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ADVANCES IN THE DEVELOPMENT OF ARTIFICIAL HEART VALVES: BIOCOMPATIBILITY AND SUSTAINABILITY

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Abstract

Artificial heart valves play a crucial role in treating valvular heart disease, providing both mechanical and biological solutions with distinct advantages and limitations. Mechanical valves provide long-term durability but require lifelong anticoagulation, increasing bleeding risk. Biological valves offer superior biocompatibility and eliminate the need for anticoagulation, but suffer from limited lifespan due to calcification and tissue degradation. Advances in biomedical engineering have led to the development of hybrid valves, combining synthetic and biological materials, and bioartificial valves using tissue engineering and 3D printing. Nanotechnology is improving surface coatings to reduce thrombosis and calcification, while artificial intelligence aids in optimizing valve design and implantation. Minimally invasive techniques such as transcatheter aortic valve implantation (TAVI) have revolutionized valve replacement, expanding accessibility to high-risk patients. Future research focuses on self-regenerating valves, enhancing long-term integration, and eliminating the need for reintervention. The ongoing advancements in materials, technology, and surgical techniques are expected to improve patient outcomes, offering longer-lasting and more biocompatible artificial valves. The combination of engineering, computational modeling, and regenerative medicine presents a promising future for next-generation heart valves that closely mimic natural physiology while ensuring durability and optimal function.

Keywords: Artificial heart valves, mechanical valves, biological valves, tissue engineering, nanotechnology, transcatheter valve implantation, regenerative medicine.

Introduction

Cardiovascular diseases remain the leading cause of morbidity and mortality worldwide, representing a major public health burden despite significant advances in prevention, diagnosis, and treatment [1]. Among these conditions, valvular heart disease accounts for a substantial proportion of cardiovascular-related disability and death, with prevalence increasing in parallel with population aging and improved survival from other cardiac pathologies [1]. Degenerative valve disease, rheumatic involvement, congenital abnormalities, and infective endocarditis are among the most common etiologies leading to progressive valvular dysfunction, ultimately resulting in heart failure, arrhythmias, and reduced quality of life if left untreated [2].

In many clinical scenarios, pharmacological management alone is insufficient to halt disease progression, making valve replacement the definitive therapeutic option. Prosthetic valve implantation aims to restore physiological cardiac hemodynamics, alleviate symptoms, and improve long-term survival [2]. Over the past five decades, the development of artificial

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heart valves has emerged as a cornerstone of cardiovascular surgery and biomedical engineering, driven by the need to optimize durability, safety, and biological integration [3]. Continuous innovation in valve design and materials has significantly improved clinical outcomes, yet the ideal prosthetic valve that fully replicates native valve function remains an unmet goal.

The selection of an appropriate prosthetic valve is a complex clinical decision that requires careful consideration of multiple interacting factors. These include patient age, life expectancy, comorbidities, thromboembolic and hemorrhagic risks, immune response, and anticipated need for long-term anticoagulation therapy [4]. From a structural and biological standpoint, prosthetic heart valves are broadly categorized into mechanical and biological types, each with distinct advantages and limitations [5]. Understanding the pathophysiological interactions between valve materials and the host cardiovascular system is essential for individualized treatment planning.

Mechanical heart valves are constructed from highly durable materials such as metal alloys, pyrolytic carbon, and advanced polymers, conferring excellent resistance to structural deterioration and fatigue over time [6]. Their longevity makes them particularly attractive for younger patients with long life expectancies. However, the non-physiological surface properties of mechanical valves promote platelet activation and thrombus formation, necessitating lifelong anticoagulation therapy [7]. This requirement is associated with an increased risk of bleeding complications, imposes significant lifestyle restrictions, and can negatively affect patient adherence and quality of life [10].

In contrast, biological heart valves are derived from porcine, bovine, or human tissues and are designed to more closely mimic native valve biomechanics and hemodynamic behavior [8]. Their superior biocompatibility results in lower thrombogenicity, allowing many patients to avoid chronic anticoagulation therapy. These characteristics make biological valves particularly suitable for elderly patients, those with contraindications to anticoagulation, or individuals with limited life expectancy [5,10].

Nevertheless, the long-term durability of biological valves remains a major limitation. Progressive calcification, collagen degradation, and structural valve deterioration ultimately lead to valve failure and the need for reintervention [9].

Patient-specific characteristics play a decisive role in prosthesis selection. Younger patients often benefit from the durability of mechanical valves despite the associated anticoagulation burden, whereas older patients or those at increased bleeding risk are more commonly treated with biological valves [5,10]. Long-term outcome studies have demonstrated that this tailored approach optimizes survival and reduces complication rates across different patient populations [7].

Ongoing research continues to focus on improving prosthetic valve performance by refining material properties, surface modifications, and valve geometry. Advances in biomaterials science aim to reduce thrombogenicity and immune activation, while preserving mechanical integrity and hemodynamic efficiency [3,6]. These efforts underscore the importance of interdisciplinary collaboration between clinicians, engineers, and material scientists to address the remaining challenges in prosthetic heart valve therapy and to improve long-term outcomes for patients with valvular heart disease.

Types of artificial heart valves

Artificial heart valves are used to replace native valves affected by pathological conditions that impair the pumping function of the heart. Based on their composition and durability, prosthetic heart valves are classified into mechanical and biological valves, each category presenting specific advantages and limitations. The choice of valve type depends on several patient-related factors, including age, the need for anticoagulant therapy, comorbidities, and the expected lifespan of the implant [9].

Mechanical heart valves are manufactured from highly durable materials such as metal alloys, pyrolytic carbon, and advanced polymers, and are designed to function reliably over long periods, often exceeding 25–30 years of use [10].

Several mechanical valve designs have been developed, including ball-and-cage valves, tilting-disc valves, and bileaflet valves. Early ball-and-cage models were widely used initially; however, their association with an increased risk of thrombosis led to their gradual replacement by more advanced designs [11]. Tilting-disc valves represented a significant improvement by enhancing blood flow characteristics, but bileaflet valves are currently the most commonly implanted due to their favorable hemodynamic performance and reduced thrombogenic potential [12].

Despite their excellent durability, mechanical valves have a major drawback: the requirement for lifelong anticoagulation therapy. The non-biological surfaces of these prostheses promote platelet activation and thrombus formation, necessitating continuous anticoagulant medication to prevent valve thrombosis and systemic embolism [13]. This requirement increases the risk of hemorrhagic complications and demands careful monitoring of coagulation parameters. Consequently, mechanical valves are preferentially selected for younger patients, in whom long-term durability outweighs the risks associated with chronic anticoagulation [14].

Biological valves represent an alternative to mechanical prostheses and are fabricated from porcine, bovine, or human tissues. Porcine valves are derived from native animal valves mounted on a synthetic stent to facilitate implantation, while bovine pericardial valves are produced from specially treated pericardial tissue to ensure adequate elasticity and mechanical strength [15]. In addition to these xenografts, homografts—human valves harvested post-mortem and preserved through cryogenic techniques—are also available. Although less frequently used, homografts are particularly valuable in selected clinical scenarios, such as pediatric patients or complex valvular reconstructions [16].

The primary advantage of biological valves is their superior biocompatibility and the absence of a requirement for long-term anticoagulant therapy. Patients receiving biological prostheses generally do not require lifelong anticoagulation, making these valves especially suitable for elderly individuals or patients with an increased risk of bleeding [17]. However, biological valves have a shorter functional lifespan compared to mechanical valves, typically ranging from 10 to 15 years, due to progressive calcification and structural tissue degeneration [18]. As a result, younger patients receiving biological valves are more likely to require reoperation during their lifetime.

To address the limited durability of biological valves, recent research has focused on advanced tissue treatments aimed at reducing calcification and preserving structural integrity. Hybrid technologies combining synthetic frameworks with biological materials have also been developed to optimize both biocompatibility and longevity [19].

Furthermore, tissue-engineered heart valves utilizing natural extracellular matrix scaffolds seeded with stem cells represent a promising strategy, offering the potential for improved integration and even in vivo regeneration. Three-dimensional printing technologies have additionally enabled the development of patient-specific valves tailored to individual anatomical characteristics [20].

Parallel to advances in valve materials, implantation techniques have evolved significantly. Transcatheter Aortic Valve Implantation (TAVI) has emerged as a major minimally invasive alternative, allowing valve deployment via a catheter inserted through the femoral artery and eliminating the need for open-heart surgery. Initially reserved for patients with high surgical risk, TAVI has progressively expanded its indications due to improvements in valve design, delivery systems, and image-guided procedural accuracy [20].

Table 1. This table compares artificial heart valves based on materials, durability, anticoagulation requirements, thrombosis and calcification risks, improvement techniques, and recommended use. Mechanical valves last longer but require lifelong anticoagulation. Biological valves are more biocompatible but degrade over time. Emerging hybrid and bioartificial valves aim to optimize durability and biological integration.

Valve type	Materials used	Durability (years)	Anticoagulation requirement	Thrombosis risk	Improvement techniques	Recommended use
Mechanical - ball	Stainless steel, pyrolytic carbon	25-30	Lifelong	High	Bioinert polymer coatings	Young patients with access to anticoagulation monitoring
Mechanical - tilting disc	Pyrolytic carbon, metal alloys	20-30	Lifelong	Moderate	Nanocoatings, optimized blood flow	Patients who tolerate anticoagulation
Mechanical - bileaflet	Pyrolytic carbon, polymers	20-30	Lifelong	Low	Nanocoatings, optimized blood flow	Patients with moderate bleeding risk
Biological - porcine	Processed porcine tissue	10-15	No	Very low	Anticalcification treatments	Elderly patients
Biological - bovine pericardial	Processed bovine pericardium	10-15	No	Very low	Enzymatic treatments to reduce calcification	Elderly patients
Biological - homograft	Cryopreserved human valves	10-15	No	Very low	Cryopreservation to maintain elasticity	Indicated in special cases (pediatric surgery)
Hybrid	A combination of synthetic and biological materials	Variable	Significantly reduced	Very low	Nanotechnology, biocompatible polymers	Patients requiring personalized solutions
Bioartificial	Extracellular matrix seeded with human cells	Potentially unlimited	No	Very low	3D printing, tissue engineering	Future solution with optimal biological integration

Biocompatibility of heart valves

The biocompatibility of artificial heart valves represents a critical determinant of long-term implant success, directly influencing biological integration, functional durability, and the prevention of postoperative complications. An ideal prosthetic valve must be well tolerated by the host immune system, avoid excessive inflammatory responses, and minimize the risks of thrombosis, infection, and tissue calcification [4,12]. Consequently, contemporary research has increasingly focused on optimizing valve materials, refining surface properties, and integrating advanced biomedical technologies to mitigate the adverse biological reactions associated with both mechanical and biological valve prostheses [3,6].

Mechanical heart valves, despite their exceptional durability, exhibit limited biocompatibility due to the synthetic nature of the materials used, such as metal alloys and pyrolytic carbon [1,6]. The non-physiological surfaces of these valves promote platelet adhesion and activation, increasing the risk of thrombus formation and systemic embolization [7,11]. As a result, lifelong anticoagulation therapy is mandatory to maintain valve patency and prevent thromboembolic events, which significantly increases the risk of hemorrhagic complications and necessitates continuous clinical monitoring [13,14]. These limitations represent a major challenge in the long-term management of patients with mechanical valve prostheses.

To improve the biocompatibility of mechanical valves, recent investigations have explored advanced surface modification strategies. These include bioinert polymer coatings, nanostructured antithrombotic surfaces, and chemical surface treatments designed to reduce protein adsorption and platelet activation [3,9]. Such approaches aim to attenuate blood–material interactions and potentially reduce the dependence on aggressive anticoagulation regimens, thereby improving patient safety and quality of life [4].

In contrast, biological heart valves demonstrate superior biocompatibility due to their derivation from natural tissues, which more closely resemble native valve structures and biomechanics [8,10]. Their reduced thrombogenicity allows many patients to avoid long-term anticoagulation therapy, making them particularly suitable for elderly individuals and patients at increased bleeding risk [14,18]. However, the principal limitation of biological valves remains progressive calcification, which leads to leaflet stiffening, structural valve deterioration, and eventual prosthetic failure [9,19].

To address these challenges, advanced tissue-processing techniques have been developed, including the use of anticalcification agents and chemical cross-linking methods aimed at stabilizing collagen fibers and inhibiting mineral deposition [19]. While these strategies have improved valve durability, calcification remains a multifactorial process influenced by mechanical stress, host immune response, and metabolic factors [16]. Consequently, ongoing research continues to refine tissue treatments to further extend the functional lifespan of biological valves.

Tissue engineering represents a promising frontier in the pursuit of improved valve biocompatibility. Tissue-engineered heart valves, constructed using decellularized extracellular matrix scaffolds seeded with autologous cells, aim to promote biological integration and adaptive remodeling within the host environment [15,20]. These constructs have the potential to overcome the limitations of both mechanical and conventional biological valves by enabling growth, repair, and regeneration, particularly in pediatric and young adult populations.

Additionally, the application of nanotechnology and smart biomaterials has opened new avenues for enhancing valve–tissue interactions. Nanocoatings with antimicrobial and antithrombotic properties can reduce the risk of prosthetic valve endocarditis and platelet adhesion, thereby improving long-term outcomes [3,20]. The development of bioresponsive and self-regenerating materials that mimic the hierarchical structure of native valvular tissue represents a transformative approach in prosthetic valve design.

In summary, biocompatibility remains a central challenge in artificial heart valve development. Nevertheless, advances in biomaterials science, surface engineering, nanotechnology, and tissue engineering have significantly improved the biological performance of prosthetic valves. As these technologies continue to evolve, they hold considerable promise for the creation of heart valve prostheses with enhanced durability, reduced complication rates, and superior biological integration [6,14].

Durability and performance of heart valves

The durability and performance of artificial heart valves are critical determinants of long-term clinical success, directly affecting patient quality of life, survival, and the need for reintervention. The choice of materials and manufacturing technologies plays a central role in defining mechanical strength, hemodynamic behavior, and susceptibility to structural deterioration or thrombotic complications [4,6]. Consequently, valve design represents a complex balance between mechanical reliability and biological compatibility.

Mechanical heart valves are characterized by exceptional durability, frequently exceeding 25 years of functional lifespan, largely due to the use of highly resistant materials such as pyrolytic carbon and metal alloys [1,6]. These materials provide excellent resistance to fatigue, wear, and structural failure under continuous cyclic loading. However, the non-

physiological surfaces of mechanical valves promote platelet adhesion and activation, increasing the risk of thrombus formation and systemic embolization [7,11]. As a result, lifelong anticoagulation therapy is required, exposing patients to an elevated risk of bleeding complications and necessitating strict therapeutic monitoring [13,14].

To enhance the performance of mechanical valves and reduce their thrombogenic potential, recent research has focused on surface optimization strategies. These include the application of nanomaterials, bioinert polymer coatings, and antithrombotic surface treatments designed to minimize platelet adhesion and adverse blood–material interactions [3,9]. Such innovations aim to preserve the superior mechanical durability of these valves while mitigating their primary clinical limitation.

In contrast, biological heart valves offer improved biocompatibility but exhibit reduced durability, with an average functional lifespan of 10–15 years [16,18]. Progressive calcification and structural tissue degeneration represent the principal mechanisms of failure in biological prostheses. Porcine, bovine, and human tissues undergo gradual loss of elasticity and leaflet stiffening, ultimately impairing valve function and necessitating replacement [9,19]. These degenerative processes are influenced by a combination of mechanical stress, metabolic factors, and inflammatory responses within the host environment [16].

To extend the longevity of biological valves, advanced tissue treatment techniques have been developed. Chemical fixation using anticalcification agents, improved cross-linking methods, and genetic modification of donor tissues to reduce immunogenicity have demonstrated promising results in delaying structural deterioration [19,20]. Additionally, hybrid valve designs combining synthetic frameworks with biological tissues have been introduced to enhance mechanical stability while maintaining favorable biological properties [3].

Valve performance is also strongly influenced by hemodynamic efficiency and flow optimization. Modern valve designs are engineered to minimize flow turbulence and reduce shear stress, both of which contribute to early structural damage and blood element activation [12]. Computational fluid dynamics simulations and numerical modeling have become essential tools in valve development, allowing precise evaluation of flow patterns and mechanical stresses before clinical implementation [6]. More recently, artificial intelligence–based approaches have been applied to patient-specific data analysis, enabling prediction of long-term valve performance and supporting personalized prosthetic valve selection [4].

A particularly promising strategy for improving valve durability involves tissue engineering approaches aimed at developing bioartificial heart valves. These valves, constructed from decellularized extracellular matrix scaffolds or produced using three-dimensional bioprinting techniques with stem cells, are designed to be repopulated by host cells and undergo adaptive remodeling over time [15,20]. Such constructs have the potential to provide long-term solutions without the risks of calcification or structural degeneration associated with conventional biological valves.

In parallel, the development of smart materials and adaptive biopolymers has opened new perspectives for creating valves capable of responding dynamically to physiological conditions. These materials may allow future prosthetic valves to adjust their mechanical properties in response to changing hemodynamic demands, further enhancing durability and functional performance [3,6].

Future perspectives and research directions

Future perspectives in the development of artificial heart valves focus on improving biocompatibility, enhancing durability, and reducing device-related complications through the integration of advanced technologies such as tissue engineering, nanotechnology, and artificial intelligence. One of the most promising research directions involves the development of bioartificial heart valves that combine synthetic scaffolds with human cells, enabling biological

integration, adaptive remodeling, and long-term functional stability [15]. These valves are commonly engineered using decellularized extracellular matrix scaffolds, which provide structural support while allowing colonization by patient-derived cells, thereby reducing immunogenicity, eliminating the need for long-term anticoagulation, and minimizing the risk of calcification [16].

Nanotechnology has emerged as a key tool in optimizing artificial heart valve performance by enabling the development of intelligent surface modifications that prevent thrombosis and inhibit calcific deposition. The application of nanocoatings on mechanical valve surfaces has demonstrated potential in improving blood–material interactions, reducing platelet adhesion, and lowering thrombogenicity, which may ultimately decrease dependence on lifelong anticoagulation therapy [3,9]. In parallel, the use of advanced biomaterials, including self-healing polymers and bioresponsive surfaces, has shown promise in extending the functional lifespan of biological valves by preserving tissue flexibility and mechanical integrity over time [19].

Artificial intelligence and computational modeling are increasingly employed to simulate valve behavior under diverse physiological conditions, allowing optimization of valve design based on patient-specific anatomical and hemodynamic parameters. Machine learning algorithms applied to large clinical datasets can identify patterns associated with valve failure, thrombosis, or degeneration, facilitating risk stratification and personalized prosthetic valve selection [4]. These approaches are particularly relevant in the context of three-dimensional printing technologies, which enable the fabrication of customized heart valves precisely adapted to individual patient anatomy, thereby reducing procedural complications and improving long-term outcomes [6].

Another important research direction involves the development of materials capable of self-repair and adaptive response to physiological stress. Smart biomaterials and biopolymers with autoregenerative properties are being investigated for their ability to prolong implant lifespan and maintain valve function despite continuous mechanical loading [3]. Such materials may allow artificial valves to dynamically adjust their mechanical properties in response to changes in blood flow and pressure, mimicking the behavior of native valvular tissue.

Stem cell–based strategies represent a transformative avenue in heart valve research. The use of autologous stem cells for valve regeneration offers the potential to replace artificial devices entirely with living, patient-specific structures capable of growth, repair, and long-term adaptation [15]. These approaches are particularly relevant for pediatric patients, in whom current prosthetic options are limited by the inability to accommodate somatic growth and progressive anatomical changes.

Future developments also include continued optimization of minimally invasive implantation techniques, particularly Transcatheter Aortic Valve Implantation (TAVI). Advances in transcatheter valve design aim to reduce paravalvular leakage, improve anchoring stability, and enhance long-term durability, thereby expanding the indications of TAVI to lower-risk and younger patient populations [5,8]. Improvements in imaging guidance, device delivery systems, and procedural planning continue to enhance procedural safety and clinical outcomes.

In conclusion, the future of artificial heart valve therapy lies in the convergence of biomaterials science, tissue engineering, nanotechnology, artificial intelligence, and minimally invasive interventions. These multidisciplinary advances are expected to drive the development of next-generation heart valves with superior durability, reduced complication rates, and

enhanced biological integration, ultimately improving long-term outcomes for patients with valvular heart disease [20].

Conclusions

Recent advances in the development of artificial heart valves have led to significant improvements in their biocompatibility, durability, and performance. The choice between mechanical and biological valves remains a trade-off between longevity and the need for anticoagulant treatment, but innovations in biomedical engineering offer solutions that could eliminate these limitations. Current research focuses on the use of nanotechnology, smart materials, and tissue engineering to develop valves that are more efficient, durable, and compatible with the human body.

Mechanical valves remain the ideal option for young patients due to their superior durability, but the need for lifelong anticoagulant treatment poses a significant risk. On the other hand, biological valves are better tolerated by the body, but have a limited lifespan, which requires resurgeries after 10-15 years. To overcome these problems, researchers are developing hybrid valves that combine the advantages of the two types, using advanced polymers and tissue treatments that reduce the calcification process and improve long-term stability.

Another important direction is the development of bioartificial valves, which allow cell regeneration and integration into the body. By using the extracellular matrix and 3D printing, structures are created that perfectly mimic natural valves, reducing the risk of rejection and improving functionality. In parallel, nanocoatings applied to valve surfaces contribute to the prevention of thrombosis and increased biocompatibility, thus reducing the need for anticoagulant therapy.

Minimally invasive implantation techniques, such as TAVI, have revolutionized the treatment of patients at high surgical risk. New generations of transcatheter valves are being developed to enhance device stability and minimize complications. In the future, these procedures may become the standard in valve treatment, significantly reducing the need for open-heart surgery and improving postoperative recovery.

The future of artificial heart valves is moving towards customized, minimally invasive, and self-renewing solutions that eliminate the need for anticoagulation and provide increased durability. As tissue engineering, nanotechnology, and artificial intelligence continue to advance, the prospect of fully biologically integrated valves capable of operating without limitations throughout the patient's lifetime is becoming increasingly realistic.

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