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The golden age of minimally invasive cardiothoracic surgery: current and future perspectives

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Abstract

Over the past decade, minimally invasive cardiothoracic surgery (MICS) has grown in popularity. This growth has been driven, in part, by a desire to translate many of the observed benefits of minimal access surgery, such as decreased pain and reduced surgical trauma, to the cardiac surgical arena. Initial enthusiasm for MICS was tempered by concerns over reduced surgical exposure in highly complex operations and the potential for prolonged operative times and patient safety. With innovations in perfusion techniques, refinement of transthoracic echocardiography and the development of specialized surgical instruments and robotic technology, cardiac surgery was provided with the necessary tools to progress to less invasive approaches. However, much of the early literature on MICS focused on technical reports or small case series. The safety and feasibility of MICS have been demonstrated, yet questions remain regarding the relative efficacy of MICS over traditional sternotomy approaches. Recently, there has been a growth in the body of published literature on MICS long-term outcomes, with most reports suggesting that major cardiac operations that have traditionally been performed through a median sternotomy can be performed through a variety of minimally invasive approaches with equivalent safety and durability. In this article, we examine the technological advancements that have made MICS possible and provide an update on the major areas of cardiac surgery where MICS has demonstrated the most growth, with consideration of current and future directions.

Keywords

minimally invasive cardiothoracic surgery; outcomes

Evolution of minimally invasive cardiac surgery

Minimally invasive cardiac surgery (MICS) has undergone numerous changes in technique and philosophy. In this article, we review the evolution of cardiopulmonary bypass (CPB) techniques, surgical incisions and approaches and technological advancements that have guided MICS to its current state. Since its first successful use by John Gibbon in 1953 [1],

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CPB has been employed by cardiac surgeons to facilitate open-heart procedures. The growing interest in laparoscopic surgery in general prompted exploration of minimally invasive techniques for use in cardiac surgery, with Cosgrove describing the first minimally invasive valve surgeries in 1996 [2]. As the movement towards MICS progressed, improvements were made to either minimize or circumvent the inflammatory processes associated with circulating blood volume through a bypass circuit. Cannulae have become smaller and are manufactured with nonkinking materials to maximize operative space. Application of carbon dioxide in the operative field has reduced the risk of air embolism by reducing intracardiac air. Advancements in transesophageal echocardiography techniques aid in visualization of intraoperative conditions, confirming cannula placement and ensuring proper deairing [3]. Coronary artery bypass graft surgery (CABG) has been routinely performed without CPB, a procedure that is addressed separately in this article.

Performing surgery without the exposure afforded by a median sternotomy prompted the development of alternative methods of CPB access. Arterial access can be achieved with central aortic cannulation or peripheral cannulation via the femoral or axillary artery. Numerous disadvantages have been highlighted with peripheral arterial cannulation, including increased incidence of vascular complications and stroke [4], that have not been observed in cohort studies that employ primarily central access techniques [5]. Venous cannulation has similarly experienced numerous variations, with vacuum-assisted drainage directly via the right atrium or with bicaval access, achieving superior vena cava and inferior vena cava cannulation, either directly or percutaneously from the femoral or internal jugular veins [6]. In a similar manner, cardioplegia can be administered either antegrade from an aortic cannula or retrograde from the coronary sinus via transjugular catheterization [7].

In order to avoid the postoperative respiratory dysfunction, chest instability, chronic pain and incidence of deep sternal wound infection associated with a median sternotomy, numerous alternative incisions were evaluated for MICS. Some early mitral and aortic valve surgeries were performed with a right parasternal incision [2,8] that necessitated resection of the third and fourth costal cartilages. While the procedures could be performed safely and effectively, this approach resulted in potential chest wall instability, difficult conversion to median sternotomy and required transecting the right internal mammary artery. Currently, the right ministernotomy in the fourth intercostal space is the incision of choice for minimally invasive mitral-valve repairs [5,9,10], allowing for central cannulation and conversion to median sternotomy if necessary. Minimally invasive aortic valve surgery is now most commonly performed via a limited skin incision, with a partial upper sternotomy that extends into the third or fourth intercostal space (also known as a ‘J’-sternotomy or reversed-L-shaped sternotomy) [11–13]. Other incisions have included a left thoracotomy [14,15], right infra-axillary thoracotomy [16], trans-sternal approach [17], inverted T-sternotomy [18] and ‘V’-incision [19].

In addition to numerous incisions, MICS has fostered the innovation of new technologies and applications. The port-access method is a system that combines endovascular balloon aortic occlusion with antegrade cardioplegia administration. It has been employed successfully with both CABG [20] and mitral-valve surgery (MVS) [21], although it has been associated with higher rates of retrograde aortic dissection, as well as the previously stated risks of peripheral arterial cannulation [22]. An alternative method is an aortic clamp developed by Chitwood, that allows for direct transthoracic aortic occlusion during MVS [23].

In order to improve visualization of the operative field with a limited skin incision, Carpentier described using video assistance during MVS [24]. Limited depth perception with the 2D videoscope led to the development of a 3D version that can be displayed on a

screen or on a head-mounted display in the operating room [25]. This technique was described in combination with a voice-controlled robotic arm (AESOP 3000, Computer Motion, Inc., CA, USA), that allowed for mitral surgery to be performed by a single surgeon [26].

Carpentier was also the first to perform an entire mitral valve operation using the Da Vinci® Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA, USA) [27], a telemanipulator that allows a human operator to remotely control surgical instruments with a hand-like device on the operative field in real-time. While initial applications of robotic systems were met with great enthusiasm, this technique has failed to gain widespread adoption. In 2006, 1700 robotic cases were performed, representing approximately seven operations per year for each Da Vinci robot in the USA [28]. Some centers are using the Da Vinci for totally endoscopic coronary artery bypass grafting (TECAB) [29] and valve repairs [30], but the vast majority of robotics are used primarily for dissection of the internal mammary artery in CABG. The operative times for robotic surgery are often greater than that for a traditional sternotomy approach and robotic surgery is associated with a significant learning curve. In the future there will likely be new, more facile robotic instruments that have the potential to decrease operative times and consequently improve patient outcomes [31,32].

Minimally invasive MVS

Mitral-valve surgery has been one of the areas of cardiac surgery most widely influenced by minimal access approaches. In the mid 1990s, Cosgrove and Cohn independently described the first minimally invasive MVS (MIMVS) [8,17]. These operations were performed through parasternal and hemisternotomy approaches. As noted previously, the second major milestone occurred in 1996, when Carpentier performed the first video-assisted mitral valve repair through a minithoracotomy [24]. With greater experience in video-assisted surgery, Chitwood described the first video-directed, mitral valve replacement using retrograde cardioplegia and a transthoracic aortic clamp [23]. In 1998, the Leipzig group described MIMVS using a port-access approach and voice-activated robotic assistance [22]. Lastly, in 1998 Carpentier described the first completely robotic mitral valve repair using the Da Vinci Surgical System [27].

Various approaches have been described for MIMVS including: partial sternotomy (using a parasternal or transternal incision, for example), minithoracotomy, video assisted using port-access technology and robotically assisted. Various technological innovations have made such approaches feasible. In addition to the technology developed for video- and robotically-assisted surgery, several innovations in surgical instruments and cannulation techniques were necessary for MIMVS. For example, arterial and venous perfusion cannulae have allowed for the development of percutaneous perfusion techniques that permit maximal exposure in the operating field. Moreover, refinement in transthoracic echocardiography allowed for optimal viewing of cannula placement. With regards to surgical instruments, the Chitwood clamp (Scanlan International, MN, USA) has enabled transthoracic aortic occlusion, so that endoaortic balloon occlusion is not necessary [33]. The most popular approach for MIMVS is through a right mini-thoracotomy, which we utilize at our institution (Columbia University Medical Center), along with percutaneous superior vena cava/inferior vena cava drainage and central aortic cannulation, in order to avoid the potential complications associated with peripheral arterial cannulation [6]. However, regardless of the variety of surgical approaches, the overall objectives of MIMVS have remained constant – to provide a safe and effective approach for MVS with the benefits associated with minimal access surgery.

In the early 1990s, much of the hypothesized benefits of a minimally invasive approach for MVS stemmed from outcomes in other areas of surgery, demonstrating decreased length of stay, decreased surgical trauma, reduced pain, improved patient satisfaction and potentially reduced hospital resource utilization. These advantages, however, have often been tempered by concerns over increased operating room times, decreased surgical exposure and a significant learning curve. In the early experience with MIMVS, weighing these potential advantages and disadvantages proved challenging, as the majority of the literature stemmed from single-institutional case reports or case series. However, over the past 10 years, there has been a growth in outcomes literature on MIMVS that has not only permitted an analysis of the procedure itself, but allowed for comparisons with the traditional sternotomy approach.

As with any clinical trial of a new therapeutic, the first step in establishing MIMVS as a viable option for MVS was demonstrating equivalent safety to the traditional sternotomy approach. No published studies to date have demonstrated a significant difference in mortality rates between MIMVS and sternotomy MVS [34–37]. At our own institution, we have observed similar outcomes with no difference in mortality rates between sternotomy MVS and MIMVS (which were 1.8 and 3.9% at 30 days and 1 year, respectively) [5].

While no studies have demonstrated an increase in mortality with MIMVS, of equal concern in the early experience with MIMVS was the potential for increased morbidity. In particular, neurological events were of concern owing to potential for inadequate deairing given the limited access. In a meta-analysis by Modi *et al.* of six eligible studies, there was no difference in neurological events between sternotomy and MIMVS groups [38]. However, this past year, an analysis of the Society of Thoracic Surgeons (STS) Database demonstrated that stroke was more common among less-invasive MVS patients, with an odds ratio of approximately two as compared with traditional sternotomy [4]. This increased risk of stroke was attributed to potentially inadequate deairing, fibrillating-heart techniques and prolonged CPB and cross-clamp times. Within our institution, we have observed low rates of stroke, with no difference between sternotomy and MIMVS groups, which may be attributed to our preference for central aortic cannulation [5]. While stroke is clearly one of the most serious perioperative complications, investigators have also examined the correlation between MIMVS and various perioperative complications and events such as bleeding and transfusion requirements, atrial fibrillation, septic complications and respiratory failure. The aforementioned STS analysis demonstrated that after risk adjustment, there was a lower probability of postoperative atrial fibrillation, perioperative red blood cell and platelet transfusion and overall major morbidity or mortality [4]. However, learning curves associated with the adoption of minimally invasive techniques cannot be ignored and it is possible that some centers had unfavorable results before reaching their published complication rates similar to those of standard cardiac surgery. While there is variation from one institutional experience to the next, the majority of the comparative safety literature suggests that MIMVS is at least as effective as the traditional sternotomy approach across most perioperative complications.

Thus, given the equivalent safety to sternotomy, for one to adopt a minimally invasive platform there must be some clinical benefits with regard to efficacy. This is especially true given the fact that the majority of outcomes analyses on MIMVS have reported increased CPB times associated with this approach [39]. One of the greatest suggested benefits of a minimally invasive approach is the potential for a decreased time in intensive care and length of stay in hospital. In a recent review by Modi *et al.*, eight of 14 studies reported decreased lengths of stay and in meta-analysis of five studies there was a trend toward decreased hospital stay, although the results did not achieve statistical significance [38]. In our experience, patients undergoing MIMVS have, on average, an approximate 2-day

shorter length of stay when compared with sternotomy patients [5]. The observed reduction in hospital stay for MIMVS is often explained by decreased postoperative pain, which has been observed in several studies [39–41]. In parallel with decreased postoperative pain, studies have also demonstrated that MIMVS is associated with improved patient satisfaction, faster return to normal physical activities and improved overall quality of life [17,23,42–44]. With regard to long-term clinical efficacy, no published studies have demonstrated significant differences in freedom from reoperation between sternotomy and minimally invasive approaches, differences in degree of postoperative mitral regurgitation or difference in long-term survival [36,39,45]. Lastly, although a formal cost-effective analysis of MIMVS has not been published in the past decade, previous studies have shown cost savings of 7, 20 and 34% associated with MIMVS [2,17,23]. Moreover, these cost savings, which are estimated based on the hospital perspective, are likely an underestimate of overall savings since studies have demonstrated that MIMVS is associated with less rehabilitation needs and therefore would be associated with increased future savings compared with cardiac surgery using traditional sternotomy. Both minimally invasive and traditional sternotomy cardiac surgeries are considered standard cardiac surgery as all patients undergo similar inpatient postsurgical cardiac rehabilitation programs. Patients from both groups are referred to subacute or outpatient rehabilitation programs as indicated. The lower cost of rehabilitation associated with minimally invasive techniques is likely to be associated with faster recovery to baseline function for these patients and decreased need for rehabilitation outside of the initial operative admission [13]. With growing national interest in cost–effectiveness analysis as well as the incorporation of costs in secondary end points of clinical trials, the potential for cost savings associated with a surgical approach or technology represents a significant achievement [46].

Over the past decade, increased experience with MIMVS has allowed for large-scale analyses of institution outcomes and national data-sets, which appear to have confirmed much of the initial perceived benefits of MIMVS, while demonstrating equivalent safety and efficacy to the sternotomy approach. One area of concern regarding the current literature is the issue of selection bias. In most published series of MIMVS versus sternotomy MVS, there are significant differences in baseline risk between groups, with MIMVS patients tending to be an overall healthier group. Although authors control for such baseline differences using techniques such as a propensity analysis, these statistical methods cannot completely overcome the issue of selection bias [47]. Moreover, MIMVS remains a challenge in patients with specific risk factors such as obesity, previous cardiothoracic surgery and pulmonary disease. Second, there is a significant learning curve associated with minimally invasive approaches and the benefits of MIMVS are likely to be realized to a greater extent in relatively high-volume centers [48]. Despite these concerns, the current literature demonstrates that MIMVS is a viable option for mitral-valve repair or replacement that will continue to grow with further experience and research in this area. Given the presumable lack of equipoise among minimally invasive cardiac surgeons, it is unlikely that a randomized clinical trial comparing the outcomes of minimally invasive to sternotomy surgical approaches will be carried out in the future. In addition, as trials emerge on the use of percutenous mitral valve repair technology and secondary end points involve such issues as quality of life, MIMVS may represent the standard on which to compare such outcome measures [49].

Minimally invasive coronary revascularization

For nearly four decades, traditional CABG, complete with full sternotomy, CPB and cardioplegic arrest, has been the gold standard for coronary revascularization in multivessel coronary artery disease (CAD) [50]. Although traditional CABG may prolong life and reduce symptoms for select patients with CAD, these benefits are tempered by risks

including mortality, cerebrovascular accident, need for transfusion, atrial fibrillation and neurocognitive dysfunction [51–54]. In an effort to improve CABG outcomes and to decrease patient recovery time, minimally invasive approaches to coronary revascularization have been developed. Evolving techniques aimed at preventing complications and attempting a safer, less intrusive version of CABG are subsequently described.

Minimally invasive direct coronary artery bypass

In 1995, the minimally invasive direct coronary artery bypass (MIDCAB) procedure was introduced into the surgical literature. The first MIDCABs were usually performed through anterolateral thoracotomies and without CPB, also referred to as off-pump coronary artery bypass (OPCAB) [55]. OPCAB can be applied to MIDCAB or traditional full sternotomy procedures. Although the technique of CPB was developed to provide the surgeon with a motionless and bloodless surgical field for precise coronary anastomoses, its inflammatory effects and spectrum of complications associated with hemodilution have always been a concern. The most significant effort aimed at reducing systemic inflammation and complications from hemodilution associated with CPB has been the development of the OPCAB [56].

The International Society for Minimally Invasive Cardiothoracic Surgery (ISMICS) recently published several recommendations regarding OPCAB versus traditional on-pump CABG based on meta-analysis of available data. These recommendations state that the employment of off-pump bypass is recommended to reduce perioperative morbidity, reduce neurocognitive dysfunction and to reduce hospital length of stay. It is also recommended that an off-pump procedure should be considered especially in high-risk patients, for example, patients with severe aortic calcification of the ascending aorta, liver cirrhosis, renal insufficiency or other systemic processes that may be exacerbated by CPB, in order to reduce morbidity and mortality [57].

The benefits of performing coronary artery bypass off-pump remain controversial. A study commissioned by the American Heart Association (AHA) concluded that the outcome of either on-pump MIDCAB or off-pump MIDCAB depends more on factors such as the experience and quality of the particular surgeon and institution, rather than the specific on- or off-pump technique used [58]. Despite controversy, it is clear that a patient-centered approach is necessary for selection of the appropriate on- or off-pump technique for surgical revascularization [56]. Introduction of peripheral cannulation techniques and endoaortic balloon occlusion has permitted MIDCAB to be performed either on- or off-pump, allowing for the selection of CPB approach to be guided by each patient’s unique preoperative characteristics and circumstances rather than the surgical incision [59–62].

Minimally invasive direct coronary artery bypass performed via a left lateral thoracotomy, with a range of incision sizes, is now often employed to achieve a multivessel revascularization [63]. The use of a 5–6 cm left lateral thoracotomy MIDCAB for left anterior descending coronary artery (LAD) harvesting and myocardial revascularization, with a mean 2.9 ± 1.08 mm grafts performed via this incision, has been reported [64]. It has also been shown that MIDCAB can be performed safely when utilized for reoperation [59–62].

Avoidance of traditional full sternotomy through the use of smaller incision types, such as thoracotomy, allows for significant reduction in chest trauma. This reduction in chest trauma has the potential to result in decreased postoperative length of stay, improved cosmetic results and faster recovery of baseline physical activity for the patient, among other benefits. Studies comparing MIDCAB versus traditional CABG using full sternotomy have suggested such favorable results for the MIDCAB patient, including shorter hospital length of stay,

earlier return to baseline physical activity and reduced transfusion requirements [65–67]. Long-term graft patency using MIDCAB has been preliminarily shown to be excellent [55].

Robotically assisted CABG

There has been growing research regarding the safety and feasibility of coronary revascularization procedures accomplished via robotic assistance since the introduction of surgical robotics in the 1990s. These reports include robotic left internal mammary artery (LIMA) harvest followed by an on-pump MIDCAB [68], off-pump MIDCAB [32], on-pump TECAB or off-pump TECAB [69,70]. A recent prospective, multicenter trial of robotically assisted TECAB demonstrated this procedure to be safe, with angiographic patency, morbidity and mortality equivalent to traditional CABG procedures [29].

Although most on- and off-pump TECABs involve only a LIMA–LAD graft, recent reports have described a series of multivessel revascularization procedures [70]. These reports have demonstrated some of the desired benefits of any minimally invasive surgery, including reduced hospital length of stay, reduced need for transfusions and a faster return to the patient's original physical function [63].

The Da Vinci Si HD Surgical System (Intuitive Surgical, Inc.) allows the surgeon to gain access to the heart via four half-inch incisions made in the intercostal space. These incisions are subsequently used for the introduction of robotic instruments and a videoscope. Seated at a robotic console, the surgeon can see into the patient's chest via high-definition, 3D optics. The console is connected electronically to the bedside robot, allowing the surgeon to manipulate the robotic instruments and the scope as if they were hand-held surgical instruments. A skilled operating team is necessary for the rapid exchange of the robotic surgical instruments; exchange is needed for each of the different surgical instruments, including forceps, needle driver, scissors and electrocautery. Using the Da Vinci System, the LIMA can be harvested from the back of the sternum, the pericardium opened, the segment of the LAD chosen for grafting stabilized and the anastomosis between the LIMA and LAD performed on- or off-pump. There have been successful outcomes reports of robotic CABG; however, owing to a well-documented learning curve, increased expense and the requirement of highly trained operating room staff for the exchange of robotic surgical instruments, the routine use of surgical robotics for CABG surgery has had difficulty in gaining widespread use [56].

There have been several attempts by institutions to address the difficult learning curve of TECAB. Central concepts used include the initial selection of patients with uncomplicated pathology, the use of a consistent operating room team, and following a modular approach to the learning curve by mastering robotic techniques one-by-one in order of increasing difficulty, that is, first mastering the technique of internal mammary artery harvesting, then pericardial opening, and finally mastering the technique of anastomotic suturing [71–73].

The main challenge associated with off- or on-pump TECAB is the difficulty of performing the anastomotic suturing. Although the use of a surgical robot with the addition of an automated anastomotic device has been used, this automated anastomotic technique is still rarely performed. In 2006, the US FDA approved the automated C-Port xA® Distal Anastomosis System (Cardica, Inc., CA, USA), which uses compressed carbon dioxide to activate a mechanism that fires multiple small staples at the same time that it incises the target artery in order to anastomose the end of the bypass graft to the target artery. The cost of this device is considerable compared with traditional hand-sewn anastomotic techniques.

There are current debates regarding the safety and efficacy of this automated anastomotic technique. A recent retrospective analysis comparing follow-up graft patency between the

automated-device anastomosis and the hand-sewn anastomosis showed equivalency via angiography at 2 years [63].

With further refinement of robotic design and surgeons' skill, robotic-assisted coronary revascularization will continue to be an option for patients with CAD in the future; however, widespread adaptation of this technique continues to face challenges.

Minimally invasive aortic surgery

Minimally invasive aortic valve replacement

Since Cosgrove and Sabik first described minimally invasive aortic valve surgery in 1996 [74], there has been a significant expansion in popularity, experience and techniques associated with minimally invasive aortic valve replacement (MIAVR). Various techniques for obtaining appropriate exposure have been developed and put into practice. With the greater use of MIAVR, there is a growing understanding of the outcomes following MIAVR compared with traditional aortic valve replacement (AVR) with median sternotomy, including survival, perioperative times and complications.

In 1996, Cosgrove and Sabik described approaching the aortic valve through a right parasternal incision with rib cartilage resection. Since then, several techniques for exposing the aortic valve have been developed, including variations of a hemi- or mini-sternotomy and the right anterior thoracotomy [75]. Currently, the most common approach used is the mini-sternotomy, using a J, inverted T or other similar incision. This approach provides several advantages over other incisions [11,75,76]. It provides adequate exposure while minimizing postoperative pain and minimally affecting thoracic cage stability [41]. If necessary, it can be extended to provide additional exposure. In addition, unlike the parasternal approach, the internal mammary artery need not be ligated.

Several cannulation methods have also been used, including completely peripheral (femoral–femoral), completely central (atrial–aortic) and variations of these (e.g., atrial–femoral and atrial–axillary) [75]. Central cannulation is generally preferred, given the avoidance of peripheral vascular injury (especially in those with peripheral vascular disease), higher CPB flow rates that are possible with larger central cannula sizes and improved cerebral perfusion over that of peripheral cannulation. Central cannulation can be achieved using a mini-sternotomy [77], but thoracotomy and parasternal approaches typically require femoral cannulation [75], although femoral/aortic cannulation is feasible [78].

Most studies have demonstrated no difference in morbidity or mortality between MIAVR and conventional AVR (CAVR) [11,77–82]. Although early studies associated MIAVR with longer CPB and aortic cross-clamp times, operative times have improved and are comparable between groups in more recent studies. This suggests that there is a learning curve, but also that minimally invasive approaches do not require longer operative times in experienced hands. Most importantly, even in studies showing longer operative times for MIAVR, there remained no evidence of a difference in major outcomes, further supporting MIAVR as a safe and feasible alternative to CAVR.

In fact, MIAVR is more often associated with improvements in postoperative outcomes. Decreased length of stay in intensive care, days of ventilator support and hospital length of stay have been demonstrated [2,17,77,82,83]. This coincides with an earlier return to work and return to normal activity in MIAVR patients as well [17]. Of interest, in-hospital postoperative pain levels have been noted to be similar in MIAVR and CAVR patients, reflecting a relatively low overall pain level for traditional median sternotomy [17,41].

However, postdischarge pain medication use has been shown to be lower for MIAVR patients [17]. Studies have demonstrated blood transfusion rates that are similar [41,81,84] or lower for MIAVR patients [12,77,83].

Transcatheter and transapical aortic valve implantation (TAVI) represent potential future treatment options for patients with aortic valve pathology. While both the CoreValve® (Medtronic, Inc., MN, USA) and Edwards Sapien valves (Edwards Lifesciences, CA, USA) have received CE Mark approval for use in Europe, the technology is still under investigation in the USA. This technique is further addressed later in this article.

Thoracic endovascular aortic repair (TEVAR) is another evolving minimally invasive aortic therapy. Dake *et al.* demonstrated the feasibility of TEVAR in the early 1990s [85]. Since then, there has been a growing comfort and a growing popularity for this intervention, especially to treat descending thoracic aorta pathology. A recent meta-analysis of TEVAR therapy in the descending thoracic aorta demonstrated lower 30-day mortality and paraplegia when compared with traditional open repair [86]. Rates of stroke, myocardial infarction, aortic reintervention and mortality beyond 1 year were all similar. The use of TEVAR in ascending aorta repairs is also advancing [87–90], although repairs involving the aortic arch require branched grafts and greater technical skill and expertise to ensure proper perfusion of the head vessels [91–93].

Minimally invasive atrial fibrillation ablation

Atrial fibrillation is the most common cardiac arrhythmia and carries a risk of increased morbidity through its untoward effects, including thromboembolic stroke [94], anticoagulation-related hemorrhage [95] and tachycardia-induced cardiomyopathy [96]. The presence of atrial fibrillation is associated with an increase in mortality in the general population [97]. Atrial fibrillation affects more than 2.2 million Americans with an annual cost in excess of 6.6 billion dollars [98].

The traditional Cox maze III consists of a series of complex biatrial incisions. The classic Cox maze III carries with it a risk of increased bleeding [99], operative time [100] and requires CPB. The newer generation Cox maze IV uses a variety of energy modalities to scar the myocardium and create a conduction block to stop the re-entrant circuits that cause atrial fibrillation [101]. In the Cox maze IV the lesions made may be single or multiple, left atrial or biatrial, endocardial or epicardial and performed on a beating or arrested heart.

A variety of methods have been used to describe a minimal access approach. These include bilateral or unilateral mini-thoracotomies, a total endoscopic approach, video-assisted thoracoscopic approach and a robotic maze. The lesion sets performed for a Cox maze IV can also be performed through a minimally invasive approach. Left atrial appendage exclusion/excision is commonly used alongside maze lesion sets and remains an important aspect of the surgical approach to atrial fibrillation chiefly owing to the most significant thromboembolic source from atrial fibrillation being removed. This exclusion or excision can easily be performed using the minimally invasive approach [102].

Studies have demonstrated that minimally invasive cardiac surgery is associated with shorter mechanical ventilation [103]. Furthermore, freedom from atrial fibrillation is similar between the minimally invasive and standard approaches, as is postoperative morbidity [102,104–110].

Energy modalities used for the Cox maze IV include radiofrequency, cryoablation, high-intensity focused ultrasound, microwave and laser, although the latter two are now obsolete. Radiofrequency works by using alternating current, to emit electromagnetic energy which

heats tissue adjacent to the applied probe [111]. Deeper layers of tissue are heated by conduction. Cryoablation uses rapid cooling of the probe to freeze the tissue leading to cell death and a homogenous, full thickness lesion [111]. High-intensity focused ultrasound works by using ultrasound waves to harmonically oscillate water molecules, generate thermal energy and directly heat the tissue in the acoustic focal volume [111]. Microwave and laser techniques have since fallen out of favor. Microwave energy, in particular, has been shown to have decreased clinical efficacy [112] and is unable to reliably produce transmural lesions on a beating heart [113–115].

The future direction of the minimally invasive Cox maze IV procedure is to perform a complete biatrial lesion set epicardially on a beating heart so as to avoid CPB. At the same time, the clinical efficacy of the surgical procedure must be preserved to make it a viable alternative to catheter ablation. Some institutions are performing a hybrid procedure with a minimally invasive Cox maze IV performed in the operating room and completion of the lesion set with catheter ablation performed at the same time or at a later date [116]. In summary, the minimally invasive Cox maze IV is a procedure in evolution with a variety of incisions, lesion sets and energy modalities in use. Further study of the safety, efficacy and cost of these different approaches will guide their continued development.

Hybrid & catheter-based therapies

Hybrid coronary revascularization

Hybrid coronary revascularization is a relatively new innovation that offers patients an alternative to traditional coronary artery bypass by employing a minimally invasive incision for LIMA–LAD bypass with stenting of other occluded coronaries during the same procedure. It should not be confused with the MIDCAB, which offers a minimally invasive incision, but no stenting [117].

Hybrid revascularization is the next logical step in the evolution of minimal access treatment of multivessel CAD. It is well established that utilizing a LIMA graft to the LAD for patients with CAD is more effective at decreasing symptoms and increasing patient survival than any other CAD therapy. Graft patency often lasts 10–15 years or more [117–121].

Hybrid revascularization allows for the benefit of both the surgical LIMA–LAD bypass graft and a minimally invasive incision, while percutaneous coronary intervention (PCI) is used for the treatment of non-LAD vessels. This combination of surgical LIMA–LAD and PCI affords the patient the best available therapy for any given set of cardiovascular lesions with minimal access and reduced heart manipulation [117]. Early hybrid revascularization techniques completed PCI and coronary bypass grafting in two separate procedures with the bypass grafting being performed on- or off-pump on a patient-to-patient basis; however, hybrid revascularization is now performed simultaneously, with the PCI and coronary artery bypass grafting occurring during the same procedure and off-pump.

Hybrid revascularization is currently used almost exclusively for patients who are high risk, likely owing to MIDCAB or off-pump full sternotomy options being available for complete multivessel revascularization, with low morbidity and mortality in lower-risk patient groups [122]. Widespread adoption of hybrid revascularization has been restricted largely by the elevated number of repeat PCIs owing to target vessel failure. These reinterventions are not customary in MIDCAB or off-pump CABG groups; however, the introduction of drugeluting stents seems to have reduced the need for repeat PCI in hybrid revascularization patients; long-term follow-up is still required [122].

In addition, there are debates concerning the conflicting perioperative management for simultaneous surgical revascularization and PCI [122], high costs associated with the procedure and drug-eluting stents and other logistical concerns. Closer cooperative collaboration between cardiac surgeons and interventional cardiologists is necessary to obtain optimal patient outcomes in the future [117]. As with many surgical techniques, patients with particular characteristics are better candidates for certain techniques. A patient-based approach for selection to hybrid revascularization must be used.

Other hybrid revascularization procedures in use include minimally invasive valve surgery combined with PCI to coronary lesions, the latter of which transforms a complex operation of valve surgery with concomitant coronary artery bypass grafting to a less invasive, minimal access valve surgery [117].

Transcatheter AVR

Replacement of the aortic valve is the only effective treatment for symptomatic aortic stenosis (AS) that alleviates symptoms and improves survival. Surgical AVR, whether utilizing traditional or minimally invasive techniques, has a low operative mortality in an otherwise healthy individual [123]; however, the mortality rate associated with surgical AVR increases considerably with the addition of patient comorbidities, including left ventricular dysfunction and chronic conditions possibly exacerbated by cardiac surgery. Patients of increased age are at a much higher risk of mortality, presumably owing to the presence of multiple coexisting conditions that typically present in persons of advanced age. Transcatheter AVR was developed with the purpose of having a therapeutic solution to offer patients with severe symptomatic AS who are not candidates for surgical AVR [124].

Initial attempts at transcatheter AVR were complicated by vascular access difficulties and lack of suitable equipment. The initial technique employed for transcatheter AVR was the ante-grade approach. Using this technique, the catheter is advanced via the femoral vein, threaded trans-septally and passed through the mitral valve *en route* to the aortic valve [125]. Valve placement using this approach is simple, because the device crosses the smooth portion of the aortic valve; however, the overall technique is challenging owing to complicated navigation of the catheter and prosthetic valve across the mitral and aortic valves, the need for trans-septal puncture and the risk for mitral-valve injury. These issues prompted technical improvements in the delivery system and incited implementation of the transfemoral (retrograde) approach [124]. In the transfemoral approach, the catheter is advanced to the stenotic aortic valve via the femoral artery. Valve deployment is accomplished by transcatheter introduction of a balloon- or self-expandable valve [11,126]. Rapid ventricular pacing (roughly 180–200 beats per min) is used to reduce cardiac motion during critical deployment of the valve. The transfemoral approach is faster and less technically difficult than the antegrade approach, although it does still carry the risk of injury to the aortofemoral vessels [125].

The transapical approach is the most recently developed technique for transcatheter AVR. The transapical AVR requires the use of a hybrid operative suite. It employs a small left lateral thoracotomy and subsequently uses direct puncture and sheath insertion directly into the apex of the left ventricle. A guide wire is used to cross the aortic valve and the rest of the procedure follows the same steps of valve deployment as the transfemoral approach [125].

Benefits of transapical AVR involve more direct access to the stenotic valve and the avoidance of potential complications owing to peripheral access. Although beneficial, the transapical approach does require the use of general anesthesia and it also carries the risk of complications related to the puncture of the left ventricle [125].

The antegrade approach to transcatheter AVR is no longer employed. Transfemoral and transapical delivery routes can be selected based on certain patient characteristics, such as the quality of vascular access and the type of aortic valve prosthesis selected for the procedure [124].

The number of transcatheter AVRs has grown significantly in just a few years and initial published data have been promising [127–129]. A multi-center, randomized trial, Placement of Aortic Transcatheter Valve (PARTNER), has completed enrollment. The trial includes patients with severe symptomatic AS who are poor or unsuitable surgical candidates. Its two treatment arms include an arm comparing outcomes of optimal medical management (including balloon valvuloplasty) with transfemoral AVR in patients considered 'inoperable' and an arm comparing outcomes of traditional surgical AVR with transfemoral AVR and traditional surgical AVR with transapical AVR in high-risk patients [124,126].

Data from the first arm comparing optimal medical management to transfemoral AVR in inoperable patients have recently been reported in 2010, with a primary end point of rate of death from any cause. The results of this arm demonstrated significantly reduced rates of all-cause mortality, reduction in the composite end point of death from any cause or repeat hospitalization and decreased incidence of cardiac symptoms. Conversely, there was a significant increase in the incidence of cerebrovascular accidents and other major vascular events associated with the transfemoral AVR approach, whose reasons have yet to be fully elucidated [126].

The final results of this trial will play a major part in determining the role of transcatheter AVR in the future. The results of the second arm are due to be released in early 2011. After these results are released, a continuation of the PARTNER trial will likely be underway, presumably with the purpose of studying outcomes in a lower-risk patient population.

Percutaneous indirect mitral annuloplasty

The percutaneous treatment of mitral stenosis is well established [130]; however, the percutaneous management of mitral regurgitation (MR) is still in early development and is a potential area of clinical benefit for both degenerative and functional MR patients.

The MitraClip® (Abbott Laboratories, Abbott Park, IL, USA) procedure is a percutaneous version of a surgical technique used in mitral valve repair, the Alfieri stitch. This surgical treatment involves suturing the midpoint of the two mitral valve leaflets together, which reduces regurgitant mitral valve flow [131].

The Evalve MitraClip uses clips placed percutaneously to approximate the surgical Alfieri stitch repair. Transesophageal echocardiographic guidance is used for the procedure. Trans-septal puncture is performed and the delivery system is delivered into the left atrium using the femoral vein. The device is guided toward the central part of the mitral valve. The arms of a clip are extended and used to grab the central portion of each of the two mitral valve leaflets. The clip arms are then closed to retain both leaflets within the clip. This approximates the Alfieri stitch described previously [131].

The Evalve technology can be used in some valves with degenerative disease, such as mitral valve prolapse or flail leaflet, provided certain anatomic requirements are met in order to ensure the ability of the clip to capture the two mitral valve leaflets. These anatomic requirements include adequate coaptation of the leaflets and a central MR jet origin along the line of leaflet coaptation. The MitraClip has also been used in patients with functional MR, where annular dilation is limited enough to allow sufficient leaflet coaptation for the clip to capture [131].

The Endovascular Valve Edge-to-Edge Repair Study (EVEREST II) trial was completed in 2010. This is the first randomized, multicenter trial of any percutaneous mitral valve therapy. Patients were randomized 2:1 (two MitraClip to one surgical mitral valve repair or replacement). Overall, 30-day safety was superior for the MitraClip and 1-year efficacy was reported as noninferior compared with surgical approach [132]. However, the general consensus is that percutaneous mitral-valve repair is not as effective in preventing long-term MR as surgery and that the future role of percutaneous mitral-valve repair is still to be decided.

As with many surgical techniques, patients with particular risk factors are better candidates for certain techniques. A patient-based approach for selection to MitraClip implantation should be implemented [132].

Future perspective

Minimally invasive cardiac surgery continues to evolve and expand with growths in technology and surgeon experience. Now that a significant amount of data has emerged on the safety and efficacy of MICS across a range of surgical operations, there is evidence to support the widespread adaptation of such techniques. In the future, there will likely be a greater request for MICS approaches by patients seeking cardiac surgical options with reduced surgical trauma that allow for a faster return to normal activities and improved quality of life. In addition, MICS itself will continue to evolve in the future through growing use of percutaneous technology, hybrid operating rooms and ongoing collaborations with interventional cardiologists.

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Executive summary

- Minimally invasive cardiac surgery (MICS) represents a safe and effective approach for a variety of cardiac surgical diseases.
- MICS does not appear to result in differences in short- or long-term survival compared with the sternotomy approach.
- MICS may be associated with lower rates of perioperative complications in certain instances.
- MICS appears to result in decreased length of hospitalization, improved pain control and faster recovery to normal activities.
- Continued research is necessary to assess long-term outcomes of minimally invasive approaches.
- With regard to outcome measures such as quality of life, minimally invasive approaches may be the standard on which to compare evolving percutaneous technologies.