Turkish Journal of Thoracic and Cardiovascular Surgery 2024;32(4):355-366

INVITED REVIEW / DAVETLİ DERLEME

Endoscopic micro-invasive cardiac surgery: State-of-the-art

Endoskopik mikroinvaziv kalp cerrahisi: Teknolojinin geldiği son nokta

Farhad Bakhtiary, Saad Salamate, Kaveh Eghbalzadeh, Ali El-Sayed Ahmad

Department of Cardiac Surgery, University Hospital Bonn, Bonn, Germany

ABSTRACT

The advancement of micro-invasive cardiac surgery techniques has introduced a viable alternative to conventional full-sternotomy operations. These approaches are designed to reduce tissue trauma, shorten recovery time, and meet the increasing demand for less invasive treatment options. In this review, we discuss current progresses in endoscopic micro-invasive cardiac surgery, which utilizes refined tools and advanced imaging technologies to perform complex heart procedures, including valve surgery, coronary artery bypass grafting, and congenital defect corrections. By reviewing our experience with these techniques, we provide practical insights for surgeons interested in adopting micro-invasive cardiac surgery. The highlighted innovations in planning and execution of micro-invasive cardiac surgery reflect the growing trend toward safer and more efficient cardiac surgeries.

Keywords: Endoscopic cardiac surgery, minimally invasive cardiac surgery, state of the art.

ÖZ

Mikroinvaziv kalp cerrahisi tekniklerindeki ilerlemeler, geleneksel tam sternotomi ameliyatlarına uygulanabilir bir alternatif sunmuştur. Bu yaklaşımlar, doku travmasını azaltmak, iyileşme süresini kısaltmak ve daha az invaziv tedavi seçeneklerine yönelik artan talebi karşılamak amacıyla geliştirilmiştir. Bu derlemede, kapak cerrahisi, koroner arter baypas greftleme ve konjenital defektlerin düzeltilmesi gibi kompleks kalp ameliyatlarını gerçekleştirmek için hassas araçlar ve ileri görüntüleme teknolojilerin kullanıldığı endoskopik mikroinvaziv kalp cerrahisindeki mevcut gelişmeler irdelendi. Bu teknikler ile olan deneyimimizi gözden geçirerek, mikroinvaziv kalp cerrahisini benimsemek isteyen cerrahlar için pratik bilgiler sunuldu. Mikroinvaziv kalp cerrahisinin planlanması ve uygulanması ile ilgili vurgulanan yenilikler, daha güvenli ve daha verimli kalp operasyonlarına yönelik artan eğilimi yansıtmaktadır.

Anahtar sözcükler: Endoskopik kalp cerrahisi, minimal invaziv kalp cerrahisi, teknoloji harikası.

Pioneered in the early 1990s, minimally invasive techniques for cardiac surgery have gained considerable popularity in the last two decades, driven by an industry-wide push toward minimal invasiveness, as well as the concurrent advances in the increasingly competing field of interventional cardiology. The drive toward these techniques presented several new challenges which, in turn, stimulated the development of new approaches and technological progress with a revolutionary potential to mark a new era in the field of cardiac surgery.[1-4] Combining advancements in peripheral vascular cannulation, instrumentations and visualization technologies, minimally invasive techniques in cardiac surgery currently constitute what can be called "micro-invasive cardiac surgery" (μICS), and are now safely employed in a wide variety of conditions and surgery, single or multiple valve surgery, aortic root and ascending aorta surgery cardiac tumors surgery, maze procedure and LAA closure, congenital malformation and defects in both adults and pediatric patients, as well as interventions in patients with rare anatomical variations.[1,2,5-7]

DEFINITIONS AND RATIONAL

There is currently no clear definition of minimally invasive cardiac surgery (MICS). While the Society of Thoracic Surgeons (STS) defines MICS as "any

Corresponding author: A. El-Sayed Ahmad, MD PhD. E-mail: ali.assayed@gmail.com

Doi: 10.5606/tgkdc.dergisi.2024.56934

Received: August 13, 2024
Accepted: August 15, 2024
Published online: October 30, 2024

Cite this article as: Bakhtiary F, Salamate S, Eghbalzadeh K, El-Sayed Ahmad A. Endoscopic micro-invasive cardiac surgery: State-of-the-art. Turk Gogus Kalp Dama 2024;32(4):355-366. doi: 10.5606/tgkdc.dergisi.2024.56934.

procedure not performed with full sternotomy and cardiopulmonary bypass (CPB) support", the American Heart Association (AHA) defined it in 2008 as "a small chest wall incision that does not include the conventional full sternotomy".[8] Chitwood et al.[1] proposed, however, that the definition of MICS should not be limited to a specific surgical procedure, but rather be defined as a "philosophy" toward cardiac procedures, entailing specific strategies to different operations. We agree with that philosophical definition of MICS and view it as a set of continually changing and adapting techniques and approaches to cardiac surgery, designed to evermore reduce the invasiveness of cardiac surgical procedures compared to what is contemporarily considered as conventional. Thus, MICS, and more specifically μICS, are constantly evolving with the advent of each new technique or technological advancement which adds to the arsenal of the cardiac surgeon.

This definition is not limited to a specific surgical access used in a procedure, but rather encompasses a multitude of standards of care at different levels of the surgery and in-hospital care designed with the goal of reducing the operative morbidity associated with cardiac surgery, as well as promoting an early mobilization, rehabilitation, and re-assimilation into society. They include the operative access and technique, the instruments used, the technological advancements enabling this micro-invasiveness, as well as standards of postoperative care. These standards are applied in a wide spectrum of cardiac surgeries, include coronary revascularization, valve surgery, and other cardiac operations.

First described in 1994, minimally invasive direct coronary artery bypass (MIDCAB) on a beating heart (off-pump) has been shown to be a safe and feasible approach for select patients, offering a short intensive care unit (ICU) stay and lower blood transfusion requirements with good postoperative outcomes and low mortality.[10] Minimally invasive approaches to valve surgeries were also introduced into the medical literature in the early 1990s; they are safely applied today in an extensive spectrum of valve-related operations via video-assisted access or totally endoscopically through a mini-thoracotomy, including single valve surgery such as aortic or mitral valve surgery,[3,4] as well as more complex operations along the lines of redo valve surgeries and valve surgery with concomitant complex procedures.[11,12] These approaches to valve surgeries have been consistently shown to be associated with several advantages over the traditional sternotomy such as, amongst others, similar surgical success and postoperative mortality rates, shortened hospital and ICU stays, decreased blood product requirements, better cosmesis, and postoperative respiratory and pain parameters.[2,4,11]

In addition to the inherent cosmetic advantages of μICS, the potential reduction in morbidity as well the shorter length of stay (LOS) both in the ICU and in-hospital complements a Cardiac Enhanced Recovery After Surgery (ERAS), promoting a reduction in perioperative physical and psychological stress to the patient and early optimal recovery.[13] Taking advantage of the recent boom in technological advancements, computational power, and computer software development, the aim of μICS remains in providing the patients with excellence; that of both safety and outcomes, compared to the traditional invasive approaches.

OPERATIVE PLANNING

Surgical access

With regards to the surgical access, our preferred approach to micro-invasive cardiac surgery is a right anterior mini-thoracotomy (RAMT) at the level of the third intercostal space (ICS) for aortic valve, aortic root surgery and for multiple valve surgery and the level of the fourth ICS for single mitral or tricuspid valve surgery with the possibility of concomitant maze procedure and/or LAA closure, as well as cardiac tumor surgery. For MIDCAB procedures, our standard surgical access is a left anterior mini-thoracotomy (LAMT) at the level of the fourth ICS. A RAMT can also be employed for MIDCAB involving the right coronary system.[14,15] The exact approach used, namely the location of the mini-thoracotomy, naturally differs from one patient to another due to inherent anatomical variations or anomalies.[6,16] A careful preoperative planning and patient assessment based on the preoperative computed tomography (CT) is, thus, mandatory for all patients selected to undergo a μICS, ensuring an optimal exposure of the surgical field on an individual basis.

Preoperative computed tomography

Computed tomography is the mainstay of preoperative planning. A CT scan of the chest as well as CT angiography of the aorta and arterial system can help to identify those inter-patient variations, particularly with regards to the position of the aorta in relation to the sternum and chest wall, the distance between skin and the ascending aorta, its angle in relation to the midline, a laterally displaced heart, and the distance between the sternum and the right ventricle. This information is crucial in deciding where the operative access should be performed. The surgeon can also obtain valuable information about other conditions that should be taken into consideration prior to the operation, such as chest wall deformities, emphysematous lungs, severe intra-thoracic adhesions and central and/or peripheral arterial calcifications, as well as severe valvular annuli calcifications.[2]

3MENSIO SOFTWARE

The increasingly small incisions employed in µICS present another challenge in endoscopic valve replacement surgery: sometimes-impractical intraoperative valvular sizing. With the help of recent advancements in computer software, CT can also be used in combination with specialized programs in a tomography-based valve sizing and prosthesis simulation, which is already a standard approach in the field of interventional cardiology for transcatheter aortic valve replacements.[17] Developed in the Netherlands, 3mensio (3mensio Medical Imaging B.V., Utrecht, Netherlands) offers software for preoperative sizing and planning enabling the simulation of a digital phantom and aortic valve prosthesis using company-given details of the prosthesis, which is, then, superimposed on the aortic annulus using the CT images avoiding potential prosthesis-patient mismatch (Figure 1).[18] This software also enables the precise measurement of the anterior mitral leaflet, mitral valve annulus and its distance from the circumflex coronary branch, which helps the surgeon to safely plan the mitral valve surgery. The 3mensio additionally gives detailed information about the anatomy, size, and the pattern of calcification of the abdominal aorta, iliac, and femoral arteries for a safe cannulation for CPB at the groin for retrograde perfusion.

MIXED-REALITY

With the advent of virtual reality, mixed and augmented reality, three-dimensional (3D) reconstructions of CT images can now be visualized intraoperatively, projected as a hologram on the operating table in real space, manipulated and interacted with in a sterile way by the surgeon (Figure 2). This holographic visualization of the patient's imaging data can be achieved through the CarnaLife Holo System (MedApp, Krakow, Poland) and an augmented reality headset (Microsoft HoloLens 2, USA). Using hand gestures in a sterile fashion, the surgeon can manipulate and customize the hologram in real time and space, plan the course of the surgery, including the peripheral cannulation for CPB, the surgical access, prosthetic valve size and type.[18] The hologram can also be adjusted during the operation according to the surgeon's preferences and the present surgical step.

Transesophageal echocardiography with 3D reconstruction

In cases of mitral valve surgery, transesophageal echocardiography with 3D reconstruction offers

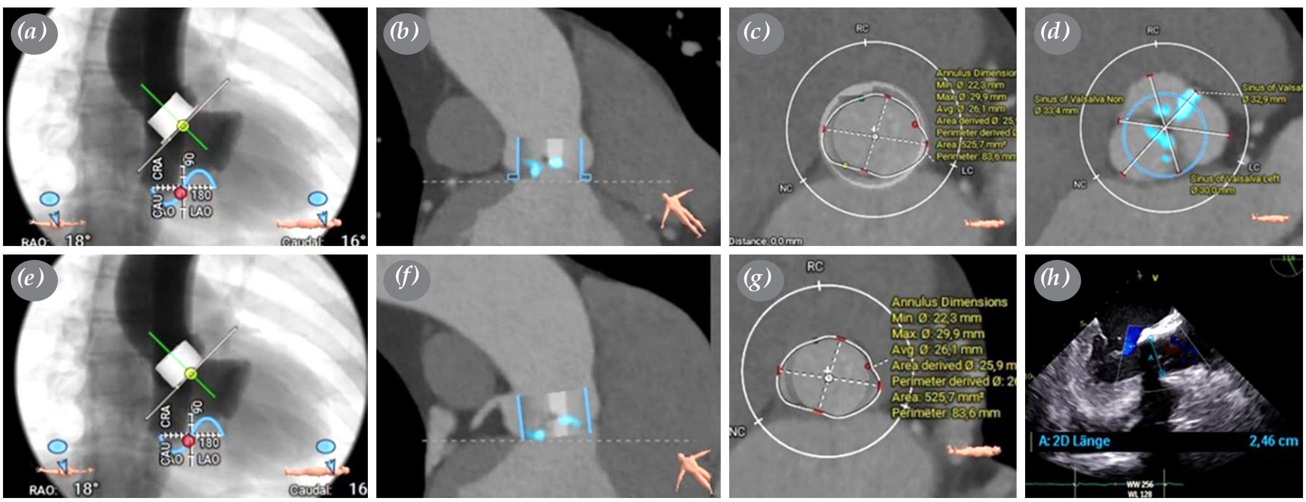

Figure 1. Computed tomography-based simulation of a 25-mm Inspiris prosthesis (Edwards Lifesciences, CA, USA) inside an aortic annulus with effective diameter of 25.9 mm using 3mensio, before endoscopic aortic valve replacement. **(a-d)** Simulation with sewing cuff (+7 mm). **(e-g)** Simulation without cuff (–7 mm). **(h)** Intraoperative echocardiography measurement. This patient received a 25-mm Inspiris prosthesis during endoscopic aortic valve replacement.

Figur 2. The CarnaLife Holo System in use intraoperatively. **(a)** using Microsoft's augmented reality headset Hololens 2, the surgeon can see in real space the 3D reconstruction of CT images in real space as a hologram, which can be manipulated with hand gestures without instruments and in a sterile way. **(b)** The hologram as visible from the point of view of the surgeon.

crucial information about the exact pathology of the mitral valve, as well as the size of the anterior mitral leaflet, thereby allowing the surgeon to choose preoperatively the right ring for the underlying pathology of the mitral valve.

Cannulation for cardiopulmonary bypass

Micro-invasive cardiac surgery, particularly valve surgeries, often requires cardiac arrest and extracorporeal circulation (ECC). While a central access for CPB is traditionally employed in surgery via sternotomy, peripheral cannulation of the common femoral vessels to achieve a retrograde ECC can be used in µICS. There has been concerns, however, about the potentially increased risk of cerebrovascular complications associated with this technique.[19] As aforementioned, the crucial preoperative CT imaging can help, however, to identify a difficult femoral cannulation, such as extensive femoral or iliac artery calcification, kinking, or stenoses, which may theoretically lead to retrograde dissection and/or retrograde embolism. Imaging can additionally enable a precise measure of the artery's size and shape, thereby aiding in the choice of the most suitable size of arterial cannula. In cases where both femoral arteries cannot be used for cannulation, the right axillary artery offers a safe and effective alternative for establishing CPB, with an added benefit of providing an antegrade circulatory perfusion as well as an antegrade cerebral perfusion, if needed.[20,21]

Femoral cannulation can be achieved in a minimally invasive manner percutaneously, in contrast to the traditional open surgical approach, where the femoral artery is cannulated under direct vision. Under intraoperative ultrasonographic control, the artery is accessed using the Seldinger technique and can be later decannulated and closed using a vascular closure device such as the MANTA device (Teleflex, Wayne, PA, USA). The MANTA device is collagen-plug-based solution dedicated to achieve arterial decannulation and hemostasis safely and effectively. Percutaneous access in combination with the MANTA device has been shown to be associated with fewer access-site complications such as wound healing disorders, lymph-related complications, and vacuum therapy, as well as a shorter procedural duration.[22-24]

Totally endoscopic approach

A totally endoscopic approach to µICS can currently be applied in a wide spectrum of procedures, including single or multiple valve surgeries, redo surgeries, aortic root and ascending aorta surgery, maze procedure and LAA closure, cardiac tumors surgery, radial artery and vein harvesting or thoracoscopic internal thoracic artery preparation/harvesting for MIDCAB, as well as coronary malformations surgery, or procedures in patients with anatomical anomalies such as situs inversus totalis.[3,10,16,25-29]

In combination with long instruments, it enables the undertaking of the µICS without the need for direct vision and/or a rib retractor and using only a soft tissue retractor (ValveGate™ Soft Tissue Retractor, Geister, Germany), thereby promoting the smallest incisions feasible and the least trauma to the chest and ribs without injuring the internal thoracic vessels.[3,30]

The smaller incisions and narrowing working space present however some challenges and steepen the learning curve of µICS. The latter can nonetheless be managed with the help of several specialized tools and instruments, standardization of the minimally invasive cardiac procedures, in addition to elaborate computer training and simulation technologies:[2,31]

3D camera

A 3D high resolution stereoscopic camera (B. Braun Aesculap® EinsteinVision®, Tuttlingen, Germany) offers an overview of the operative field with a high degree of spatial perception. It enables the secure placement of the Chitwood aortic cross-clamp, as well as an excellent visualization of the smallest details of cardiac structures (Figure 3).[2]

Automated suturing technologies

During valve replacement surgeries, obstacles due to the limited remote working space and reduced direct visualization can also be overcome using automated suture technologies, including the RAM® device, the SEW-EASY® device, as well as the COR-KNOT MINI® device from LSI SOLUTIONS® (Victor, NY, USA) (Figure 4). Such customized solutions aim at providing task specific functions, which are originally developed to enable the concise and precise resolution of specific and repetitive steps through tiny surgical access incisions. Detailed descriptions and steps using those devices were previously published.[25,30] In short, the RAM® device is an automated annular suturing device, simultaneously driving two curved needles in the valvular annulus, thus placing the initial bites of a horizontal mattress suture (Figure 5). Using two RAM® devices simultaneously in each of both hands facilitates the suturing of some difficult to reach parts of the valvular annulus, if the latter is angled or deeply recessed outwards. By engaging the first device on a portion of the ring adjacent to the problematic region without releasing the lever, this "Bonn's maneuver" allows the surgeon to use the first RAM® device as a forceps, and with a simultaneously light pulling centripetal and rotating motion, exposes the adjacent receded part of the annulus (Figure 6). The latter can, then, be placed in the jaw of the second RAM® device for suture placement. Using the latter as a starting step of the Bonn's maneuver permits it to be performed continuously in a daisy-chain fashion.

The SEW-EASY® device drives the ends of the annular suture through the sewing cuff of the prosthetic valve using straight needles, completing the horizontal mattress suture. The COR-KNOT MINI® device is used after the placement of the prosthetic in its position above the valvular annulus

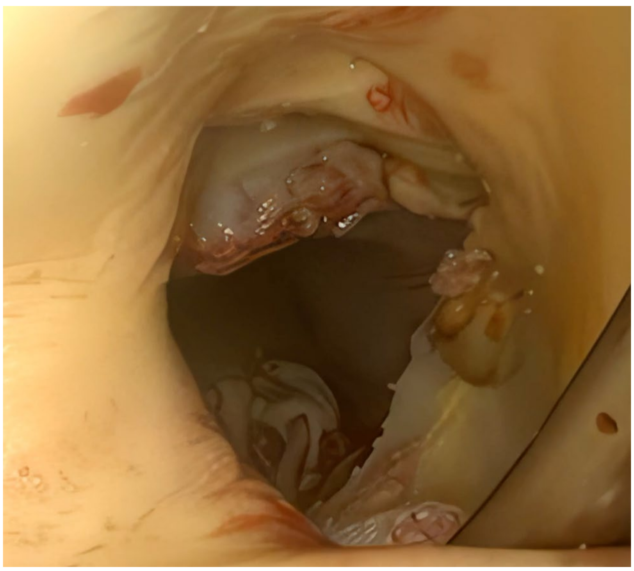

Figure 3. Endoscopic view of the aortic annulus after native aortic valve excision during an endoscopic aortic valve replacement surgery.

Figure 4. Automated suturing technology used for micro-invasive valve replacement procedures. Reprinted with permission from LSI Solutions Inc.

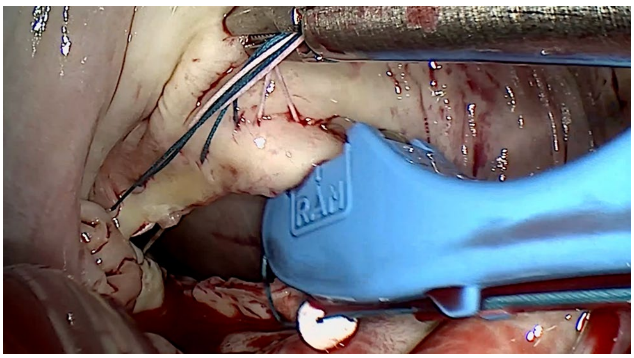

Figure 5. The RAM device being used to place an annular suture during a totally endoscopic mitral valve replacement surgery.

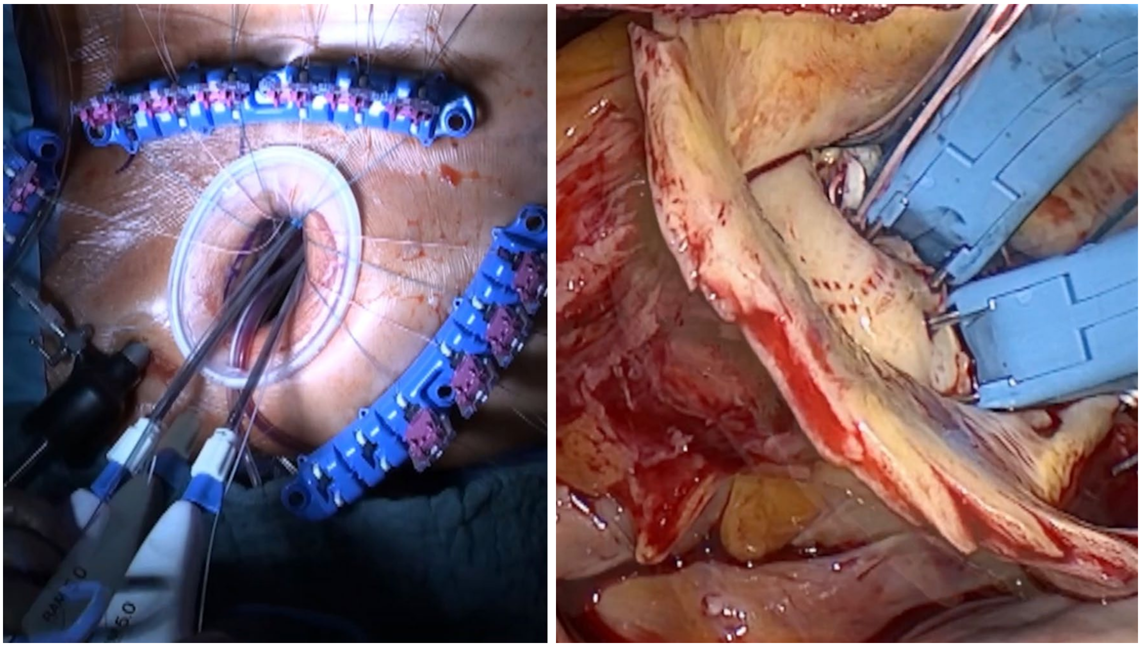

Figure 6. The Bonn-Maneuver: The first RAM® device being used as a forceps to expose the adjacent receded part of the annulus. The latter can then be placed in the jaw of the second RAM® device for suture placement.

to crimp a titanium fastener securing the suture and trim the suture tails in a single motion. Also aiming at reducing suture times, and subsequently ischemic times, this more automated approach to annular suturing facilitates the adoption of MICS in a wider population of surgeons by flattening some of the learning curve, offering the advantages of a less traumatic valvular replacement surgery to more patients.

AVR-Navigator™ aortic root retractor system

In addition to the technologies mentioned above, developed with the goal of flattening the learning curve of endoscopic μICS by automating surgical steps and shortening the procedural times of endoscopic µICS, other specialized instruments aim at improving the exposure of the surgical field, particularly the intracardial structures operated on. The AVR-Navigator™ (LSI Solutions Inc., NY, USA)

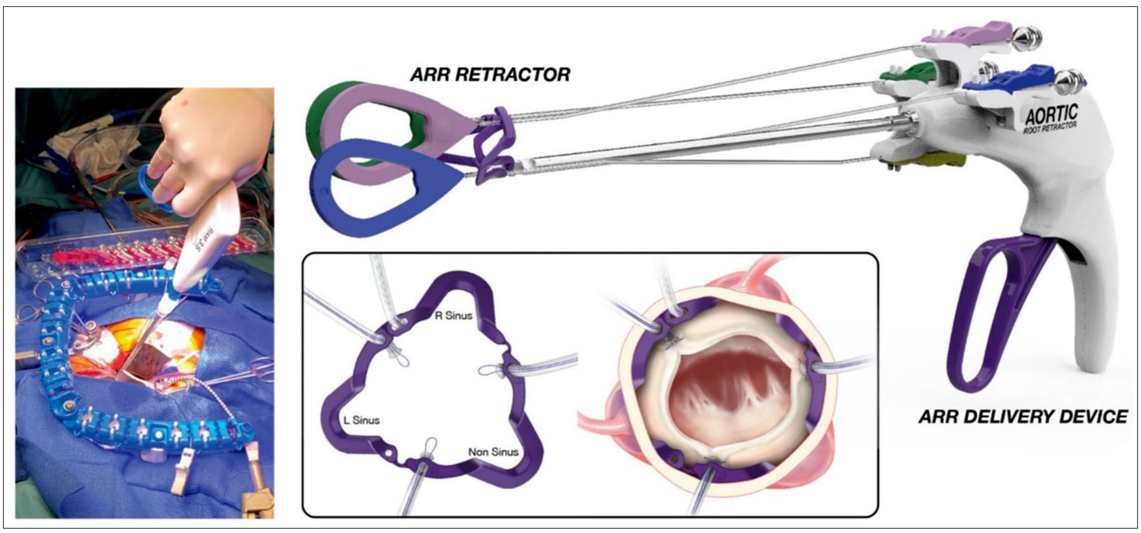

Figure 7. AVR-Navigator™ system which consists of a soft three-lobed aortic root retractor and a delivery device.

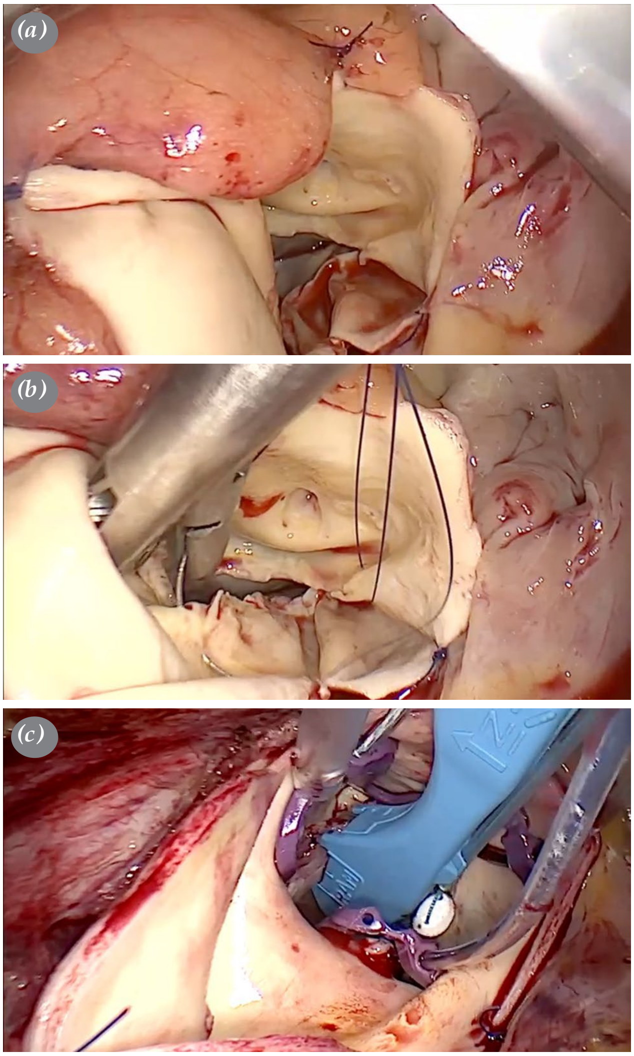

Figure 8. AVR-Navigator™ aortic root retractor system in use during an endoscopic aortic valve replacement surgery. **(a)** Aortic root following the excision of the native aortic valve prior to the use of the aortic root retractor. **(b)** shows the location of the third fixating suture, placed at the commissure between the left coronary sinus and the coronary sinus at the sinotubular junction. **(c)** The RAM® device being used to place the first annular suture in combination with the aortic root retractor.

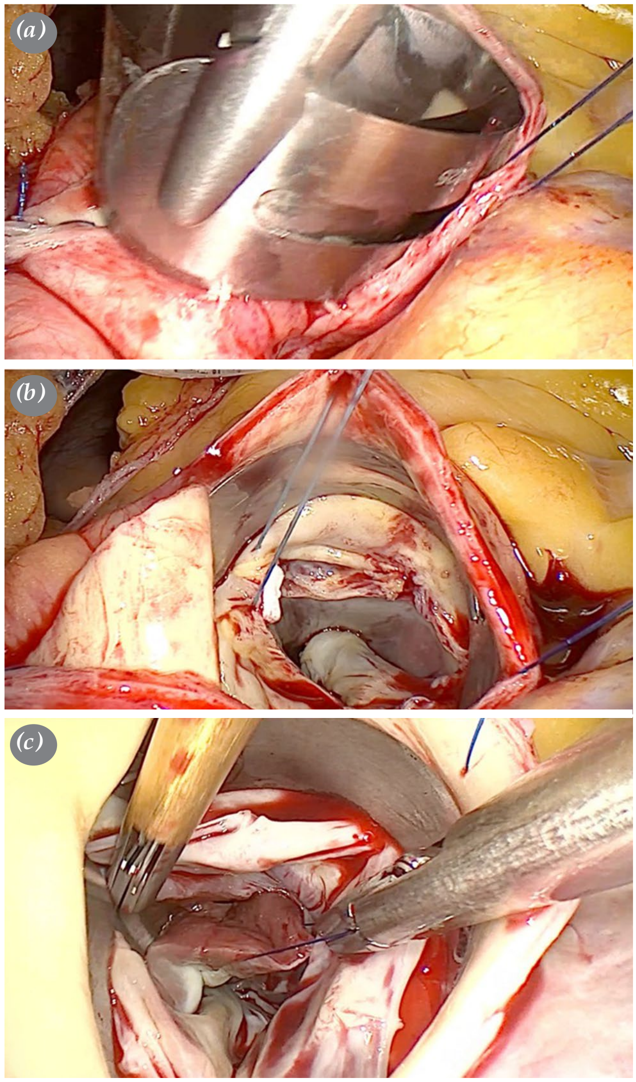

Figure 9. The SOMOHA retractor being used in an endoscopic micro-invasive surgery, **(a, b)** show the SOMOHA retractor employed in an endoscopic aortic valve surgery both before deployment in a "rolled" state and after deployment and placement of an annular suture, respectively. **(c)** An endoscopic septal myectomy performed while using the SOMOHA retractor for a better exposure of the septum.

is a novel aortic root retraction system designed to optimize the visualization and stabilization of the aortic annulus during endoscopic aortic valve replacement surgery.[32] This flexible aortic root retractor comes with a delivery device and consists of a three-lobed plastic frame fixed by expansion and three sutures that are placed in the aortic root below the sinotubular junction (Figure 7). Its positioning and deployment can easily be performed by fixating three sutures in the aortic wall at the sinotubular junction after the total excision of the aortic valve prior to the annular suture placement (Figure 8). The sutures are, then, passed through each flexible conduit with the help of a looped wire before parachuting the retractor in using the delivery device and guided by the fixating sutures, in a similar fashion to parachuting a valvular prosthesis. It can be, then, used to adjust the angulation of the aortic annulus in relation of the surgical access and 3D-camera, thus providing an excellent exposure of the aortic root while ensuring its stability. The design of the AVR-Navigator™ system allows it to be used in combination with the

RAM® device without hindering the access to the aortic root its visibility (Figure 8).

SOMOHA

The SOMOHA retractor developed by Fehling Instruments GmbH (Karlstein, Germany) is a novel and simple self-expanding retractor which can substantially improve the visualization of the aortic valve during endoscopic aortic valve repair or replacement. Consisting of a flexible metallic sheet with guiding tabs and a guiding bar at each end, its assembled very easily by bringing both ends on top of each other and inserting the guiding tabs into the insertion opening, due to the springy nature of the metallic retractor, releasing the pressure on both ends of the retractor allows it to try to expand, guiding the tabs into the bar and locking the retractor in a rolled state. Deploying the retractor *in situ* starts with reversing the lock by pushing the guiding tabs back toward the insertion opening and passing them back through. While the retractor held in a "rolled" state with a forceps, it is, then, introduced in the ascending aorta above the sinotubular junction and let to self-expand (Figure 9). It allows for an increased stability of the ascending aorta and aortic root, while the increased diameter of the valvular annulus maintains an increased field of view of the left ventricular outflow tract and intraventricular structures (Figure 9). Although its design and practical application are markedly uncomplicated, the SOMOHA retractor offers an invaluable way to avoid some of the technical challenges of the narrow work field of micro-invasive valve surgery.

Remote suturing system

The C1® device (LSI Solutions Inc., NY, USA) for automated suture placement is optimized to facilitate minimally invasive surgery providing precise remote suture placement with features to enhance visualization and reduce needle exposure.

It is available with an angled shaft for optimized remote suture delivery and incorporates a viewing window for maximal tissue visualization. Moreover, this device features a rotational knob with integrated indicator fin for enhanced suturing ergonomics. All these features enable an automated closure of the left atrium in endoscopic mitral valve surgery and presents a potential solution for aortotomy closure in endoscopic aortic valve surgery, as well as for prosthetic tube graft suturing in endoscopic ascending aorta replacement.

Left atrial appendage closure

Epicardial LAA clip occlusion using the AtriClip® (AtriCure, OH, USA) in patients with atrial fibrillation is a simple and quick procedure providing a safe, effective, and durable left appendage isolation for patients with atrial fibrillation.[33] The AtriClip® provides an epicardial exclusion, thereby avoiding an implant in the blood stream, while maintaining a dynamic closing force maintaining the LAA exclusion even after the atrial tissue ischemic changes. Furthermore, the two parallel legs of the clip minimize the occurrence of tissue folds ensuring a durable and effective closure of the LAA ostia, while still being atraumatic without any incisions. With the AtriClip® PRO.V model, which offers a port compatibility for endoscopic surgery and a tip-first closure design, LAA clip closure can be easily performed either concomitantly with other surgeries or as a solo procedure totally endoscopically.

Cryoablation

The Cox-maze procedure (CMP) is an established effective treatment of atrial fibrillation. It has, nonetheless, originally been technically challenging and time-consuming due the nature of the "cut-and-sew" maze, which hindered its adoption.[34] The development of cryoablation devices such as the ATS Medtronic Cryo probe and clamp has, however, reintroduced the CMP (CMP-IV) as a time efficient and simple procedure. Using argon to reach minimum temperatures of –185.7°C, the CMP has the goal of terminating atrial fibrillation and isolating foci of arrhythmogenicity by creating a pattern of lesions on both atria.[35] In µICS, the CMP-IV procedure can be done endoscopically through RAMT, which allows both epicardial and endocardial cryoablation of both atria.

In combination with LAA exclusion via AtriClip®, cryoablation therapy is the mainstay of atrial fibrillation surgery that can be achieved in a micro-invasive manner totally endoscopically.

TOTALLY ENDOSCOPIC CORONARY ARTERY BYPASS (TECAB)

The advantages of micro-invasive surgery also apply to coronary artery revascularization surgery. The MIDCAB has already been established as a safe and effective approach to bypass surgery, while offering the benefits of the lesser trauma, including fewer transfusions, shorter LOS, and lower hospital costs in contrast to the traditional coronary artery bypass grafting (CABG) via sternotomy.[10,36,37]

Although MIDCAB was initially more commonly employed in cases of single vessel coronary artery disease of the left anterior descending artery (LAD)

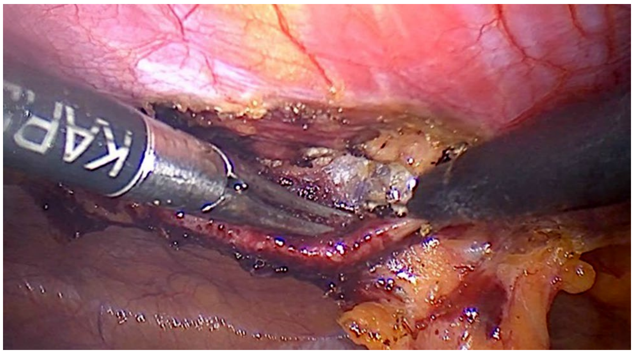

Figure 10. Endoscopic harvesting of the RIMA.
RIMA: Right internal mammary artery.

or in combination with interventional cardiology as part of a hybrid revascularization approach, current advances and techniques in endoscopic μICS allow for the surgical treatment of patients with multiple vessels disease with several bypasses on both the right and the left coronary artery systems.[14,38-40] A TECAB can, thus, be achieved with the help of stabilization systems such as the Octopus® Nuvo tissue stabilizer (Medtronic Inc., MN, USA), which are introduced in the chest cavity through a stab incision and used to safely perform the anastomosis on the target coronary artery during endoscopic off-pump CABG. Endoscopic right coronary artery bypass can also be safely performed through a RAMT, while multiple bypasses can be achieved with multiple grafts using a T-graft or a Y-graft, which can be prepared endoscopically intra-thoracically. When extreme manipulation and luxation of the heart is needed to reach the posterior wall for example, cardioplegia and CPB can be achieved using a transthoracically-placed Chitwood aortic cross clamp and peripheral percutaneous cannulation for ECC, which is used in combination with the MANTA system for arterial closure, as is standard in micro-invasive valve surgery. Peripheral cannulation and ECC without cardioplegia can also be performed to achieve partial CPB, helping to decompress the heart while performing on-pump beating heart TECAB.

Endoscopic graft harvesting

A totally endoscopic approach to coronary revascularization surgery should also be applied to other aspects of the procedure, including grafts harvesting. Both right and left internal thoracic arteries (RIMA and LITA, respectively) can be safely prepared endoscopically, sparing the patient the need for spreading the ribs for better exposure of the needed length for the bypass conduit responsible for some of the postoperative pain associated with MIDCAB surgery (Figure 10). The most favorable positioning of the camera port and instrument ports can be guided by the preoperative CT based tools such as 3mensio and intraoperatively using the CarnaLife Holo System by helping in visualizing the exact location of the internal thoracic arteries and the optimal location of the graft-coronary anastomosis.

Furthermore, endoscopic vessel harvesting (EVH) of the radial artery, as well as the great saphenous vein significantly reduces wound-related complications, postoperative LOS, and outpatient wound management while improving patient satisfaction.[41] It can be performed using the Hemopro family of closed tunnel EVH devices (Maquet GmbH, Rastatt, Germany).

Robotic surgery

The recent popularity and acceptance of a minimally invasive approach in cardiac surgery has also revived the interest in robotics. Stemming in the late 80s, in part from development and funding from DARPA, a research and development agency of the United States Department of Defense, robotic cardiac surgery culminates currently with the daVinci XI surgical system (Intuitive Surgical Inc., Sunnyvale, CA, USA). The daVinci XI features many advances such as a laser targeting system, seven degrees of ergonomic freedom, tremor-free dexterity for both hands, a 3D endoscope and "wrist-like" instrument movements and articulations.[1] These state-of-the-art technological advances enable trained surgeons to perform a variety of cardiac surgical procedures ranging from isolated internal mammary artery dissection to complete valvular surgeries with improved outcomes compared to conventional approaches, although they are associated with a greatly steep learning curve and a prohibiting increased financial burden.[42,43] A 2023 propensity-matched retrospective review of the STS adult cardiac surgery database compared the outcomes of robotic totally endoscopic mitral valve repair to both sternotomy and mini-thoracotomy over a period of seven years across 103 hospitals found that, despite similar mortality and morbidity, patients undergoing robotic surgery had a shorter LOS and fewer 30-day readmissions, while mortality and mortality were lower in high volume centers.[44] Furthermore, a retrospective study of 720 patients undergoing robotic TECAB surgery included 93 patients selected for a postoperative Day 1 discharge in combination with the ERAS protocols and showed lower readmission rates and a trend toward earlier return to work, *albeit* not statistically significant.[45] The major hindrance to the adoption of robotics in cardiac surgery remains the costs associated with the purchasing, implementation, and maintenance of the daVinci System, as well as the per case costs incurred to both the healthcare provider and to the patient.

Criticisms and resolutions

Despite the several advantages of minimally invasive techniques in cardiac surgeries, which extent beyond the better cosmetic results, μICS, and more extensively MICS, have yet to achieve a widespread adoption. Its perceived difficulty and steep learning curve, which in association with potentially longer operative and ischemic times, represent the core of the obstacle to its general acceptance. In our experience, however, it has not been associated with longer procedural durations compared to sternotomy, and in some cases, endoscopic valve surgery was indeed shown to take less time overall when used with some of the technologies presented in this paper, such as the RAM® device, COR-KNOT® device, and the MANTA® device used for femoral artery closure following peripheral decannulation.[4,24] Some of the devices and solutions presented in this review have been specifically developed with time effectiveness in mind, automating repetitive and difficult routines, which may also help to oppose some of the time challenges of MICS. We believe that after overcoming the initial learning curve, which can be considerably flattened with the appropriate technologies and instruments, μICS can be safely and punctually performed in most patients.

Although these innovative technologies and instruments are invaluable tools for the cardiac surgeon facing the steep learning curve of μICS, the latter remains a significant challenge to overcome. An appropriate simulation-based training is an effective way to ease this challenge while remaining safe. During the 36th European Association of Cardiothoracic Surgery annual meeting, a 2-h simulation-based training in placing an annular suture at the posterior mitral valve annulus endoscopically was set up.[31] Forty-six participants were included in a study measuring the accuracy and time gains following the simulation, showing a significant improvement in both time and accuracy of the suture. Such simulation-based training programs can be of great value, not only in workshops during conferences and meetings, but also in cardiac surgery centers, where residents and surgeons can undergo a regular continued training, and experienced surgeons can keep developing their skills and techniques to further advance their respective fields.

Other concerns about the cost-effectiveness of MICS have also been raised.[46] The decreased trauma rates, morbidity, blood requirements, and LOS both in-hospital and in the ICU, in combination with the ERAS philosophy of early enhanced recovery, offset the operative costs associated with MICS, at least on the short and middle term.[13]

In conclusion, the recent trend toward minimal invasiveness and technological advances represents a significant turn of events for cardiac surgery, ushering the era of micro-invasive heart surgery. The latest advancements and techniques discussed in this review are a defining step in defining the future of this field. In combination with the philosophy of enhanced recovery after surgery, micro-invasive cardiac surgery is a way to provide patients a high standard of care with satisfying results and early return to normal life and to work.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: Idea/concept, controlle/supervision: F.B.; Data collection and/or processing; writting the article: S.S.; Litterature review; critical review: K.E.; Design, analysis and or Interpretation: A.E.S.A.

Conflict of Interest: Farhad Bakhtiary reports a relationship with Edwards Lifesciences, Medtronic and LSI that includes consulting or advisory and speaking and lecture fees. All other authors have nothing to disclose with regard to commercial support.

Funding: The authors received no financial support for the research and/or authorship of this article.

REFERENCES

1. Chitwood WR Jr. Historical evolution of robot-assisted cardiac surgery: A 25-year journey. Ann Cardiothorac Surg 2022;11:564-82. doi: 10.21037/acs-2022-rmvs-26.
2. El-Sayed Ahmad A, Salamate S, Bakhtiary F. Lessons learned from 10 years of experience with minimally invasive cardiac surgery. Front Cardiovasc Med 2023;9:1053572. doi: 10.3389/fcvm.2022.1053572.
3. Bakhtiary F, El-Sayed Ahmad A, Amer M, Salamate S, Sirat S, Borger MA. Video-assisted minimally invasive aortic valve replacement through right anterior minithoracotomy for all comers with aortic valve disease. Innovations (Phila) 2021;16:169-74. doi: 10.1177/1556984520977212.
4. Bakhtiary F, Salamate S, Amer M, Sirat S, Bayram A, Doss M, et al. Comparison of right anterior mini-thoracotomy versus partial upper sternotomy in aortic valve replacement. Adv Ther 2022;39:4266-84. doi: 10.1007/s12325-022-02263-6.

5. Monsefi N, Alaj E, Sirat S, Bakhtiary F. Postoperative results of minimally invasive direct coronary artery bypass procedure in 234 patients. Front Cardiovasc Med 2023;9:1051105. doi: 10.3389/fcvm.2022.1051105.
6. El-Sayed Ahmad A, Bakhtiary F. Video-assisted minimally invasive aortic valve replacement through left anterior mini-thoracotomy in a patient with situs inversus totalis. Eur J Cardiothorac Surg 2020;58:1095-96. doi: 10.1093/ejcts/ezaa161.
7. Alsarraj MK, Nellis JR, Vekstein AM, Andersen ND, Turek JW. Borrowing from adult cardiac surgeons-bringing congenital heart surgery up to speed in the minimally invasive era. Innovations (Phila) 2020;15:101-5. doi: 10.1177/1556984520911020.
8. Schmitto JD, Mokashi SA, Cohn LH. Minimally-invasive valve surgery. J Am Coll Cardiol 2010;56:455-62. doi: 10.1016/j.jacc.2010.03.053.
9. Felger JE, Nifong LW, Chitwood WR Jr. The evolution of and early experience with robot-assisted mitral valve surgery. Surg Laparosc Endosc Percutan Tech 2002;12:58-63. doi: 10.1097/00129689-200202000-00010.
10. Monsefi N, Alaj E, Sirat S, Bakhtiary F. Postoperative results of minimally invasive direct coronary artery bypass procedure in 234 patients. Front Cardiovasc Med 2023;9:1051105. doi: 10.3389/fcvm.2022.1051105.
11. El-Sayed Ahmad A, Salamate S, Giammarino S, Ciobanu V, Bakhtiary F. Transmitral septal myectomy and mitral valve surgery via right mini-thoracotomy. Thorac Cardiovasc Surg 2023;71:171-7. doi: 10.1055/s-0042-1744261.
12. Monsefi N, Makkawi B, Öztürk M, Alirezai H, Alaj E, Bakhtiary F. Right minithoracotomy and resternotomy approach in patients undergoing a redo mitral valve procedure. Interact Cardiovasc Thorac Surg 2022;34:33-9. doi: 10.1093/icvts/ivab228.
13. Salenger R, Lobdell K, Grant MC. Update on minimally invasive cardiac surgery and enhanced recovery after surgery. Curr Opin Anaesthesiol 2024;37:10-5. doi: 10.1097/ACO.0000000000001322.
14. Hecker F, von Zeppelin M, Van Linden A, Scholtz JE, Fichtlscherer S, Hlavicka J, et al. Right-sided minimally invasive direct coronary artery bypass: Clinical experience and perspectives. Medicina (Kaunas) 2023;59:907. doi: 10.3390/medicina59050907.
15. Hasde AI, Sarıcaoğlu MC, Kılıçkap M, Durdu MS. Single or combined valve surgery and concomitant right coronary artery bypass through right anterior minithoracotomy approach. Thorac Cardiovasc Surg 2023;71:614-19. doi: 10.1055/s-0041-1731284.
16. Salamate S, El-Sayed Ahmad A, Bayram A, Sirat S, Bakhtiary F. Case report: Video-assisted minimally invasive mitral and pulmonary valve replacement as reoperation in patient with situs inversus totalis. Front Cardiovasc Med 2023;10:1053923. doi: 10.3389/fcvm.2023.1053923.
17. Francone M, Budde RPJ, Bremerich J, Dacher JN, Loewe C, Wolf F, et al. CT and MR imaging prior to transcatheter aortic valve implantation: Standardisation of scanning protocols, measurements and reporting-a consensus document by the European Society of Cardiovascular Radiology (ESCR). Eur Radiol 2020;30:2627-50. doi: 10.1007/s00330-019-06357-8.
18. Silaschi M, Späth A, Hamiko M, Kruse J, Akhavuz Ö, El Sayed Ahmad A, et al. Proposal for computer tomography-based valve sizing and prosthesis simulation in endoscopic aortic valve surgery. JTCVS Tech 2024;25:52-4. doi: 10.1016/j.xjtc.2024.02.022.
19. Murzi M, Cerillo AG, Miceli A, Bevilacqua S, Kallushi E, Farneti P, et al. Antegrade and retrograde arterial perfusion strategy in minimally invasive mitral-valve surgery: A propensity score analysis on 1280 patients. Eur J Cardiothorac Surg 2013;43:e167-72. doi: 10.1093/ejcts/ezt043.
20. Newman JS, Patel NC. Cannulas and cannulation options for minimally invasive surgery. Innovations (Phila) 2022;17:76-82. doi: 10.1177/15569845221082119.
21. Kruse J, Silaschi M, Velten M, Wittmann M, Alaj E, Ahmad AE, et al. Femoral or axillary cannulation for extracorporeal circulation during minimally invasive heart valve surgery (FAMI): Protocol for a multi-center prospective randomized trial. J Clin Med 2023;12:5344. doi: 10.3390/jcm12165344.
22. Ando T, Briasoulis A, Holmes AA, Takagi H, Slovut DP. Percutaneous versus surgical cut-down access in transfemoral transcatheter aortic valve replacement: A meta-analysis. J Card Surg 2016;31:710-7. doi: 10.1111/jocs.12842.
23. Ma K, Kastengren M, Svenarud P, Green R, Dalén M. Routine use of percutaneous femoral cannulation in minimally invasive cardiac surgery. Eur J Cardiothorac Surg 2023;63:ezad020. doi: 10.1093/ejcts/ezad020.
24. El-Sayed Ahmad A, Bayram A, Salamate S, Sirat S, Amer M, Bakhtiary F. Percutaneous versus surgical femoral access in minimally invasive cardiac operations. Eur J Cardiothorac Surg 2022;61:1348-54. doi: 10.1093/ejcts/ezab520.
25. Bakhtiary F. μAVR: Endoscopic microinvasive aortic valve surgery with automated suturing technology for enhanced patient outcomes. Innovations (Phila) 2023;18:365-71. doi: 10.1177/15569845231185819.
26. Hamiko M, Salamate S, Nassari MA, Spaeth A, Sirat S, Doss M, et al. Totally endoscopic replacement of the ascending aorta and the aortic root including the aortic valve via right mini-thoracotomy: A multicenter study. J Clin Med 2024;13:2648. doi: 10.3390/jcm13092648.
27. Salamate S, Bayram A, Hojeij A, Silaschi M, Akhavuz Ö, El-Sayed Ahmad A, et al. Total endoscopic surgical treatment of a gigantic coronary arteriovenous fistula between circumflex artery and superior vena cava through right anterior mini-thoracotomy. J Surg Res (Houst) 2023;6:448-452.
28. Alom S, Yang N, Bin Saeid J, Zeinah M, Harky A. Harvesting internal mammary artery: A narrative review. J Cardiovasc Surg (Torino) 2020;61:790-801. doi: 10.23736/S0021-9509.20.11216-3.
29. Eckey H, Heseler S, Hiligsmann M. Economic evaluation of endoscopic vs open vein harvesting. Ann Thorac Surg 2023;115:1144-50. doi: 10.1016/j.athoracsur.2022.09.017.
30. Bakhtiary F, Salamate S, Ahmad AE. Totally endoscopic micro-invasive aortic valve replacement. Multimed Man Cardiothorac Surg 2024;2024. doi: 10.1510/mmcts.2023.094.
31. Checheili Sobbi S, Jung Y, Fillet M, Bakhtiary F, Maessen JG, Sardari Nia P. Simulation-based training for endoscopic mitral valve repair: The impact on basic surgical skills for placement of sutures at mitral valve annulus during 2-h

training workshop. Interdiscip Cardiovasc Thorac Surg 2024;38:ivae003. doi: 10.1093/icvts/ivae003.

32. Werner P, Poschner T, Gross C, Gaster A, Bartunek A, Scherzer S, et al. A Novel System For Enhanced Annulus Access and Visualization During Minimally-invasive Aortic Valve Replacement. 22 ISMICS Annual Scientific Meeting, June 16-18, 2022, Warsaw, Poland. ISMICS; 2022.
33. Emmert MY, Puippe G, Baumüller S, Alkadhi H, Landmesser U, Plass A, et al. Safe, effective and durable epicardial left atrial appendage clip occlusion in patients with atrial fibrillation undergoing cardiac surgery: First long-term results from a prospective device trial. Eur J Cardiothorac Surg 2014;45:126-31. doi: 10.1093/ejcts/ezt204.
34. Mehaffey JH, Krebs E, Hawkins RB, Charles EJ, Tsutsui S, Kron IL, et al. Variability and utilization of concomitant atrial fibrillation ablation during mitral valve surgery. Ann Thorac Surg 2021;111:29-34. doi: 10.1016/j.athoracsur.2020.05.125.
35. McGilvray MMO, Barron L, Yates TE, Zemlin CW, Damiano RJ Jr. The Cox-Maze procedure: What lesions and why. JTCVS Tech 2022;17:84-93. doi: 10.1016/j.xjtc.2022.11.009.
36. Xu Y, Li Y, Bao W, Qiu S. MIDCAB versus off-pump CABG: Comparative study. Hellenic J Cardiol 2020;61:120-4. doi: 10.1016/j.hjc.2018.12.004.
37. Detter C, Reichenspurner H, Boehm DH, Thalhammer M, Raptis P, Schütz A, et al. Minimally Invasive Direct Coronary Artery Bypass grafting (MIDCAB) and Off-Pump Coronary Artery Bypass grafting (OPCAB): Two techniques for beating heart surgery. Heart Surg Forum 2002;5:157-62.
38. Issa HMN, Ruel M. Beating heart multi-vessel minimally invasive direct coronary artery bypass grafting: Techniques and pitfalls. J Vis Surg 2023;9:5. doi: 10.21037/jovs-22-5.
39. Yilmaz A, Claessens J, Kaya A. Multi-vessel endoscopic coronary artery bypass grafting. In: Zacharias J, editor. Endoscopic cardiac surgery. Cham: Springer International Publishing; 2023. p. 217-235.
40. Leonard JR, Rahouma M, Abouarab AA, Schwann AN, Scuderi G, Lau C, et al. Totally endoscopic coronary artery bypass surgery: A meta-analysis of the current evidence. Int J Cardiol 2018;261:42-6. doi: 10.1016/j.ijcard.2017.12.071.
41. Ferdinand FD, MacDonald JK, Balkhy HH, Bisleri G, Hwang HY, Northrup P, et al. Endoscopic conduit harvest in coronary artery bypass grafting surgery: An ISMICS systematic review and consensus conference statements. Innovations (Phila) 2017;12:301-19. doi: 10.1097/IMI.0000000000000410.
42. Husen TF, Kohar K, Angelica R, Saputro BIL. Robotic vs other surgery techniques for mitral valve repair and/or replacement: A systematic review and meta-analysis. Hellenic J Cardiol 2023;71:16-25. doi: 10.1016/j.hjc.2022.12.011.
43. Liu Z, Zhang C, Ge S. Efficacy and safety of robotic-assisted versus median sternotomy for cardiac surgery: Results from a university affiliated hospital. J Thorac Dis 2023;15:1861-71. doi: 10.21037/jtd-23-197.
44. Mori M, Parsons N, Krane M, Guy TS, Grossi EA, Dearani JA, et al. Robotic mitral valve repair for degenerative mitral regurgitation. Ann Thorac Surg 2024;117:96-104. doi: 10.1016/j.athoracsur.2023.07.047.
45. Nisivaco S, Patel B, Coleman C, Kitahara H, Torregrossa G, Balkhy HH. Postoperative day 1 discharge after robotic totally endoscopic coronary bypass: The ultimate in enhanced recovery after surgery. Innovations (Phila) 2023;18:159-66. doi: 10.1177/15569845231164374.
46. Santana O, Larrauri-Reyes M, Zamora C, Mihos CG. Is a minimally invasive approach for mitral valve surgery more cost-effective than median sternotomy? Interact Cardiovasc Thorac Surg 2016;22:97-100. doi: 10.1093/icvts/ivv269.