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REVIEW ARTICLE

# The Technology and Techniques of Valve Repair and Replacement: A Comparative Investigation

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ABSTRACT: The field of cardiac surgery is dynamic; it continues to evolve through innovations in technique and technology. However, despite these developments, there is a lack of systematic evaluation of data due to limited datasets and inconsistent comparisons over time. Thus, this review provides a comparative analysis of valve repair and replacement techniques, identifying trends and discussing patient impact, future directions, and unmet clinical needs. Literature was identified through PubMed, Scopus, and Google Scholar; studies were prioritized from 2013 onwards, with earlier studies retained where contemporary data were limited. Studies were included if they reported at least one of three metrics (procedural success rate, 30-day mortality, 30-day readmission rate) in adult patients without prior cardiac surgery and a minimum sample of 10, and excluded if they were case reports, pediatric-only, or lacked outcome data. Findings were cross-examined to reduce bias. Minimally invasive approaches appear to be associated with higher success rates and lower mortality than replacement counterparts. Annuloplasty shows inconsistency across valve types, possibly suggesting underexplored anatomic variables. Percutaneous balloon valvuloplasty shows the least favorable readmission rates across valves, which may imply complexity unrelated to anatomy. By consolidating varied datasets, this review identified trends and under-researched areas, providing a foundation for prospective studies.

KEYWORDS: Medical and Health Sciences, Cardiology, Cardiac Surgery, Valvular Heart Disease, Valve Repair and Replacement.

## Introduction

Valvular heart disease (VHD), or valvular disease, is a disease that encompasses a range of conditions affecting the heart valves, leading to dysfunction, such as stenosis (narrowing) or regurgitation (leakage). This condition can arise from a multitude of causes, including congenital defects, degenerative changes, infections, and trauma—especially in patients with comorbidities.[1,2]

There are three types of valvular disease: aortic stenosis, mitral regurgitation, and tricuspid regurgitation. The most common types of VHD are mitral regurgitation and aortic stenosis, with degenerative diseases being the primary cause.[3] Aortic stenosis is commonly seen in older adults, often linked to age-related calcification.[4] Mitral regurgitation can result from structural changes or functional impairment of the valve. Lastly, tricuspid regurgitation is often secondary to right heart failure or pulmonary hypertension.

Valve repair and replacement are critical surgical interventions utilized to manage valvular heart disease. They are often necessary for conditions like infective endocarditis (infection of the heart's inner lining), particularly when significant valve destruction occurs. These procedures can be performed using traditional open-heart surgery or minimally invasive techniques, including percutaneous methods. The choice between repair and replacement often depends on the specific valve involved, the severity of the condition, the patient's overall health status, anatomical factors, and the expertise of the surgical team.

Valve repair often includes procedures such as balloon valvuloplasty and annuloplasty. Aortic valve repair has gained traction due to its ability to avoid long-term complications associated with prosthetic valves.[5] At the same time, valve replacement involves the complete removal of the damaged valve and its replacement with a prosthetic valve. It is often preferred for severe cases, especially in the aortic valve.[5,6]

The objective of this research is to collect large-scale data of current advancements in valve repair and replacement to provide a comparative analysis, identify trends and gaps, and opportunities for future research and clinical application. This paper will also evaluate the many challenges associated with these innovations, such as technical complexity, patient selection, and long-term durability. Note that it is essential to recognize that no single technique is universally superior; rather, clinical decision-making must be individualized. Factors such as valve anatomy, patient frailty, comorbidity burden, institutional experience, and patient preference all influence the optimal management strategy. This review presents comparative statistical data to inform, not prescribe, clinical choices.

The significance of this paper lies in its contribution to providing an accurate dataset and comprehensive comparison of the surgical techniques and technologies used in valve repair and replacement, enabling the public to stay updated on the latest surgical methods and technologies. Creating this dataset of innovative techniques can highlight approaches that reduce complications, enhance recovery, and improve the longevity of valve repairs or replacements. It allows for the identification of trends, gaps, and opportunities for future research and



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clinical application, serving as a resource for surgeons looking to improve management strategies for valvular heart disease. Lastly, it provides a basis for evidence-based decision-making, ensuring that patients are aware of available treatments and can decide which is best suited to their conditions and advancements in the field.

## Methods

This study employed a structured narrative review with a systematic search methodology and quantitative data extraction. Literature was identified through searches of PubMed, Scopus, and Google Scholar using the following terms: "valve repair," "valve replacement," "mitral valve outcomes," "aortic valve outcomes," "tricuspid valve repair," "pulmonary valve replacement," "annuloplasty," "balloon valvuloplasty," "transcatheter valve," and "surgical valve." Studies were prioritized if published during and after 2013. For techniques with limited post-2013 data, earlier seminal studies were retained.

Studies were included if they: (1) were human clinical studies, registries, or systematic reviews; (2) enrolled adult patients (≥18 years) without prior relevant cardiac surgery for the technique under study—except percutaneous balloon aortic valvuloplasty (PBAV) data being drawn from studies spanning congenital presentations, which may include younger patients as dedicated adult-only PBAV data are limited; (3) reported at least one of the three primary outcome metrics: procedural success rate, 30-day mortality, or 30-day readmission rate; and (4) had a sample size of ≥10 patients. Studies were excluded if they were case reports, pediatric-only populations, or lacked reportable outcome data for at least one of the three defined metrics. Note that the inclusion criteria applied to outcome-reporting clinical studies (refs 9-56). General background literature was cited separately for contextual information.

Three outcome metrics were extracted and compared across techniques: 30-day mortality, 30-day readmission rate, and procedural success rate. Findings were cross-examined across multiple independent studies to reduce bias. For advancements with varied statistics, averages were calculated in their place. Key clinical trials and outcome comparisons were analyzed to assess efficacy, safety, and durability, providing comprehensive insights into these advancements and how they are reshaping the management of valvular heart disease, improving outcomes, and addressing unmet clinical needs.

## Results

Valve repair and replacement techniques consist of mitral, aortic, tricuspid, and pulmonary—all of which have evolved significantly, offering various approaches tailored to specific valve pathologies.

### *Mitral Valve Repair Techniques:*

Mitral valve repair has seen advancements in techniques such as annuloplasty, leaflet resection, percutaneous balloon valvuloplasty, chordal replacement, and MitraClip, which are crucial for addressing degenerative mitral regurgitation.

Annuloplasty involves the implantation of a prosthetic ring around the annulus to restore the valve's shape and function, often used with leaflet resection to remove prolapsing tissue.[7] The ring is typically constructed from a core material that determines its rigidity and is covered in a cloth material through which the sutures are placed. The core material is typically silicone or metal, and the cloth material is either Dacron or polyester.[8]

There are two types of prosthetic rings: remodeling or non-remodeling, in which the type of ring used depends on the patient's needs. The size of the ring is determined by the height of the anterior leaflet and the inter-commissural or inter-trigonal distance.

A remodeling annuloplasty aims for a more complete correction of the annulus's geometry. In contrast, a restrictive non-remodeling annuloplasty focuses on reducing the annular size to address leakage without altering the overall shape.

Leaflet resection involves the surgical removal of a damaged valve leaflet to address issues like prolapse or excess tissue. There are multiple techniques used in leaflet resection, including triangular resection, quadrangular resection, sliding plasty, and fold plasty.

Triangular resection removes a triangular section of the leaflet, often used for smaller, localized prolapses, whereas quadrangular resection is used for more extensive prolapse, removing a larger quadrangular section of the leaflet. Both are standard approaches for posterior leaflet lesions, with quadrangular resection oftentimes being combined with sliding plasty.

Sliding plasty involves incisions and reapproximation of the leaflet edges, while fold plasty involves folding and suturing the leaflet to reduce its height without resection. There are types of fold plasty, such as hourglass resection and non-resectional fold plasty. Hourglass Resection is an improvement on fold plasty, resecting a specific hourglass shape to address prolapse and reduce tension on the posterior leaflet. Non-resectional fold plasty is a specific type of fold plasty that involves folding the leaflet tissue and suturing it without removing tissue.

Percutaneous balloon valvuloplasty is a minimally invasive procedure used to open narrowed heart valves (valve stenosis) by inserting a catheter with a balloon on the tip into a blood vessel, typically in the groin, and inflating it to widen the valve opening, improving perfusion.[9] The effectiveness of percutaneous balloon valvuloplasty will vary according to the type of valve and the cause of stenosis. For mitral stenosis, percutaneous balloon mitral valvuloplasty is the preferred treatment for patients who have a pliable, non-calcified mitral valve.

Chordal replacement is a surgical technique used to repair mitral valve prolapse. It consists of utilizing artificial chords made from expanded polytetrafluoroethylene to replace damaged chordae tendineae (the small tendons that connect the mitral valve leaflets to papillary muscles).[10]

MitraClip is a minimally invasive procedure using a small device to repair mitral regurgitation without open-heart surgery, improving blood flow and reducing symptoms like shortness of breath and fatigue. The MitraClip device is moved through the catheter and carefully positioned on the mitral valve leaflets, clipping the leaflets together.

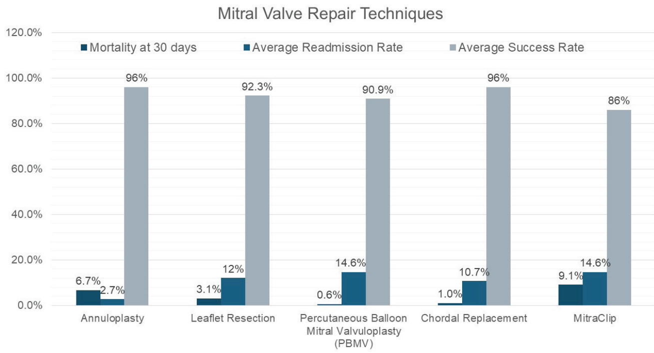


**Figure 1:** A graph comparing the various techniques of mitral valve repair mentioned is compiled from different sources.[11-24] Overall, success rates across all techniques ranged from 83% to 96%, with percutaneous balloon valvuloplasty (PBMV) and MitraClip having the lowest rates at 83.3% and 86%, respectively. Average readmission rates ranged from a low 2.7% to 14.6%, generally considered good. The mortality at 30 days across all the mitral valve repair techniques varied from an astronomically low 0.6% to 9.1%.

Statistically, annuloplasty and chordal replacement are tied for the highest average success rate (Figure 1). Annuloplasty also has the lowest average readmission rate of all the mitral valve repair techniques. Finally, the technique with the lowest mortality at 30 days is PBMV, with MitraClip having the highest at 9.1%.

***Mitral Valve Replacement Techniques:***

Across all four valves, there are generally two types of replacement: surgical valve replacement (SVR) and transcatheter valve replacement (TVR). While SRV takes the open-heart surgical approach, TVR is minimally invasive, aided by a catheter. SVR has long-term durability with greater procedural risks and longer recovery, whereas TVR has less durability, lower procedural risk, and shorter recovery. This applies to surgical mitral valve replacement (SMVR) and transcatheter mitral valve replacement (TMVR) as well.

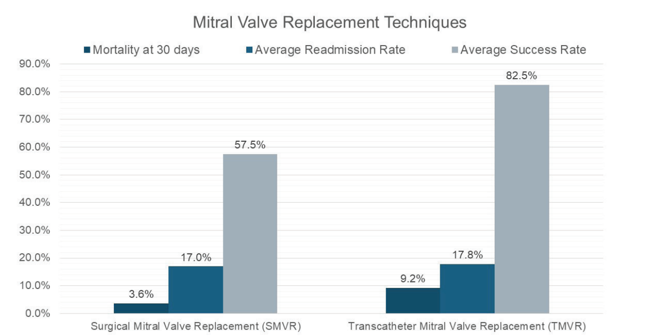


**Figure 2:** A graph comparing the various techniques of mitral valve replacement mentioned above, compiled from different sources.[25-29] The success rates of the two techniques contrasted quite strongly, with SMVR's at 57.5% and TMVR's at 82.5%. Both average readmission rates were around 17%, albeit TMVR's was slightly higher. TMVR's 9.2% mortality rate at 30 days is just under triple SMVR's, with SMVR's being 3.6%.

TMVR's higher success rate may be associated with its minimally invasive approach and the higher-risk patient selection typical of open surgical candidates. However, compared to SMVR's mortality at 30 days and readmission rate, TMVR's is higher, further exemplifying that despite its ease in performance, it offers less durability than SMVR. This trade-off between procedural success and longer-term durability reflects the complex clinical decisions involved in valve replacement and must be contextualized within individual patient risk profiles.

***Aortic Valve Repair Techniques:***

Aortic valve repair techniques like valve-sparing root replacement and cusp plication are gaining traction with time. Valve-sparing root replacement preserves the patient's native valve, reducing the need for anticoagulation and maintaining hemodynamics. Cusp plication is used to correct leaflet prolapse, often combined with annuloplasty to enhance valve competence.[30]

Percutaneous balloon valvuloplasty and aortic valve annuloplasty are also techniques used in aortic valve repair, albeit less often. Percutaneous balloon valvuloplasty is usually a temporary measure to improve symptoms before surgical or transcatheter aortic valve replacement, or for patients who are high-risk for surgery. In contrast, aortic valve annuloplasty is used to repair aortic valve regurgitation or stenosis, sometimes involving external or internal rings.

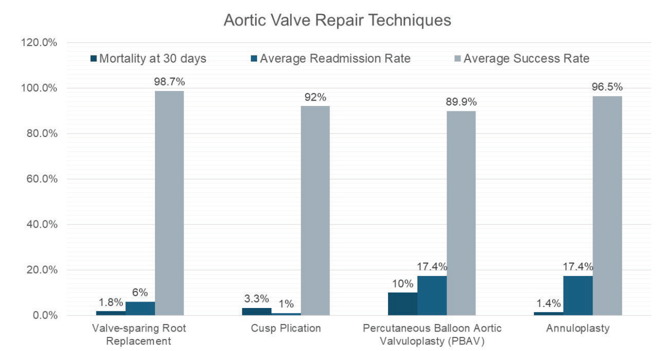


**Figure 3:** A graph comparing the techniques of aortic valve repair mentioned above, which is compiled from different sources.[31-42] Overall, success rates across all techniques ranged from 89.9% to 98.7%, with percutaneous balloon valvuloplasty and cusp plication having the lowest rates at 89.9% and 92%, respectively. Average readmission rates ranged from 1% to 17.4%. The mortality at 30 days across all aortic valve repair techniques varied just slightly, from a low 1.3% to 10%.

Note that due to the absence of readmission data for aortic annuloplasty (AA) and PBAV, readmission rates reported for transcatheter aortic valve replacement (TAVR) and surgical aortic valve replacement (SAVR) have been referenced for contextual purposes due to their similarities to PBAV and AA, reaching an ultimate readmission rate of 17.4% [42] (Figure 3).

In comparing the aortic repair techniques, valve-sparing root replacement has the highest success rate, annuloplasty has the lowest mortality at 30 days, and cusp plication has the lowest average readmission rate. Readmission rates of TAVR and SAVR were used as reference points for AA and PBAV due to the shared aim of treatment of aortic valve disease, patient populations, and overlapping risks like conduction disturbance and heart failure influencing early readmissions. Note that these comparisons do not directly reflect the outcomes of the


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procedures under investigation but serve as guidelines to estimate plausible readmission rates due to a lack of data.

Interestingly, when compared to its mitral counterpart (Figure 1), AA's readmission rate and mortality at 30 days show a significant difference in rates, suggesting clear differences in the complexity of the procedures—likely due to valvular anatomy—and the patient populations. This also shows a further need for improvement and research of AA, given the lack of usage in operations and the absence of dedicated readmission data. PBAV similarly warrants attention: it displays the worst readmission rates among the aortic repair techniques, a pattern shared with its mitral counterpart PBMV. Importantly, this does not reflect poor overall performance—PBMV demonstrates favorable success and mortality outcomes in appropriately selected patients—but the consistent pattern of elevated readmission across anatomically distinct valves may suggest operational complexity independent of valvular anatomy.

### *Aortic Valve Replacement Techniques:*

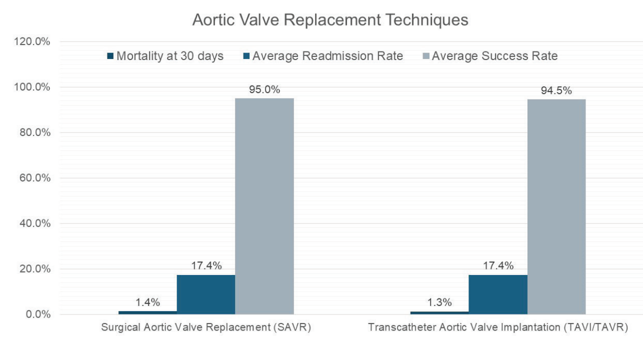


**Figure 4:** A graph comparing the techniques of aortic valve replacement is compiled from different sources.[42-44] The success rates of the two techniques are quite similar, with SAVRs at 95.0% and TAVI/TAVRs at 94.5%. Both average readmission rates are 17.4%, and mortality at 30 days only differ slightly, with SAVR at 1.4% and TAVR at 1.3%.

Overall, there is very little difference between the two techniques in terms of statistics, with TAVI/TAVR having lower mortality at 30 days and a marginally lower success rate (Figure 4).

### *Tricuspid and Pulmonary Valve Repair Techniques:*

While mitral and aortic valve repairs are well-established in the medical world, tricuspid and pulmonary valve repairs are considered emerging fields. These repairs are less common but are gaining attention as techniques improve. Their general focus is on addressing regurgitation and stenosis with emerging surgical and transcatheter approaches.

Tricuspid valve repair techniques that are gaining prominence consist of transcatheter edge-to-edge repair (TEER) and use of the KyrinTM tricuspid TEER system. TEER has gained relevance due to its minimally invasive nature and effectiveness in reducing tricuspid regurgitation. The use of three-dimensional echocardiography is crucial in assisting TEER by providing detailed anatomical insights, which enhance procedural accuracy and outcomes.[45,46]

The KyrinTM tricuspid TEER system is a novel device that has shown promising results in initial human studies, achieving high procedural success (91%). It involves the use of a delivery catheter to place clips on the tricuspid valve leaflets, significantly reducing regurgitation and improving patient symptoms. Though not as prominent, annuloplasty is also used to repair the tricuspid valve, with the procedure ultimately functioning the same as other types of annuloplasty.

Regarding pulmonary valve repair, percutaneous balloon valvuloplasty is a technique used as a common treatment for pulmonic stenosis, particularly in young children.

### *Tricuspid and Pulmonary Valve Replacement Techniques:*

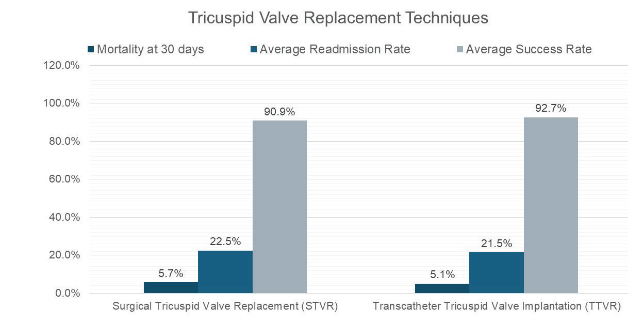


**Figure 5:** A graph comparing the replacement techniques of the tricuspid valve, compiled from different sources.[47-51] The success rates of the two techniques differed very slightly, with STVRs at 90.9% and TTVRs at 92.7%. Likewise, their average readmission rates differed very little, STVRs being 22.5% and TTVRs being 21.5%. Mortality at 30 days was just over 5% for both, with STVRs at 5.7% and TTVRs at 5.1%.

The statistics are similar, though TTVR shows better outcomes in all the categories (Figure 5). However, note that there is no robust data published on the average 30-day readmission for TTVR, but it is assumed to be around 18–25%. The average of such was calculated for the graph, which ultimately aligned with the rest of the statistics.

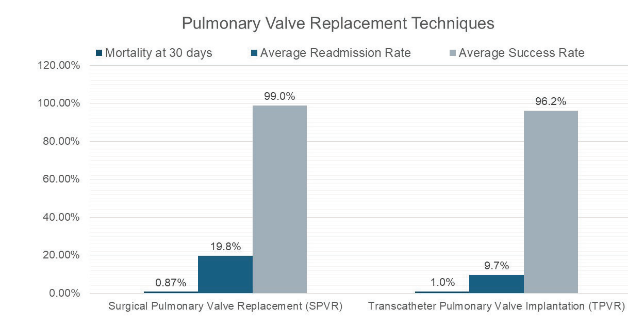


**Figure 6:** A graph comparing the replacement techniques of the pulmonary valve, compiled from different sources.[52-56] The success rates of the two techniques lie above 90%, SPVRs being at an outstanding 99.0% and TPVRs at 96.2%. On the other hand, their average readmission rates show great contrast, with SPVR's being 19.8% and TPVR's being 9.7%. Both their mortality rates at 30 days are quite low, with SPVRs at 0.87% and TPVRs at 1.0%.

The statistics vary more in this valve type, with SPVR having a near-perfect success rate but over double TPVR's average readmission rate (Figure 6). The mortality at 30 days is fairly similar between the two, but note that due to limited registry and institutional reports, precise pooled estimates for TPVR are not available. However, it is widely estimated to be around 1 to 2%.

## Modern Advancements and Findings

***Transcatheter Valve Repair and Replacement:***

TAVR has significantly evolved over the past two decades, becoming a standard treatment for aortic stenosis across various patient risk profiles. The following sections detail the key aspects of TAVR's indications and advancements.

TAVR is primarily indicated for symptomatic patients with severe degenerative aortic stenosis, particularly those at intermediate or higher surgical risk.[60,61] However, recent studies have shown TAVR's effectiveness in lower-risk patients, those with bicuspid aortic valves, and in cases of moderate aortic stenosis or pure aortic regurgitation.[61,62]

Transcatheter valve repair has also seen significant advancements in the treatment of mitral and pulmonic valve diseases. Mitral Valve Edge-to-Edge Repair provides a less invasive option for patients with mitral regurgitation. This technique is particularly beneficial for older patients with comorbidities.[63] For pulmonic valve diseases, the development of transcatheter pulmonic valve implantation represents a significant advance for patients with congenital heart disease, offering a minimally invasive option for valve replacement.[63]

Additionally, advances in catheter technology have led to smaller delivery systems, enhancing procedural safety and reducing vascular complications.[64,65] However, while TAVR has transformed the management of aortic stenosis, there is still a need to minimize complications such as pacemaker dependency and vascular injuries.

***Heart Valves:***

Traditionally, heart valve replacements have fallen into two categories: mechanical and bioprosthetic. Evaluation of longevity, anticoagulation needs, and associated risks dictates the choice between mechanical and bioprosthetic valves for valve replacement. Mechanical valves are crafted from durable, non-biological materials like carbon and metal, whereas bioprosthetic valves are primarily made from animal tissue—usually porcine aortic valve or bovine pericardium.

Mechanical valves are known for their durability, often exceeding 20 years and lasting a lifetime. However, they require lifelong anticoagulation, increasing the risk of bleeding and thromboembolic events. In contrast, bioprosthetic valves do not typically need long-term anticoagulation, but are consequently prone to structural deterioration over time—generally lasting 10-15 years, often necessitating reoperations.[57,58] Mechanical valves are often recommended for younger patients due to their longevity, whereas bioprosthetic valves are favored for older populations.[59]

Special sub-types of bioprosthetic valves include the sutureless and rapid deployment valves, which represent innovative approaches in aortic valve replacement (AVR). These bioprosthetic valves, such as the Perceval and Intuity, facilitate quicker deployment and reduced surgical trauma, leading to improved patient outcomes. The absence of subannular pledgets in these valves results in better hemodynamic performance, characterized by larger effective orifice areas and reduced turbulent flow.[66] Compared to traditional methods, they significantly decrease aortic cross-clamp and cardiopulmonary bypass times.[67,68] Nonetheless, the long-term benefits of sutureless and rapid deployment valves compared to traditional options require further investigation to establish their role in AVR fully.[68] While they can lead to fewer early complications, issues such as paravalvular leakage and the need for pacemaker implantation remain concerns.[66,68] Optimal outcomes are contingent on careful patient selection and technical proficiency, particularly in complex cases or reoperations.[69]

However, recent research has led to the development of a third valve type, one aiming to combine the best of both mechanical and bioprosthetic valves: synthetic polymeric valves. These valves are made from advanced polymer materials designed to replicate the flexibility and function of native valves while avoiding the calcification and wear seen in bioprosthetic valves. While currently in its experimental stage, synthetic polymeric valves are expected to have great overall durability with reduced paravalvular regurgitation and complications compared to other valves.[60]

***Artificial Intelligence, Machine Learning, and Robot-Assisted Surgery:***

Artificial intelligence (AI) and machine learning (ML) are expected to further cardiac surgery by enhancing precision medicine and improving patient outcomes through advanced imaging and predictive analytics. Specifically, these technologies leverage vast datasets to predict surgical risks more accurately than traditional methods, thereby facilitating better clinical decision-making. Such models have shown promise in predicting postoperative outcomes in congenital heart surgeries, consistently outperforming traditional risk stratification tools.[70] Studies also indicate that ML models significantly outperform traditional scoring systems in predicting mortality and complications in cardiac surgery.[71] This technological growth has brought advances to computational modeling and 3D printing, which, when paired with enhanced preoperative planning, ensure precise valve sizing and placement, optimizing outcomes.

Robot-assisted surgery (RAS) and technologies have revolutionized the field of cardiac surgery, cementing themselves as its future. With their recognized potential, they have seen significant advancements in recent years, serving to improve surgical outcomes, recovery times, and patient safety. Such advancements include the field's robotic systems—such as the da Vinci surgical system—and refinement of minimally invasive techniques.

With this approach and these technologies, RAS allows for minimally invasive surgery to be performed at a precise and accurate level. Specifically, RAS offers superior visualization and dexterity, allowing surgeons to navigate complex cardiac anatomy with greater accuracy, which is essential to minimally invasive cardiac surgery.[72] This is because it requires great detail, utilizing techniques such as minute incisions and port


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access, ultimately having lower physical trauma compared to traditional sternotomy.

Overall, these progressions highlight the significance of technological innovation and surgical ingenuity in advancing.

## Discussion

### *Overview of Emerging Trends:*

Advances in valve repair and replacement have altered the management of valvular heart disease, shifting the field from a traditionally surgical approach to a diverse spectrum of catheter-based therapies, bio-engineered gear, and minimally invasive techniques. The body of this review paper has detailed the technological innovations and comparative outcomes of such, allowing for a detailed understanding of their effectiveness. It is critical to emphasize, however, that valve procedure selection is inherently patient-specific. The trends identified below should not be generalized as universally applicable guidelines, as clinical decisions depend on individual patient anatomy, risk profile, comorbidity burden, institutional expertise, and shared decision-making between the patient and the surgical team. With that caveat in mind, it remains important to step back and consider the broader implications of these advancements collectively: they facilitate the improvement of long-term durability, the reduction of procedural risk and trauma, and the refinement of techniques tailored to specific patient needs.

When comparing valvular repair and replacement, the statistical data reveal distinct trends across all valve types. Replacement techniques consistently show the highest average readmission rates, a finding likely attributable to their more invasive nature, which necessitates more frequent postoperative surveillance, anticoagulation management, and prosthesis-related follow-up. This pattern underscores why repair is generally preferred over replacement when anatomically feasible. Minimally invasive approaches, across valve types, demonstrate higher success rates and lower perioperative mortality, reinforcing their clinical appeal in patients who are poor candidates for open surgery. That said, these techniques demand substantial institutional experience and operator expertise, and centers without high-volume programs may achieve superior outcomes with conventional surgery. The preference for minimally invasive approaches should therefore be weighed against the availability of specialized expertise rather than adopted as a standard.

Data clustering has revealed the areas of the field that necessitate further work. For one, there is a lack of robust data for TTVR, SAVR, and the repair of the tricuspid and pulmonary valve. Another trend data clustering has uncovered is the greater variety of techniques each valve's repair encompasses. The singular exception is pulmonary valve repair, which has fewer techniques than its replacement counterpart.

Certain techniques, such as annuloplasty, show inconsistencies across valve types, suggesting underexplored variables influencing success, such as anatomic variability. Specifically, AA's readmission rate and mortality at 30 days differ significantly from its mitral counterpart, showing clear differences in their complexity. Percutaneous balloon valvuloplasty also shows notable inconsistency across valves: while PBMV demonstrates favorable success and mortality rates in appropriately selected patients, both PBMV and its aortic counterpart, PBAV, show the least favorable readmission rates within their respective valve categories. This shared pattern across anatomically distinct valves may suggest operational complexity independent of valvular anatomy, rather than a technique-specific failure confined to one valve type.

### *Challenges and Barriers:*

While the future of cardiac surgery holds promise through technological innovations and interdisciplinary collaboration, the persistent challenges of accessibility and resource allocation must be addressed to ensure that advancements benefit all populations equally.

There is a significant gap in access to cardiac surgery between high-income and low-income countries, necessitating targeted efforts to improve accessibility and reduce health costs.[74] This further exemplifies developing countries' need for substantial investment in healthcare infrastructure to support cardiac surgery capabilities and training for healthcare professionals.

From a practical standpoint, the implementation of robotic systems requires specialized training and incurs higher costs, which may limit widespread adoption. As such, continued emphasis on specialized training for surgeons is especially crucial for maximizing the benefits of robotic surgery.

There is a definite need for more robust statistical data on pulmonary and tricuspid valves, made evident by limited registry and institutional reports. This lack of information and robust data also highlights the need for high-volume, multidimensional data, especially as such information enhances the predictive performance of ML models.

Regarding the intricacies of modern technology, the integration of AI raises ethical questions, such as technical robustness, autonomy, and data integrity. These are only further hindered by the aforementioned lack of long-term data related to newer technologies. Hence, this only compels the need for the development of regulatory frameworks to ensure safe use.[71, 75]

Additionally, most advancements in valve repair and replacement also face challenges regarding patient selection and anatomical variability, due to many technologies catering to the majority. Consequently, those who face late comorbidities and have complex valve morphologies are put at a higher risk, with many having only limited long-term solutions.

### *Call for Research:*

Despite the rapid pace of advancement, the field of valve repair and replacement faces unanswered questions that require focused attention and research.

While mitral and aortic valve repairs are well-established in the medical world, tricuspid and pulmonary valve repairs are still considered emerging fields. There is a definite need for more robust statistical data on pulmonary and tricuspid valves, made evident by limited registry and institutional reports. Additionally, while percutaneous balloon valvuloplasty is considered the cornerstone of pulmonary valve repair, there is a very limited variety of pulmonary repair techniques, especially in comparison to other valve types. This does, however, present an opportunity for innovation in developing novel percutaneous and surgical repair strategies, particularly for patients with complex anatomies or combined pulmonary valve pathologies, in which replacement is the default.

Certain techniques of aortic valve repair also require further research, such as PBAV and AA. When compared to its mitral counterpart, AA's readmission rate and mortality at 30 days show a significant difference, suggesting clear differences in the complexity of the procedures. While this is likely due to valvular anatomy, this also shows a need for improvement of AA, underscored by its lack of usage in operations and the absence of data. PBAV, on the other hand, displays the worst readmission rates when compared to the other aortic techniques, a pattern it shares with its mitral counterpart, PBMV. Notably, while PBMV demonstrates favorable success and mortality outcomes in appropriately selected patients, both techniques show the least favorable readmission rates within their respective valve categories, suggesting operational complexity independent of valvular anatomy. Moving focus to the aortic replacement techniques, TAVR has transformed the management of aortic stenosis, offering a minimally invasive approach. However, challenges remain, including the need to minimize complications such as pacemaker dependency and vascular injuries.

With the rise of AI and ML, it would prove useful for future research to focus on collaboration between clinicians and data scientists to develop ethical AI systems and improve clinical workflows.[71] With this, there is also a need for training programs to equip healthcare professionals with the skills to utilize AI technologies to their greatest advantage effectively.

A major player in the call to research would be the collaboration between multiple medical fields. For cardiac surgery, a prominent one is the intersection of cardiology and oncology. This is becoming increasingly important as cancer survivors face cardiovascular risks due to treatment, but traditional surgical approaches to valve repair and replacement are often complicated by prior thoracic radiation and comorbidities. Consequently, there is an urgent need for research into durable and minimally invasive valve interventions specifically tailored to cancer survivors.[73]

In relation to this, the challenges faced by patients of high frailty and anatomical variability necessitate the need for technologies catering to not just the majority, but them as well. This also relates to the value of researching the current development of synthetic polymeric valves. Synthetic polymeric valves are expected to have great durability with reduced regurgitation and complications compared to other traditional valves. Just as bioprosthetic valves have special sub-types—which include the sutureless and rapid deployment valves—once viable, synthetic polymeric valves could be attuned to cater to specific valve anatomies and comorbidities, with the help of 3D bioengineering.

***Limitations:***

A key limitation of this study is the scarcity of large-scale data on 30-day or long-term readmission rates specific to AA and PBAV. Consequently, readmission rates reported for TAVR and SAVR were used for contextual reference. However, these procedures differ significantly in terms of patient selection, procedural invasiveness, and clinical indication. As such, the extrapolation of TAVR or SAVR readmission data to annuloplasty or PBAV populations may not fully reflect their distinct postoperative trajectories. This is also the same case for TTVR and SAVR, with TTVR having no robustly published data on its 30-day readmission rate, and SAVR's direct success rate not being reported. Similarly, due to a lack of data on the repair techniques of the pulmonary and tricuspid valve, a graph could not be made, limiting the comparisons that could be drawn.

Another key limitation would be heterogeneity. Because data were averaged across heterogeneous studies with varying patient populations and study designs, all comparative conclusions should be interpreted as hypothesis-generating, approximate descriptive benchmarks, not precise effect estimates.

## Conclusion

By consolidating the statistical data, the rates display running trends. Replacement techniques have the highest average readmission rates. This is likely due to their invasiveness, requiring further readmission to the hospital. The data also suggest that minimally invasive approaches are associated with higher average success rates and lower perioperative mortality rates, though these associations must be interpreted in light of patient selection differences. Future prospective, randomized studies with standardized outcome definitions will be needed to establish more robust conclusions about the comparative effectiveness of these techniques.

Another trend this clustering has uncovered is that valve repair generally has a greater variety of techniques compared to its replacement counterpart. The singular exception to this is pulmonary valve repair, which has fewer techniques than its replacement counterpart. This collection has also revealed the techniques that require further research. TTVR, SAVR, and the tricuspid and pulmonary repair techniques do not have robustly published data on their rates. Annuloplasty is inconsistent across valve types, suggesting underexplored variables influencing statistics, such as anatomic variability. PBAV and PBMV show the least favorable readmission rates when compared to the other techniques of their respective valves. While both demonstrate acceptable success and mortality outcomes in appropriately selected patients, the shared pattern of poor readmission rates across anatomically distinct valves may suggest operational complexity independent of valvular anatomy.

Future innovations should account for anatomic variability and frailty, with models trained to adapt to patient-specific features using multi-dimensional data. High-volume data is also a must for the enhancement of ML models, though note that data collection needs to be handled ethically. It should prioritize patient privacy through de-identification, patient


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consent, and adherence to international government standards. Collaborations between hospitals and regions can allow for diverse datasets while minimizing bias, helping reduce the lack of robust data. Finally, ensuring proper global adoption of surgical advancements means integrating these technologies into surgical training through simulations and continuous education programs. Partnerships with healthcare systems in low-resource regions can also allow for the worldwide usage of refined technologies.

Ultimately, this research paper highlights the importance of data-driven approaches in evaluating and guiding innovation in cardiac surgery. By consolidating varied datasets within an experimental analytical model, this study was able to identify technique-associated outcome differences and trends, refine current practices, and provide a solid foundation for further prospective clinical studies.

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