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Short Commentary

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The future of minimally invasive aortiv valve replacement

Adam R Kowalówka, MD, PhD*[1,2]

[1]Department of Cardiac Surgery, Upper-Silesian Heart Center, Katowice, Poland.

[2]Department of Cardiac Surgery, Medical University of Silesia, Faculty of Medical Sciences, Katowice, Poland.

Introduction

Aortic valve disease represents the most prevalent valvular pathology in developed countries, with its incidence expected to rise substantially as populations age [1]. While conventional Aortic Valve Replacement (AVR) through full sternotomy has achieved remarkable outcomes, with contemporary perioperative mortality rates below 2% in low-risk patients [2], the field has witnessed a paradigm shift toward minimally invasive approaches. The convergence of surgical innovation, technological advancement, and evolving patient demographics is reshaping the landscape of aortic valve surgery, positioning Minimally Invasive Aortic Valve Surgery (MIAVS) at the forefront of this transformation.

Current state of minimally invasive approaches

Minimally invasive aortic valve surgery encompasses multiple surgical approaches, primarily partial upper ministernotomy and right anterior minithoracotomy, which have become established alternatives to conventional sternotomy [3]. Recent propensity-matched analyses demonstrate that MIAVS offers comparable perioperative, operative, and 5-year survival outcomes to conventional approaches [4]. A multicenter meta-analysis revealed that MIAVS significantly reduces postoperative atrial fibrillation rates, shortens hospital length of stay, and provides superior cosmetic results without compromising safety or efficacy [5].

The introduction of novel access routes, such as the right transaxillary approach, has further expanded the minimally invasive armamentarium. Early reports demonstrate excellent clinical outcomes with low stroke and mortality rates, even during the initial implementation phase at experienced centers [6]. These findings suggest a potentially lower learning curve than previously anticipated, encouraging broader adoption across cardiac surgical programs.

The TAVR challenge and surgical response

The emergence of Transcatheter Aortic Valve Replacement (TAVR) has fundamentally altered treatment algorithms for aortic stenosis. The landmark PARTNER 3 trial's 7-year follow-up data revealed comparable clinical, hemodynamic, and valve durability outcomes between TAVR and surgical AVR in low-risk patients [7]. The 2025 ESC/EACTS guidelines reflect this evolution, emphasizing Heart Team decision-making that considers clinical characteristics, anatomical features, relative risks, and informed patient preferences [8].

However, TAVR's limitations remain clinically relevant. Paravalvular leak, though typically mild, occurs more frequently following TAVR than surgical replacement [7]. The inability to perform concomitant procedures—including surgical ablation for atrial fibrillation, mitral or tricuspid valve interventions, or coronary artery bypass—represents a significant constraint in patients with multivalvular or complex cardiac disease [9]. Additionally, concerns regarding long-term durability beyond 10 years and the feasibility of valve-in-valve reinterventions continue to favor surgical approaches in younger patients with extended life expectancies [10].

Technological innovation and future directions

Robotic-assisted aortic valve surgery

The integration of robotic assistance represents a quantum leap in surgical precision and capability. While FDA-approved since

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Correspondance: *Adam R Kowalówka, Department of Cardiac Surgery, Upper-Silesian Heart Center, & Medical University of Silesia, Faculty of Medical Sciences, Upper-Silesian Heart Center, Ziołowa 45-47, 40-635 Katowice, Poland.*

Tel: +48-32-359-86-44; Email: adam.kowalowka@sum.edu.pl

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2002, robotic aortic valve surgery remained in its infancy until recently [11]. Current systems enable surgeons to perform highly complex procedures with enhanced precision, three-dimensional visualization, and tremor filtration, potentially reducing human error and improving patient outcomes [12].

Robotic platforms facilitate a truly endoscopic approach via the same transaxillary working incision used for valve replacement, enabling concomitant procedures including maze operations, aortic root enlargement, septal myectomy, and multivalve interventions [12]. This versatility addresses a critical limitation of TAVR while maintaining the benefits of minimal invasiveness. As institutional experience accumulates and learning curves flatten, robotic AVR is positioned to become the standard approach for selected patients requiring surgical intervention.

Artificial intelligence and predictive modeling

Artificial intelligence is revolutionizing preoperative planning and intraoperative decision-making. AI-powered echocardiographic analysis accelerates and enhances the accuracy of valve abnormality detection [13]. Predictive modeling analyzes comprehensive patient datasets to recommend optimal treatment strategies, while virtual surgery planning simulates TAVR and surgical procedures before actual intervention, potentially reducing complications and improving outcomes [14].

Machine learning algorithms can identify subtle patterns in imaging data, surgical technique, and patient characteristics that predict long-term outcomes with unprecedented accuracy. This capability will enable increasingly personalized approaches to valve intervention, matching specific surgical techniques and prostheses to individual patient phenotypes.

Sutureless and rapid-deployment valves

Sutureless bioprosthetic valves represent a convergence of surgical and transcatheter technologies. These devices significantly reduce cardiopulmonary bypass and aortic cross-clamp times compared to conventional sutured valves, with multicenter European trials reporting mean cross-clamp times of 34 minutes [15]. The facilitation of right anterior thoracotomy approaches through sutureless valve technology has expanded MIAVS applicability, though concerns regarding paravalvular leak rates and long-term durability require continued surveillance [16].

Bioengineered and regenerative valve technologies

The frontier of valve replacement lies in regenerative medicine and tissue engineering. Stem cell-based approaches aim to create living valve substitutes capable of growth, remodeling, and self-repair [17]. Bioengineered valves incorporating regenerative properties to repair minor damage autonomously represent a paradigm shift from prosthetic replacement to biological restoration. While these technologies remain largely experimental, early preclinical studies demonstrate promising hemodynamic performance and reduced immunogenicity compared to conventional bioprostheses.

Evolving patient demographics and selection criteria

Contemporary cardiac surgical practice confronts an aging, increasingly comorbid patient population. The 2024 ACC/AHA valvular and structural heart disease performance measures emphasize documentation of risk assessment and Heart Team discussion before surgical or transcatheter AVR, recognizing the complexity of modern decision-making [18]. For octogenarians and nonagenarians, TAVR has emerged as the predominant intervention. However, for younger patients, particularly those under 65 years with preserved life expectancy, surgical AVR—especially via minimally invasive approaches—offers potential advantages including superior hemodynamics, lower paravalvular leak rates, and the flexibility to address concomitant cardiac pathology [19].

The future will likely witness increasingly nuanced patient stratification, with biomarkers, genetic profiles, and AI-driven risk prediction guiding individualized treatment algorithms. Minimally invasive surgical approaches will occupy a critical niche for patients who benefit from surgical precision and versatility while desiring reduced surgical trauma and accelerated recovery.

Integration of multimodal imaging

Advanced cardiac imaging modalities are transforming surgical planning and execution. High-resolution CT angiography enables precise preoperative assessment of vascular anatomy, aortic root dimensions, and optimal surgical access routes [20]. Intraoperative transesophageal echocardiography provides real-time feedback on valve positioning, paravalvular leak assessment, and immediate hemodynamic evaluation. The integration of three-dimensional echocardiography with augmented reality systems may soon allow surgeons to visualize cardiac anatomy with unprecedented clarity during minimally invasive procedures.

Fusion imaging techniques combining multiple modalities will facilitate hybrid approaches, where preoperative CT reconstructions guide intraoperative decisions, potentially reducing operative times and enhancing procedural accuracy. This technological synergy between imaging and surgical execution will be essential for the continued refinement of minimally invasive techniques.

Challenges and future perspectives

Despite remarkable progress, several challenges persist. Minimally invasive approaches require specialized training and infrastructure, potentially limiting accessibility to high-volume centres with dedicated expertise. Longer operative times, particularly during the learning curve phase, may increase cardiopulmonary bypass duration and associated risks [21]. Cost considerations, including robotic system acquisition and maintenance, remain substantial barriers to widespread adoption.

Future research must address optimal patient selection criteria through prospective, multicenter registries and randomized controlled trials. Head-to-head comparisons between minimally invasive surgical approaches and TAVR in intermediate-risk, younger patients will inform evidence-based guidelines. Long-term durability data extending beyond 10-15 years are essential for establishing minimally invasive surgery's role in younger populations.

Conclusion

The future of minimally invasive aortic valve surgery is characterized by technological convergence, surgical innovation, and personalized medicine. As robotic platforms mature, artificial intelligence enhances decision-making, and regenerative technologies emerge from experimental phases, minimally invasive surgical approaches will increasingly complement and, in selected populations, potentially surpass transcatheter interventions. The optimal treatment paradigm will likely involve a spectrum of interventions—from fully percutaneous TAVR for elderly, high-risk patients to robotic-assisted minimally invasive surgery for younger, lower-risk individuals requiring durable solutions with the flexibility for concomitant procedures.

The Heart Team model, incorporating cardiac surgeons, interventional cardiologists, imaging specialists, and AI-driven decision support systems, will orchestrate this complex treatment landscape. Ultimately, the goal remains unchanged: delivering safe, durable, patient-centered care that optimizes both immediate outcomes and long-term quality of life. Minimally invasive aortic valve surgery, empowered by emerging technologies and guided by evidence-based practice, is poised to fulfill this mission for generations to come.

Declarations

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