and resection of myxomas can also be performed through this

approach. However, combined aortic valve surgery, ascending aorta replacement, and coronary artery bypass surgery most often would require a median sternotomy. Contraindications for minimally invasive mitral valve surgery are shown in Table 2. Complex MV repairs can be performed through a minimally invasive approach. However, the level of complexity of MV repair has to be in accordance with the expertise and experience of the surgeon and his entire team. Complications are inherent to any surgery; nevertheless, they occur more often during the operator's learning curve and subsequently reduce over time with increasing experience. The optimal procedure rate for obtaining good results is considered to be at least one to two procedures a week [20]. Results of complex MV surgery performed by experienced teams are comparable with those achieved through a median sternotomy [8, 15, 20, 21].

In high-volume centers, minimally invasive MV repair provides good results in high-risk patients such as those requiring MV reoperations [21–24], in the elderly [25, 26] and obese patients [27, 28] as well as in patients presenting with MV endocarditis without large peri-annular abscesses [29].

Preoperative screening

A detailed transthoracic echocardiography (TTE) is required for the evaluation of the ventricular function, assessment of the degree, etiology, mechanism, and complexity of MV disease and other valve pathologies, and the presence and grade of pulmonary hypertension. If the latter is severe, a right heart catheterization may be considered to differentiate between pre- and post-capillary pulmonary hypertensions and to assess its reversibility. For complex valve pathology, 2D and 3D transesophageal echocardiograms are recommended for a better planning of the repair. Routine lung function tests and chest X-ray should also be performed before surgery. A computed tomogram (CT) of the thorax is not routinely required. However, it is strongly recommended in patients with significant chest deformities and morbid obesity and those requiring reoperations and in patients who have received prior radiation to assess the density and extent of adhesions. 3D CT reconstruction models are commonly available nowadays to facilitate preoperative planning. This imaging modality is a useful and feasible method of determining the operative strategy and excluding patients unsuitable for a minimally invasive approach, thus preventing potential complications [30].

Coronary artery disease screening is not required in patients under 40 years of age as long as they do not have any predisposing risk factors [2]. Patients older than 40 but younger than 60 years of age without cardiovascular risk factors may be screened with CT coronary angiography [2]. Patients older than 60 years or younger patients with cardiovascular

Table 1 Complexity levels of minimally invasive cardiac surgery

Level	Incision size	Description
I	10–15 cm	Direct visualization
II	4–6 cm	Direct visualization and video assistance
III	1.5–4 cm	Video-directed and robot-assisted
IV	< 1.5 cm	Robotic telemanipulation and totally endoscopic port access

Modified from [1]

risk factors should undergo a preoperative coronary angiogram [2].

In case of a suspected carotid artery disease, Doppler examination and carotid CT studies should be performed. Patients with confirmed peripheral vascular disease or with risk factors for the same should also undergo tomographic or ultrasound imaging for aortoiliac disease.

Special considerations

Peripheral femoro-femoral cannulation is the most commonly used approach for CPB in minimally invasive MV surgery. Some surgeons prefer direct aortic cannulation via the mini-thoracotomy incision, arguing that antegrade flow to the brain as well as avoidance of groin cannulation is beneficial. However, a larger thoracotomy incision is required for this approach. The choice between direct aortic clamping and balloon endoclamping varies from center to

center. Femoral artery cannulation and endoaortic balloon occlusion should be avoided in patients with severe aortic atherosclerosis or a dilated ascending aorta. In such cases, the right axillary artery is the optimal site for arterial cannulation. Direct aortic clamp proponents encourage its use on the pretext of the reduced adverse neurological events in comparison with endoclamping. Nevertheless, Casselman et al. observed similar mortality and stroke rates using balloon endoclamping when compared with results from other centers [31].

A wide variety of modified small sternal, parasternal, and mini-thoracotomy incisions have been described to access the cardiac valves. Recently, a modification of the right mini-thoracotomy known as the periareolar incision has been developed. It achieves very good cosmetic results without compromising surgical exposure [32–34]. The successful performance of the periareolar technique requires appropriate patient selection, as shown in Table 3. Other groups approach the MV through a lower partial sternotomy, keeping the manubrium intact [35].

Further advances such as 3D thoracoscopy or even totally endoscopic surgery via port access are being used on a more frequent basis. Totally endoscopic technique refers to incisions no larger than 0.5 to 1.5 cm and usually implies a robot-assisted approach [36]. Nevertheless, some surgeons also consider a small mini-thoracotomy without the use of rib-spreading as “totally endoscopic” [37], but it still requires a 4-cm thoracotomy incision [38].

Table 2 Absolute and relative contraindications for minimally invasive mitral valve surgery

Absolute

Previous right thoracotomy
Severe mitral annular calcification
More than moderate aortic AR
Concomitant CABG indicated

Relative

Aortic root/ascending aorta calcification and/or dilatation
Severe peripheral arterial disease
Severe irreversible pulmonary hypertension (> 60 mmHg)
Severe pulmonary disease
Reduced RVEF
Recent stroke or TIA
Severe liver dysfunction (the Child-Pugh B or C)
Significant coagulopathy

CABG coronary artery bypass grafting, AR aortic regurgitation, RVEF right ventricular ejection fraction, TIA transient ischemic attack

Modified from [1]

Surgical management

Operative setup

The right mini-thoracotomy through the fourth intercostal space (ICS), with 2D or 3D video assistance, is our standard approach [1, 8]. Orotracheal intubation is performed with a single lumen endotracheal tube. A 30° left lateral position is given and the right arm is located posteriorly (Fig. 1). Cardiopulmonary bypass is established via femoral artery and vein cannulation through a 2–3-cm oblique incision in

Table 3 Special considerations for minimally invasive periareolar approach

Gender	Possible in both genders
Areolar diameter	> 3 cm
Incision	< 180°
Obese patients	Not a contraindication, as breast tissue flattens around the areolar region after patient is positioned on the surgical table.
Breast implants	Not a contraindication, as the breast implants can be explanted and kept in saline solution with antibiotics during the procedure (plastic surgeon required)
Contraindications	History of breast irradiation or cancer surgery with breast reconstruction

Modified from [34]

the groin using an open Seldinger's puncture technique under direct visualization (Fig. 2). It is important to confirm that the wire is held taut by the nurse during insertion of the cannula to prevent the intra-abdominal segments of the vessels from injury. The arterial cannula is then fixed to the skin with a suture to avoid displacement/dislocation. Correct positioning of the tip of the multiport venous cannula in the superior vena cava is confirmed by transesophageal echocardiography (TEE). A second venous cannula is inserted into the right internal jugular vein by the anesthesiologists at the time of induction in patients weighing more than 90 kg or those requiring right-sided heart procedures. For concomitant right-sided procedures, temporary occlusion of superior and inferior vena cava is accomplished with tourniquets or large bulldog clamps.

Body temperature is maintained at 34 °C and vacuum-assisted venous drainage is used throughout the procedure. A 5–6-cm right lateral mini-thoracotomy incision is made just inferolateral to the nipple in men and in the submammary crease in women (Fig. 3). All steps of the procedure can be performed under direct visualization through the right mini-thoracotomy, even in the absence of a thoracoscope. The length of the incision may be increased to approximately 8 cm if necessary. The incision can be reduced in size with increasing

experience as the surgeon overcomes the learning curve. After skin incision, the thorax is entered through the 4th ICS.

A dedicated instrument set designed for minimally invasive valve surgery is used to perform the operation. A soft tissue retractor with or without a small thoracic retractor is utilized to spread the ribs. The pericardium is opened 3–4 cm anterior and parallel to the right phrenic nerve to avoid injury or traction to it and extends from the distal ascending aorta to the diaphragm. This incision is extended posteriorly toward the IVC at its inferior end (Fig. 4). A thoracoscope and a trans-thoracic Chitwood aortic cross-clamp are inserted via the 2nd and 3rd right ICS, respectively. Antegrade cardioplegia is delivered directly into the aortic root through a long cardioplegia needle. We prefer to use long-acting crystalloid cardioplegia allowing 90–120 minutes of safe ischemic time. A left atriotomy is performed through a paraseptal incision (the Sondergaard groove) and a left atrial retractor is used to expose the MV (Fig. 5). Thereafter, standard MV repair techniques are used, as described below.

Once MV repair has been accomplished, the water test is used to confirm MV competency (Fig. 6). Thereafter, the left atrium is closed and de-aired. The surgeon should be careful not to include the posterior wall of the right superior pulmonary vein in the left atrial suture line, which is possible due to

Fig. 1 Patient position: 30° left lateral position. The axilla (black dot) has to be within the operative field. The left arm (black hatched line) is positioned downwards and outwards

Fig. 2 Femoral arterial and venous cannulation

Fig. 3 The inframammary incision in females (black hatched arrow)

the inability to clearly visualize the 2 walls in a minimally invasive approach. The patient is temporarily weaned from CPB and TEE assessment of the MV repair is performed. Additionally, the presence of new regional wall motion abnormalities should be specifically looked for on TEE to rule out injury, stenosis, or occlusion of the left circumflex artery. CPB is then resumed, the cardioplegia needle vent is removed after sufficient de-airing, hemostasis is ensured, and the pericardium is closed. The last step is extremely important to prevent the development of adhesions between the right lung and right atrium, which are extremely difficult to take down, if the patient needs a reoperation. CPB is then weaned off, protamine is administered, and the patient is decannulated. The chest is then closed (Fig. 7).

MV repair techniques

The fundamental principle of MV repair that we try to follow is “*respect rather than resect.*” All techniques of MV repair

Fig. 4 The pericardial incision: 3–4 cm anterior to phrenic nerve (white double-headed arrow), extends up to the diaphragm and further posteriorly to the inferior vena cava (yellow arrows)

Fig. 5 The setup shows the incision and soft tissue retractor (blue hatched circle), the thoracoscope port (black hatched arrow), the entry site of the transthoracic aortic clamp (black arrow), the left atrial retractor and holding arm (yellow hatched arrows), and the left atrial vent (yellow line)

that are performed through a sternotomy approach can be performed with similar dexterity and finesse through a minimally invasive approach. Surgeons must be familiar with standard repair techniques and should have mastered them before using the minimally invasive approach. We usually perform the following MV repair techniques:

Neochordae implantation Leaflet prolapse (Fig. 8a) is corrected by inserting artificial chordae comprising polytetrafluorethylene (PTFE) sutures between the papillary muscle and the leaflet segments that have elongated or ruptured chordae tendinae. For minimally invasive MV surgery, PTFE neochordae placement is facilitated by the “Leipzig loop technique” [7]. The correct length of the PTFE loops is determined using a caliper (Fig. 8b) that measures the distance from the point on the papillary muscle to which the loops will

Fig. 6 The water test. The line of coaptation should be located in the posterior third of the mitral valve orifice and should be parallel to the posterior mitral annulus

Fig. 7 The closed incision in males (blue circle) with drains and a pacing wire (yellow arrow)

be attached to the plane of the mitral annulus. The length of the prolapsing segment, especially in patients with posterior mitral leaflet (PML) prolapse, should be taken into consideration while selecting the appropriate length of the loops. The loops are then attached to the papillary muscle (Fig. 8c) and to the free edge of the prolapsing segment(s) (Fig. 8d, e). This

technique can be used for both anterior mitral leaflet (AML) and PML prolapse. Additionally, the midline rule for placement of neochordae should be observed to maintain the geometry of the leaflets.

Chordal transfer This technique is used for repair of AML prolapse. Chordae tendineae with a small strip of leaflet tissue are transferred from the PML to the free edge of the unsupported prolapsing segment of the AML. The defect thus created in the PML may be then repaired as for a triangular or quadrangular resection. Chordal transfer may also be performed by transfer of secondary AML chordae to the unsupported prolapsing free edge. Because normal chordae are used in both techniques, there is no need for chordal length measurement [39].

Triangular resection This technique is ideal for patients with PML prolapse. The extent of leaflet resection is identified by finding normal chordae on either side of the prolapsing segment. A triangular-shaped segment of tissue is excised with a curved scissor. Continuous or interrupted 4–0 polypropylene suture is used to close the defect in the leaflet.

Quadrangular resection with sliding plasty This technique is employed in patients with markedly elongated leaflets and redundant tissue (Barlow's disease) inducing an extensive,

Fig. 8 a P₂ prolapse. b Measurement of length of loops. c Loops attached to the antero-lateral papillary muscle. d, e PTFE sutures passed through the loops and then through the free margin of P₂

redundant PML prolapse. The prolapsing, excessively tall segment of posterior leaflet is excised and then the remaining segments of the PML are detached from the annulus and advanced centrally, “sliding” them over, to meet one another. The secondary chords to the sliding segments have to be severed to reduce the tension on the reconstructed PML. The lateral and medial PML segments are reapproximated and the base of the PML is reattached to the annulus with a continuous 4–0 polypropylene suture.

Alfieri stitch The figure of eight edge-to-edge Alfieri’s stitch may be performed in the elderly or significantly morbid patients, in whom reduced operative times are important. This technique is also recommended in pathologies with a high probability of development of systolic anterior motion (SAM) following repair. Commissural prolapse can be easily corrected with this stitch. It can also be used as a bail out technique in cases in which a complex repair that has consumed excessive CPB time is not perfect or has failed. Nonetheless, the surgeon should always be aware of maintaining adequate valve orifice area, when using this technique.

Annuloplasty All repairs are supported by insertion of an annuloplasty ring (usually complete and semi-rigid) or band. Functional MR is repaired by means of a downsized, complete, rigid annuloplasty ring with or without subvalvular procedures.

Concomitant cardiac procedures

As previously mentioned, a minimally invasive approach is also feasible in patients requiring other concomitant right-sided heart procedures. Direct closure of a patent foramen ovale can be easily performed through the left atriotomy, but ASD closure usually requires separate right atrial access. Once MV repair is completed, tricuspid valve surgery may be performed without aortic cross-clamp in order to shorten myocardial ischemia time [8].

Postoperative outcomes

Mortality following MV repair procedures is similar for both the median sternotomy and the right mini-thoracotomy approach. Nevertheless, this finding is based on retrospective observational studies. There are no well-powered randomized multicenter studies comparing both approaches in the literature. Large retrospective series have demonstrated a 30-day mortality for both approaches ranging from 0.2 to 2.6% [8, 40, 41]. Similar studies have demonstrated a comparable long-term survival following minimally invasive MV repair with conventional MV surgery [42, 43]. The “Leipzig experience” showed survival rates of $87.0 \pm 0.7\%$ at 5 years and $74.2 \pm 1.4\%$ at 10 years after minimally invasive MV repair [8].

Additionally, the rate of repair following minimally invasive MV repair is $> 90\%$, which is similar to that following median sternotomy for MV repair [8, 40, 41, 44]. Furthermore, recurrent MR and freedom from repeat MV surgery have been reported to be similar between both approaches [41, 45]. Our experience showed a freedom from reoperation of $96.6 \pm 0.4\%$ and $92.9 \pm 0.9\%$ at 5 and 10 years, respectively [8]. Current guidelines recommend TTE before hospital discharge and lifelong annual echocardiographic surveillance for all patients undergoing MV repair [2, 46].

Advantages and disadvantages

More patients demand minimally invasive surgery because of perceived advantages. Reduced postoperative pain and faster return to normal activity has been observed in several studies [9, 27, 47, 48]. Recovery is more rapid and less painful than after their previous sternotomy procedure in patients undergoing reoperations through a minimally invasive approach [49, 50]. Less bleeding (although without reduction of re-exploration for bleeding), reduced mechanical ventilation times, less AF or post-operative arrhythmias, decreased wound infections, and shorter hospital stays are also other benefits observed in patients undergoing minimally invasive MV repair [20, 27, 43, 48–50].

Moreover, minimally invasive MV surgery is a great opportunity for learning since port-access video assistance allows excellent visualization of the MV for the entire surgical team. In addition, several simulators are available for practicing manual skills and familiarizing oneself with long instruments required to perform these techniques.

However, minimally invasive approach to the MV does have some drawbacks. Myocardial ischemic and CPB times are longer than those during a conventional median sternotomy approach, due to the increased surgical demands of working through a reduced space [10]. Several steps performed by an assistant during conventional surgery have to be performed by the surgeon himself, which obviously leads to an increase in operative time. Nevertheless, operating times in high-volume centers approach those required through median sternotomy [11].

Stroke rates have been reported to be higher in patients undergoing minimally invasive surgery [51], presumably because of retrograde body perfusion during CPB. This dreaded complication occurs in up to 2.6% of patients undergoing minimally invasive MV surgery [8, 41]. Nevertheless, one recently published meta-analysis showed that minimally invasive surgery was no longer associated with an increased risk of stroke [52]. The choice between direct aortic clamping and balloon endoclamping varies from center to center. Similar stroke rates have been observed using either of these techniques, if correctly employed [31, 53], since balloon migration during endoaortic clamping has been associated with increased stroke rates [51]. Therefore, intraoperative TEE

confirmation and surveillance of endoaortic balloon position are recommended for preventing cerebral ischemia.

Peripheral cannulation during minimally invasive surgery may potentially be associated with complications such as groin seroma and superficial groin wound infections, which are amongst the most commonly reported complications occurring in 1 to 7% of patients [31, 53–57]. Leg ischemia is very rarely observed. Retrograde aortic dissection is a rare but serious and life-threatening complication of peripheral cannulation. Unilateral pulmonary edema is an infrequent but life-threatening complication of minimally invasive MV surgery [58]. Phrenic nerve injury could also be a possible complication, but it is a major problem only for patients with preoperatively compromised pulmonary function. It is avoided by opening the pericardium 3–4 cm anterior to the nerve. When closing the pericardium, strong traction on the lower pericardial edge must be avoided as it causes diaphragmatic paresis due to stretching of the phrenic nerve. Finally, conversion to median sternotomy (most commonly for bleeding) is another described complication of minimally invasive MV surgery, occurring in up to 3.9% of patients [8, 31, 40, 41, 59].

Although minimally invasive techniques are well established in referral high-volume centers, future innovations and research should concentrate on decreasing complexity of these procedures as well as improving its reproducibility in low-volume centers with a reduced budget.

Compliance with ethical standards

Ethical statements Not required being a review article.

Informed consent Not required being a review article.

Conflicts of interest Nothing to declare.

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References

- Marin Cuartas M, Javadikasgari H, Pfannmueller B, et al. Mitral valve repair: Robotic and other minimally invasive approaches. *Prog Cardiovasc Dis*. 2017;60:394–404.
- Nishimura RA, Otto CM, Bonow RO, et al. 2017 AHA/ACC focused update of the 2014 AHA/ACC guideline for the management of patients with valvular heart disease: a report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. *J Am Coll Cardiol*. 2017;70:252–89.
- Bruton TL. Preliminary note on the possibility of treating mitral stenosis by surgical methods. *Lancet*. 1902;1:352–86.
- Cutler EC, Levine SA. Cardiomy and valvulotomy for mitral stenosis. *Boston Med Surg J*. 1923;188:1023–7.
- Souttar HS. The surgical treatment of mitral stenosis. *Br Med J*. 1925;2:603–6.
- Carpentier A. Cardiac valve surgery—the “French correction”. *J Thorac Cardiovasc Surg*. 1983;86:323–37.
- Von Oppell UO, Mohr FW. Chordal replacement for both minimally invasive and conventional mitral valve surgery using premeasured Gore-Tex loops. *Ann Thorac Surg*. 2000;70:2166–8.
- Davierwala PM, Seeburger J, Pfannmueller B, et al. Minimally invasive mitral valve surgery: “The Leipzig experience”. *Ann Cardiothorac Surg*. 2013;2:744–50.
- Cohn LH, Adams DH, Couper GS, et al. Minimally invasive cardiac valve surgery improves patient satisfaction while reducing costs of cardiac valve replacement and repair. *Ann Surg*. 1997;226:421–6.
- Gammie JS, Zhao Y, Peterson ED, et al. J. Maxwell Chamberlain Memorial Paper for adult cardiac surgery. Less-invasive mitral valve operations: trends and outcomes from the Society of Thoracic Surgeons Adult Cardiac Surgery Database. *Ann Thorac Surg*. 2010;90:1401–8.
- Iribarne A, Easterwood R, Russo MJ, et al. A minimally invasive approach is more cost-effective than a traditional sternotomy approach for mitral valve surgery. *J Thorac Cardiovasc Surg*. 2011;142:1507–14.
- Carpentier A, Loumet D, Carpentier A, et al. Open heart operation under video surgery and minithoracotomy. First case (mitral valvuloplasty) operated with success. *C R Acad Sci III*. 1996;319:219–23.
- Carpentier A, Loumet D, Aupele B, et al. Computer assisted open heart surgery. First case operated on with success. *C R Acad Sci III*. 1998;321:437–42.
- Falk V, Walther T, Autschbach R, Diegeler A, Battellini R, Mohr FW. Robot-assisted minimally invasive solo mitral valve operation. *J Thorac Cardiovasc Surg*. 1998;115:470–1.
- Mohr FW, Falk V, Diegeler A, Walther T, van Son JA, Autschbach R. Minimally invasive port-access mitral valve surgery. *J Thorac Cardiovasc Surg*. 1998;115:567–74.
- Mohr FW, Onnasch JF, Falk V, et al. The evolution of minimally invasive mitral valve surgery-2 year experience. *Eur J Cardiothorac Surg*. 1999;15:233–8.
- Rosengart TK, Feldman T, Borger MA, et al. Percutaneous and minimally invasive valve procedures. A scientific statement from the American Heart Association Council on Cardiovascular Surgery and Anesthesia, Council on Clinical Cardiology, Functional Genomics and Translational Biology Interdisciplinary Working Group, and Quality of Care and Outcome Research Interdisciplinary Working group. *Circulation*. 2008;117:1750–67.
- Chitwood WR, Rodriguez E. Minimally invasive and robotic mitral valve surgery. In: Cohn LH, editor. *Cardiac Surgery in the Adult*. 4th ed. New York: McGraw-Hill; 2008. p. 1080–100.
- Loumet DF, Carpentier A, Cho PW, et al. Less invasive techniques for mitral valve surgery. *J Thorac Cardiovasc Surg*. 1998;115:772–9.
- Holzhey DM, Seeburger J, Misfeld M, Borger MA, Mohr FW. Learning minimally invasive mitral valve surgery: a cumulative sum sequential probability analysis of 3895 operations from a single high-volume center. *Circulation*. 2013;128:483–91.
- Seeburger J, Borger MA, Falk V, et al. Minimal invasive mitral valve repair for mitral regurgitation: results of 1339 consecutive patients. *Eur J Cardiothorac Surg*. 2008;34:760–5.
- Ricci D, Pellegrini C, Aiello M, et al. Port-access surgery as elective approach for mitral valve operation in re-do procedures. *Eur J Cardiothorac Surg*. 2010;37:920–5.
- Murzi M, Miceli A, Di Stefano G, et al. Minimally invasive right thoracotomy approach for mitral valve surgery in patients with previous sternotomy: a single institution experience with 173 patients. *J Thorac Cardiovasc Surg*. 2014;148:2763–8.

24. Ghoneim A, Bouhout I, Mazine A, et al. Beating heart minimally invasive mitral valve surgery in patients with patent coronary bypass grafts. *Can J Cardiol*. 2016;32:987.
25. Moscarelli M, Fattouch K, Casula R, Speziale G, Lancellotti P, Athanasiou T. What is the role of minimally invasive mitral valve surgery in high-risk patients? A meta-analysis of observational studies. *Ann Thorac Surg*. 2016;101:981–9.
26. Lamelas J, Sarria A, Santana O, Pineda AM, Lamas GA. Outcomes of minimally invasive valve surgery versus median sternotomy in patients age 75 years or greater. *Ann Thorac Surg*. 2011;91:79–84.
27. Santana O, Reyna J, Grana R, Buendia M, Lamas GA, Lamelas J. Outcomes of minimally invasive valve surgery versus standard sternotomy in obese patients undergoing isolated valve surgery. *Ann Thorac Surg*. 2011;91:406–10.
28. Reser D, Sündermann S, Grünenfelder J, et al. Obesity should not deter a surgeon from selecting a minimally invasive approach for mitral valve surgery. *Innovations (Phila)*. 2013;8:225–9.
29. Folkmann S, Seeburger J, Garbade J, et al. Minimally invasive mitral valve surgery for mitral valve infective endocarditis. *Thorac Cardiovasc Surg*. 2017. <https://doi.org/10.1055/s-0037-1604206>.
30. Heuts S, Maessen JG, Sardari Nia P. Preoperative planning of left-sided valve surgery with 3D computed tomography reconstruction models: sternotomy or a minimally invasive approach? *Interact Cardiovasc Thorac Surg*. 2016;22:587–93.
31. Casselman F, Aramendi J, Bentala M, et al. Endoaortic clamping does not increase the risk of stroke in minimal access mitral valve surgery: a multicenter experience. *Ann Thorac Surg*. 2015;100:1334–9.
32. Poffo R, Pope RB, Selbach RA, et al. Video-assisted cardiac surgery: results from a pioneer project in Brazil. *Rev Bras Cir Cardiovasc*. 2009;24:318–26.
33. Poffo R, Pope RB, Toschi AP, Mokross CA. Video-assisted minimally invasive mitral valve repair: periareolar approach. *Rev Bras Cir Cardiovasc*. 2009;24:425–7.
34. Marin Cuartas M, Saldaña LD, Quintero AA, Jaramillo JS, Rendon JC. Minimally invasive cardiac surgery through periareolar approach. *s: CTSNet, Inc; July 2018*. <https://doi.org/10.25373/ctsnet.6815693>.
35. Bouhout I, Morgant MC, Denis B. Minimally invasive heart valve surgery. *Can J Cardiol*. 2017. <https://doi.org/10.1016/j.cjca.2017.05.014>.
36. Glower DD. Surgical approaches to mitral regurgitation. *J Am Coll Cardiol*. 2012;60:1315–22.
37. Glauber M, Miceli A. State of the art for approaching the mitral valve: sternotomy, minimally invasive or total endoscopic robotic? *Eur J Cardiothorac Surg*. 2015;48:639–41.
38. Taylor BS, Vanermen H. Totally endoscopic mitral valve surgery. *Oper Tech Thorac Cardiovasc Surg*. 2007;12:226–34.
39. Gillinov AM, Cosgrove DM. Chordal transfer for repair of anterior leaflet prolapse. *Semin Thorac Cardiovasc Surg*. 2004;16:169–73.
40. Glauber M, Miceli A, Canarutto D, et al. Early and long-term outcomes of minimally invasive mitral valve surgery through right minithoracotomy: a 10-year experience in 1604 patients. *J Cardiothorac Surg*. 2015;10:181.
41. McClure RS, Athanasopoulos LV, McGurk S, Davidson MJ, Couper GS, Cohn LH. One thousand minimally invasive mitral valve operations: early outcomes, late outcomes, and echocardiographic follow-up. *J Thorac Cardiovasc Surg*. 2013;145:1199–206.
42. Lange R, Voss B, Kehl V, Mazzitelli D, Tassani-Prell P, Günther T. Right minithoracotomy versus full sternotomy for mitral valve repair: a propensity matched comparison. *Ann Thorac Surg*. 2017;103:573–9.
43. Goldstone AB, Atluri P, Szeto WY, et al. Minimally invasive approach provides at least equivalent results for surgical correction of mitral regurgitation: a propensity-matched comparison. *J Thorac Cardiovasc Surg*. 2013;145:748–56.
44. Reser D, van Hemelrijck M, Pavicevic J, et al. Repair rate and durability of video assisted minimally invasive mitral valve surgery. *J Card Surg*. 2014;29:766–71.
45. Galloway AC, Schwartz CF, Ribakove GH, et al. A decade of minimally invasive mitral repair: long-term outcomes. *Ann Thorac Surg*. 2009;88:1180–4.
46. Baumgartner H, Falk V, Bax JJ, et al. 2017 ESC/EACTS Guidelines for the management of valvular heart disease. *Eur Heart J*. 2017;38:2739–91.
47. Yamada T, Ochiai R, Takeda J, Shin H, Yozu R. Comparison of early postoperative quality of life in minimally invasive versus conventional valve surgery. *J Anesth*. 2003;17:171–6.
48. Glower DD, Landolfo KP, Clements F, et al. Mitral valve operation via Port Access versus median sternotomy. *Eur J Cardiothorac Surg*. 1998;14:S143–7.
49. Casselman FP, Van Slycke S, Wellens F, et al. Mitral valve surgery can now routinely be performed endoscopically. *Circulation*. 2003;108:II48–54.
50. Felger JE, Chitwood WR, Nifong LW, Holbert D. Evolution of mitral valve surgery: toward a totally endoscopic approach. *Ann Thorac Surg*. 2001;72:1203–8.
51. Cheng DC, Martin J, Lal A, et al. Minimally invasive versus conventional open mitral valve surgery: a meta-analysis and systematic review. *Innovations (Phila)*. 2011;6:84–103.
52. Cao C, Gupta S, Chandrakumar D, et al. A meta-analysis of minimally invasive versus conventional mitral valve repair for patients with degenerative mitral disease. *Ann Cardiothorac Surg*. 2013;2:693–703.
53. Krapf C, Wohlrab P, Häußinger S, et al. Remote access perfusion for minimally invasive cardiac surgery: to clamp or to inflate? *Eur J Cardiothorac Surg*. 2013;44:898–904.
54. Lamelas J, Williams RF, Mawad M, LaPietra A. Complications associated with femoral cannulation during minimally invasive cardiac surgery. *Ann Thorac Surg*. 2017;103:1927–32.
55. Akowuah E, Burdett C, Khan K, et al. Early and late outcomes after minimally invasive mitral valve repair surgery. *J Heart Valve Dis*. 2015;24:470–7.
56. Reser D, Walser R, van Hemelrijck M, et al. Long-term outcomes after minimally invasive aortic valve surgery through right anterior minithoracotomy. *Thorac Cardiovasc Surg*. 2017;65:191–7.
57. Aybek T, Dogan S, Risteski PS, et al. Two hundred forty minimally invasive mitral operations through right minithoracotomy. *Ann Thorac Surg*. 2006;81:1618–24.
58. Tutschka MP, Bainbridge D, Chu MW, Kiai B, Jones PM. Unilateral postoperative pulmonary edema after minimally invasive cardiac surgical procedures: a case-control study. *Ann Thorac Surg*. 2015;99:115–22.
59. Vollroth M, Seeburger J, Garbade J, Borger MA, Misfeld M, Mohr FW. Conversion rate and contraindications for minimally invasive mitral valve surgery. *Ann Cardiothorac Surg*. 2013;2:853–4.