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Review

Surgical Aortic Valve Replacement: Current Status and Future Perspectives in the Era of Catheter-Based Therapies

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Abstract

Aortic stenosis (AS) is the most prevalent valvular heart disease in the developed world. Over the past two decades, the treatment of AS has undergone a profound transformation with the introduction of transcatheter aortic valve replacement (TAVR). TAVR has evolved from being an alternative treatment for patients with a prohibitive risk for surgical aortic valve replacement (SAVR), to becoming the first-line therapy for low-surgical-risk patients over 75 years old. Recent data have shown a significant increase in TAVR procedures compared to SAVR, surpassing both isolated SAVR and all SAVR interventions in most registries worldwide. Nevertheless, SAVR remains a key option in clinical practice, especially for younger patients with a longer life expectancy, patients with a complex aortic anatomy unsuitable for TAVR, and patients needing additional surgical interventions. The aim of this review was to examine the current state and future perspectives of SAVR in the expanding era of transcatheter therapies. While TAVR is expected to expand further, SAVR will likely continue to play an important role in some clinical scenarios. A multidisciplinary approach by a "Heart Team" that considers specific clinical and anatomical factors is crucial for ensuring the best long-term outcome for each patient.

Keywords

aortic stenosis (AS); transcatheter aortic valve replacement (TAVR); surgical aortic valve replacement (SAVR); life expectancy; younger patients; future perspectives; Heart Team

Introduction

Aortic stenosis (AS) is the most prevalent valvular heart disease in developed countries and represents one of the most critical cardiovascular conditions in the aging population. The Helsinki Aging Study provided evidence of increased calcification and degeneration of the aortic valve with increasing age, affecting over 3% of individuals aged >75 years and up to 10% of those aged >80 years [1]. This increase is largely attributed to demographic aging and the growing burden of comorbidities, including hypertension, diabetes, dyslipemia and chronic kidney disease [2]. Degenerative AS is characterized by the gradual accumulation of calcium in the valve leaflets over many years, ultimately leading to obstruction of left ventricular outflow which if left untreated can result in heart failure and death [3].

Surgical aortic valve replacement (SAVR) has traditionally been the cornerstone of treatment for symptomatic severe AS, with well-established long-term outcomes in terms of survival, symptom relief, and prosthetic valve durability [4]. Advances in surgical techniques, prosthesis design, and perioperative care have further improved the safety profile of SAVR, particularly in younger patients, those with complex aortic anatomy, or those requiring concomitant cardiac surgery [5].

The advent of transcatheter aortic valve replacement (TAVR) over the past two decades has revolutionized the therapeutic landscape of AS. Initially developed for patients with a prohibitive or high surgical risk, TAVR is now a validated alternative across all surgical risk categories. Randomized clinical trials such as PARTNER 3 and Evolut Low Risk have demonstrated non-inferiority of TAVR compared with SAVR in selected, low-risk patient groups [6,7]. As a result, current guidelines recommend TAVR as the preferred therapy for patients aged ≥75–80 years and with favorable transfemoral access anatomy [8].

The use of TAVR has seen rapid expansion thanks to increasing operator experience and continuous technological refinement. In several healthcare systems, the number of annual TAVR procedures now surpasses that of isolated SAVR [9]. This trend underscores the success of transcatheter therapies, but also raises important questions regarding the future role of SAVR. Although it has been suggested that SAVR may become obsolete, the current evidence suggests otherwise [10].

Despite the appeal of TAVR as a minimally invasive alternative to SAVR, there are still a number of key uncertainties. Chief among these is the long-term durability of transcatheter bioprosthesis, particularly in younger patients with longer life expectancy [11]. Additionally, TAVR is associated with several procedure-specific complications, such as conduction disturbances requiring pacemaker implantation, paravalvular leak (PVL), impaired coronary access, prosthesis–patient mismatch (PPM), and suboptimal outcomes in anatomically complex situations such as bicuspid aortic valves or annuloaortic ectasia [11].

SAVR remains the gold standard in specific clinical scenarios, including active infective endocarditis, significant aortopathy requiring ascending aortic replacement, and cases of extensive annular calcification [12]. Furthermore, lifetime treatment planning is essential in patients <65 years. This includes evaluation of anatomical suitability, comorbidities, and anticipation of future interventions such as valve-in-valve procedures within a strategic and staged approach [12,13].

In parallel with the evolution of transcatheter and surgical techniques, current literature indicates a growing interest in the optimal timing of aortic valve intervention. Several recent publications advocate for a more proactive approach in the selection of asymptomatic patients, or in patients with a reduction in echocardiographic global longitudinal strain, which indicates early changes in contractile function before deterioration of left ventricle (LV) ejection fraction [14]. Early treatment may preserve left ventricular remodeling and prevent irreversible myocardial fibrosis, especially in younger individuals with long life expectancy and evidence of subclinical damage [15]. This emerging perspective has led to a re-evaluation of the traditional "watchful waiting" strategy, and reinforces the need for dynamic, patient-specific algorithms that integrate imaging markers and biomarkers. Current international guidelines recommend their use for risk stratification [16].

In this evolving context, SAVR should not be viewed as having a diminished role, but rather as needing to adapt to meet new clinical challenges. A tailored, patient-centered approach guided by a multidisciplinary Heart Team is essential to optimize outcomes [17]. Shared decision-making that weighs both short-term procedural risks and long-term management goals remains at the heart of modern aortic valve therapy [6].

This review aims to provide a comprehensive, critical analysis of the current role of SAVR in the TAVR era. We present contemporary guidelines, analyze key clinical trials and registries, and discuss anatomical and patient-specific factors that influence the choice of therapy. The overall focus is on lifetime management strategies for aortic valve disease.

Current Status of TAVR vs SAVR

Recommendations According to International Guidelines

Over the past two decades, TAVR has dramatically reshaped the management of severe AS, evolving from an experimental option reserved for inoperable patients, to a standard therapy across the full spectrum of surgical risk. This expansion has been driven by robust randomized trials, the evolution of medical devices, and growing clinical experience [18,19]. Nonetheless, SAVR remains the reference standard in many situations, especially in younger and anatomically complex patients [20].

Current international guidelines reflect this paradigm shift. According to guidelines from the 2020 American College of Cardiology (ACC)/American Heart Association (AHA) and the 2021 European Society of Cardiology (ESC)/European Association for Cardio-Thoracic Surgery (EACTS), TAVR is preferred in patients aged ≥75–80 years and in those with high surgical risk, suitable transfemoral access, and a life expectancy of <10–15 years. SAVR remains indicated for younger patients, particularly those aged <65 years, with longer life expectancy (>20 years) or unfavorable anatomy for TAVR, as well as those requiring concomitant procedures or presenting with complex aortic root anatomy [18,21,22]. However, several gray zones remain. In patients aged 65–75 years or at intermediate surgical risk, both strategies are acceptable, and individualized decision-making, integration of comorbidities, anatomical considerations, and patient preference are essential [23].

Both guidelines underscore that SAVR remains the treatment choice in patients with bicuspid aortic valves, ascending aortic aneurysms, extensive annular or LVOT calcification, or coronary artery disease (CAD) requiring bypass [22,24]. Due to concerns about the durability of bioprosthetic valves, mechanical valves are still indicated in patients aged <50–60 years with acceptable anticoagulation profiles. In this context, there has been an increasing trend toward biological prostheses, even in younger patients, due to comparable mortality between mechanical and bioprosthetic SAVR in patients aged 50–69, and the burdens of lifelong anticoagulation [18].

Importantly, the American guidelines highlight the need for life-long management strategies, especially in younger patients. These should consider valve durability, the feasibility of future valve-in-valve procedures, and access to coronary arteries [22].

Despite the increasing number of TAVRs performed worldwide, the guidelines stress that SAVR is not obsolete. Instead, the field has evolved toward personalized treatment pathways that are determined by clinical, anatomical, and procedural factors [20]. Achieving optimal outcomes ultimately relies on shared decision-making and Heart Team-based evaluations that balance short-term procedural success with long-term durability, risk of re-intervention, and the overall patient trajectory.

Evidence From Randomized Clinical Trials

Multiple randomized controlled trials have established the clinical efficacy and safety of TAVR across different risk categories. The PARTNER 1 trial demonstrated a survival advantage for TAVR in inoperable patients, and non-inferiority compared to SAVR in high-risk patients. The PARTNER 2A and SURTAVI trials expanded this evidence to intermediate-risk populations. Subsequently, the PARTNER 3 and Evolut Low Risk trials showed that TAVR had non-inferiority to SAVR in carefully selected low-risk patients with favorable anatomy [17,19,23].

TAVR was associated with shorter hospital stays, lower rates of major bleeding, and fewer episodes of new-onset atrial fibrillation [7]. However, these advantages were offset by higher rates of permanent pacemaker implantation, PVL, and potential difficulty in coronary access, particularly with self-expanding prostheses [11]. Moreover, younger patients were under-represented in these trials (median age 74 years), and firm evidence for the use of bioprosthesis in younger patients is still lacking [20].

The NOTION trial is the only RCT with 10-year follow-up data. In this randomized trial comparing TAVI to SAVR in predominantly low-risk patients, the 10-year results showed similar rates of all-cause mortality between the two groups (TAVI: 51.8% vs. SAVR: 52.6%). Importantly, the incidence of structural valve deterioration (SVD) was significantly lower in the TAVR group (13.9%) compared to the SAVR group (28.3%; $p < 0.001$). However, bioprosthetic valve failure (BVF), which includes reintervention, severe hemodynamic dysfunction, or valve-related death, was comparable between groups (TAVR: 8.7%, SAVR: 10.5%) [25]. These findings highlight the limitations of current durability definitions and the need for harmonized endpoints [26,27]. Regarding hemodynamic performance, transcatheter valves showed consistently lower mean transvalvular gradients throughout the follow-up period, with a mean gradient of 8.1 mmHg in the TAVR group versus 12.7 mmHg in the SAVR group at 10 years. This suggests sustained superior hemodynamics in TAVR prostheses [25].

Ongoing trials such as NOTION-2 that are specifically designed to evaluate TAVR in younger patients may help to clarify its long-term performance, thereby guiding future recommendations [28].

Emerging data also reveal that a significant proportion of low-risk TAVR candidates have coexisting CAD. Unlike SAVR, which allows concomitant coronary artery bypass grafting (CABG), the ability of TAVR to address CAD is more restricted, and coronary re-access post-TAVR remains an unresolved issue [19]. Moreover, clinical trials have not clearly established which coronary lesions should be treated before TAVR [21].

Trends in International Registries

Real-world data confirm the increasing adoption of TAVR. In countries such as the United States and Germany, TAVR volumes have now surpassed those of isolated SAVR, particularly since 2018. In east Denmark, nearly two-thirds of isolated severe AS patients are treated with TAVR. This shift has been most pronounced among elderly and low-risk patients, with the median age of TAVR recipients decreasing over the past decade [29].

Nevertheless, SAVR remains the predominant approach in patients aged <65 years and in those with bicuspid valves, active endocarditis, extensive valve or annular calcification, or when multiple procedures (e.g., ascending aortic replacement, multivalvular disease, or concomitant CAD) are indicated [10]. In high-volume surgical centers, outcomes after SAVR have improved significantly over time, further reinforcing its role in complex or younger patients [29].

The Ross procedure, in particular, has gained renewed interest in young adults and offers excellent long-term survival and hemodynamic outcomes [28,30,31]. Additionally, some registries have reported increasing adoption of biological valves over mechanical ones, even in patients aged 50–69 years, suggesting a shift in the balance between valve durability and quality of life considerations [32,33].

Limitations of TAVR in Clinical Practice

Despite its minimally invasive nature and excellent short-term outcomes, TAVR has several limitations, particularly in younger patients with longer life expectancy and complex anatomy [34]. In the absence of clear recommendations for certain anatomic scenarios, it is essential to understand both the limitations and advantages of each strategy, and how they can be integrated within the lifetime management of patients [35,36]. In this context, the role of the Heart Team becomes central [37].

Durability of Transcatheter Bioprosthesis

Valve durability is arguably the most critical limitation of TAVR in younger patients, who have a projected life expectancy that often exceeds 20 years. The risk of re-intervention if TAVR valves fail prematurely is therefore substantial. For a 65-year-old patient with a life expectancy close to that of the general population, the durability of TAVR would ideally need to be at least 15 years in order to avoid early re-intervention [19,34].

TAVR prostheses have shown good mid-term outcomes (5–8 years) in elderly and high-risk populations where valve longevity often exceeds life expectancy. However, long-term outcomes (i.e., beyond 10–15 years) and evidence from younger, low-risk cohorts remains to be determined [5]. Most TAVR trials to date have included patients with a median age of >75 years, and very few patients aged <65 years have been systematically studied. Increased calcium metabolism, collagen cross-linking, and leaflet stress may accelerate valve degeneration in younger patients [11].

Factors that are unique to TAVR, such as valve crimping, asymmetric deployment, non-circular annular expansion, and residual PVL may predispose to early degeneration [34]. Microscope studies suggest that crimping may damage leaflet collagen and promote thrombosis and early calcification.

Although the NOTION trial reported comparable valve performance between TAVR and SAVR at 8–10 years follow-up, definitions of structural valve deterioration (SVD) vary across studies [10]. In contrast, the durability of surgical bioprostheses is better established, with many valves lasting 15–20 years [4].

Conduction Disturbances and Pacemaker Implantation

One of the most frequent complications following TAVR is conduction system injury. This includes new-onset left bundle branch block (LBBB) and the need for permanent pacemaker implantation, both of which occur at significantly higher rates than with SAVR. In PARTNER 3 and Evolut Low Risk, the 30-day pacemaker implantation rate ranged from 6.5% to 34%, especially with self-expanding (SE) valves and deeper implantation depths [19].

The new persistent LBBB has been identified as a predictor of increased mortality, especially when associated with balloon-expandable (BE) valves [38]. In contrast, SE valves are more frequently associated with direct mechanical compression of the conduction system, resulting in even higher rates of pacemaker implantation. Accumulating evidence indicates that pacemaker implantation after TAVR is associated with significant clinical consequences. This includes pacing-induced dyssynchrony, which can lead to left ventricular remodeling, reduced ejection fraction, and the development of heart failure. Furthermore, a pacing dependency of >40% is associated with higher risks of rehospitalization and all-cause mortality [39].

The elevated risk of conduction disturbances must be carefully considered when deciding between TAVR and SAVR, particularly in younger patients. In this context, SAVR continues to offer a more favorable conduction safety profile [19,38].

Paravalvular Leak

PVL remains a distinctive and potentially significant complication of TAVR, but is less frequently observed after SAVR. It is the leading cause of post-procedural aortic regurgitation in TAVR, with mild PVL observed in more than one-third of patients. It is also associated with increased morbidity and mortality, especially when moderate to severe in degree [40]. Moreover, the presence of PVL may complicate the interpretation of imaging and the application of future valve-in-valve procedures [9].

Whereas SAVR involves complete excision of native leaflets and thorough decalcification of the aortic annulus and left ventricular outflow tract, TAVR is constrained by residual native anatomy that may interfere with optimal prosthesis expansion and sealing [41]. Prosthesis design also plays a key role, with PVL being more frequent in SE transcatheter heart valves compared to BE devices [11]. Newer-generation BE valves with outer sealing skirts display a reduced incidence of PVL, but still exceeding that of SAVR [5].

Coronary Access and Risk of Myocardial Infarction

Coronary re-access post-TAVR remains a major concern, particularly in younger patients with a higher risk of progressive CAD. CAD coexists with AS in 40–80% of patients, and acute coronary syndrome following TAVR has been reported in up to 10% of patients within the first two years [19,40].

Coronary access after TAVR poses unique anatomical and technical challenges, including low coronary height (<12 mm), small sinus of Valsalva (<30 mm), commissural misalignment, and tall stent frames (particularly in SE or supra-annular valves) [34].

Although quite rare (<1%), acute or delayed coronary obstruction is potentially fatal, with delayed presentation due to thrombus or tissue ingrowth [40]. Consequently, the likelihood of future coronary interventions must be integrated into procedural decision-making algorithms, particularly for younger individuals [9].

Prosthesis–Patient Mismatch

Prosthesis–patient mismatch (PPM) occurs when the effective orifice area (EOA) of a normally functioning valve prosthesis is too small relative to the patient's body surface area, typically defined as an indexed EOA <0.65 cm^2/m^2. PPM is more frequently observed after SAVR, especially in patients with small aortic annuli [19].

PPM is linked to adverse clinical outcomes, including increased mortality, structural valve deterioration, and rehospitalization for heart failure, particularly within 5-years of follow-up. The impact is particularly pronounced in younger patients (<70 years) and in those with high BMI [42]. Supra-annular SE TAVR valves generally offer superior hemodynamic performance compared to BE valves and SAVR, although newer-generation BE devices may have reduced EOA due to external sealing skirts, potentially increasing PPM [43].

Younger age is considered a risk factor for PPM in TAVR, warranting the consideration of surgical aortic root enlargement in such cases to optimize prosthesis size and future valve-in-valve options [44].

Bicuspid Aortic Valve Anatomy

Bicuspid aortic valve (BAV) is the most common congenital cardiac malformation, affecting 1–2% of the general population. It is frequently associated with AS and diagnosed in younger patients. Up to 49% of younger patients (<70 years) in SAVR cohorts have bicuspid anatomy [45].

BAV anatomy involves complexities including the presence of raphe, leaflet calcification, annular asymmetry, small sinuses of Valsalva, calcification of the LVOT, and associated ascending aortic aneurysm (≥45 mm). These factors significantly influence outcomes such as annular rupture, stroke, asymmetric valve expansion, PVL, conversion to open surgery, and procedural mortality [5,11].

Although TAVR with BE valves and cerebral embolic protection devices may mitigate some complications, current guidelines favor SAVR for most BAV patients, particularly younger individuals or those with concomitant aortic aneurysms [18].

Neurological Risk and Stroke

Stroke remains a significant and serious complication post-TAVR, particularly within the first 30 days post-procedure, with reported rates of up to 4–5% in high-risk patients due to aortic arch atherosclerosis, valvular calcification, and catheter manipulation [6,7].

Although cerebral embolic protection devices have reduced silent brain infarcts, their routine use remains controversial. The risk of stroke has declined with newer-generation devices, however their unpredictable nature warrants careful consideration, especially in younger, active individuals [5].

SAVR and TAVR: Competition or Complementarity?

Rather than viewing TAVR and SAVR as competing strategies, current evidence supports their complementary nature. SAVR remains indispensable in scenarios such as infective endocarditis, aortic root aneurysms, concomitant mitral or tricuspid disease, and complex anatomies [11,18]. Conversely, TAVR is now standard in older patients with intermediate- to high-risk and suitable anatomy. Furthermore, its role in low-risk cohorts continues to evolve [6,7].

The Heart Team approach remains essential, ensuring individualized therapy that incorporates anatomical complexity, frailty, patient preferences, and long-term management strategies [8].

AVR Approaches: Expanding the Armamentarium

Full Sternotomy Vs Minimally Invasive AVR

SAVR has traditionally been conducted through full sternotomy, providing extensive anatomical exposure, excellent reproducibility, and established safety profiles. However, full sternotomy is associated with considerable drawbacks, including increased postoperative pain, higher incidence of deep sternal wound infections, prolonged hospitalization periods, and slower recovery processes [5].

To address these issues, minimally invasive aortic valve replacement (MiAVR) techniques are increasingly being adopted, including partial sternotomy and right anterior minithoracotomy. Observational studies have consistently reported the substantial benefits associated with minimally invasive approaches, including reduced surgical trauma, diminished postoperative pain, reduced need for blood transfusions, expedited functional recovery, and shorter hospital stays [11,46].

A comprehensive systematic review and meta-analysis by Mohamed *et al.* [46] involving 50 studies and more than 12,000 patients presented robust evidence in support of the superiority of minimally invasive approaches. Specifically, mini-sternotomy was associated with significantly lower rates of pulmonary complications (OR: 0.69, 95% CI: 0.54–0.88; $p = 0.003$), less postoperative bleeding (weighted mean difference: –115 mL; 95% CI: –137 to –94 mL; $p < 0.001$), reduced transfusion requirements (OR: 0.65, 95% CI: 0.57–0.74; $p < 0.001$), shorter stays in the intensive care unit (ICU), and shorter duration of overall hospitalization. However, the authors found no significant differences in short- and mid-term mortality or stroke incidence between the two surgical approaches [46].

Despite these advantages, it is important to acknowledge the technical challenges of MiAVR. These include limited operative visibility, which potentially prolongs the duration of cardiopulmonary bypass and aortic cross-clamping, and a steep learning curve. Consequently, surgical proficiency and adequate patient selection are crucial determinants of procedural success [19,46]. Sutureless aortic bioprostheses have increasingly been adopted to facilitate minimally invasive aortic valve replacement [47].

Transfemoral Vs Non-Transfemoral Approaches

TAVR via transfemoral (TF) access has emerged as the standard approach due to its minimal invasiveness, rapid patient recovery, and proven clinical effectiveness [6]. Nonetheless, certain patient populations present anatomical limitations such as extensive peripheral vascular disease or severe calcifications in iliofemoral vessels, rendering the transfemoral approach unfeasible and prompting alternative access routes.

The following alternative (non-transfemoral) approaches are noteworthy:

• Transapical: This is currently the most common alternative to TF, providing direct left ventricular access via a small left thoracotomy. Despite its effectiveness, this method is associated with increased pulmonary complications and extended recovery periods compared to TF access [48].

• Direct Transaortic: Employing either partial sternotomy or right anterior minithoracotomy, this approach is advantageous when both transfemoral and transapical routes are unsuitable. Favorable clinical outcomes are achieved using the direct transaortic access technique, matching other alternative routes in terms of procedural success and complication rates [48].

• Transcarotid and Transaxillary: These vascular approaches serve as viable options when conventional methods are contraindicated, despite involving greater technical complexity and elevated neurological risk, particularly with transcarotid access. However, recent data suggest that careful patient selection and meticulous procedural execution can substantially mitigate these risks [49].

• Transcaval: This innovative and emerging strategy involves crossing from the inferior vena cava to the abdominal aorta via an interventional catheterization technique. Preliminary clinical experiences have shown promising outcomes in challenging anatomical scenarios where conventional alternatives have been exhausted, although long-term safety and efficacy data remain limited [50].

Future Perspectives for SAVR

Despite significant advances in TAVR and its widespread adoption, SAVR continues to maintain critical relevance, particularly in complex clinical and anatomical scenarios, concomitant cardiac pathologies, and in the management of younger patient populations requiring lifelong valve management strategies [11].

Anatomical Factors

Complex anatomical conditions remain a primary indicator in favor of SAVR. Bicuspid aortic valves, severe aortic annuloectasia, extensive annular and left ventricular outflow tract (LVOT) calcification, and low coronary height represent significant anatomical challenges for TAVR. Such conditions substantially increase the risk of procedural complications such as annular rupture, coronary obstruction, PVL and stroke, thereby making SAVR a preferable or complementary treatment modality [5,6,11].

• Bicuspid Aortic Valve: Bicuspid valve anatomy is frequently encountered in younger patients and poses particular challenges for TAVR due to the heterogeneous leaflet morphology and associated extensive calcifications. This increases the procedural complexity and risks of significant PVL, valve embolization, and annular rupture. Surgical AVR remains preferable due to its capacity for precise decalcification, tailored sizing, and anatomical correction [5,45].

• Severe Aortic Annuloectasia: This condition is characterized by marked dilation of the aortic annulus and root, necessitating intricate surgical techniques including root enlargement or total root replacement (Bentall, David, or Yacoub procedures). Such interventions enable precise customization to patient-specific anatomical features, thereby mitigating risks inherent to TAVR such as annular rupture or suboptimal prosthetic anchoring [11,44].

• Heavy Annular and LVOT Calcification: Extensive and asymmetric calcification patterns significantly increase the risks of annular rupture (mortality rate $>$50% in case of rupture), significant PVL (moderate-to-severe incidence ranging from 0.6% to 3.6%), and embolic strokes, especially when balloon post-dilation is required. Thus, patients with pronounced calcifications should be strongly considered for SAVR to mitigate these risks and ensure superior procedural outcomes [4,11].

• Low Coronary Height: Low coronary ostia ($<$10 mm above the annulus), effaced sinuses, and a narrow or low sinotubular junction significantly increase the risk of coronary obstruction during TAVR procedures. This is particularly relevant in bicuspid valve, TAVR-in-SAVR, and TAVR-in-TAVR scenarios. Although techniques such as chimney stenting or intentional laceration of bioprosthetic scallops (BASILICA) have shown favorable mid-term outcomes in intermediate-to-high-risk surgical patients, SAVR remains the gold standard for low-risk patients due to the critical need for reliable procedural control and reduced complication rates [21,51].

• Pure Native Aortic Valve Regurgitation: Patients with isolated aortic regurgitation often exhibit minimal leaflet calcification and significant dilation of the ascending aorta and valvular annulus, thereby complicating TAVR anchoring and valve positioning, and resulting in a higher incidence of PVL. Consequently, SAVR remains the preferred treatment, particularly in low-risk surgical candidates, given its superior procedural efficacy and clinical outcomes [11,52].

• Small Aortic Annulus: Defined variably as an annular diameter of $<$21–23 mm, or annular area of $<$430 mm^2, a small aortic annulus is prevalent in approximately 17% of patients with AS, predominantly older females. Small annuli significantly increase the risk of severe PPM, adversely impacting long-term survival. Although TAVR allows prosthesis oversizing, the risks of severe mismatch remain significant (4–20%), alongside increased risks of an-

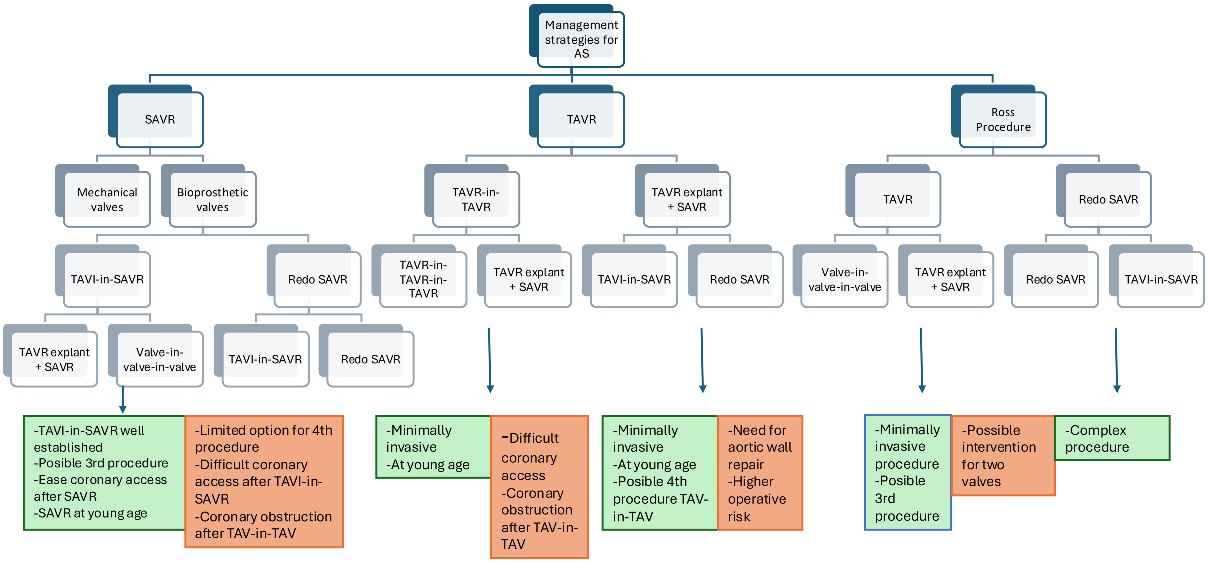

Fig. 1. Procedure sequence showing the risks and benefits in the lifetime management of patients with severe AS. AS, Aortic stenosis.

nular rupture and coronary obstruction. In contrast, SAVR with concomitant aortic root enlargement significantly reduces the incidence of severe PPM by up to 50%, thus improving short- and long-term clinical outcomes and facilitating future valve-in-valve interventions. The ongoing SMART and VIVA trials comparing TAVR and SAVR outcomes in patients with small aortic annuli are expected to further validate the continuing relevance of SAVR in these scenarios [44,53].

• Infective Endocarditis: Regardless of whether it affects native valves or prosthetic valves, infective endocarditis is another crucial indication that strongly favors SAVR. Surgical management enables extensive debridement and excision of infected and necrotic tissues, meticulous reconstruction of affected structures, and a significant reduction in the risk of recurrent infection compared to conservative or transcatheter approaches. In particular, prosthetic valve endocarditis typically involves complex pathology with periannular abscesses, dehiscence, or fistula formation, requiring intricate surgical techniques such as annular reconstruction or root replacement to restore anatomical integrity and effective function. Thus, SAVR offers superior outcomes in terms of infection control, structural integrity, and long-term survival in infective endocarditis [54].

Further cardiac surgical interventions are also anticipated due to indications for mechanical valve implantation in younger cohorts. These scenarios highlight the ongoing relevance and necessity of surgical intervention strategies, particularly SAVR, within comprehensive cardiac care [20].

Clinical Factors and Concomitant Pathologies

The presence of concomitant cardiac pathologies significantly influences the surgical strategy, especially conditions that require simultaneous intervention. These include CAD necessitating coronary artery bypass grafting (CABG), aortic root pathology (aneurysm/dissection), or mitral and/or tricuspid valve pathology requiring surgical correction. Furthermore, patients with chronic atrial fibrillation may also benefit from surgery by undergoing concomitant ablation of atrial fibrillation using the MAZE procedure [11].

Combined SAVR-CABG or SAVR-mitral valve interventions deliver comprehensive management, reduce the cumulative operative risk, and provide durable outcomes that are superior to staged or isolated TAVR interventions [8].

Large-scale registry analyses and clinical trials have consistently validated this combined surgical approach, highlighting the importance of evaluation by a multidisciplinary Heart Team for optimal patient selection and management [9].

Young Patients

Management of aortic valve disease in younger patients represents a significant and increasingly complex clinical challenge due to their extended life expectancy, potential for prosthetic valve deterioration, and the anticipated necessity of multiple future interventions. Current guidelines and emerging evidence advocate a proactive early surgical approach, even in minimally symptomatic or asymptomatic young individuals. This can prevent irreversible myocardial remodeling, left ventricular dysfunction, and progression toward heart failure. Recent pivotal studies, including RECOVERY and EARLY-TAVR, underscore the substantial survival benefits, improved cardiovascular morbidity profiles, and enhanced long-term quality of life when early surgical interventions are implemented compared to more conservative management strategies (Fig. 1) [55,56].

Strategic Considerations in Initial Valve Selection

The initial valve selection in young patients profoundly impacts subsequent therapeutic pathways. Decisions regarding valve type must balance immediate procedural risks, long-term durability, and the feasibility of subsequent interventions, particularly transcatheter valve-in-valve (ViV) procedures [11,20].

• Ross Procedure

The Ross procedure utilizes a pulmonary autograft for aortic valve replacement. It is the only approach that can restore life expectancy comparable to the general population [30]. Its notable advantages include superior long-term survival, optimal hemodynamic performance, excellent freedom from anticoagulation, and low incidence of endocarditis and thromboembolic events [31,32].

Nevertheless, the Ross procedure has certain limitations, including significant technical complexity, higher re-intervention rates involving both the autograft and pulmonary homograft, and the necessity for highly specialized surgical expertise. Consequently, the current guidelines recommend this procedure (class IIb indication) primarily for selected patients aged <50 years, and exclusively in centers of proven surgical excellence [11].

• Mechanical Valves

Mechanical valves offer unmatched durability, thereby minimizing the risk of reintervention. However, their lifelong requirement for anticoagulation therapy introduces cumulative risks of bleeding and thromboembolic complications, thereby significantly influencing lifestyle considerations and patient compliance [33].

• Bioprosthetic Valves

Biological valves remove the need for chronic anticoagulation, thus providing lifestyle advantages that are particularly relevant for younger, active individuals. Despite these benefits, the limited lifespan of bioprosthetic valves necessitates multiple interventions due to SVD, emphasizing the strategic importance of initial valve choice to maximize long-term clinical outcomes [11,33].

Advanced Surgical Bioprosthesis for Future TAVR Viability

Recent advances in surgical valve technology have produced bioprostheses designed to optimize compatibility with subsequent TAVR interventions. Well known examples include the Edwards Inspiris Resilia valves and the Epic Plus valves. The former incorporates Resilia tissue technology, which significantly enhances durability through superior resistance to calcification and structural degeneration. Its innovative and expandable stent frame (VFit technology) allows controlled expansion or fracture during future ViV procedures, thereby minimizing PPM and optimizing hemodynamic performance [35,57]. Similarly, the Epic Plus bioprosthesis employs advanced anti-calcification measures and a flexible stent design to facilitate future TAVR-in-SAVR procedures, ensuring excellent long-term hemodynamic outcomes and durability [58].

Management Strategies Following Initial Valve Intervention

Re-Interventions After Initial TAVR. Patients initially treated with TAVR require careful planning for potential re-interventions. Two primary strategies are currently employed:

• TAVR Explantation (Redo-SAVR)

This invasive surgical approach is usually indicated when TAVR-in-TAVR is impractical due to endocarditis, severe PVL, structural valve deterioration, or PPM. Recent registry data (EXPLANT-TAVR) have highlighted substantial risks associated with TAVR explantation, including significant operative complexity, high perioperative morbidity and mortality rates (13% at 30 days, and 28% at one year), and the frequent need for complex aortic root replacement [59].

• TAVR-in-TAVR

This less invasive alternative is characterized by favorable short-term outcomes, but has several potential complications including coronary obstruction, sinus sequestration, and significant PPM in >30% of cases [36,60]. Current limitations in durability data and hemodynamic outcomes necessitate cautious patient selection.

Patients undergoing PCI after TAVR experience prolonged procedure times, higher procedural failure rates, and increased mortality, highlighting the importance of commissural alignment during initial valve implantation to preserve future coronary accessibility. Post-TAVR CT of 66 patients treated with Evolut R or Evolut PRO valves identified features of unfavorable coronary access in 34.8% (n = 23) of cases for the left coronary artery and in 25.8% (n = 17) for the right coronary artery. For 345 patients treated with SAPIEN 3 valves, unfavorable coronary access was observed in 15.7% (n = 54) for the left coronary artery and in 8.1% (n = 28) for the right coronary artery. In both groups, the success rates for selective coronary engagement were significantly lower in patients with CT-identified features of unfavorable coronary access compared to those with favorable coronary access: Evolut R/Evolut PRO (0.0% vs. 77.8%; $p = 0.003$), and SAPIEN 3 (33.3% vs. 91.4%; $p = 0.003$) [21,60].

Reinterventions After Initial SAVR. In patients initially undergoing SAVR, redo-SAVR remains the preferred strategy for younger, lower-risk individuals in whom anatomical considerations limit the feasibility of TAVR-in-SAVR [11]. Conversely, older or higher-risk patients typically benefit from less invasive TAVR-in-SAVR approaches, contingent upon them having favorable coronary anatomy

[21]. However, the potential complications of TAVR-in-SAVR (e.g., elevated residual gradients, thrombotic risks, valve malposition) highlight the critical importance of initial valve sizing and selection [19].

Multidisciplinary, Patient-Centric Decision-Making

A comprehensive, multidisciplinary approach is required for the optimal management of young patients with aortic valve disease. Detailed clinical assessment, advanced imaging modalities, individualized anatomical evaluations, and strategic planning are essential. Specialized Heart Teams should incorporate cardiologists, cardiac surgeons, imaging experts, and patient input to develop personalized, lifelong management strategies [8]. By aligning early surgical decisions with long-term treatment considerations, healthcare providers can ensure optimal clinical outcomes, procedural success, and enhanced quality of life throughout the lifespan of patients.

Conclusions

TAVR has become the predominant treatment modality for patients with severe AS, demonstrating safety, reproducibility, rapid recovery, and efficacy across all surgical risk profiles. Despite its widespread adoption and technological refinement, unanswered questions remain, particularly regarding long-term durability and optimal patient selection. SAVR continues to play a vital role despite the evolution of transcatheter technologies, especially in younger patients, those with complex anatomies, and patients requiring concomitant procedures.

A multidisciplinary Heart Team is essential for guiding the treatment strategy and balancing patient-specific factors such as age, life expectancy, anatomical characteristics, surgical risk, and long-term treatment planning. While TAVR may become the first-line therapy for the majority of patients, SAVR will likely remain the preferred approach in certain clinical scenarios. In the future, many of these patients may be treated with a hybrid approach that combines TAVR with PCI.

The notion of lifetime management is especially important in younger patients, whose treatment extends beyond immediate procedural outcomes. Long-term strategies should take into account the durability of bioprosthesis, the potential for re-intervention, coronary access, anticoagulation tolerance, and patient preferences.

Until more definitive long-term data from low-risk TAVR trials becomes available, careful patient selection remains critical. The evolving relationship between TAVR and SAVR should be viewed as complementary rather than competitive, with the Heart Team playing a central role in aligning clinical decisions with the individual needs and preferences of each patient.

Availability of Data and Materials

All data points generated or analyzed during this study are included in this published article.

Author Contributions

All authors contributed to the design of this work and to the interpretation of data. FEC and CMD drafted the work. JJLC and EMG revised critically for important intellectual content. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethics Approval and Consent to Participate

Not applicable.

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Conflict of Interest

The authors declare no conflict of interest.

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