Keynote Lecture Series

Lateral access fully robotic aortic valve replacement "RAVR": from novel to normal

Ghulam Murtaza[1], Lawrence Wei[2]

[1]Division of Cardiac Surgery, SSM Health Heart & Vascular Care Center, Madison, WI, USA; [2]Department of Cardiovascular and Thoracic Surgery, West Virginia University, Morgantown, WV, USA

Correspondence to: Ghulam Murtaza, MD, MBA. Division of Cardiac Surgery, SSM Health Heart & Vascular Care Center, 700 S. Park St, Madison, WI 53715, USA. Email: gmcvts@gmail.com.

Right lateral access robotic-assisted aortic valve replacement (RAVR) may represent a significant advancement in minimally invasive cardiac surgery. This review examines RAVR's development, technical specifications, clinical outcomes, and future trajectory in cardiac surgery. Multicenter RAVR experiences have demonstrated promising results with low rates of operative mortality (0.9%), stroke (0.9%), and permanent pacemaker placement (2.9%). In propensity-matched comparisons with transcatheter aortic valve replacement (TAVR), RAVR had significantly lower rates of paravalvular leak (0.7% *vs.* 21.5%) and one-year mortality (1.4% *vs.* 12.5%). With a 3-cm working incision at the level of the anterior axillary line, the lateral access approach offers distinct advantages including improved surgical visualization, reduced tissue trauma, and standardization potential across various cardiac procedures. While learning curve considerations exist, these are minimal for experienced robotic mitral teams. RAVR programs have expanded to include implementation of complex procedures such as aortic root enlargement. As robotic systems become more prevalent and surgical expertise grows, RAVR shows promise to evolve from an innovative technique to a standard therapeutic option in aortic valve surgery. This evolution, supported by growing clinical evidence and technological advancement, positions RAVR as a potentially transformative development in cardiac surgery, offering patients the benefits of minimally invasive approaches while maintaining the durability of traditional surgical valve replacement.

Keywords: Robotic aortic valve replacement (RAVR); right lateral access; robotic cardiac surgery; aortic valve replacement (AVR)

Submitted Mar 09, 2025. Accepted for publication Mar 30, 2025. Published online May 29, 2025.
doi: 10.21037/acs-2025-ravr-0049
View this article at: https://dx.doi.org/10.21037/acs-2025-ravr-0049

Introduction

Aortic valve disease is one of the most common valvular conditions, affecting 2.5% of the general population, with incidence rising in the elderly (1). Treatment for aortic valve disease has evolved significantly over the past three decades. While surgical aortic valve replacement (SAVR) via median sternotomy was the gold standard for most of the 20th century, the early 21st century has seen a remarkable expansion of therapeutic options (2). The introduction of transcatheter aortic valve replacement (TAVR) in 2002 marked the start of a new era. Surgical techniques have advanced through innovations such as mini-sternotomy, right anterior thoracotomy, and robotic-assisted techniques (3). Robotic aortic valve replacement (RAVR), via right lateral access, is one of the latest advancements in this trend (4).

This review examines RAVR's development and initial experiences to one that has the potential to become routine in clinical practice. By evaluating the technical details, clinical efficacy, and patient outcomes associated with RAVR, we explore its potential to transform AVR surgery. We consider its future in cardiac surgery, seeking to answer an essential question: can RAVR evolve from a "novel" procedure to a "normal" option for aortic valve surgery?

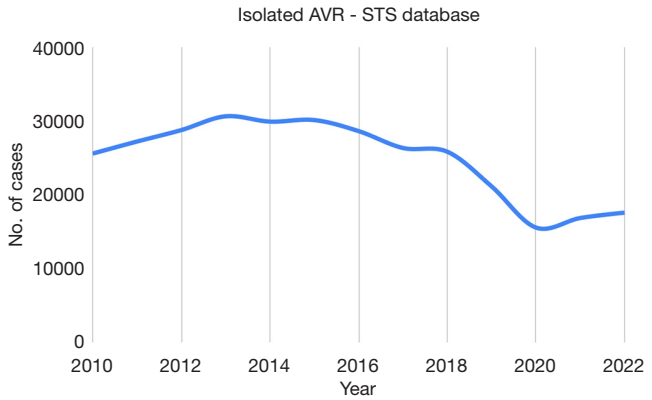

Figure 1 Yearly cases of isolated AVR from STS database (6,7). AVR, aortic valve replacement; STS, Society of Thoracic Surgeons.

Historical context and evolution of AVR techniques

Traditional aortic valve replacement (AVR)

Aortic valve replacement (AVR) has long been the definitive treatment for patients suffering from severe aortic stenosis and aortic regurgitation. Traditionally, this procedure has been performed as an open surgery requiring a full sternotomy. Over the years, surgeons have developed minimally invasive approaches, including mini-sternotomy and right anterior thoracotomy. These techniques aim to reduce the invasiveness of AVR by accessing the heart through smaller incisions and avoiding a full sternotomy.

The Food and Drug Administration (FDA) approved TAVR for high-risk patients with aortic stenosis in 2011 (5). This approval indirectly led to a rise in isolated SAVR volumes, which reached over 30,000 cases annually by 2013 (6). With TAVR now available as an alternative, many patients previously considered too high-risk for traditional SAVR—and thus left untreated—were able to access a potentially life-saving intervention. Additionally, many patients who were not in the high-risk category also sought treatment, further contributing to the increase in SAVR volumes as awareness and accessibility of aortic stenosis treatment options expanded.

As TAVR technology advanced, its indications gradually expanded to encompass intermediate- and low-risk patients, and TAVR began to emerge as a dominant option for a larger segment of the population. This expansion led to a substantial decline in SAVR volumes as TAVR use increased.

In recent years, however, SAVR volumes have shown signs of stabilizing (7) (*Figure 1*). This trend reflects the continued need for SAVR in specific cases where TAVR may not be appropriate, such as for younger patients or those with anatomical considerations that favor surgical intervention. The stabilization of SAVR volumes underscores the need for ongoing innovation within SAVR techniques with the goal of minimizing surgical trauma, accelerating recovery times, and providing the best possible outcomes for patients requiring surgery. As aortic stenosis treatment continues to evolve, it is essential to maintain a balanced approach between TAVR and SAVR, along with ongoing advancements in each modality to ensure optimal, individualized care for patients.

Advent of robotic-assisted surgery in cardiac procedures

The introduction of robotics into the operating room has transformed many surgical fields by providing surgeons with enhanced precision, stability, and visualization. The first robotic cardiac procedures were exploratory and primarily focused on coronary artery bypass grafting (CABG) and mitral valve repair, where the precision of robotic instruments proved beneficial.

The earliest report of robotic use for AVR was done via a 7–8 cm anterior thoracotomy in the 3rd intercostal space by Folliguet *et al.* in 2005 (8,9). While initially favorable, after five cases where the robot was used for limited portions of the procedure, the approach was abandoned. Balkhy *et al.* furthered this technique in 2018 with initial cases of right anterior RAVR using sutureless valves (10).

Development of robotic aortic valve replacement at West Virginia University

Between 2015 and 2019, initial proof-of-concept cadavers trials validating the feasibility of a right lateral approach using robotic techniques for AVR using conventional stented valves were carried out at West Virginia University. These foundational experiments paved the way for clinical applications.

In 2019, the first 10 cases of direct vision and videoscopic non-robotic aortic valve replacements were performed through a 3–4 cm right lateral thoracotomy. This transitional phase allowed for the refinement of surgical techniques, setting the stage for the integration of robotic systems. By January 2020, the first fully robotic RAVR procedures were successfully performed, marking a pivotal milestone in the field (4).

Progress continued with the completion of the first

double valve replacement combined with a biatrial Maze procedure in July 2020. By November 2021, the program reached its 100th RAVR case, including numerous concomitant procedures, further highlighting the technique's versatility (11).

In November 2022, a global community of robotic surgeons convened to share expertise and expand the practice. As of June 1, 2023, 206 RAVR operations had been performed worldwide, with 35 conducted outside of West Virginia (12). By December 2024, the program at West Virginia University achieved a remarkable milestone of completing over 300 consecutive operations, with nearly 50 performed globally.

Technical aspects of RAVR

Patient selection criteria

Ideal anatomical candidates for RAVR include those with horizontal aortic valves and slightly longer aortas, which position the native aortic valve lower in the chest, readily facilitating access from a lateral approach. RAVR is particularly suited for patients with contraindications to TAVR, such as younger patients requiring mechanical valves or concomitant procedures, those with severe aortic insufficiency, bicuspid valves, or left ventricular outflow tract (LVOT) calcification. Conversely, patients with specific anatomical variations or comorbidities may be better suited to alternative surgical approaches. These include severe chest deformities, extensive aortic calcification, prior sternotomy or right thoracotomy, or prior right lung resection.

The selection process necessitates comprehensive preoperative screening. Imaging studies, including computed tomography (CT) scans, are essential to assess chest structural anatomy and peripheral vasculature. Coronary angiograms are performed to rule out coronary artery disease (*Table 1*). Preoperative screening algorithms originally developed for robotic mitral valve surgery can be adapted to guide patient selection for RAVR (13).

These assessments enable the surgical team to evaluate the feasibility of a robotic approach and to plan for any necessary adjustments. By carefully selecting candidates—particularly during the early adoption phase—surgical teams can optimize the safety and effectiveness of lateral access RAVR. Once teams have established their RAVR program, some of the aforementioned contraindications may become relative, as robotic access may actually aid in decreasing co-morbidity in certain higher risk patients.

Anesthesia and patient preparation

Before the patient is brought into the operating room, the anesthesia team administers a regional anesthetic for post-operative analgesia. Options include an erector spinae plane block or single-dose intrathecal morphine. Upon arrival in the operating room (OR), a double-lumen endotracheal tube is placed, and single-lung ventilation is initiated.

A brachial arterial line is placed in the left arm for continuous blood pressure monitoring, while oximetry pads are positioned on both calves. Transcutaneous cerebral oximetry monitoring is employed to ensure adequacy of cerebral perfusion.

The anesthesia team uses ultrasound guidance to place a 20-Fr peripheral arterial cannula through the right internal jugular vein into the superior vena cava (SVC). This cannula is primed and later connected to the cardiopulmonary bypass circuit. Alternatively, a 5-Fr angiocatheter (micropuncture femoral arterial line kit) is initially placed in the right internal jugular vein and prepped into the surgical field. The surgical team then replaces this catheter with the cannula to facilitate SVC venous drainage.

The patient is then shifted toward the right side of the operating table. A small blanket roll is positioned under the right chest to elevate the right hemithorax, and the right arm is suspended with draw sheets to hang below the table's edge. This positioning optimally exposes the lateral chest wall and axilla (*Figure 2*).

Once the patient is positioned, the rib spaces are marked using the angle of Louis as a landmark to identify the 4th intercostal space.

A thorough review of the CT scan may also help delineate rib angles and identify rib spaces. On the coronal views of the CT scan, drawing a straight line from the apex of the heart, passing through the middle of the aortic valve, and extending towards the right rib cage can guide the access incision placement.

Next, the midclavicular line and anterior axillary line are marked. The access incision is then marked at the 4th intercostal space at the anterior axillary line, posterior to the anterior axillary fold. The port sites are planned around the main access port to allow for triangulation. Arm 1 and 4 ports are made 3–4 cm behind the midclavicular line, one or two intercostal space(s) above and below the access incision. The Arm 3 port is placed anterior to the midclavicular line, in the 5th intercostal space. The Arm 2 port (camera) is placed through the access incision (*Figure 3*).

A dual-team approach is typically used: one performs

Table 1 Purposes of preoperative screening

Test	Purpose	Details
CT angiography	Evaluation of peripheral vasculature and surgical planning	Ensures that peripheral vessels can accommodate a minimum of 7 mm diameter, required for 17–19 Fr cannula
	Evaluation of aortic valve location relative to the ribcage	Assesses the position and orientation of the aorta; a short or vertical aorta is a relative contraindication for robotic access
	Mapping of chest anatomy for port placement	Helps plan port positioning for robotic arms to avoid injuring critical structures and optimize ergonomics
Coronary angiogram	Assessment of coronary artery disease	Identifies significant coronary artery disease, potentially requiring revascularization with CABG
	Prefer radial artery access	Radial artery access reduces complications from groin cannulation, especially for patients requiring femoral access during surgery
PFT	Assesses lung function and tolerance for one-lung ventilation	Ensures adequate lung capacity for single-lung ventilation, essential for optimal exposure during surgery
	Evaluation of respiratory reserve	Identifies patients with compromised pulmonary function who may be at higher risk of perioperative respiratory complications
Carotid ultrasound	Evaluates risk for cerebrovascular disease and stroke	Detects carotid artery stenosis or plaques that increase the risk of perioperative stroke
Echocardiography	Detailed assessment of cardiac structure and function	Assesses ventricular function, valve anatomy, and any structural abnormalities to tailor the surgical approach
	TEE or TTE	TEE is used intraoperatively for real-time monitoring, while TTE can provide preoperative insight
Laboratory tests	Baseline health assessment, risk stratification, and coagulation status	Includes CBC for infection/anemia, BMP for kidney function, LFT for liver health, and coagulation profile (PT/INR, aPTT)
BNP/NT-proBNP	Cardiac risk stratification for heart failure	Assesses heart failure severity; elevated levels may indicate high perioperative risk
Blood type and crossmatch	Prepares for potential blood transfusions during surgery	Ensures availability of compatible blood if transfusion is necessary due to intraoperative blood loss
Anesthesia consultation	Tailors the anesthesia plan to the patient's unique needs	Reviews the patient's history and discusses anesthesia strategy, including considerations for one-lung ventilation

aPTT, activated partial thromboplastin time; BNP, brain natriuretic peptide; BMP; CABG, coronary artery bypass grafting; CBC, complete blood count; INR, international normalized ratio; LFT; NT-proBNP, N-terminal pro-brain natriuretic peptide; PFT, pulmonary function test; PT, prothrombin time; TEE, transesophageal echocardiography; TTE, transthoracic echocardiography.

right groin cannulation while the other makes the chest incisions.

Peripheral cannulation

Ultrasound is used to identify common femoral artery bifurcation and helps guide the incision site. A 1–2 cm incision is made above and parallel to the inguinal crease, over the right common femoral vessels, and deepened to expose the anterior aspect of the vessels. Circumferential dissection around the vessels is avoided. Purse-string sutures are placed on the common femoral vein and artery.

Cannulation is performed after systemic heparinization and under transesophageal echocardiogram guidance. The tip of the venous cannula is positioned in the SVC.

Bicaval cannulation is recommended primarily to optimize venous drainage and secondarily to standardize the platform for lateral access robotic cardiac surgery. This allows for the seamless inclusion of concomitant intracardiac procedures (e.g., mitral, tricuspid, Maze).

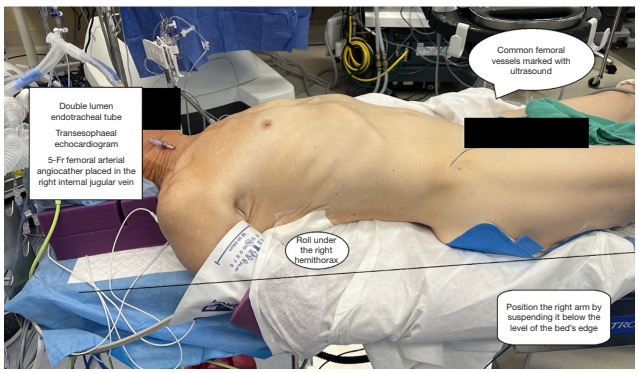

Figure 2 Patient positioning.

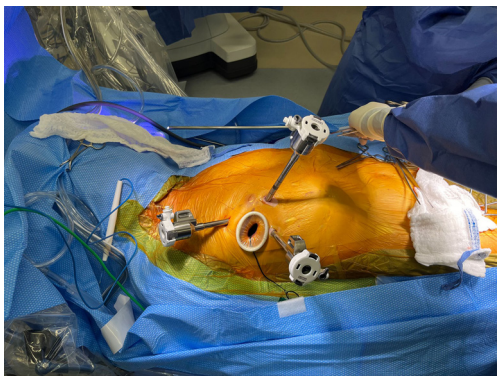

Figure 4 Robotic port placement in relation to access port.

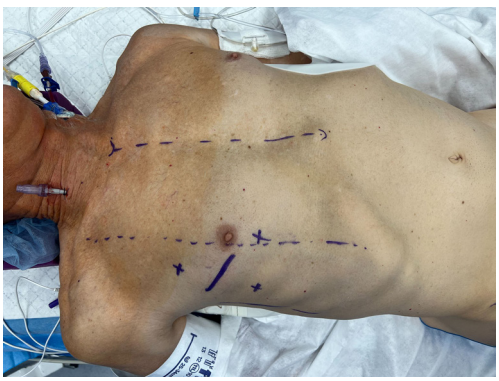

Figure 3 Landmarks and incision planning. 4th intercostal space is marked as the access incision. Robot port sites are placed one space below and above the robot Arms 1 and 4. Arm 3 port is placed in the midclavicular line.

Surgical access

A 4-cm incision is made in the 4th intercostal space and deepened through the soft tissue to the rib cage, posterior to the pectoralis major muscle. A small, soft tissue retractor is then inserted. Optional diaphragmatic retraction is achieved with one or two silk sutures placed through the central tendon with two or three linear bites, which are externalized via the 6th intercostal space in the anterior axillary line using an Endo Close trocar site closure device (Medtronic, Minneapolis, MN, USA).

The pericardial fat pad is excised superiorly to the innominate vein, carefully avoiding the phrenic nerve. The pericardium is incised anteriorly, adjacent to the sternum, using electrocautery. The incision extends superiorly to the aortic reflection, inferiorly toward the diaphragm, and posteriorly to approximately 2 cm anterior to the right phrenic nerve. Three pericardial stay sutures are externalized along the posterior axillary line directly posterior to the access incision using the Endo Close device, creating a pericardial shelf to separate the lung from the access port.

Three robotic ports are positioned circumferentially around the access port according to pre-draping markings, conforming to the established robotic mitral platform configuration. Placing the number one and four port sites two interspaces above and below the working incision creates more working space for the tableside assistant. Two more stab incisions, for later placement of the left ventricular (LV) vent and transthoracic aortic cross-clamp are created now (*Figure 4*).

Cardiopulmonary bypass setup

After systemic heparinization, peripheral cannulation is performed. The cannulae are primed and connected to the cardiopulmonary circuit. The previously placed neck line is connected to the venous line in a Y-configuration. If a 5-Fr right internal jugular catheter was initially placed, it is exchanged for a 20-Fr femoral arterial cannula using the Seldinger technique under transesophageal echocardiographic guidance.

Distal limb perfusion is routinely implemented using a 1/16" line extended from the arterial cannula side port into the distal common femoral artery via a 5-Fr sheath (femoral micropuncture arterial line kit).

Upon initiation of cardiopulmonary bypass, a mattress suture secures a long aortic root cannula to the posterolateral aspect of the distal ascending aorta. A LV vent is then placed in the right superior pulmonary vein, with the aortic root catheter brought through the working

incision and the LV vent externalized through a posterior axillary line stab incision.

To ensure optimal exposure of the aortic root and unobstructed visualization of the valve and annulus, a double-armed 4-0 pledgeted polypropylene suture is superficially placed on the aortic (medial) side of the base of the right atrial appendage. Both needles are passed through the pericardium and diaphragm to facilitate retraction.

Robotic system deployment

The robotic system is docked with the following instrument configuration:

- Left arm (Arm 1): DeBakey forceps;
- Access port (Arm 2): camera;
- Middle arm (Arm 3): long tip forceps;
- Right arm (Arm 4): curved scissors and large needle driver.

The transthoracic clamp is positioned with the slight convex side positioned cephalad to avoid interference with robotic Arm 1. It is placed distal to the antegrade cardioplegia catheter.

Valvectomy

Following aortic cross-clamping, antegrade cold blood micro cardioplegia is administered. For patients with aortic insufficiency, antegrade cardioplegia is attempted while watching for LV distension on echocardiography. The LV vent is set to suction, and the proximal aorta is monitored for distension and pressurization. Ostial cardioplegia is administered if unable to arrest the heart with antegrade cardioplegia.

The aorta is incised obliquely in a hockey-stick fashion, extending transversely toward the main pulmonary artery on the left side and proximally into the center of the non-coronary sinus on the right side to the level of the sinotubular junction.

Robotic instruments are used to excise the valve, adhering to established surgical principles. The long tip forceps optimize exposure, while curved scissors excise leaflets and debride calcific plaques efficiently. The scissor blades are used to elevate the calcium by finding the plane between calcium and annulus, rather than cutting through calcium. The bedside assistant maintains visualization through meticulous suction and irrigation of the aortic root, ensuring complete removal of debris.

Valve replacement

The curved scissors are then swapped with a large needle driver. Circumferential annular sutures are placed clockwise, starting from the non-left commissure to the left-right commissure, then progressing through the right and non-coronary sinuses. Valve sizing is performed using modified sizers, guided by preoperative imaging to prevent patient-prosthesis mismatch.

During passage of the sutures through the prosthetic valve sewing cuff sutures *ex vivo*, the prosthesis is positioned on the annulus under robotic guidance and secured using the long Cor-Knot device (LSI Solutions, Victor, NY, USA).

Completion

The aortotomy is closed in two layers with 4-0 polypropylene sutures, tied in the middle. Standard deairing maneuvers are performed, and warm blood cardioplegia is administered. Pacing wires are placed on the right ventricular surface and medial surface of the right atrium before aortic unclamping.

After robot undocking and successful weaning from cardiopulmonary bypass, decannulation is performed systematically. One or two chest tubes are inserted via robotic port incisions. The pericardium is closed, and all remaining incisions are approximated with absorbable sutures.

Clinical outcomes

The safety and efficacy of RAVR is supported by early data, which indicate that outcomes are at least comparable or perhaps offering some advantages to traditional open and minimally invasive AVR.

The initial report by Badhwar *et al.* described outcomes in 20 patients with a mean age of 67.5±5.4 years and a Society of Thoracic Surgeons (STS) predicted risk of mortality of 1.6%±0.7% (4). The results were excellent, with no 30-day mortality or major morbidity. Patients experienced rapid recovery, with a median hospital length of stay of 4.5 days.

A follow-up single-center study of 50 patients was published in 2022 (11). The study excluded patients with severe peripheral vascular disease, low ejection fraction (<25%), previous cardiac surgery, or those requiring concomitant procedures. Among the included patients,

one-third received mechanical valves, and 14% underwent additional cardiac procedures. The outcomes were exceptional, with no mortality or major morbidity reported. The majority of patients (84%) were extubated in the operating room, with the remaining patients extubated within 4 hours. Complications were minimal, with only one patient requiring a pacemaker and another needing a blood transfusion. The median hospital stay was 5 days. Both intraoperative and 30-day echocardiography showed no evidence of paravalvular leak.

These findings were subsequently validated by a multicenter international study (12). The study included 212 patients across 4 centers spanning four continents. Patient characteristics were consistent across centers, with a mean age of 67 years and a median STS predicted risk of mortality of 1.7%. The results were again excellent, establishing the reproducibility of RAVR, with low rates of complications: stroke and operative mortality (0.9% each), renal failure (1.4%), reoperation (7.6%), and permanent pacemaker placement (2.9%).

Long-term outcomes from an international multicenter experience were recently presented at the 38th Annual Meeting of the European Association for Cardio-Thoracic Surgery in October 2024. The data revealed a 150% increase in the number of participating centers and a 50% growth in RAVR volume, covering all six continents. Outcomes remained consistent, with low rates of mortality (0.7%), stroke (1%), renal failure (1.7%), and pacemaker implantation (2.3%).

Jagadeesan *et al.* recently published a propensity-matched analysis of RAVR versus TAVR in low- to intermediate-risk patients (14). While there was no difference in 30-day mortality between the groups, TAVR patients experienced higher rates of permanent pacemaker implantation (7.6% *vs.* 2.1%), vascular complications (9.0% *vs.* 0%), and paravalvular leak (21.5% *vs.* 0.7%). At one-year follow-up, TAVR patients showed significantly higher mortality (12.5% *vs.* 1.4%) and paravalvular leak rates (32.6% *vs.* 2.3%), although mean valve gradients were similar between groups. The RAVR group had more bicuspid valves (46.5% *vs.* 13.8%) and experienced more post-operative hemothorax requiring reoperation (5.6%), while the TAVR group had a trend toward higher stroke rates (4.2% *vs.* 0.7%).

The case for standardizing the lateral access approach to cardiac surgery

The lateral access RAVR presents a compelling alternative to traditional sternotomy and anterior chest or minimally invasive sternotomy techniques, offering potential advantages in both surgical execution and patient outcomes. By leveraging anatomical benefits and procedural consistency, this platform underscores the importance of standardization in robotic cardiac surgery.

Enhanced anatomical access

The lateral transaxillary incision capitalizes on the significantly wider intercostal spaces in this region. This wider anatomical window eliminates the need for rib resection or aggressive rib spreading, thereby reducing the risk of trauma to surrounding structures. Additionally, this access improves the ease of prosthetic valve delivery through the incision while preserving the essential technical aspects of traditional open SAVR.

Muscle-sparing incision

The incision is deliberately "muscle-sparing", with meticulous care taken to stay posterior to the pectoralis major muscle while deepening the incision to the rib cage. Preserving the integrity of the muscle ensures better postoperative recovery by minimizing pain, maintaining chest wall strength, and reducing the risk of functional impairment. This approach demonstrates a commitment to reducing the invasiveness of the procedure while maintaining excellent surgical exposure.

Procedural homogeneity across robotic cardiac surgery

The lateral transaxillary platform is identical to that used for robotic mitral valve surgery, creating an opportunity for standardization across robotic cardiac procedures. This procedural homogeneity minimizes the learning curve for surgical teams, allowing them to master a single access technique applicable to various cardiac surgeries.

Robotic cardiac surgery is not just a series of individual operations with different approaches; it is a comprehensive platform. By unifying the approach, the lateral transaxillary platform used for RAVR simplifies surgical planning and execution, enhancing predictability and efficiency. Procedures that can be performed via this platform include mitral and tricuspid valve repair or replacement, Maze procedures, left atrial appendage obliteration, atrial septal defect repair, ventricular septal defect repair, intracardiac tumor resection, epicardial pacemaker lead placement,

septal myectomy, and even aortic valve repair.

The lateral transaxillary approach to RAVR sets a new benchmark in minimally invasive cardiac surgery. By improving technical execution, enhancing ergonomic efficiency, and simplifying procedural standardization, it potentially maximizes surgical outcomes while minimizing patient trauma.

Challenges

Learning curve

The successful implementation of RAVR requires unique skill sets. For surgeons accustomed to traditional open AVR, the transition to robotic procedures may represent a significant learning curve. Mastering robotic techniques, particularly through the lateral approach, requires additional training and ongoing practice to maintain proficiency. This should start with robotic mitral valve surgery and mitral replacement prior to commencement of RAVR as the skillset is very similar (12). For teams with an extensive experience in mitral surgery, the learning curve may be as little as 5–10 cases (4).

Cost and accessibility

The demonstrated clinical benefits shown in studies, including lower one-year mortality rates and fewer complications compared to TAVR, make a compelling case for expanding RAVR programs. As robotic systems become more prevalent across surgical specialties, hospitals can leverage existing infrastructure and surgical expertise to add RAVR capabilities. The learning curve and costs could be distributed across multiple surgical service lines, making the investment more feasible. Additionally, as more surgeons are trained in robotic techniques during their residency and fellowship programs, the specialized workforce needed for RAVR may naturally grow. With potential benefits in patient outcomes and the broader trend toward minimally invasive approaches, RAVR could follow a similar adoption trajectory to other robotic procedures that have become standard of care, moving from select centers to wider availability as experience grows and costs optimize over time.

Future prospects and the path to routine use

Technological advancements and improved accessibility

As robotic technology continues to evolve, advancements in robotic systems will likely address current limitations and expand the accessibility of RAVR. Future iterations of robotic platforms may incorporate features such as enhanced haptic feedback, improved visualization, and increased automation, enabling even greater precision and safety.

Surgeon training and standardization

To realize the full potential of RAVR, training programs and standardized protocols must become more widespread. Establishing structured robotic cardiac surgery fellowships and training pathways can create a consistent pipeline of skilled surgeons who are capable of performing RAVR safely and effectively. As more surgeons gain proficiency, surgical times and complication rates are expected to decrease, making the procedure more feasible for routine use.

Adoption of the established standardized approach for RAVR, including patient selection criteria, procedural protocols, and postoperative care, will assist in obtaining predictable and reproducible outcomes (12). Developing and disseminating these guidelines can help ensure that RAVR is performed consistently and safely, reducing variability in outcomes across institutions. Furthermore, collaboration between institutions to share data, experiences, and best practices can promote continuous improvement and foster a culture of excellence in robotic cardiac surgery.

Large-scale, multicenter trials may provide a solid evidence base for lateral access RAVR, further establishing its clinical value. Research that tracks patient outcomes over extended periods will be particularly important in assessing valve durability and overall survival, helping to determine whether RAVR can match or exceed the long-term outcomes of traditional AVR and TAVR.

Potential for complex robotic aortic surgery

RAVR is currently established for straightforward valve replacements, however emerging experience led by the West Virginia team has established the feasibility of additional procedures such as aortic root enlargement, aortic valve repair and trans aortic septal myectomy or LV mass excision (15-17). This success opens the door to potentially expanding robotic techniques to other complex aortic procedures in the future, including root replacement, valve resuspension, annular enlargement, and aortic aneurysm repair. The precision offered by robotic assistance could be particularly valuable in these technically demanding

procedures where meticulous suture placement and tissue handling are critical. These developments would represent a significant evolution in aortic surgery, potentially offering patients the benefits of robotic assistance—including smaller incisions and faster recovery—even for procedures that traditionally require full sternotomy. Although most of these applications remain hypothetical and require careful research and validation, the successful implementation of robotic aortic root enlargement provides an encouraging proof of concept for future expansion.

Conclusions

The emergence and reproducibility of RAVR represents a significant advancement in cardiac surgery, supported by compelling clinical outcomes. The standardization of the lateral transaxillary robotic platform across various cardiac procedures not only optimizes surgical workflow but also provides a foundation for expanding robotic cardiac surgery programs beyond isolated valve replacement.

While technical complexity and a learning curve may present initial challenges, these obstacles appear readily surmountable through structured training programs and clinical experience. The successful implementation of complex procedures such as aortic root enlargement demonstrates the platform's potential for expansion into more advanced aortic surgeries.

As robotic systems become more prevalent and surgical expertise grows, RAVR is well-positioned to follow the adoption trajectory of other minimally invasive techniques that have become standard of care. This evolution represents a fundamental shift in cardiac surgery, offering patients the benefits of minimally invasive approaches while maintaining the durability of traditional surgical valve replacement. The continued refinement and expansion of RAVR techniques, coupled with ongoing technological innovations, suggests that this approach will play an increasingly central role in the future of aortic valve disease treatment.

Acknowledgments

None.

Footnote

Funding: None.

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

Ethical Statement: The West Virginia University Institutional Review Board approved this study with waiver of consent (Protocol #2210660362).

References

1. Nkomo VT, Gardin JM, Skelton TN, et al. Burden of valvular heart diseases: a population-based study. Lancet 2006;368:1005-11.
2. Kanwar A, Thaden JJ, Nkomo VT. Management of Patients With Aortic Valve Stenosis. Mayo Clin Proc 2018;93:488-508.
3. Ilcheva L, Risteski P, Tudorache I, et al. Beyond Conventional Operations: Embracing the Era of Contemporary Minimally Invasive Cardiac Surgery. J Clin Med 2023;12:7210.
4. Badhwar V, Wei LM, Cook CC, et al. Robotic aortic valve replacement. J Thorac Cardiovasc Surg 2021;161:1753-9.
5. Smith CR, Leon MB, Mack MJ, et al. Transcatheter versus surgical aortic-valve replacement in high-risk patients. N Engl J Med 2011;364:2187-98.
6. Kim KM, Arghami A, Habib R, et al. The Society of Thoracic Surgeons Adult Cardiac Surgery Database: 2022 Update on Outcomes and Research. Ann Thorac Surg 2023;115:566-74.
7. Wyler von Ballmoos MC, Kaneko T, Iribarne A, et al. The Society of Thoracic Surgeons Adult Cardiac Surgery Database: 2023 Update on Procedure Data and Research. Ann Thorac Surg 2024;117:260-70.
8. Folliguet TA, Vanhuyse F, Magnano D, et al. Robotic aortic valve replacement: case report. Heart Surg Forum 2004;7:E551-3.
9. Folliguet TA, Vanhuyse F, Konstantinos Z, et al. Early experience with robotic aortic valve replacement. Eur J

Cardiothorac Surg 2005;28:172-3.
10. Balkhy HH, Lewis CTP, Kitahara H. Robot-assisted aortic valve surgery: State of the art and challenges for the future. Int J Med Robot 2018;14:e1913.
11. Wei LM, Cook CC, Hayanga JWA, et al. Robotic Aortic Valve Replacement: First 50 Cases. Ann Thorac Surg 2022;114:720-6.
12. Badhwar V, Pereda D, Khaliel FH, et al. Outcomes following initial multicenter experience with robotic aortic valve replacement: Defining a path forward. J Thorac Cardiovasc Surg 2024;167:1244-50.
13. Chemtob RA, Wierup P, Mick SL, et al. A conservative screening algorithm to determine candidacy for robotic mitral valve surgery. J Thorac Cardiovasc Surg 2022;164:1080-7.
14. Jagadeesan V, Mehaffey JH, Darehzereshki A, et al. Robotic Aortic Valve Replacement vs Transcatheter Aortic Valve Replacement: A Propensity-Matched Analysis. Ann Thorac Surg 2024. [Epub ahead of print]. doi: 10.1016/j.athoracsur.2024.10.013.
15. Darehzereshki A, Wei LM, Comas G, et al. Feasibility and safety of robotic aortic root enlargement in conjunction with robotic aortic valve replacement. JTCVS Tech 2023;22:178-80.
16. Wei LM, Darehzereshki A, Comas GM, et al. Robotic-assisted repair of aortic valve leaflet prolapse by cusp plication and annuloplasty. JTCVS Tech 2023;21:59-61.
17. Mitchell KG, Podgorsek B, Fiorito DE, et al. Robot-Assisted Resection of Left Ventricular Papillary Fibroelastoma Arising From the Mitral Chordal Apparatus. Innovations (Phila) 2023;18:100-2.

Cite this article as: Murtaza G, Wei L. Lateral access fully robotic aortic valve replacement "RAVR": from novel to normal. Ann Cardiothorac Surg 2025;14(3):192-201. doi: 10.21037/acs-2025-ravr-0049

